Philip E. van Beynen
Editor

Karst Management

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Cover illustration: A sinkhole covers a street intersection downtown Guatemala City, Wednesday June 2, 2010. Authorities blamed heavy rains caused by tropical storm Agatha as the cause of the crater that swallowed a three-story building but now say they will be conducting further studies to determine the cause. (AP Photo/Moises Castillo) (100602043877)

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To Kaya, Merik and Siena

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Chapter 1
Introduction

Philip E. van Beynen

1.1 What Is Karst and Karst Management?

Karst is a landscape created by the dissolution of carbonate rocks, although similar features can also be found in volcanic and permafrost areas. Water and its involvement in the process of dissolution is the most significant factor in the creation of karst. It is also of great importance for karst aquifers which are rapidly becoming the most significant issue for karst management. Surface features characteristic of karst include poljes, sinkholes (dolines), swallow holes, karren, pavement of various scales, and dry and blind valleys. Subsurface karst is most commonly thought of by the general public as caves. However, many of these voids cannot be entered by humans as they have no entrances, and it is through these voids or conduits that groundwater can flow. In fact, the presence of these conduits makes karst aquifers difficult to study due to their high degree of heterogeneity with respect to flow rates within the bedrock. Karst can be found around the world, with large regions in Europe, Asia, North and Central America, and the Caribbean. South America, Australia, and Africa also have areas of karst but to a lesser extent. Subsurface karst can also be found at various depths, with conduits very close to the surface down to thousands of meters deep in not only mountainous areas but also relatively low relief regions such as Florida, USA.

The term “karst,” meaning stony ground, originates in the Dinaric Plateau in the Balkans region of Eastern Europe. This is also where the field of karst science began. Although he may not have been the very first scholar to study karst, Jovan Cvijić was probably the scientist who laid the foundation for our modern understanding of geomorphic processes in the late nineteenth century. Since then, karst science has expanded to include other types of karst such as relict, paleokarst,

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pseudokarst, volcanokarst, fluviokarst, and thermokarst (Ford and Williams 2007). Now in the twenty-first century, the science of karst has greatly advanced, incorporating an improved understanding of karst environments, their fragility and their value to human development.

1.2 Karst as a Resource

Twelve percent of the terrestrial surface of our planet is covered by carbonate rocks and 25% of the world's population gets its water from karst aquifers (Ford and Williams 2007). While there may be some debate about the accuracy of these numbers, there is little disagreement on the overall importance of karst environments, not only for the value of the minerals and aquifer resources that they contain, but also for their aesthetic and, consequently, tourism value. Regionally, karst's importance for resource extraction varies from being extensively exploited in Asia, Europe, and North America to less so in Africa and South America. Much of the Middle Eastern oil reserves are held in carbonate rocks. Limestone, marble, and tufa are commonly quarried for building materials around the world. Zinc, lead, and silver are common minerals extracted from carbonate rocks, and lime can be used in iron works and for soil modification. Even when the karst rock is not being actively used or extracted, the landscape also serves as a basis for agricultural production in Asia, Europe, Central America, and the eastern half of the USA. Karst landscapes have also been urbanized in many of these same regions.

1.3 Management of Karst Resources

Environmental management is the attempt to purposely control or influence human interactions with their physical surroundings. Karst management, the focus of this book, is addressed through the multitude of methods and regulations used by planners, engineers, farmers, scientists, and politicians in conventional karst environments. These include everything from specific regulations to protect karst aquifers to the building of dams and reservoirs. This book does not address vulcanokarst, thermokarst, or pseudokarst – environments all with their own management intricacies that are beyond the scope of this text.

1.4 Rationale for Producing Text

No one book can be an absolute, comprehensive text covering every aspect of karst or karst management. Many excellent texts have been produced, most notably, John Gunn's (2004). Encyclopedia of Caves and Karst Science, Ford and Williams' (2007) benchmark text on the physical processes of karst environments, Beck's edited volumes from the proceedings on sinkholes and the engineering and environmental impacts of karst, and the edited volume by Parise and Gunn (2007) on environmental hazards in karst. In addition, White's (1988) book on karst and Palmer's (2007) text on cave geology are two other excellent works. While this is not meant to be an exhaustive list of important karst texts, each of these books are indispensable and should be consulted by any karst student or researcher interested in this field of science.

To date, no single text specifically focuses on the management of karst environments. This book attempts to fill this void as experts from around the world have been asked to summarize their knowledge on their specialties pertaining to karst management in an aim to create a text that gives this topic a comprehensive overview. If any pertinent issues are not covered, I apologize for the fault of this exclusion. Additionally, while the chapters cover the main karst regions of the world, I regret that there is not more extensive coverage of Asia, Africa and South America. However, I would suggest that many of the case studies outlined in this book and their proposed management solutions can be applied to most karst regions throughout the world. Finally, this book presupposes that readers will have a basic understanding of the unique physical processes and scientific terms associated with karst environments. If you are still gaining this core knowledge, please refer to any of the previously mentioned texts as you enter the field of karst science.

1.5 Structure of This Text

The book is divided into four Parts: (1) surface karst, (2) subterranean realm of karst, (3) karst aquifers, and (4) management of karst regions as integrated units.

Part I on surface karst outlines the problems associated with living and building on karst. Beck and Zhou (Chap. 2) investigate the major engineering issues of constructing buildings and other structures on karst landscapes, calling special attention to the problems of subsurface voids and the various methods for remediation. Dams and reservoirs are the particular focus of Chap. 3. From his vast experience as an engineering consultant throughout the world, Petar Milanović provides insight into common problems that arise in dam construction on karst and mitigation efforts for small fissures to large conduits in size under and around these structures. For a regional perspective from Russia, Vladimir Tolmachev and Mikhail Leonenko give a case study of assessing risk in both carbonate and sulfate bedrocks in Chap. 4. They outline a method of evaluating the risk of karst collapse and the various laws that govern sinkhole development. The laws and methods they suggest are applicable to most karst areas. Drawing on her expertise on how agricultural activities impact the karst environment in Western Europe, particularly Ireland, Catherine Coxon delves into the impacts of deforestation, fertilizers, pesticides and animal waste in Chap. 5. Risk evaluation methods and strategies to minimize these impacts are also discussed.

Part II on the subterranean realm of karst primarily deals with managing caves and their physical, biotic, and cultural features. David Gillieson introduces in Chap. 6 the major human impacts for caves, the importance of cave inventories and monitoring, and common management techniques that can lessen human impact. As a case study of this topic, Mario Parise presents the latest information of show caves from southeastern Italy, clearly demonstrating the local challenges confronting cave conservationists (Chap. 7). Philip Reeder, in Chap. 8, outlines geophysical techniques for finding subsurface archaeological materials in karst setting in the Middle East and Central America. Management of cave biota is the subject of Chaps.9 and 10. In Chap. 9, Daniel Fong outlines the importance of protecting the connections between the surface and the cave for maintaining essential energy flows to cave biota. In doing so, he highlights the challenges faced by cave managers, especially from encroaching urban development. In Chap. 10, Diana Northup describes the vast array of microbiota living in caves, their potential value for new biomedical drugs and how humans can negatively impact these organisms.

Part III is devoted to the critical importance of managing karst aquifers. A world expert of human interaction with carbonate aquifers, Stephen Worthington, discusses the importance of the high permeability of karst aquifers and the complexity of their flow (Chap. 11). Examples of the susceptibility of these aquifers to surface contaminants are introduced in this chapter. Michel Bakalowicz continues this discussion on the exploitation of karst aquifers from a European perspective in Chap. 12. He also discusses their management from both quality and quantity view points with many examples from around the world. The final chapter on karst aquifers is by William Humphreys (Chap. 13), who addresses the vulnerability of groundwater species to human impact. Much of this vulnerability stems from these species' narrow endemic ranges and distinctive adaptations. Humphreys concludes with some management actions that could lessen the disturbance of these groundwater species.

Part IV treats the karst environment as an integrated whole. In recognition of the importance of karst to nations, National Karst Institutes have been created to coordinate and focus scientific research and be a gateway for increasing public education of karst. In Chap. 14, George Veni, the current Director of the National Cave and Karst Research Institute for the USA, discusses the efforts of his and other institutes around the world. On a more local level, the policies and regulations pertaining to karst management and urban planning are outlined by Spencer Fleury in Chap. 15. While his focus is mainly based on US policies and regulations, these efforts could be equally applied wherever there is karst. The sustainable use of karst is probably the desired goal of every country that benefits from the development of karst resources. In Chap. 16, Robert Brinkmann and Sandra Jo Garren discuss the meaning of true sustainability and how this can be applied to karst environments. Philip and Kaya van Beynen, in Chap. 17, cover the various ways humans can disturb karst environments and how these disturbances can be measured. They also introduce methods on how karst aquifers can be protected using intrinsic vulnerability models. Mick Day and others, in Chap. 18, take this idea of human disturbance and discuss the implementation of the Karst Disturbance Index in the Cockpit Karst of Jamaica, and how it can be used to delineate boundaries for areas that can be designated for protection.

Derek Ford provides an extensive case study on the creation of a karst national park in Canada (Chap. 19) and outlines the decade's long challenges to foster adequate political will and effective management policies. In a similar vein, in the Caribbean, Central American, and South Asian countries, Mick Day discusses the issues of protected karst lands in developing countries in Chap. 20. While many countries may have large karst territories officially protected under law, enforcing these regulations with limited resources is the real challenge. In the final chapter of the book (Chap. 21), Paul Williams outlines international efforts taken by the IUCN to create world heritage sites for karst areas, specifically discussing the challenges of their creation and some of the successes of their conservation.

I hope that after you have read this book you will have a strong knowledge of the main issues facing resource managers who have to work with karst on a daily basis. In addition, it was my aim to provide you with some potential solutions to these issues. While not every management issue could be covered, this book should serve as a starting point for you on your journey to other resources and to a more in-depth understanding of karst management.

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Part I
Management of Surface Karst

Chapter 2
Engineering Issues on Karst

Wanfang Zhou and Barry F. Beck

Abstract The design and construction of engineering structures in karst regions must deal with such challenges as difficulty in excavating and grading the ground over pinnacled rockheads, instability of ground surface, and unpredictable groundwater flow conditions. Detailed subsurface investigation using boring exploration, geophysical techniques, tracer testing, and groundwater monitoring helps optimize foundation designs and minimize uncertainties inherent in their construction. Based on the maturity of karst landscapes, depth and dimension of karst features, and vulnerability of groundwater contamination, methods that have been established to control surface water and groundwater and minimize sinkhole development include relocating structures to a safer site, filling voids/fractures with concrete, soil reinforcement, constructing deep foundations, and remediating sinkholes.

2.1 Introduction

Karst terrane is commonly formed by limestone, dolomite, and gypsum. It is characterized by sinkholes, caves, and bountiful springs and does not form the way other landscapes do. Most landscapes form as the surface runoff, rivers, wind, waves, and even glaciers break down and wear away the rocks. This is not the case with karst. Karst-susceptible rock simply dissolves (Fig. 2.1), leaving behind just a few insoluble materials, mostly clay and silica. Additionally, water sinks into the ground through sinkholes rather than flowing away in rivers. In fact, a river-like drainage system of tributaries may form underground, in openings dissolved in the rocks.

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Fig. 2.1 Classic limestone karst in Kentucky, USA

Karst poses a unique set of geotechnical and environmental problems that influence the land uses in karst terrane. Sinkholes, either a sudden, catastrophic collapse of the ground surface or a slow, imperceptible subsidence, can be damaging to structures. Surface water sinks underground and flows rapidly through subterranean conduits. A highly irregular epikarst creates havoc for the engineer. The bedrock may be riddled with voids, creating unpredictable and unreliable foundation conditions. The design of foundations in such highly irregular bedrock requires careful planning and execution of the works from preliminary to detailed subsurface investigation, analysis and design, and up to the construction stage where continuous feedback is essential for the satisfactory performance of the foundations. Detailed field investigation is instrumental in developing the subsurface picture of the foundation sites.

A sinkhole is a geologic feature that is characteristic of karst areas (Fig. 2.2). Although its shape changes over time, it is usually thought of as a closed funnel-shaped or bowl-sloped depression. A depression can range from a few centimeters to several kilometers; however, the typical sinkhole size that is closely related to engineering activities ranges from tens to hundreds of meters in diameter. A sinkhole is formed by internal erosion and/or gravitational deformation of soil in addition to rock material into underground voids. Human-induced modifications of karst lands can accelerate the dissolution processes. The inexorable and continuous dissolution of soluble bedrock dictates that formation of sinkholes is a dynamic process. A sinkhole can be a natural drain to the subsurface, an entrance to a cave, or a collapse that destroys buildings and roadways. Surface water that funnels into a sinkhole percolates downward through the soil at its bottom or quickly drains into the subsurface if the sinkhole has an open swallet. Losing or sinking streams develop

Fig. 2.2 A sinkhole that occurred in South China

as solution-enlarged features, such as sinkholes or ponors drain water from surface streams. However, water can also percolate underground via solutionally enlarged joints or fractures.

A sinkhole provides an apparently convenient place to deposit trash. People who have sinkholes in their yards may want them to be filled in the hope that it will increase their property values or make their yards more usable. However, a sinkhole is not just a hole in the ground. It has geological and hydrological significance. Within the karst hydrologic system, a sinkhole usually develops as a drainage point into a subsurface conduit system. The conduits not only carry the recharge water from the sinkhole into the aquifer but also transmit any suspended sediment carried by the turbulent flow and any materials resulting from human activities, including contaminants. A sinkhole may also be a part of an integrated ecological system that supports atypical species of plants or animals (Friend 2002). Disposal of materials into a sinkhole requires very careful geological and hydrological consideration. Any contaminants disposed of in sinkholes may end up in caves, springs and water wells in the area of the sinkhole (Zhou et al. 2005).

Commercial development of an area with sinkholes requires a comprehensive work plan to manage the sinkholes. A significant design aspect for deterring sinkhole development is to understand and control the surface and subsurface water. Too often, karst problems are tackled with various forms of engineering programs, such as grouting, without careful consideration of their effects on the subsurface water flow. The advantages and disadvantages of grouting should be evaluated before it is implemented. Grout programs can provide a means to increase soil density for structure support. They can also seal an epikarst drain that directs shallow water into the underlying aquifer. However, the effect of sealing a subcutaneous drain may result in pooling and saturation of the peripheral area with a consequence of increased subsurface drainage to adjacent epikarst drains. In some karst areas, grouting of one sinkhole will only divert the underground flow elsewhere, resulting in the development of new sinkholes. Using grout to seal a natural drain also has the potential to restrict or occlude the under-draining conduit, which can lead to back-flooding. Without an understanding of the processes that cause the sinkhole hazards, restricting the water flow into the existing sinkholes may adversely change the flow dynamics in the area.

2.2 Engineering Conditions on Karst

Some of the most difficult ground conditions that have to be investigated in civil engineering are found in karst. Limestone is dissolved by water, and because the water can most easily permeate into the rock along fractures, the top of bedrock in karst is usually a highly irregular surface. Deep, solution-widened discontinuities alternate with pinnacles of limestone that have not yet been dissolved (Fig. 2.3a, b). This irregular surface is buried beneath the soil and is made up of the insoluble leftovers from the limestone. Given enough time, the deep v-shaped, clay-filled fissures may become tens of feet deep and just as wide. The residual blocks of limestone between the fissures may be of similar dimensions or larger depending on the frequency of the fractures.

Imagine now a few exploratory borings provided to characterize a site for removal of the overburden (Fig. 2.4). Based on the depth to rock from those borings, a contractor assumes that the overburden can be removed with conventional earth moving equipment, and bids the work accordingly. Unexpectedly, excavation encounters areas of solid limestone, first one and then another, and another. Suddenly the job becomes more complicated and is way over budget.

Discontinuity planes are widened by dissolution of the rock. The upper few tens of feet of the limestone are dissected by numerous solution-widened cracks forming a permeable, interconnected network. This zone of highly-weathered rock is known as the epikarst zone. Water percolates down into this network of cracks and then moves laterally downgradient to the main drains. In some cases, these subterranean drainage features become plugged with sediment. Over geologic time, the former depression is filled with sediment and the basin is no longer obvious. In other areas, more recent geologic processes, such as glaciation or marine deposition, may completely cover karst terrane, leaving no surface evidence of its existence. This makes karst identification during subsurface exploration programs even more difficult.

Voids form in any soluble bedrock and overburden where there is an adequate flow of water. The voids can be clay-, air- or water-filled. Flow rates and the water's aggressiveness (degree of chemical undersaturation) mainly determine rates of void enlargement, which originates in bedding planes and tectonic fractures.

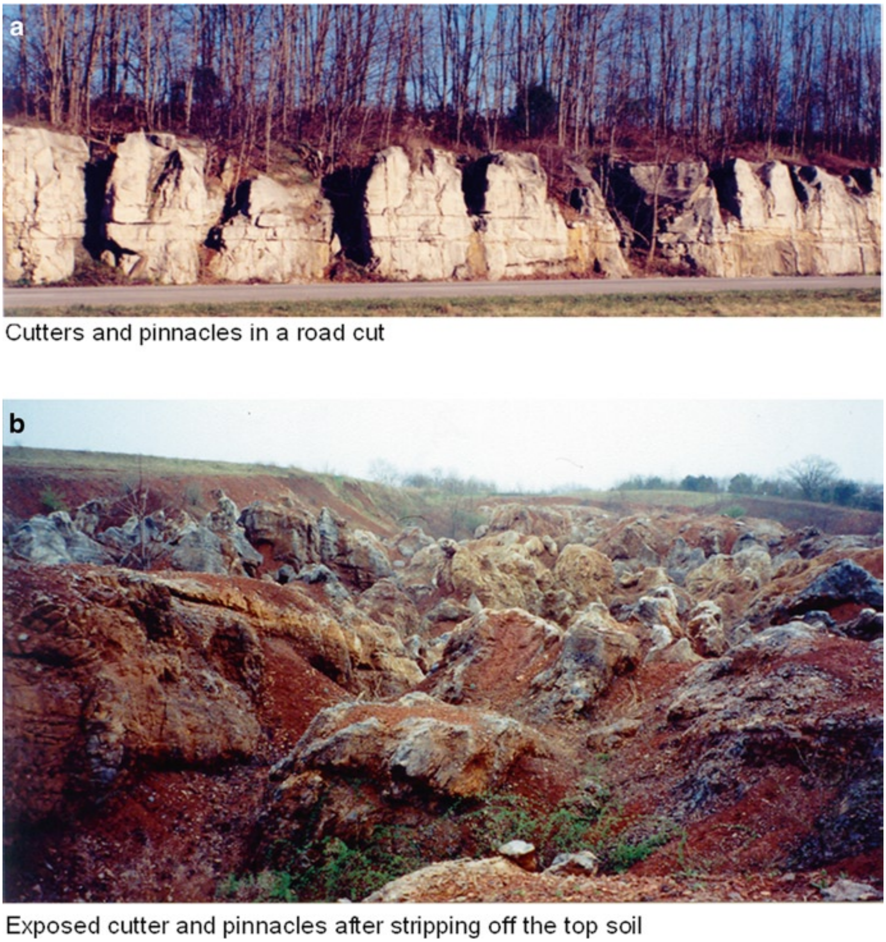


Fig. 2.3 (**a**, **b**) Cutters and pinnacles in karst

These enlarge to networks of open fissures, and favorable flowpaths are enlarged selectively into caves. Caves may be abandoned when their water is captured by other preferred routes; they may be wholly or partially filled with clastic sediment or secondary calcite deposits, or they may collapse when their dimensions create unstable roof spans. Filled caves may appear as sand or clay-filled pipes within the solid rock. Progressive roof collapse and cavity stopping that propagates upward may create a pile of fallen rock in a breccia pipe within the solid limestone.

A major difficulty in karst investigations is finding underground cavities. There may be little alternative to deep and closely spaced probes; a density of 2,500 per ha is needed to have a 90% chance of finding one cavity 2.5 m in diameter. Probes beneath every pile foot and column base are a better option and are essential at many sites on mature, cavernous karst. Exploration of pinnacled rockhead in a mature

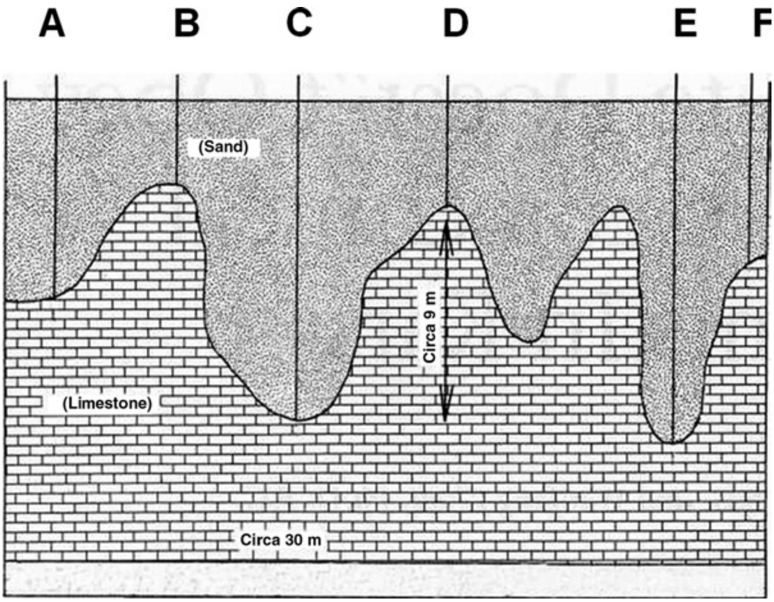


Fig. 2.4 Borings in karst terrane. How would interpreted cross section look if only borings *B*, *D* and *F* were drilled, or if borings *A*, *C* and *E* were drilled?

karst may demand extensive probing, but there is no definitive answer to the question of how many probes are needed. Construction of a viaduct on karst in Belgium initially had 31 boreholes for five pier sites; two caves were missed and were revealed only during excavation for foundations. A second phase of investigation with another 308 probes found no more caves (Waltham and Fookes 2003). Investigation of 31 boreholes was inadequate; drilling 339 holes was overcautious. At many karstic sites, the true ground conditions are not discovered until foundations are excavated.

The depth probed should be a function of the likely cavity size. In juvenile and young karst, caves more than 5 m wide are unusual, and probing 3.5 m should therefore confirm rock integrity. Engineering practice varies considerably: probing 5 m of rock beneath pile tips in cavernous Florida karst (Garlanger 1991), 4 m under foundations in South Africa (Wagener and Day 1986), 2.5 m under caissons in Pennsylvania (Foose and Humphreville 1979), and only 1.5 m under lightly loaded bridge caissons in North Carolina (Erwin and Brown 1988). The limestone in Florida is weaker than at the other sites, but there is no consistency in empirical data from engineering practice on karst. Caves are usually unpredictable. Every site in karst has to be assessed individually in the context of its geomorphology, and engineering works must respond to the local conditions. Local records and observations may indicate typical and maximum cave sizes, and these define the minimum of sound rock to be proven by drilling beneath structural footings. Geophysical techniques may be useful tools in such investigations.

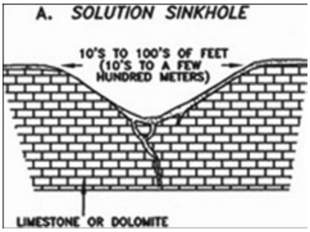
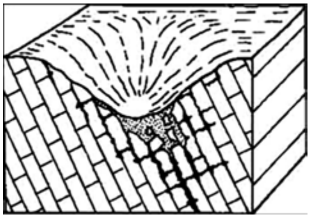
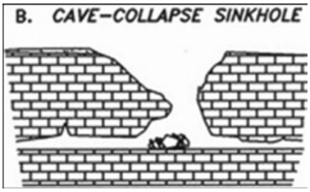
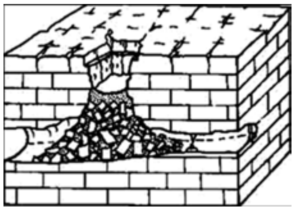
2.3 Sinkholes and Their Formation

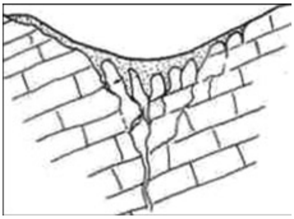
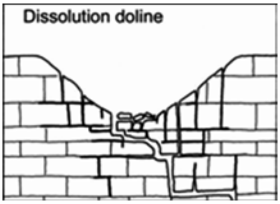
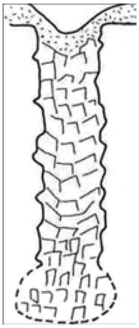
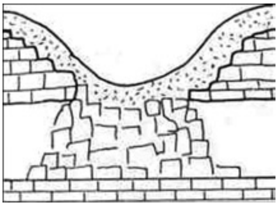
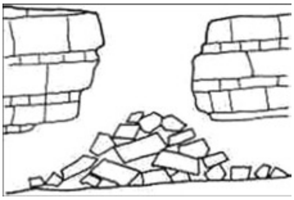
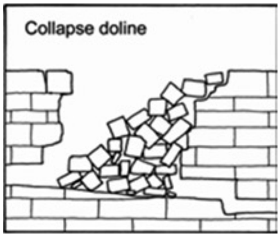
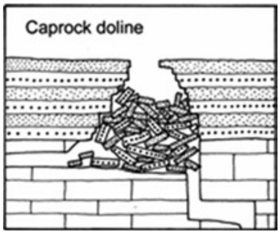
Karst areas are prone to sinkhole formation because of their intrinsic defects including irregular bedrock surfaces, voids in the underlying rock formation, brecciated bedrock, and eroded and loosened soils with low penetration resistance. A sinkhole is a surface symptom of the complicated erosion and deformation processes that occur on the surface and in the subsurface. Table 2.1 lists five commonly used engineering classifications of sinkholes. In modern literature, both doline and sinkhole are used to refer to closed depressions and are no longer distinguished geomorphologically by the mechanism of formation. Clearly, each classification system is based on the investigator's own experience dealing with the geotechnical and environmental problems in certain geographic settings. Sinkholes can also be classified by their hydrogeological, geomorphological or ecological properties. Although there is no consensus in sinkhole classification, most of the investigators agree on the processes that lead to sinkholes. A more comprehensive but genetic classification of sinkholes is recently proposed by Gutiérrez et al. (2008) based on exposures of evaporite paleokarst in Spain.

When defining the type of sinkholes in an area, the geologist or engineer should consistently follow one classification system. It may cause inconsistencies and confusion if more than one classification system is used. For practical purposes, the primary criterion is the type of surface material that moves downward. Sinkholes can occur in bedrock outcrops, caprocks, and in the overburden soils. The secondary criterion can be the mode at which the surface material moves. For example, sinkholes can be either a catastrophic collapse feature or a slow subsidence feature. It is important to note that the primary and secondary criteria focus on the processes acting at or just beneath the surface. One should not confuse these surface processes with what may have happened in the subsurface to create the necessary conditions for a sinkhole to occur. Some sinkholes occur suddenly; however, the processes leading up to a collapse may take years or even centuries. On the other hand, some sinkholes appear to occur slowly as subsidence features; however, the processes of creating them may be considered to be geologically fast. Any further division of the sinkholes can be based on the exact causes that lead to the formation of sinkholes.

Williams (2003) takes a different approach to classify the sinkholes (dolines, as preferred by Williams). The primary criterion used by Williams is the formation mechanisms for the enclosed depressions. He listed four main mechanisms: dissolution, collapse (dropout), suffosion and regional subsidence. This classification may be theoretically logical and scientifically sound. However, practical application of this system faces challenges because many sinkholes result from multiple mechanisms. When a sinkhole is polygenetic in origin, it can be classified into more than one type. In addition, the exact mechanisms for the formation of a sinkhole are often not readily known. Many formation mechanisms are actually hypotheses, and convincing evidence to prove these hypotheses is difficult to collect in practice. However, understanding the genetic mechanisms is essential for proper risk and engineering management.

Table 2.1 Selected types of sinkhole

Types of sinkhole		Typical diagrams: Beck (2004)	Typical diagrams: Jennings (1985)
Country rock sinkhole	Solution		
	Subsidence		
	Rock collapse		
Caprock sinkhole	Caprock collapse		

	Typical diagrams	
White (1988)	Ford and Williams (1989)	Waltham and Fookes (2003)
		
		
		
		

(continued)

Table 2.1 (continued)

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<tr><th colspan="2" rowspan="2">Types of sinkhole</th><th colspan="2">Typical diagrams</th></tr>
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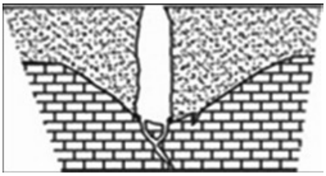
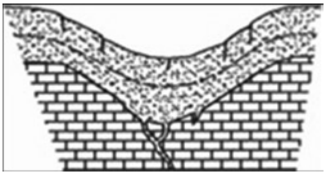
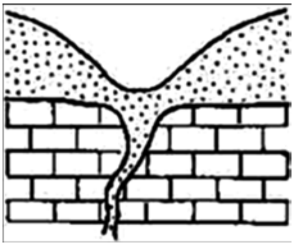
<tr><td rowspan="4">Country rock sinkhole</td><td>Caprock subsidence</td><td></td><td></td></tr>
<tr><td>Cover collapse</td><td></td><td></td></tr>
<tr><td>Cover subsidence</td><td></td><td></td></tr>
<tr><td>Suffosion sinkhole</td><td></td><td></td></tr>
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	Typical diagrams	
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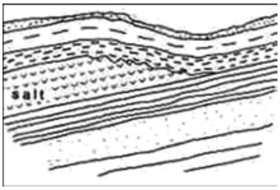
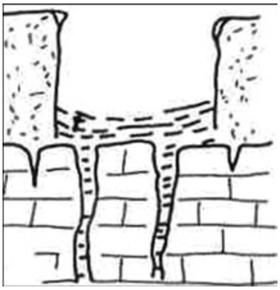
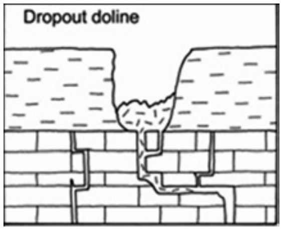
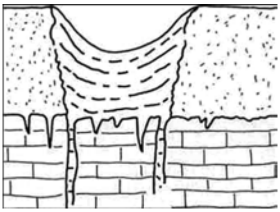
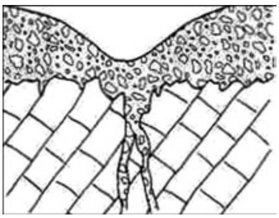
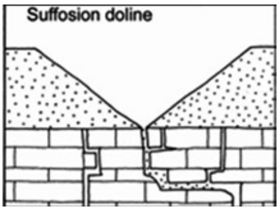
		
		
		
		

2.3.1 Sinkholes in Soluble Bedrocks

When a sinkhole occurs in the soluble bedrock, it is a bedrock sinkhole. Such a type of sinkhole can have numerous shapes and sizes. Solution sinkholes and cave collapse sinkholes are two types of bedrock sinkholes that are often encountered in bare karst areas. Solution sinkholes emphasize the chemical processes that dissolve the rock over time. A typical chemical reaction in limestone can be expressed by:

$$C_aCO_3 + H^+ \longrightarrow HCO_3^- + C_a^{2+}$$
$$C_aCO_3 + H_2O + CO_2 \longrightarrow 2HCO_3^- + C_a^{2+}$$

The bedrock dissolution continues as long as the water in contact with the rock remains unsaturated. The dissolution process occurs on the surface, in the thin soil cover or in the bedrock itself, where the water is mildly acidic. More rock is dissolved at locations where the water flow is more rapid and turbulent. Mixing of waters with different geochemical properties may increase the power of dissolving carbonate rocks.

Collapse sinkholes result from mechanical breakdowns, although chemical processes are important in developing the cave in the bedrock and removing the collapsed materials. Caves develop when the dissolution process occurs within the bedrock. If the rocks above the cave are rigid, they collapse only when they cannot support the weight above the cave. Dissolution and mechanical breakdown are not mutually exclusive in sinkhole formation. The cave collapse sinkholes are the result of both, while the solution sinkholes may not necessarily involve mechanical failures.

2.3.2 Sinkholes in Caprocks

Sinkholes can occur in nonsoluble rocks when they are underlain by soluble ones. Under such geologic conditions, the overlying nonsoluble rock, such as sandstone, is referred to as caprock, and the sinkhole formation processes occur in the subsurface. The contacts between the soluble and nonsoluble rocks can be favorable locations for karst development. The caprocks can help preserve the karst voids as they are enlarged by dissolution. Mechanically, the formation processes of caprock sinkholes are similar to the impact of underground mining on the land surface. Depending on the mechanical properties of the caprock, the caprock sinkholes can be collapse features or broad bedrock subsidences as a result of gradual sagging. Factors such as paleokarstification in the underlying soluble rocks, interstratal karstification, and vertical percolation of water and fracture characteristics of the caprock control the formation of this type of sinkhole. Bedrocks above a void tend to be more fractured, which enhances vertical flow, while the enhanced flow can further enlarge the void. The void enlargement and enhancement of vertical flow are closely interrelated, and the processes are self-accelerating.

While mining-induced subsidence occurs within relatively short periods due to either rock removal or pumping down of aquifers, caprock sinkhole formation develops over geological time scales. Solution-enlarged voids may exist in most carbonate rocks; however, not all caprocks develop sinkholes. In addition to the typical carbonate acid solution, other geologic processes may be involved in the caprock sinkhole formation. One of the processes may involve gypsum dissolution, which can significantly accelerate limestone dissolution. The basic chemical reaction of gypsum dissolution is expressed by:

$$C_aSO_4 \bullet 2H_2O \longrightarrow SO_4{}^{2-} + C_a{}^{2+} + 2H_2O$$

In areas where thin layers of gypsum are interbedded with limestone or dolomite, the potential for the dissolution of the gypsum is large. When dissolution occurs, it results in cavities followed by collapse and formation of layered breccia deposits. When gypsum is in contact with carbonate rocks, the water chemistry associated with the dissolution is different from that for limestone alone. Waters rich in calcium carbonate can aggressively dissolve gypsum and simultaneously deposit calcite. When this occurs, the breccia caused by the dissolution of the gypsum may be cemented. Gypsum dissolves easily in flowing water and increases the amount of sulfate in solution. In addition, the presence of sodium, magnesium and chloride ions can enhance the dissolution of gypsum. However, the solubility of gypsum in calcium carbonate-rich waters may be decreased by the common ion effect. Lu (1996) shows that the presence of sulfate in water increases the dissolution rate of dolomite. For water with an SO^{2-} content of 1 mg/l, the dissolution amount for dolomite was 1.67 mg/l, while the dissolution for limestone was only 0.94 mg/l. The result of this groundwater chemistry on karstification is that very intense and pervasive leaching of the carbonate deposits, especially dolomites, can occur resulting in a honeycomb structure of very little strength. This dissolution process facilitates the development of collapse columns or breccia pipes that may propagate upward through several strata.

In China, coal mining has induced ~3,000 caprock collapses in 45 mining areas. The greatest concentration of caprock collapses is in Xishan Mine, Shanxi Province, where 1,300 such collapses have been recorded in 18 km^2. These collapses have diameters from several tens of meters to several hundreds of meters. They penetrate through the overlying Carboniferous and Permian coal sequences. Some caprock collapses occur in sedimentary rocks as young as Triassic age, even though these young rocks have now been eroded away from the local area. These caprock collapses can be as deep as 300–500 m. The majority of the exposed caprock sinkholes in the coal mines are within the zones where subsurface paleokarst is present. These paleokarst features functioned as preferential flow paths in the geologic past, and they can still be hydrologically active in groundwater flow and contaminant transport (Zhou and Li 2001).

The fact that the caprock collapses in the coal mines are common along geological structures suggests that the oxidization of pyrite may be another source of acid for the groundwater. Pyrite commonly occurs in the coal strata. The chemistry of pyrite weathering has been extensively investigated because of its direct relation with acid mine drainage. Oxidization of pyrite provides sulfuric acid that reacts with the limestone to produce gypsum.

$$2F_eS_2 + 7O_2 + 2H_2O \longrightarrow 2F_e^{2+} + 4SO_4^{2-} + 4H^+$$
$$4F_e^{2+} + O_2 + 2H^+ \longrightarrow 4F_e^{3+} + H_2O$$

Then

$$F_e^{3+} + 3H_2O \longrightarrow F_e(HO)_3 \downarrow + 3H^+ \quad \text{When} \quad pH > 4$$
$$14F_e^{3+} + F_eS_2 + 8H_2O \longrightarrow 15F_e^{2+} + 2SO_4^{2-} + 16H^+ \quad \text{When} \quad pH \leq 4$$

The continuous solution of gypsum is enhanced by the continuous movement of groundwater.

2.3.3 Sinkholes in Overburden

When a karst area is mantled by unconsolidated materials, the sinkhole formation processes become more complicated because of the involvement of internal soil erosion. In general, there are two types of sinkholes that occur in the overburden, cover-collapse, and cover-subsidence. Such a classification emphasizes the rate at which the surface subsides, although the subsidence rate is a descriptive term. Cover-collapse sinkholes often occur suddenly, and their damages to properties are noticeably quick. Cover-subsidence sinkholes are not readily perceptible, and their damages are more progressive.

Formation of a cover-collapse or cover-subsidence sinkhole is probably preceded by formation of a void at the soil/rock contact by subsurface erosion of soil into an opening in the bedrock. It is common that exploratory boreholes encounter a zone of soft soil just above the bedrock. This soft zone may be indicative of an on-going sloughing process of the soil. The strength of this soft soil is very low, and it can be easily transported into the opening in the bedrock. If the strength of overlying soil is strong enough, the roof of the soil void tends to approach a no-tension cylindrical or domal shape. If this condition has been reached, the load is carried in compression. Stress-strain analysis indicates that the collapse or stability of the residual soil void is controlled by the relationship between the diameter of the void and the thickness of overburden when the cohesion remains constant (Yang and Drumm 1999). For soils with cohesion of 25 kPa, the void tends to enlarge when the overburden thickness is less than 2.5 times of the diameter of the void. Such relationships were also illustrated by experiments of physical models for weakly cemented sand (Gooding and Abdulla 1999). For cemented sand with cohesion of 43 kPa, the void could progress to the surface if the thickness of sand is less than one-fourth of the void diameter. The physical experiments indicate that the weakly cemented sand behaves similar to badly fractured rock, in which a cavity roof could remain stable when its thickness exceeds approximately one-fourth of the cavity width (Peck et al. 1974).

Fig. 2.5 Sinkholes that occurred in a detention pond in Tennessee

Clearly, such analyses emphasize the self-weight of the overburden as a driving force to enlarge the void. Practical investigations, however, have suggested that sinkholes occur above relatively small soil voids. Cavities of 0.2 m in diameter can cause sinkhole collapse in over 15 m thick overburden. Tank experiments, as discussed in Zhou (1997) demonstrated that collapse could reach the surface regardless of the thickness of the soil, as long as the fracture system was not blocked by the collapsed soil. The collapse process ceased every time when the fracture was filled with the soil and restarted after the filled soil was removed. The reason for such a discrepancy is that the stress-strain models ignored the effect of water on the sinkhole formation.

It is our experience that water is the most important factor in development of cover-collapse or cover-subsidence sinkholes and in developing solution and cave-collapse sinkholes. Water is an enabling agent. As water seeps downward through the soil overburden or as the water level fluctuates in the formations, soil is eroded into solution-enlarged cracks in the underlying bedrock. Temporary formation of a dome-shaped void often concentrates seepage in that direction, thereby accelerating the erosion/raveling process. Continuing downward seepage enlarges the void upward toward the seepage source, shortening the seepage path. Openings as small as a few centimeters may be all that is necessary to allow the exit of entrained soil from an erosion-raveling dome several meters high if the water and the suspended solids can be transported into the network of solution-enlarged conduits (Fig. 2.5).

Dome formation and enlargement in overburden soil occur naturally; however, these processes can be accelerated by changes in water flow conditions. A rise in the groundwater level from below the soil-rock interface to above will increase the degree of saturation of the soil, decreasing its strength. Erosion may not start immediately because the rising water helps support the soil. However, a subsequent drop of that groundwater level is accompanied by the loss of the buoyancy support, which may initiate the acceleration of the raveling process. Presence of a large void may not be a necessary prerequisite for a cover-collapse sinkhole to form if rapid water level drawdown occurs.

The impact of water on sinkhole formation was analyzed by Anikeev (1999) and Sharp (1997, 2003) based on hydrofracturing theory. Anikeev (1999) proposed a simple hydrofracturing criterion that is controlled by the ratio of soil cohesion to the loss of buoyancy. A 3 m drawdown in the water level could cause hydrofracturing in soil with cohesion of 25 kPa. Sharp's numerical analyses indicate that hydrofracturing was unlikely to occur under steady-state pore pressure, while transient pore pressure is a more probable cause of failure. For an in-depth explanation of this process, please see Sharp (2003).

In general, there are five ways through which water flow may increase the pore pressure gradient around a soil void and/or decrease the shear strength in the soil:

- Surface water percolating downward: Water sources include parking lots, roadways, roof down-sprouts, catch/detention basins, irrigation lands, construction sites, and runoff from impervious surfaces and reservoirs.
- Near-surface water percolating downward: Water sources in this category include leakages of water lines, stormwater drainage system, sewer lines or irrigation systems, and natural water flow within epikarst zones.
- Groundwater level fluctuations: Water sources include mine dewatering, water inrush in quarries and mines, pumping at supply wells, long durations of dry and wet weathers. Extensive dewatering in a thick limestone aquifer may result in two or more temporary aquifers that have different water levels but are hydraulically connected.
- Water percolation from a shallow aquifer to a deeper aquifer: This often occurs in a dual aquifer system where the water level in the shallow aquifer is higher than the potentiometric pressure in the deeper aquifer. It can also occur in a thick aquifer system where perched water is present in the upper section.
- Water uprising from a deep confined aquifer to a shallow aquifer or to surface. This occurs when a confined aquifer is hydrologically connected to a shallow aquifer or to a surface water body.

Sudden ground collapses, small or large, are often referred to as "drop outs," which can be 5, 10, 15, or more feet deep and wreak havoc with foundation plans. These features are specifically termed cover-collapse sinkholes and are intimately tied to the larger drainage basins in the rock. Downward drainage into dissolved shafts and enlarged cracks in the rock carry the overburden down with them. The sediment is eroded from the bottom upward, giving no sign of the ongoing erosion or the impending collapse at the ground surface.

The scale and rate of this cover-collapse process is variable, from small dropouts to, under the right circumstance, gigantic collapses that envelope roads, houses, or buildings. When the karst is covered, it is difficult to anticipate where these collapses will occur. The erosion process can occur slowly, even imperceptibly, an inch or less per year. The shallow depression that eventually forms on the ground surface is also a sinkhole: a cover-subsidence sinkhole. An inch per year adds up to about

2 ft of settlement in 25 years. Suppose this process develops under the footing of a house, then major cracks result, chimneys fall over, and the house becomes unlivable. There do not need to be large cavities below the surface for this damage to occur. Although this process of collapse of large cavities does occur, experts agree that it is so rare on a human timescale that it is virtually negligible.

2.4 Design Considerations for Foundations

There is no doubt that construction activity increases the rate of sinkhole formation in a soil-covered karst by imposing changes in various environmental parameters. Good practices attempt to minimize these impacts, and pay particular attention to drainage disturbance, especially in the areas of water-table decline. Positive action can be undertaken on difficult sites to correct potential detrimental defects. This can include surcharging the soil to precipitate small fractures before construction, compaction, grouting to stabilize the soil cover, grouting the bedrock fissures or the use of driven piles instead of caissons.

Although detailed subsurface investigation helps optimize the foundation designs and minimize uncertainties inherent in foundation construction in carbonate rock formations, the inherent heterogeneity of the subsurface conditions in karst areas may prevent geologists from identifying the "problem" areas at a site. However, with a detailed subsurface exploration completed and the earthwork and design parameters of the structure determined, a hazard assessment of this site should be made as an integral part of the design of the structure. This should include an overall qualitative and quantitative assessment of the probability of future subsidence occurrences. The client should be informed of the risk of future subsidence. The design professionals must be prepared to provide foundation alternatives to reduce or eliminate the risk. These alternatives, in general, are regular shallow spread footings with or without soil improvement, rigid mats and grade beams and deep foundations (piles and piers).

When the overburden is thin, the preferred choice for settlement-sensitive structures will be shallow footings placed on bedrock or engineered fill over the bedrock. The concern in use of shallow foundations is the potential for significant seepage inflow during excavation, particularly from the shattered or highly weathered limestone. Alternatively, these structures may be carried on pile foundation socketed into competent bedrock, which minimizes the excavation and dewatering difficulties but carries uncertainties related to the quality of competent or moderately competent rock and consequently the socket resistance.

If the heavy and settlement-sensitive buildings are located in an area with deeper bedrock, the obvious choice for foundation will be piles. The choice of piles will depend on the nature and relative density of the overburden, the presence and depth of softer, normally consolidated layer at depth, and the depth and condition of the bedrock. Lighter and nonsettlement-sensitive buildings can be carried on shallow footings located in the clayey silt or the sandy silt strata. Geogrid may be used beneficially to improve load distribution on softer overburden material left in place.

2.4.1 Ground Improvements

Engineering design may recommend some ground improvement methods for areas at different levels of hazard. One such method is dynamic compaction, which involves dropping a substantial weight (on the order of 10–15 t) from a height of 20–20 m. The resulting impact can collapse subsurface voids within the overburden. The pattern of ground deformation developed during dynamic compaction often indicates many areas of active and potential sinkhole development. Once unstable areas are identified either through investigation or dynamic compaction, various remedial methods can be employed:

- Excavating the overburden to rock (if shallow enough for the available excavation equipment) to reveal the actual opening in the underlying rock. The opening can then be sealed with concrete or rock plugs and the excavation backfilled with engineered fills.
- In case of very shallow rock areas with highly fractured epikarst, the area can be stripped and then sealed by slush grouting.
- Where rock is deep and the area of concern is widespread, injection of grout through boreholes can successfully plug the majority of the solution channels. A cement grout tailored to the specific applications through the addition of accelerators or thickeners is typically used for the initial, secondary, and possibly tertiary grouting holes. Grouting can be used to either seal the surface, preventing further soil erosion, or to completely fill the subsurface voids.
- Acceptance criteria for cavity treatment using grout vary based on the specific subsurface conditions. For soil within the treatment zone, the individual SPT-N value at any point is no less than 20 and the average SPT-N value is no less than 25. Verification borings do not encounter voids. If the treated section is tested for strengths, the unconfined compressive strengths of the core are in excess of 2 N/mm^2 or other design requirements.

2.4.2 Foundation Options in Karst Terrains

2.4.2.1 Foundations on Shallow Overburden Strata

When designing and building structures in karstified areas with shallow overburden strata, there are certain positive characteristics of these sites that come into play for construction. These include:

- Limited dewatering if water level is close to surface.
- Suitable for lightly loaded structures under engineered fill pad.
- Smaller quantities of engineered fill required as compared to foundations bearing on limestone.
- Bearing capacity may be increased by increased engineered fill thickness.

However, there are also significant negative characteristics which must be considered when building in these areas, including:

- Relatively low bearing pressure to control differential settlement
- May not be suitable for heavy and settlement-sensitive structures due to settlement constraints (detailed study required to ascertain suitability)
- Uncertain thickness due to bedrock topography and impact on differential settlements
- Presence of voids in soil may result in collapse of the foundation.
- Subsurface erosion continues as a result of seepage and water-table fluctuations.
- Frost susceptibility of silts.
- Required use of synthetic materials (geogrid and geotextile) at silt/engineered fill interface.

Consequently, when construction does proceed, certain characteristic features of these shallow overburden strata have to be considered:

- Pinnacles: Pinnacles are columns or cones of limestone or marble left by preferential dissolution of the surrounding rock along joints or fractures. Pinnacles are often surrounded by cutters. The surface manifestation of this cutter-pinnacle condition ranges from the formation of sinkholes as the overlying soil moves downward through the cutters to differential settlement in response to loading at the ground surface.
- Slump zone: Zones of weakness often occur immediately above the bedrock of limestone. The slump zone is usually identified by the very low SPT-N values or low cone resistance where SPT-N values of zero are often detected. The formation is either due to subsurface erosion as a result of overburden slumping into cavities in the limestone or renewed weathering of paleokarst features.
- Voids in soil: One of the most "notorious" byproducts of karst activity is the occurrence of voids in the soil above the soil-rock interface. These features represent transient conditions that need to be carefully assessed with regard to their stability to remain stable over the design life of a project. The inherent stability of small voids (<5 ft in diameter) can be analyzed following the approach proposed by Yang and Drumm (2002). Perhaps the subsurface conditions that present the biggest analytical challenge are those that involve relatively large voids (>6 ft in diameter). Over the design life of a project, it is quite likely that these large voids will collapse, regardless of the soil strength. If the void is larger, close to surface, or if water is actively moving soil from the void, then it is quite likely that a sinkhole will develop and this possibility should be considered explicitly in the design. In cases where the condition is found to be unstable, an appropriate repair strategy should be formulated. If, however, the void is located at depth and water is not actively removing soil from the void, the foundation may be stable even when the void collapses, due to the substantial amount of overburden above that void. The surface expression of the collapse may be small enough to not adversely impact the constructed facility. Adverse impacts usually result in excessive settlement and strain at the level of the ground surface. Dynamic compaction can improve

soil in the top 3–20 m depth range by collapsing soil cavities, but this does not entirely remove the chance of future piping and subsidence, even in the less permeable compacted soil.
- Lighter and nonsettlement-sensitive buildings can be carried on shallow footings located in the clayey silt or the sandy silt overburden. Geogrid may be used beneficially to improve load distribution on softer overburden material left in place.
- Surface runoff should be managed properly to reduce water percolation.

2.4.2.2 Foundations on Weathered or Shattered Bedrock or Epikarst Zone (Overlying Overburden Removed)

When designing and building structures in karstified areas with weathered or shattered bedrock or epikarst zone (where the overburden has been removed), there are certain positive aspects that are characteristic of these sites that come into play for construction. These include:

- Competent bearing stratum in undisturbed conditions for lightly loaded structures.
- With engineered fill cover suitable for light, as well as heavy and settlement-sensitive structures.
- Engineered fill can be placed partly under water, thus minimizing the extent of required dewatering.

However, there are also significant negative characteristics which must be considered when building in these areas, including:

- Dewatering required at the bottom of shattered/weathered limestone.
- Costly and challenging dewatering of weathered limestone.
- Uncertain thickness/deformation characteristics.
- Risk of bearing stratum disturbance and loss of bearing capacity due to seepage.

Consequently, when construction does proceed, certain factors characteristic to these shattered/weathered bedrock or epikarst zones have to be considered:

- Excavation to a shallow pinnacled rockhead and placement of a coarse rock backfill can achieve a firm footing, or a crushed rock mattress can be established in the soil. In either case, a concrete floor slab formed on the fill should be reinforced so that it can safely bridge any soil cavity that may reasonably be expected to form beneath. Generally, soil over 15 m deep removes any direct subsidence hazard, unless there is a subsequent watertable decline.
- Dental filling: Fill the exposed bedrock fissures and depressions with cement or a mixture of cement and engineered fill.
- Voids at rock/soil contact where the roof of the rock void is in the epikarst zone. An initial assessment can be performed using the equations for caves in bedrock. Ultimately, a design condition often considers the potential collapse of the roof.
- Slump zone: Zones of weakness often occur immediately above the bedrock of limestone. The slump zone is usually identified by the very low SPT-N values or

low cone resistance where SPT-N values of zero are often detected. The formation is either due to subsurface erosion as a result of overburden slumping into cavities in the limestone or renewed weathering of paleokarst features.

- Very uneven limestone bedrock surfaces demand careful foundation designs. Where pinnacle tops lie at accessible depths, they may support structural loads once their integrity has been proven by exploratory boreholes. Reinforced ground beams can be designed to bear on stable pinnacles. Similar beams can simply span buried sinkholes. In view of the difficulty of proving the integrity of the buried limestone, reinforced slabs or beams may be used.
- A water management plan is necessary to reduce subsurface erosion by surface water and groundwater.

2.4.2.3 Shallow Foundations on Competent Limestone (All Overburden, Including Shattered/Weathered Limestone, Removed)

There are certain advantages and disadvantages when designing and building structures in karstified areas with shallow foundations on competent limestone after all the overburden, including shattered/weathered limestone, has been removed. The main advantage is that the sites are now suitable for all foundations, including those for heavy loads and settlement intolerant structures. However, the main disadvantages include:

- Deep and costly dewatering down to bedrock (including shattered/ weathered limestone) required.
- Presence of structural defects in limestone, voids, vugs, solution-enlarged fractures could result in differential settlement over foundation span (probability low for shallow spread and slab foundations).
- Engineered fill may be required to fill depressions. Additionally, engineered fill placed partly under water may be used to reduce the depth of dewatering.

Consequently, when construction does proceed, certain factors characteristic to these zones with competent rock have to be considered:

- Voids in rock: Caves are the most unpredictable byproduct of karst activity. In terms of assessing stability, it is well known that the roofs in rock caverns can span large distances for long periods of time. The shape of the cave contributes to its inherent stability. Methods for assessing their stability can be found in White (1988), Criss et al. (2008) and Çanakcı and Güllü (2009). The parameters used in the equations that most significantly influence the analyses results are the span of the roof and the thickness of the "competent" rock in the roof of the void. Filling these cavities with concrete is an obvious measure to correct the defect. Any loose materials are excavated and replaced with concrete. It is most effective if the concrete bonds with the rock. When voids are partially filled with soil, the grout may extend out in sheets or fingers. This may block further solution and cavity enlargement. However, if subsurface erosion continues, the grout breaks apart and any benefit can be lost.

- Very uneven limestone bedrock surfaces demand careful foundation designs. They may support structural loads once their integrity has been proven by exploratory boreholes. Reinforced ground beams can be designed to bear on stable pinnacles.
- Floaters: Exploratory boreholes may be needed to ensure the bedrock is continuous and competent.
- A water management plan is necessary to reduce subsurface erosion by surface water and groundwater.

2.4.2.4 Socketed Caissons and Piles, Including End Bearing Piles

There are both advantages and disadvantages to using socketed caissons and piles, including end bearing piles. The advantages include:

- Bearing/socketed piles in solid limestone bedrock.
- Possibility exists for contact grouting in case of adverse karst features in limestone.
- Dewatering/engineered fill is not required.
- Lateral and uplift (due to frost) resistance is provided by socketing.
- Only light equipment needed for micro-pile installation (i.e., lower cost of work pads).
- Depending on the stratum thickness, these can bridge problematic karst features in the underlying limestone.

However, there are disadvantages, which include:

- Visual inspection of holes is difficult or impossible (due to small diameter and water inflow from bedrock in micro-piles; water inflow in cast-in place caissons). This means relying on airlift cleaning only.
- Uneven bedrock topography requires detailed exploration for designing socket lengths.
- Concentrated loads may be above karst voids (necessitating pilot hole at each pile location to increase confidence, adding extra cost).
- There are also mobilization/demobilization costs.

There are certain factors that need to be considered or may arise when using these types of foundations. These include:

- Steeply inclined bedrock surfaces: Steeply inclined bedrock surfaces in limestone pose significant difficulties for piled foundations, such as inadequate end-bearing resistance and breakage during installation of driven piles, especially for bedrock with problematic geologic features such as vertical joints.
- Steel piles can easily suffer deflection, bending, curling, or poor seating when driven to a pinnacled rockhead, although they can be driven through any rubble zone or even through weathered limestone to solid rock. Driven concrete piles are more difficult to place on pinnacles, and more numerous small diameter piles provide safer load distribution. Alternatively, bored piles can be placed a few

meters into the bedrock where the fissure densities are reduced, although pile lengths may vary considerably where buried sinkholes exist. In view of the difficulty of proving the integrity of the buried limestone, reinforced slabs or beams are best designed so that they can survive the failure of any one pile support.

- Pinnacles with soft or loose overburden immediately above them challenge the proper seating of piles on the rock, particularly for driven concrete piles, as well as causing difficulty of rock socketing for bored piles. Piles (driven or auger cased) may be deflected (doglegged) on pinnacles or may deviate on sloped rock, and it is difficult to discern their actual bearing capacity.
- Driven and jacked-in piles: Driven/jacked-in piles are generally used for low-rise buildings, with various degrees of success. A high percentage of damaged piles can result from excessive tilting/deflection, rotation, distortion, bending, cracking, and shattering. In the design of driven piles, sloping bedrock/steeply inclined bedrock surface, floating boulder and cavities should be considered. With the introduction of high capacity jacked-in piling systems, jacked-in piles can also be adopted for high-rise buildings.
- Drilled piles: Drilled piles are generally used for high-rise buildings. The size of bored piles ranges from 600 to 1,500 mm in diameter, although it can go up to 3,000 mm in diameter.
- Micropiles: Extreme variation in ground conditions inevitably create challenges during design and installation of deep foundation systems. For example, the elevation of rockhead may vary greatly over short distances, and for substantial depths below the rockhead, one may anticipate the presence of major solution features. Such features may be entirely open or may be partially or completely filled with sediments. High capacity micropiles have proved to be technically and economically viable for deep foundation systems in such terrain. Micropiles in limestone areas are usually designed as rock-socketed piles in the bedrock to carry either compression load or tension load. They are small in diameter (<305 mm), bored, grouted-in-place, and incorporate steel reinforcement. All micropiles are designed to transfer load through the shaft friction, and end-bearing at the tip is generally negligible due to its small base area.
- The design of pile foundations to cater for highly erratic bedrock profiles and sloping bedrock may include:

  – Provision of compensation piles within the pile group (if necessary) to ensure that the induced rotation within the group is within tolerable limits, i.e., within the bending moment capacity of the pile, and that no pile in the group is overstressed. This applies to situations where significant differences in pile length are observed in the same pile group due to the highly irregular bedrock surface. Such large differences in pile length will induce bending and uneven distribution of loads within the pile group.
  – Adjustment of rock sockets based on the actual bedrock surface encountered during construction to ensure sufficient socket capacity for bored piles or micropiles, especially in steeply inclined bedrock areas with problematic geologic features. This illustrates the importance of input during the construction stage for successful foundation design. The bedrock level can be continuously updated as piling work progresses.

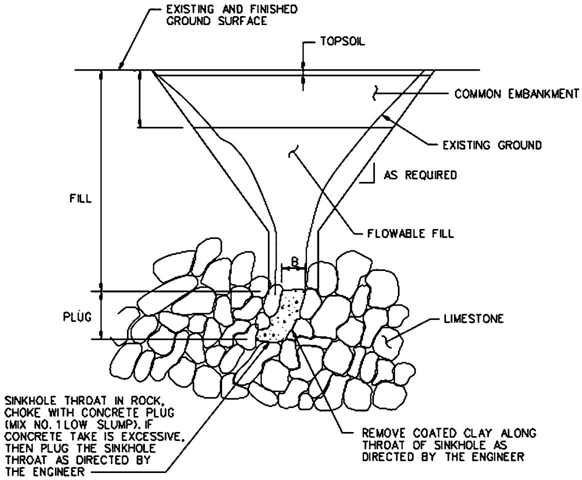
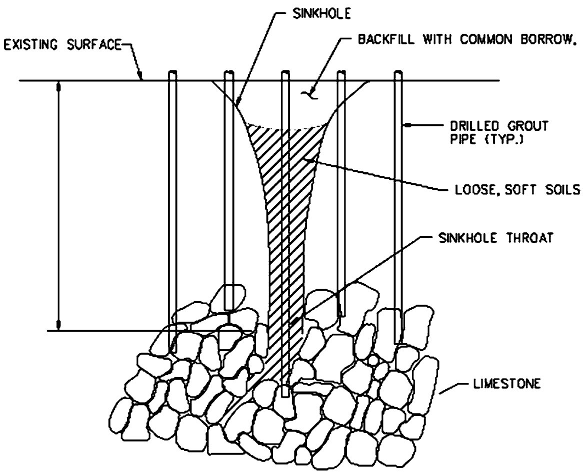
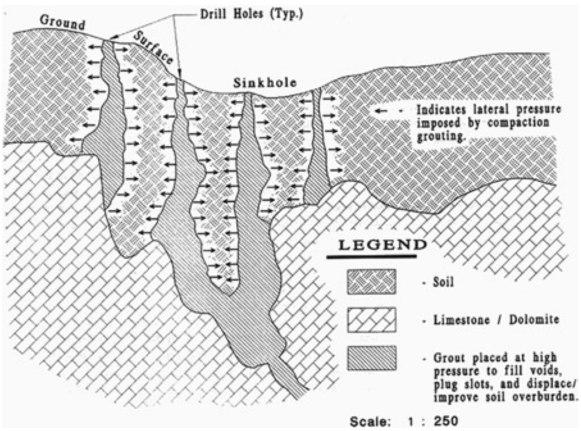
– The effect of laying the pile foundation on a floating boulder is that the axial load in the piles laid on the intended founding layer increases, while the axial load in the piles on the floater decreases. This will induce uneven settlement in the pile group. Preboring is needed through the floater prior to installation of driven or jacked-in piles. This is to ensure that the piles reach the intended founding layer.

The interpreted bedrock profile serves as reference during pile driving. The hammer height is reduced when approaching the interpreted bedrock to prevent slipoff of pile point. However, the engineers should be aware that the interpreted bedrock profile is only a rough estimate as the limestone is usually highly irregular at depth, and therefore, good engineering judgment must be exercised. When the pile point has come into contact with the rock surface, which normally can be recognized by a sudden change in the response to the hammer, pile driving is then continued with very small heights of drop of the ram (100–200 mm). After the pile has been subjected to a series of blows until the penetration of the pile is negligible, the fall is increased to double the height. The steps can be repeated until the required termination criterion is achieved. The procedure is intended to socket the pile into competent bedrock and to prevent sliding of the pile point at the contact of the rock surface. High strain dynamic pile tests should be conducted to calibrate the permissible drop height to prevent damage to piles during installation of the driven piles.

2.5 Sinkhole Treatment Options

Sinkhole mitigation is to repair damage caused by the existing sinkhole and to prevent its reactivation in the future. To successfully remediate a sinkhole, a thorough geotechnical study should be performed by knowledgeable professionals such as geotechnical engineers and geoscientists who understand how it is formed. The characteristics of the sinkhole and the intended use of the sinkhole site determine the mitigation approach. For sinkholes that are related to water activities, the most intuitive and straightforward means of preventing sinkholes from occurring is to eliminate the various water sources. Elimination of the water sources eliminates the internal erosion processes that lead to sinkhole formation. When this approach is not possible, the second choice is to work on the passageways through which the water moves. The third option is to reinforce the strength of soils/rocks. The overall purpose of the engineering measures is to either eliminate or significantly reduce the erosion processes. Success in sinkhole mitigation relies on the extent to which the internal erosion and deformation processes are eliminated. The engineering measures for sinkhole mitigation should be tailored to each sinkhole and its geologic and hydrologic conditions. Sinkholes that are in a springhead or wellhead protection area should be treated differently from those outside the protection area. Table 2.2 lists eight commonly used remediation methods. These methods provide

Table 2.2 Selected options for sinkhole remediation

<table>
<tr><th>Sinkhole remediation</th><th>Typical diagrams</th></tr>
<tr><td>Shallow sinkholes with visible throats (Kutschke 2004, personnel communication)</td><td>
</td></tr>
<tr><td>Deep sinkholes with known throats (Kutschke 2004, personnel communication)</td><td>
</td></tr>
<tr><td>Compaction grouting (Siegel et al. 1999)</td><td>
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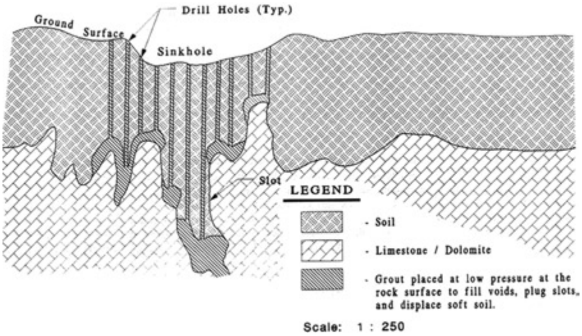
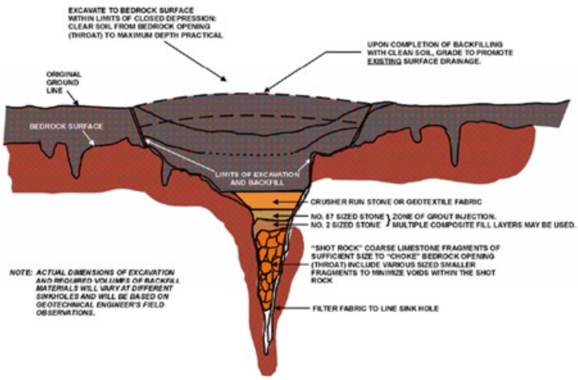
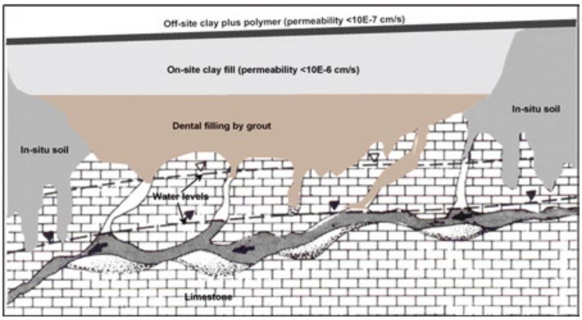
(continued)

Table 2.2 (continued)

<table>
<tr><th>Sinkhole remediation</th><th>Typical diagrams</th></tr>
<tr><td>Cap grouting (Siegel et al. 1999)</td><td>
</td></tr>
<tr><td>Graded backfilling (Fort Campbell Environmental Division 2003)</td><td>
</td></tr>
<tr><td>Dental filling by grout</td><td>
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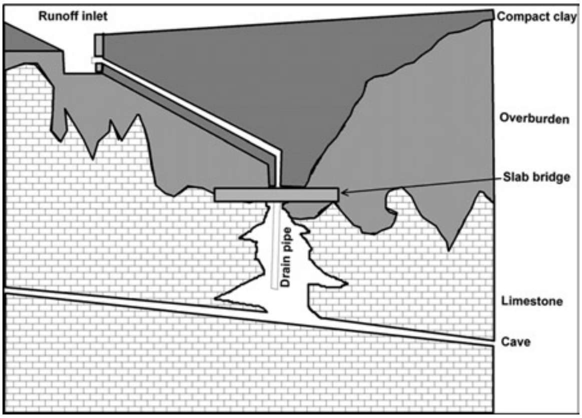
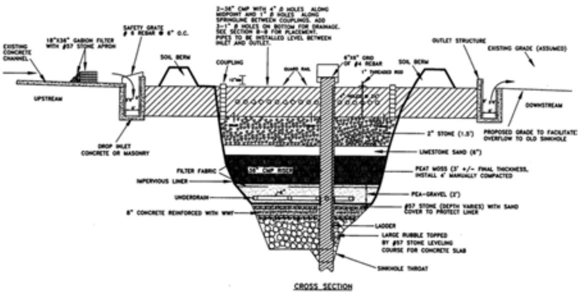
(continued)

Table 2.2 (continued)

Sinkhole remediation	Typical diagrams
Backfilling with drain pipes	
Designed filtration system (Beck and Zhou 2002)	

only the basic principles of sinkhole remediation, and they are not engineering designs. A direct copy of any of the selected approaches is not recommended. Although there is no option that fits all sinkholes, it is our experience that successful sinkhole mitigation should include treatment of sinkhole throat, filling of sinkhole body, and construction of sinkhole cap. In some areas, sinkhole remediation may be regulated, and any engineering measures should be reviewed by regulatory agencies and local engineering offices.

2.5.1 Treatments of Sinkhole Throat

There are many ways to treat sinkhole throats. Because the configuration of each sinkhole is unique, knowledgeable professionals are needed to determine the most appropriate approaches. In general, selection of treatment methods depends on the complexity and uncertainty about the sinkhole and its depth. For mitigation purposes, sinkholes can be divided into shallow and deep sinkholes. Shallows sinkholes are those reachable by a regular backhoe. Deep sinkholes are beyond the reach of a regular backhoe, and drilling rigs are needed to reach to their bottoms.

2.5.1.1 Shallow Sinkholes

For shallow sinkholes, excavating and plugging its throat is the most intuitive and simplest solution of remediation approaches. In many cases, it is cost effective and may work for a long time. It is relatively a quick solution for constructions that can tolerate minor subsidence. Selection of this option assumes that a sinkhole throat exists and the throat can be exposed by excavation. The excavation process should make sure that the sinkhole throat is free of clayey materials. One rock piece or a layer of large stones can be used to plug the drain. The plugs should be compacted to ensure that they are jammed in the throat and are structurally stable. The plugging materials can also be made of concrete blocks. A grout plug is probably the most effective approach to remediate a sinkhole (Sowers 1996). The objective is to plug the sinkhole throat with concrete to an approximate depth of 1.5 times the width of the throat. To the extent possible, any clay coating along the throat should be removed before concrete placement to secure a good bond between the concrete and rock.

If the sinkhole lacks a throat but instead is drained via many discrete fractures, these can be rendered impermeable by dental infilling grout. Pressure wash is recommended to help identify the fractures in the exposed bedrock surface at the sinkhole bottom. Grout pockets are scraped at the fracture zones. If necessary, pressure wash should be applied to ensure that the grout pockets are free of clay. The pockets are filled with high/low slump flowable fill to plug and cap the fractures.

2.5.1.2 Deep Sinkholes

For deep sinkholes, their bottoms cannot be exposed for visual inspection. The characteristics of sinkhole bottoms can only be interpreted through borehole exploration or/and geophysical surveys.

Compaction grouting is often used to plug the throat of a deep sinkhole. Grouting holes are drilled into the sinkhole and its vicinity. A relatively high grout pressure of 1,380 kPa or greater is used in the grouting holes to fill voids, plug fissures around each hole, and displace/improve the soil/rock within a sinkhole. Primary grouting hole spacing is typically 3.5–5.0 m. Higher grout pressure, greater grout hole spacing, higher grout quantity refusal criteria and overburden treatment generally result in a larger grout intake. Compaction grouting is typically performed in the soil overburden or/and shallow rock within sinkholes. This technique may not work well in wet silts and clays.

Although drilling tools usually allow penetration through boulders and rock lenses, the large primary grout hole spacing may make it possible to miss the sinkhole throat or other major karst features. Secondary holes may be required. In between, permeability tests are recommended to determine the effectiveness of grouting.

Compaction grouting may cause additional fractures due to hydrofracturing if it is not designed properly. Because of the wide spacing, this technique may be less effective in pinnacled rock. Potential sinkhole features may be located between the grout holes and grout may not be delivered to the sinkhole features. Another concern of compact grouting is that compact grouting can inadvertently seal off conduits that may be groundwater passageways.

When the infilling of a sinkhole throat is too stiff to displace with high pressure, a more effective technique, jet grouting, may be successful. This process involves pumping a fluid grout into the soil with a rotating high pressure jet. The jet erodes soil and cuts stiff clays and soft erodible rock into gravel or small boulder-sized pieces. Pressures of 30–50 MPa are typical at the grout nozzle. The pressure dissipates rapidly within the soil and does not cause heave when the volume of the grout is properly controlled. The larger particles of soil, including sand and gravel in the sinkhole filling, mix with the grout, producing a mixed-in-place concrete.

Cap grouting is often a viable choice when a sinkhole is associated with small but discrete fractures at the bedrock surface and the area to be treated is extensive. Cap grouting uses low grout pressure (140 kPa or less) to pump lean cement into the bedrock-overburden interface to seal the sinkhole bottom, fill voids, plug fissures and displace soft soil. This operation provides support to the upper layer and disconnects or reduces any vertical hydrologic connections. Grout hole spacing is typically 0.9 m. In general, cap grouting does not consume as much grout as compaction grouting. On the other hand, a good coverage to intersect sinkhole features requires closer grout hole spacing, which in turn requires greater drilling footage. Auger drilling may not extend to bedrock due to shallow refusal on floaters. Although the use of hydrofracturing is limited for such an operation, the ground surface elevation is monitored for heave.

Because of the uncertainties in sinkhole characterization, other options should also be considered. For extremely deep sinkholes in which bedrock is not reachable within a reasonable depth by boring, sinkhole mitigation occurs within unconsolidated soil or materials collapsed into the sinkhole. Several approaches including jet grouting (discussed above), vibro-compaction or dynamic compaction may be applicable. The latter is a system generally used to compact granular soils to depths of ~3–12 m. The technique involves dropping heavy weights, 5–30 short tons, on the soils from a predetermined height. Vibro-compaction uses larger diameter vibrators to compact and strengthen granular soils or to create stone columns in mixed or layered fine-grained soils.

Slurry grouting can be another option. This method involves the injection of various mixtures of very fluid grouts into the ground. It fills cavities at virtually any depth that can be drilled. It can run along planes of weakness in the limestone and overburden, forming very effective seals. Because little to no compaction of overburden soil takes place, the potential remains for building settlement problems.

2.5.2 Filling of Sinkhole Bodies

After the appropriate treatment of the sinkhole bottom, the sinkhole itself can be backfilled with selected materials compatible with future loadings. If a sinkhole remediation area is outside the footprint of a structure, settlement of the backfill material may not be a significant concern. Therefore, the backfill material could consist of common borrow tamped in place. If a sinkhole remediation area is within the footprint of a structure, settlement of the backfill material is of concern. The backfill material should be relatively noncompressible, and its placement procedures should be compatible with the anticipated loading and tolerable settlement. It is also essential that the filling materials should be analyzed for chemical compositions to ensure that they are not contaminated. Prior to filling, it is a common practice to line the sinkhole bottom and walls with a geotextile filter fabric. If a sinkhole is expected to continue as a drainage point, some drainage structures may have to be constructed to facilitate this purpose. If the water is contaminated, a filtration system may be necessary to treat the runoff prior to directing into the sinkhole. To prevent the sinkhole from reactiviating, the three filling methods discussed below are recommended.

1. The fill practice creates an impermeable body to stop both vertical and lateral water flow. It consists of compacted clay with a permeability of less than 10^{-6} cm/s. Thin layers are recommended as the compaction pressure transmitted to the soil decreases with depth. A high degree of compaction breaks down most aggregated or flocculated clay particles and makes them less permeable. Compaction helps to break up the vertical structure of the soil and greatly slow leakage.
2. An inverse aggregate graded filter consists of placing boulders wider than about half the throat opening width into the solution-enlarged fracture to arch across the bottom opening. Successive layers are sized finer than the underlying layer but coarse enough not to pass through the interstitial spaces of the bed beneath. It can be permeable from top to bottom. In most cases, this kind of filter is permeable at the lower section and impermeable at the upper part. This design allows subsurface water moving at the soil/bedrock interface to access the epikarst drain and groundwater recharge to occur. Geotextile filter fabrics and even cement-grout mixes may be used when the stone layers are emplaced. Vibration should be used to consolidate the seal and promote the infiltration of the grout into stone pores. The grouted zone should not penetrate below the groundwater level.
3. Development of filtration techniques may help reduce the concentration of contaminants in the runoff prior to flowing into a sinkhole. Keith et al. (1995) discuss the installation and contaminant removal efficiency of rock and peat filters constructed within sinkholes. Preliminary findings indicate that one peat filter removed ~80% of suspended particulate materials (measured as total suspended solids [TSS] and selected total recoverable metals) and about 50% of the dissolved copper and zinc. Rock filters removed approximately 33–76% of the TSS and 35–55% of the total recoverable metals. The field tests of an above-ground peat filtration system in Eastern Knoxville, Tennessee, indicate that the system

can decrease the concentrations of polyaromatic hydrocarbons by 95% and the total lead by 70%. The system was not efficient at removing the total petroleum hydrocarbons, zinc, and the total dissolved solids. The removal efficiency varies with the concentration of the contaminants in the runoff (Beck and Zhou 2002).

This third remediation technique considers not only the stability for the site but also the water drainage. This kind of filters is permeable to surface water percolation but stops any lateral flows into the sinkhole. This technique is viable when the sinkhole is an indispensable drainage point. It requires an engineering design of a filtration system based on the sinkhole configuration and the amount of runoff flowing into the sinkhole. The filter materials need to be selected according to the water quality of the runoff, so that the contaminants can be removed prior to recharging into the aquifer. The filtration system is also designed to support the stability of the sinkhole site. When sinkholes are improved for drainage purpose, they are considered to be Class-V Injection Wells. Therefore, this option needs to be evaluated according to the relevant state laws.

2.5.3 Construction of Sinkhole Caps

The filled sinkhole needs to be capped by a clay layer about 0.2–0.5 m below the planed surface to further prevent water percolation. It is advisable to use the native soil to bring surface grade to at least 0.15 m above the surrounding ground surface to ensure a positive drainage. The purpose of surface or near-surface grading is to further reduce the probability of water infiltration. One commonly used method is clay compaction. A high degree of compaction breaks down most aggregated or flocculated clay particles and makes them less permeable. When clay compaction is used in areas where cycles of drying and wetting or freezing and thawing occur, one needs address the possibility of reaggregation of the particles.

Permeability of coarse-grained soils (sands and gravels) can be greatly reduced by mixing the soils with bentonite. Bentonite is clay with a high shrink-swell ratio. It can be mixed with existing soils and compacted in layers. Upon wetting, the bentonite will swell to many times its dry volume, which can seal soils that lack clay-size particles. Bentonite is most effective on soils that contain <50% fines and with plasticity indices <15. Only sodium bentonite should be used for pond or reservoir sealing.

To seal sinkholes where there are water ponds, it may be necessary to add a chemical dispersant. As with bentonite, these chemicals should be thoroughly incorporated into the soil. Soda ash, sodium chloride, and sodium polyphosphate are chemical dispersants. They change the soil structure by replacing a bivalent calcium ion with a monovalent sodium ion. Chemical additives work only when the clay particles are present in clusters. For best results with chemical sealing, the soil should be fine grained at least 15% finer than clay size (0.002 mm). Soluble salts should be <0.5% of dry soil weight. Dispersants should be mixed in 0.15 m lifts of soil and compacted. The amount of compaction will affect the permeability rate. The minimum thickness of the finished treated blanket should be 0.15 m for water depths of 2.5 m or less and proportionally thicker for greater water depths. ESS-13 is another soil sealant, which is a vegetable-oil-based liquid polymer emulsion (www.ess13.com). Because the ESS-13 molecule is larger and lighter than water, it envelops around each soil particle and prevents cation exchange. It also helps fill any voids in the soil profile.

Polyethylene, vinyl and butyl rubber membranes, when properly installed, can be used to prevent seepage. The membranes must be protected from puncture during installation and use. The lining must be secured by burying the top 0.2–0.3 m in a trench 0.2–0.25 m deep and approximately 0.3 m wide. The trench must be located above the usual waterline. Because of their weakness, all polyethylene and vinyl membranes should be protected from damage by a cover of earth not less than 0.2 m thick. Butyl rubber membranes need not be covered unless the area is subject to damage by livestock or to danger from puncture by swimmers or fishermen. To protect against livestock, swimmers, and fishermen, a minimum of 0.25 m of earth or a mixture of earth and gravel should cover all types of membranes. The bottom 0.1 m should be no coarser than fine sand. All earth covers must be free of large clods, sharp rocks, sticks, and other objects that could puncture the membrane, and they must be carefully placed.

2.6 Sinkhole Management Plans

It is generally acceptable not to construct any facilities within a sinkhole because of concerns of flooding, future collapses, and potential impact on groundwater. However, whether a safety zone around an existing sinkhole can be defined depends on the site-specific conditions and the type of facility to be constructed. In areas where sinkhole data is available, geostatistical methods may be used to determine the radius of influence of a sinkhole, although this is somewhat difficult at times (Gutierrez et al. 2008). The spatial distribution of the sinkholes in a particular area is often clustered (Gutiérrez-Santolalla et al. 2005). New sinkholes tend to develop in the vicinity of the old ones because the hydrogeologic and topographic settings for the old sinkholes are favorable for sinkhole development, and the existing sinkholes may further enhance the solution and erosional processes. Stochastic analysis of the sinkhole distribution along Interstate 70 near Frederick, Maryland, indicated that the radius of influence of a sinkhole was approximately 30 m (Zhou et al. 2003). At another study site in Missouri, the radius of influence of a sinkhole was estimated to be approximately 244 m (Zhou et al. 2005). These quantitative analyses may provide technical background for the determination of the necessary setbacks due to sinkholes.

Very often, the sinkhole data is not available for an area or the data are not systematically analyzed. Under such circumstances, the setbacks can be determined by discussions among different groups including developers, regulators, and concerned citizens but preferably based on objective data and scientific-technical criteria.

For residential and commercial buildings, relatively small setbacks are often used. In Monroe County of Indiana, the setback is 7.6 m (25′) for sinkholes no more than 0.1 ha. For sinkholes larger than 0.1 ha the setback should be 15 m of the postdevelopment sinkhole flooding area or 7.6 m from the rim of the sinkhole, whichever is less. In Knox County and the town of Farragut, Tennessee, a 15 m setback is recommended around an existing sinkhole. Any construction within 15 m radius should not compromise the drainage function of the sinkhole and should not cause any adverse impact on groundwater, and the developer should obtain all permits from the Tennessee Department of Environment and Conservation and provide evidence that there is no more danger from building in this area than there would be in other areas. This discussion relies on the clear delineation of the edge a sinkhole, which may not always easy to discern (Gutierrez et al. 2008).

Construction of liquid manure storage sites requires relatively larger setbacks. In Minnesota, for example, any liquid manure storage facility should not be constructed within 91 m of the outside edge of a sinkhole (Minnesota Pollution Control Agency 2000). Kentucky, Missouri, Wisconsin, and Iowa have setbacks from sinkholes of 46, 91, 122, and 152 m, respectively (*ibid*.). Many states also rely on the engineering designs to ensure the safety of the facilities.

Construction of landfills around sinkholes is more complicated. The U.S. EPA and several states including Kentucky, Indiana, Maryland, Pennsylvania, Georgia, and West Virginia have specific requirements for such facilities (Davis 1997). Whether the area adjacent to a sinkhole is suitable for landfill sitting or how far away the facility should be constructed from the sinkhole depends on the degree to which the karst develops. Travis et al. (2000) and Hatheway (1996) provided detailed discussions on this topic.

Little surface runoff is present on well-developed karst lands. Overland flow during storms disappears into sinkholes and grikes to enter the groundwater system as internal runoff. In many engineering designs, surface runoff and the associated contaminants are disposed of into the existing sinkholes. Runoff from roadways, parking lots, and other impervious areas frequently discharges into sinkholes carrying highly turbid water, road salt and hydrocarbon contaminants from automobiles.

A sinkhole that has been modified or altered to promote or accept stormwater drainage is considered to be a Class-V Injection Well. Class-V Wells are regulated under the authority of the Safe Drinking Water Act, U.S. EPA Underground Injection Control Regulations, and the relevant state rules. When a sinkhole is permitted and managed as a Class-V Well, it should prevent any injection activity from endangering underground sources of drinking water.

Sinkhole terrains, especially in regions with a shallow water table, are flood prone. Sinkhole flooding can be caused by surface runoff and groundwater flow. When the soil within a sinkhole is less permeable, a temporary pond or lake may be perched above the local groundwater table after rains. Sinkhole ponds may take days or weeks to drain. On the other hand, when sinkholes lack impermeable soil, they connect the underlying groundwater system through their drains, and they are part of the aquifer system. Rising of groundwater levels forces water back up through the drain to flood the sinkhole. The sinkhole functions as a large-diameter monitoring well. The standing water level in the sinkhole is the surface expression of the groundwater table, and such a sinkhole can be considered as a karst window. A spring forms when water spills out of a sinkhole. Grouting, when it is used to remediate sinkholes or sinkhole-prone areas, can also cause sinkhole flooding. Grouting may inadvertently seal off the subsurface drains and dam the groundwater flow. Special zoning restriction or other stormwater runoff control measures may be required to control the flooding problem.

In rural areas, sinkholes represent lost acreage from farming. In urban areas, sinkholes may be efficient drains for sewage or contaminated stormwater runoff from streets and parking lots. Because sinkholes are the loci of water recharge to the karst aquifer, waste placed in them or the leachate can be carried directly into the groundwater. Once underground, these materials acts as source of pollution which can continue to function for long periods of time, even long after remedial measures have been taken on the sinkhole itself (Loop and White 2001).

Selected best management practices for sinkholes as listed in Table 2.1 include:

- On-site personnel should be thoroughly briefed on the special protective measures recommended for sinkholes and the safety concerns associated with operating within and around them.
- If a previously unidentified sinkhole is encountered during construction, operating activities should cease until the feature is properly assessed.
- Avoid excavation activities during storm events or periods of sustained heavy rainfall to reduce the potential for soil erosion and sediment transport into the subsurface.
- Maintain the natural surface drainage pattern as much as possible to avoid disrupting natural subsurface flow.
- Pile any surplus surface materials away from sinkholes.
- Minimize clearing of vegetation within sinkholes as much as possible to provide suitable areas for infiltration of surface runoff.
- If blasting is necessary, controlled blasting techniques should be used to minimize the vibration and sound waves.
- Avoid fuelling or servicing machinery near sinkholes.
- In areas where the sinkhole is a common occurrence, conduct geophysical investigation to understand the subsurface conditions and identify any buried sinkholes.
- Document all information regarding the sinkhole including dimensions, shape, drainage area, swallet information, and type.
- Design erosion and sediment control and stormwater management facilities so that the excavated materials do not drain into sinkholes.
- Depending on the size of the tributary drainage area, the runoff water quality, and the difficulty of establishing an alternate outlet, sinkholes may need to continue accepting some or as much water as in the past. A filtering system design may be necessary to prevent lateral erosion while allowing water to pass. A Class-V Injection Well permit is required for this operation.
- If the sinkhole may undermine the safety of the construction site, the sinkhole should be remediated appropriately or engineering measures should be taken to assure that the facility remains undamaged.

- Keep the wheels or tracks of vehicles away from the edge of the sinkhole for safety of the operators.
- Whenever uncertainties arise, always work with a qualified geoscientist with experience in karst to develop specific best management plans for each sinkhole.

In general, stormwater runoff management constitutes the most important part of sinkhole management plans in karst lands. In a sinking stream where a portion or all of the stream flow recharges into the underlying karst aquifer through a sinkhole, the sinkhole management will include the surface watershed upstream of the sinking point. Such a sinkhole is not listed in Table 2.1, but is often referred to as alluvial streamsink doline (Jennings 1985), swallet, or ponor. The management of such a sinkhole should be included in the watershed management plan of the surface stream (EPA 2005). The surface watershed management should emphasize the potential impacts of land development on both the surface water and groundwater systems.

2.7 Conclusions

Karst frequently presents "difficult ground conditions" to engineers, and its complexity is often inadequately appreciated. The maturity of karst development, number of existing sinkholes, frequency of voids encountered, type of overburden soil, the irregularity of bedrock surface, and groundwater conditions are factors to be considered in development and planning of foundation designs on karst. The key in any engineering design is the understanding of the local karst processes. The consequence of structural failure should also be considered in selection of proper foundations. Sinkholes are a surface symptom of often complicated subsurface erosion and deformation processes. Although sinkholes vary in size, shape, and type, water is the dominant enabling force for their formation. Proper land use in sinkhole-prone areas should include a sinkhole management plan that prevents new sinkhole from occurring and avoids groundwater contamination. Various techniques are available for sinkhole mitigation, and their use depends on the physical, hydrological and ecological properties of the sinkhole and tolerance of the construction to collapse or subsidence. The engineering measures need to be tailored to address the specific conditions of that particular sinkhole. In general, a sinkhole remediation consists of plugging of the throat, filling of the void and capping. When the remediation requires continued surface runoff through that sinkhole, it may be necessary that both the water quality and quantity need to be addressed.

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Chapter 3
Dams and Reservoirs in Karst

Petar Milanović

Abstract Construction of dams and reservoirs in karst is historically known as a very risky task. Inspite of very detailed geophysical investigations and repeated sealing treatments, the possibility for dam failure cannot be eliminated. In the karst environment, with its highly random distribution of dissolution features, some uncertainties always remain. The final determination of the adequacy of sealing measures comes after the first reservoir impoundment or even later. In many worldwide examples, watertightness treatment during dam construction was only partially successful, with some remedial work after impoundment being quite common. However, in some cases, the problem is simply too complicated and cannot be overcome.

Special approaches have to be undertaken in order to prevent seepage from reservoirs. The key elements are a good geological map and proper geophysical investigations. These investigations are key prerequisites of dam construction in karst and cutting costs through restricting them usually results in increasing the chance of project failure. To deal with karst successfully, innovation, engineering practice, execution feasibility, and commercial understanding have to be undertaken. Grouting alone is definitely not adequate in the case of large karst conduits. Special treatment of large caverns and flexibility during grout curtain execution, including modifications and adaptations on the basis of the geological findings, should be the standard procedure for dam construction in karst to minimize risk. Such an approach is the basic worldwide rule in the fight against leakage from dam sites and reservoir abutments.

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3.1 Introduction

In many karst regions of the world, the only resource available for economic development was the large groundwater aquifer. Because of that, karst terranes have been modified and adapted through a range of human activities to meet such needs as drinking water, flood control, irrigation, and hydroelectric power. The subsequent development of karst groundwater and rudimentary investigations of this resource date back several millennia to old Greek, Persian, and Chinese times. However, construction of large dams and reservoirs in karstified rocks is relatively new. The large projects started during the first part of twentieth century, but the intensive construction period started after World War II.

The right geological conditions are the basis for the construction of safe dam structures and watertight reservoirs. Due to the specific and complex nature of karst, it is not easy to select sites for dams or reservoirs that would be acceptable, without additional remedial measures. Successful solutions require serious and complex geological, hydrogeological, and geotechnical investigation programs and close cooperation of a wide spectrum of scientists and engineers. Each karst region is unique, and changes in the physical landscape can be unpredictable and can occur very rapidly. It has been found that some methods already applied to other geological environments had to be modified for karst settings. Finding new and better investigation methods in geology, hydrology, and geophysics was of great importance.

During dam, reservoir, and tunnel construction, unique problems are posed by the presence of caverns. The most frequent technical difficulties are water leakage at dam sites and from reservoirs, and breaching by water and mud during tunneling and other underground excavations. Natural or induced subsidences are also frequent failures related to characteristic structures in karst (Sharp 1997; Romanov et al. 2003; Beck 2004; Criss et al. 2008).

Because of the nature of karst, it is not easy to select the dam site location that would be acceptable for construction without serious, large-scale underground or surface impermeabilization. The common underground structures are grout curtain, plugging of karst caverns and channels, and construction of different cut-offs. The common geotechnical methods at the surface are compaction of the bottom surface, shotcrete, grouting, geosynthetics, plugging, and cylindrical dams or dikes to isolate large swallowholes.

Construction of dams in evaporates is a particularly risky task because solution rates are orders of magnitude higher compared to other carbonates. A number of dam failures in evaporates has resulted in large-scale mortality and great financial loses. Technology of watertightness remedial works in evaporates is still rudimentary compared to other karstified limestone and dolomites.

3.2 Overview of Dam and Reservoirs Construction in Karst

Inadequate selection of the construction site results in either a structural failure causing the project to be abandoned or leads to long, unpredictable remediation works. From the experiences at the very beginning of dam construction in karst during the first part of twentieth century, karstified rock has been considered unsuitable for these kinds of projects. Dried reservoirs or reservoirs with unacceptably high leakage confirm that opinion: McMilan Dam (USA, 1893), Hales Bar Dam (USA, 1913), Camarasa Dam (Spain, 1920), Montejaque Dam and Reservoir (Spain, 1920), Great Falls Dam (USA, 1925), Fodda Dam (Morocco, 1928), Vrtac Reservoir (Montenegro, 1952), May Dam (Turkey, 1959), Cevizli and Keban Dam (Turkey, 1979/80), Lar Dam (Iran, 1978), Kalecik Dam (Turkey, 2001). These examples have led to the opinion that reservoirs in karst may fail to fill, despite an extensive investigation program and sealing treatment. Since the risk due to karstification could not be eliminated, the Darwin Project in Tasmania was abandoned in 1920. However, after several phases of long-term investigations (1950, 1983, 1986, 1989), construction was finished and reservoir filled in 1992 (Giudici 1999). Another dam project in Tasmania, the Lower Gordon Dam, was aborted due to legal and environmental reasons in 1983. This dam would have flooded caves of great archeological importance (Kiernan 1988).

After World War II started an era of intensive dam construction in karst environments (Ford and Williams 2007). Many dam projects have been successfully developed in countries with large karst regions, mostly at Dinarides, Helenides, Taurides, Zagros, and China. Nevertheless, the road to those successes was, in some cases, paved with failures. New investigation techniques and new sealing technologies were developed and applied in different karst projects. Large-scale underground or surface impermeabilization techniques were applied. Long and deep grout curtains were constructed, including plugging of underground caverns and channels. In the case of surface sealing, the most common geotechnical methods were clayey blankets, shotcrete blankets, different kinds of geotextiles, and surface grouting.

However, in the case of dam and reservoir construction in karst, the risk component cannot be eliminated in spite of detailed and long-term investigations. The risk can be minimized to an acceptable level, but never absolutely eliminated. Consequently, proper risk reduction strategy is important during all phases of dam and reservoir construction. Changes caused by dam and reservoir construction impact ecological, infrastructure, social, and political systems. Some of these impacts are positive and predictable, but they can be also negative and unpredictable. This text is focuses on engineering problems.

3.3 Role of Geological and Geomorphological Conditions

Carbonate rocks and evaporates are prone to the intensive fluvial erosion and chemical dissolution at the same time. Many gorges and deep canyons are developed in those rock masses. From the geomorphological, geological engineering, and geotechnical viewpoint, limestone gorges are perfect for dam construction, particularly for concrete dams. However, in many cases, karst processes deteriorate hydrogeological properties of those rock masses.

Intensity and depth of karstification depends on different geological properties and processes: lithology, structural composition, tectonic (particularly recent) movement, density of discontinuities, position of important erosion base levels, corrosion (dissolution), and hydraulic action (Milanović 1981). Karst is a product of processes that operate on continental land masses, especially when the land masses are uplifted above sea level. In the most complex cases, karstification occurred in discontinuous phases of bedrock uplift or submersion caused by epirogenic and orogenic movements. For instance, the Dinaric geosyncline karst was formed over various discontinuous periods, generating a combination of the recent karst and stratigraphically different paleokarsts.

Two different types of karst porosity are most common:

1. Vuggy porosity found in limestone bedrock. Some of these vugs are interconnected, but most are isolated. The hydrogeological role of vuggy porosity is secondary, hence it can be easily grouted.
2. Classical karst porosity, represented by open solution channels, discontinuities enlarged by solution, and caverns developed along the faults, joints, and beddings, which create a well-connected network of conduits. This network represents the highest potential for leakage pathways.

According to generalized geomorphological and geological properties, deep and narrow canyons usually feature shallower karstification than wide river valleys or karst depressions (poljes). The deepest erosion base levels in narrow canyons usually correspond to riverbeds, which are manifestations of the surrounding karst aquifer and its water table, e.g., Piva Dam (Montenegro), Tange Duk (Iran), and Grančarevo Dam (Bosnia-Herzegovina, hereafter B-H). The same conclusion has been drawn by Chinese karstologists. However, this is not a hard and fast rule as there are some very narrow dam sites, such as the Abol Abas (Iran), where the groundwater level (GWL) is 50 or more meters beneath the bottom of the dam site. A deeper water table allows greater karstification between the GWL and the surface of the bedrock, causing engineers to design a more comprehensive grout curtain below the dam, increasing costs and time of construction.

Below the wide karst river valleys, situated at high elevation, deep karstification can be expected. The hanging rivers along these valleys are mostly temporary. Depending on the position of the surrounding erosion base levels, the carbonate rock mass can be karstified well below the valley floor, such as Keban (Turkey) and Lar (Iran).

Dam sites located at the upstream section of river bends need greater exploration than those in the straight part of the river valley. During the karst aquifer evolution, the section of river valley downstream from a bend plays a role of local base level of erosion. Gradients between upstream and downstream river sections are much steeper than along the riverbed. If monocline limestone structures occur between the upstream and downstream river sections, then underground hydrogeological connections through the karst channels are to be expected, e.g., Keban (Turkey), Salakovac (B-H), Karun III (Iran) and Dokan (Iraq).

On a regional scale, structural relationships have an important role in forming the hydrogeological properties in a karst region. If an anticline structure exists between the reservoir and the lower erosion base level, the possibility for karstification perpendicular to the structure is considerably reduced. Of particular importance is the reservoir watertightness, which for many dam sites and reservoirs is based on the hydrogeological role of large anticlines, e.g., Karun III and Salman Farsi Dams (Iran), Bileća Reservoir (B-H). If the folding structures are extensively compressed by tectonic forces with prevailing horizontal stress, then the anticline cores will be resistant to karst processes. The karst channels are mostly developed in the direction of axial planes rather than perpendicular to them. An example of the hydrogeological role of such geological settings is the "Lastva anticline," which has a core predominantly of dolomite (Fig. 3.1). This structure acted as a hydrogeological barrier between reservoir and lower erosion base levels. The huge "Bileća Reservoir" in B-H, situated completely on karstified limestone, operates without leakage because of positive hydrogeological role of this type of geological structure (Milanović 2006).

In contrast, large karst depressions (poljes) are hydrogeologically complex places for reservoir construction. Long zones with concentrated infiltration points (ponors and estavelles) with swallowing capacities ranging from a few m^3/s to 100 m^3/s are common hydrogeological features along the border of poljes. During the dry season, the water table is deep beneath the bottom of a possible reservoir. If estavelles are prevailing hydrogeological features, the problem of artificial impermeabilization is more complex than in the case of only ponors. In the case of estavelles associated with huge uplift, building watertight structures are problematic. Active uplift can easily demolish these structures or create new openings in the protected estavelles.

Huge caverns and a deep GWL below the dam foundation and bottom of reservoirs are common in karst. Some examples are listed below:

(a) In the case of Keban Dam (Turkey), the largest cavity, called the Crab Cavity, was discovered at a depth of 320 m below the crest level. This cave was filled with 64,000 m^3 of concrete and injection solids.
(b) The lowest GWL is 200 m below the Mornos Reservoir storage level (Greece).
(c) Below the Lar Dam site (Iran), a large cavern, 27 m high and 68 m wide, was discovered at a depth of 210 m below the riverbed. The volume of the cavern was determined to exceed 90,000 m^3. A few other caverns have been discovered at the depth of 250–430 m below the riverbed.
(d) In the case of Perdika Reservoir (Greece) the GWL was about 70 m below the reservoir bottom, in the karstified bedrock.
(e) Numerous large water-bearing karst channels were detected ~180 m beneath the river level at Canelles Dam site (Spain).
(f) At Wujiangdu Dam site (China), many karst cavities, particularly in the left bank, are found down to the depth of about 250 m beneath the riverbed.
(g) Part of Akkopru Reservoir in Turkey is located on highly karstified limestone with number of vertical shafts. GWL in this part is about 100 m below the reservoir bottom.
(h) The water table below the Hutovo Reservoir in B-H, in drought conditions, is more than 100 m deep. With abrupt rising of the water levels, the air current from piezometers can reach a velocity of 15 m/s.
(i) Large karst caverns were detected at depth of more than 100 m below the Chichik Dam site (Uzbekistan).

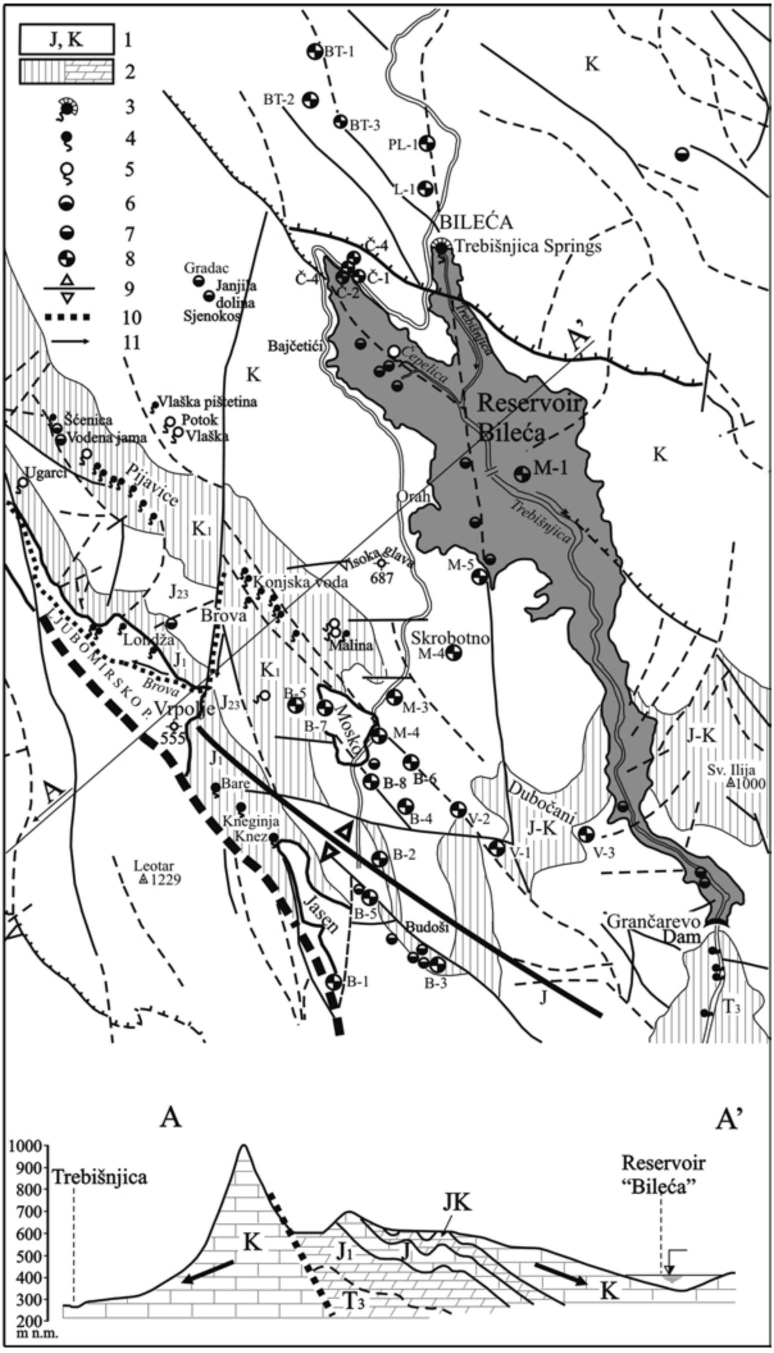

Fig. 3.1 Right abutment of "Bileća" reservoir and position of lastva anticline, B-H; *1* Limestone; *2* Dolomite; *3* Large spring; *4* Small permanent spring; *5* Temporary spring; *6* Ponor; *7* Karst shaft; *8* Borehole; *9* Anticline; *10* Regional fault; and *11* General direction of underground flows

In some cases, reservoir construction in closed karst depressions was abandoned after extensive subsurface investigations or its designation was changed. Due to huge leakage through the number of estavelles from the Vrtac Reservoir in Montenegro, the reservoir's role has been redesigned for temporary retention rather than a permanent water reservoir (Milanović 2010). Because of karstified limestone at one section of Aliakmon River (Elati basin), the Ilarion Dam project (Greece) was suspended. Detailed investigations and analysis have resulted in the relocation of some projects such as the Miatlinskaya Dam (Russia) and the Havasan Dam (Iran) (Milanović 2010). The seepage problems with Hales Bar Dam (USA) started immediately after the first filling (1905). Unable to overcome this problem, the dam was demolished in 1968 and replaced with Nickajak Dam, 10 km downstream (Bruce 2003).

One of the most complex problems related to the geology of some dam sites and reservoirs is karstification created by the simultaneous influence of phreatic and thermal waters, e.g., Višegrad Dam (Bosnia), Salman Farsi and Karun IV Dams (Iran), Pengshui Dam (China), Chichik Dam (Uzbekistan), and Hamam Grouz (Algeria). Sources of the heat for these thermal waters are usually very deep and detection of its position is a complicated task. Consequently, the location of karst features created by thermal water also needs complex investigations, particularly deep boreholes for thermal measurements (for more information, see Ballard et al. 1983 and Fazeli 2007). For successful grout curtain design, particularly its inclination and depth, the exact determination of the location of karst channels produced by the upward hot water flows is essential.

In China, construction of a number of underground dams and reservoirs has taken place. Lu (1986) and Yuan (1999) show that these dams have storage capacities between 1×10^5 and 1×10^7 m^3. One of the largest underground reservoirs was built on the Linlangdong underground river in Qiubei, Yunnan Province, by constructing a 15 m high underground dam (1955-1960) with an underground flow discharge varying from 23.8 to 100 m^3/s. Underground dams have also been constructed for Yuhong Power Plant (Hunan), Beilou Power Plant (Quangsi), and Wulichong Reservoir (Yunnan Province). Several underground dams have also been constructed in the limestone in Japan (Okinawa and Miyako Islands).

One of the largest underground projects is the Ombla Underground Dam and Reservoir (Croatia), which takes discharge (Q) from the Ombla Spring (mean Q = 24.4 m^3/s). At the dam, deep flysch sediments act as a hydrogeological barrier and get progressively higher on each side of the spring, forming a "V" cross-sectional profile. All structures (dam, reservoir, and power plant) are situated underground. The dam's grout curtain, including cut-off structures and concrete plugs, has been tightly connected to the impervious flysch sediments. The crest elevation of the arch-like underground dam is 100 m above sea level with a grout curtain 150–200 m below sea level. Underground storage water volume ranges between 10×10^6 m^3 and 12×10^6 m^3.

One of specific characteristics of reservoirs in karst is large storage deep within the reservoir banks. This storage is the active part of the reservoir. Based on calculation of Gunay et al. (1985) the bank storage rate was determined to be 35–40%

of water stored in the Oymapunar Reservoir (Turkey). In the case of Bileća Reservoir (B-H), the bank storage was estimated to be 10–15% of water stored in the reservoir.

Due to dam construction in karst, large and permanent karst springs have been affected by the new regional, higher hydraulic head created by the reservoir. In those cases, it was important to understand whether any leakage may occur. Dumanli Spring (Q = 25 to >100 m^3/s) was flooded by 120 m from the Oymapinar Reservoir (Turkey; Trebišnjica Spring (Q_{av} = 80 m^3/s) had an increase in the hydraulic head of 75 m from the Bileća Reservoir (B-H); Pivsko Oko Spring (Q_{av} = 25.5 m^3/s) was flooded by a 70 m water column of the Piva Reservoir (Montenegro). After impounding and many years of operation of these aforementioned reservoirs, no negative influence of the spring submergence was observed, especially with regard to water losses from reservoirs.

3.4 Investigation Methods in Karst

A good geological map, including hydrogeological, geostructural, and geomorphological analysis, represents the basis for dam and reservoir construction in any geological environment including karst. The key investigation targets in karst are watershed zones, the evolution process of karst aquifer, depth of the base of karstification, location of karst conduits, and the groundwater regime. The most common methods applied in dam construction in karst are specific hydrogeology/hydrology, tracer tests, geomorphological analysis, specific geophysical investigations, speleology and dissolution tests in the case of evaporates.

Hydrogeological and hydrological investigations are closely connected due to the very complex relationship between surface water and groundwater (Milanović 1981; Bonacci 1978). Depending upon the hydrogeological composition, hydrological conditions, and karst aquifer evolution, there can be considerable variation in connections between surface and underground waters. The relationship depends on the capacity of underground and surface systems to convey water. Hydraulic pressures, gradients, and friction also significantly influence the connection from the surface waters to groundwater circulation.

Tracer tests are frequently used at the regional scale to delineate the difference between the hydrogeologic and topographic watersheds. Watersheds with very distinct and permanent boundaries are rare in karst. For this reason, tracer tests in different hydrological stages are strongly recommended. For regional tracer tests, the most commonly used dyes are fluorescein and Rhodamin B, lycopodium spores, inorganic salts, and radioactive salts. Short distance tracer tests are applied at the dam site areas and reservoir banks to determine position of concentrated filtration zones, degradation of grout curtains, and velocity of concentrated flows prior to grouting.

Geomorphological analysis is based on the close genetic relationship of geomorphology with karst aquifer evolution. Sinkholes, collapses, dry valleys,

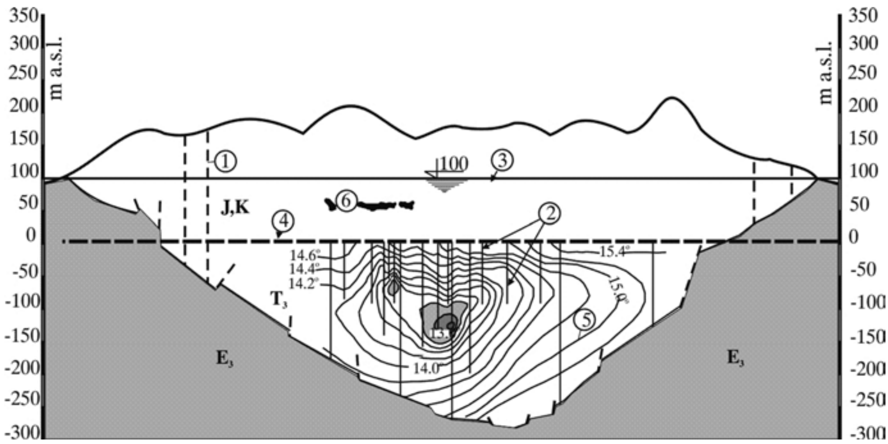

Fig. 3.2 Ombla underground dam site (Croatia). Thermal measurements indicate the position of major underground flows. (J, K) limestone, (E_3) Eocene flysch, *1* Boreholes drilled from surface, *2* Boreholes drilled from gallery, *3* Proposed level of underground reservoir, *4* Gallery, *5* Isotherms, *6* Caverns

and karst poljes are a consequence of karstification and provide unique information related to the geology and hydrogeology of dam sites, reservoirs, and catchments areas. Finding the position and the characteristics of main discontinuities and folding structures are crucial during dam site selection and later for the efficient design of the grout curtain.

Geophysical methods are very important for investigation of those parts of carbonate rocks that are not directly observable. The best results for estimation of the regional zone of the base of karstification are provided by the method of electrical sounding. The charged body method (Milanović 2001, 2004) can be appropriate to determine the route of an active karst conduit away from a ponor or in the catchment area close to a spring. In the case of closely spaced boreholes, the seismic cross-hole method is frequently used. Thermal logging appears as one of the best methods (Milanović 2004) for concentrated underground flow detection (Fig. 3.2).

Reported thermal logging measurements were used at the Ombla underground dam project (Croatia) (Ravnik and Rajver 1998), Maotiahoe Fourth Dam (China) (Chengjie 1988), Buško Blato Reservoir (B-H) (Borić 1980), Ataturk Dam (Turkey), and Salman Farsi Dam (Iran) (Milanović 2004). Thermal measurements in the karst of France (Drogue 1985) were very useful for underground flow detection, particularly along the grout curtain routes. Besides thermal logging, the following methods can provide useful data for karst environments: caliper, gamma, gama-gama, neutron, flow meter, televiewer, and borehole radar. Experiments with the "geo-bomb" (a specific kind of seismic method) encourage the further development of this particular method (Arandjelović 1976). Recently, good results were provided from magnetic resonance sounding and the transient electromagnetic method (Legchenko et al. 2008).

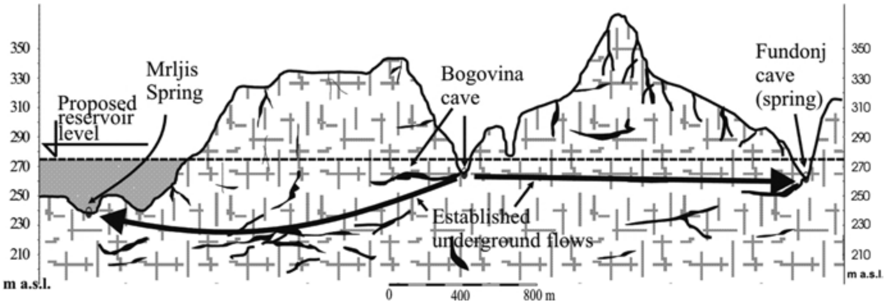

Fig. 3.3 Bogovina Dam project revised on the basis of speleological investigations (Milanović 2005)

Speleology is the only investigation method for direct observations in karst underground. In a majority of dam projects in karst, speleological investigation has played an important role. For instance, the examination of large caverns of Sklope Dam (Croatia), Salman Farsi (Iran), Ombla Underground Dam (Croatia), Keban Dam (Turkey), and Marun Dam (Iran) helped with the placement of a number of grout curtain routes (Milanović 2004). The building of numerous underground dams in China and the Buško Blato Reservoir (B-H) were aided by speleological studies. After detailed speleological investigations of a cavernous system at the Bogovina Dam site (Serbia), the proposed height of the dam was lowered by 9 m (Milanović 2005; Milanović et al. 2010) (Fig. 3.3).

3.5 Common Problems and Failures

In many cases, if dam and reservoir sites are selected in a rock mass with suitable geological conditions, leakage is not a problem or can be considerably reduced with properly designed and implemented impermeabilization works. Some of those sites are Ekbatan Dam (Iran), Bileća Reservoir (B-H), Castillon (France), Peruća (Croatia), Altinapa (Turkey), Genisiat (France), Nebana (Tunisia), Berke (Turkey), Rama (B-H), Globočica (FYR Macedonia), Quinson (France), Punta Del Gall (Switzerland), La Angostura (Mexico), Bin al Ouidance (Morocco), Greoux (France) and Santa Guistina (Italy).

However, it is well known that seepage problems, even failures, are common in karst. With respect to the construction of dams and reservoirs in karst, failure or water loss can occur in the form of:

1. Concentrated leakage during the first filling of the reservoir.
2. Slow but constant erosion of the natural fills from joints and caverns, including degradation of grout curtain and consequently constant increasing seepage.
3. Abrupt failure (collapses in reservoir and huge seepage) after many years of successful reservoir operation.

Concentrated leakage during the first filling of reservoir is a problem at more than 50% of reservoirs in karst. Some regrouting or other types of treatment, after first impoundment, are quite common in karst and the designers/contractors need to be prepared for such work. In many cases, additional treatment is successful and the dam/reservoir operates at full capacity. Examples from Milanović (2004) include Great Falls (USA), Tiangiao and Guanting (China), Canelles (Spain), Dokan (Iraq), El Cajon (Honduras), Mavrovo (FYR Macedonia), Marun (Iran). Sometimes after remedial treatments, leakage can be kept at acceptable levels: Keban (Turkey), Camarassa (Spain), Slano (Montenegro), Buško Blato and Hutovo (B-H), Mornos (Greece). However, remedial treatments are not always capable of overcoming the seepage problem: Lar (Iran), Hales Bar (USA), Vrtac (Montenegro), Montejaque and Maria Cristina (Spain), Vrtac (Montenegro), Salakovac (B-H). For more information on these specific examples, see Milanović (2004).

Progressive erosion is also a common problem in engineering projects undertaken in karst. A typical example is the Višegrad Dam on the Drina River (B-H). During initial filling of the reservoir in 1989, several new springs developed downstream of the dam, with combined discharge of 1.3 m^3/s. Large quantities of clay in the discharge of these new springs indicated intensive subsurface erosion. The seepage gradually increased to 14.0 m^3/s by 2008/09 and the depth of siphon seepage flows also gradually increased from 60 to 110 m (or deeper) below the dam foundation. These values were determined using a number of different techniques including water table investigations, chemical analyses, tracer tests, geostructural analyses, and thermal measurements of water in boreholes. During the last investigation (2009) by divers, a huge karst shaft (3 m in diameter, 45 m deep) was discovered ~150 m upstream from the dam on the former riverbed.

Increased seepage due to progressive erosion also occurred at the following dams as discussed in Milanović (2004): Great Falls Reservoir (USA), where water loss rose from 0.47 m^3/s in 1926 to 12.7 m^3/s in 1945; Slano Reservoir (Montenegro), where losses increased from 3.5 m^3/s in 1971 up to 4.5–7 m^3/s (depending on reservoir level) by 2001 and Gorica Dam (B-H), where there was a seepage from 1.5 m^3/s in 1966 to 4.4 m^3/s in 2003 (maximum level). Gradual and long-term seepage was registered at the Špilje Dam (FYR Macedonia), Mosul Dam (Iraq), and Wolf Creek Dam (USA).

Abrupt failures due to collapses occurred in the Hamam Grouz Reservoir (Algeria) after 17 years of successful operation, in Mavrovo Reservoir (FYR Macedonia) after 25 years of operation (alluvium collapsing into karstified marbly limestone – Milanović 2004) and in the Slano Reservoir (Montenegro) after 30 years of operation (new ponors created by grouting operations – Milanović 2004). Additional examples of massive leakage either after initial filling of the constructed reservoir or as results of complicated sealing works are presented in Table 3.1.

Table 3.1 Dam/Reservoir leakage after initial filling or resulting from sealing operations

Location	After first filling (m^3/s)	After sealing works (m^3/s)
Keban (Turkey)	26	<10
Camarasa (Spain)	0.2	2.6
Lar (Iran)	10.8	No success
Ataturk (Turkey)	11–14	?
Salakovac (B-H)	>10	No sealing works
Marun (Iran)	10	Negligible
Mavrovo (FYR Macedonia)	9.5	Negligible
Great Falls (USA)	9.5	0.2
Canelles (Spain)	8	Negligible
Buško Blato (B-H)	5	3
Dokan (Iraq)	6	No leakage
Hutovo (B-H)	3	1
El Cajon (Honduras)	1.65	0.1
Hales Bar (USA)	50?	Abandoned
Montejaque (Spain)	4	Abandoned

3.6 Leakage Prevention in Karst

Concentrated underground flows through channels and caverns represent the main potential risk for reservoirs in karst. Impermeabilization of those flows needs special approaches and technologies at the surface and subsurface.

3.6.1 Surface Treatment

To reduce water losses from reservoirs and sinking rivers, the following methods are currently applied:

- Using impervious clay, asphalt, or asphalt-concrete blankets
- Covering karstified limestone with shotcrete
- Construction of heavy reinforced concrete slabs
- Plugging of surface karst channels by self-compacting concrete
- Using different kinds of geotextile or sandwich-type geotextile/clay liners
- Surface compacting to protect from sinking zones in the alluvial overburden
- Enclosing large ponors and estevelles with cylindrical dams
- Closing estavelles with concrete plugs equipped with nonreturned valves
- Isolating large ponors (swallowholes) with dikes
- Plugging large open cracks with grout injections (dental treatment)
- Protecting impervious blankets with aeration tubes

Blanketing with several layers of compacted clay was used in the case of Altinapa Reservoir (Turkey), Cuber and Majorque (Spain), Tel Yeruham Dam (Israel), Hamam Grouz, Ourkis, and Saf-Saf Reservoirs (Alger), High Mill Dam (Georgia, USA), part of the Mavrovo Reservoir (FYR Macedonia), and the Seshpir Reservoir (Iran). Loam blankets and asphalt blankets were applied to prevent leakage at particular areas of the Perdicas Reservoir (Greece); however, these were ineffective in cases of high storage levels. Asphalt was used as an antiseepage blanket for the May Reservoir (Turkey).

Reinforced shotcrete represents an efficient technology to seal shallow reservoirs, riverbeds, and tunnels located in karstified carbonate rocks. This method was used in the case of exposed carbonate rock. To prevent leakage along the Trebišnjica River in B-H, 62.5 km of riverbed was blanketed by shotcrete (Popovo Polje, B-H). Natural seepage losses amounted to 75 m^3/s through ponors (swallowholes) and cracks widened by disolution along the riverbed (Milanović 2004). The flanks of reservoir at the end of river were also blanketed by shotcrete. Altogether an area of 2.2×10^6 m^2 was blanketed with shotcrete. At some places of the karst channel beneath the lining, the shotcrete was demolished due to localized uplift (Milanović 2004). After additional remedial works (including construction of nonreturned valves) the losses at those places were eliminated. Seepage was simultaneously measured at 16 hydrological/hydrogeological stations along the riverbed in three different flow periods (wet, dry, and average flow).

In some cases, (if a dam is not equipped with a bottom outlet) to avoid the potential risk of reservoir failure, the most reliable method of preventing seepage is using a heavily reinforced concrete slab. In solving the problem of watertightness of the 100 m deep Akkőprű Reservoir (Turkey), a 1 m thick reinforced concrete slab was constructed over the part of reservoir floor and the corresponding bank to cover 250,000 m^3 of extremely karstified limestone (Gunay and Milanović 2007). A number of vertical karst shafts were plugged with concrete before the slab construction. To prevent filtration below the concrete slab, it was recommended that a long cut-off diaphragm wall (connected with slab) be constructed (Fig. 3.4).

Compacting the surface layer in conjunction with different types of plastic foils and geotextile sheeting is the frequently used method to prevent leakage through the alluvial reservoir bottom affected by karstified bedrock. In the case of Hutovo Reservoir (B-H), large capacity karst channels are situated below the reservoir bottom (Fig. 3.5). During rainy seasons, huge amounts of water flow through this zone. To prevent this leakage from the reservoir, three different impermeabilization approaches were applied: (1) compacting of natural alluvial deposits, (2) shotcrete protection of reservoir banks (exposed limestone) and (3) plastic foil placed above the main ponor openings in the alluvium. As the reservoir was filled, the water table rose quickly and displaced air from the caverns. Such displacement creates a strong pressure whereby the confined air inflates a plastic foil which could explode. To prevent this from occurring, aeration pipes were constructed to evacuate the confined air from below the reservoir bottom (Milanović 2004).

To isolate the broad ponor (swallowhole) zone at the edges of storage reservoirs, earth-filled dikes are used at the Buško Blato Reservoir (B-H) and the Mavrovo Reservoir (FYR Macedonia). In the case of large ponors and estavelles, with single and large openings, cylindrical dams were constructed around ponor

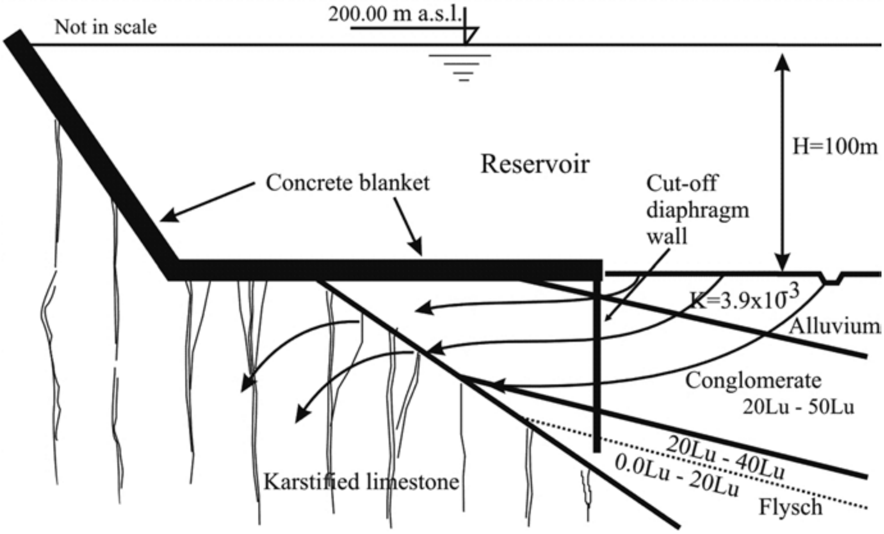

Fig. 3.4 Akkőprű reservoir, Turkey. Seepage protection – concrete slab and vertical cut-off diaphragm wall (Solution proposed by DSI, Ankara, Turkey)

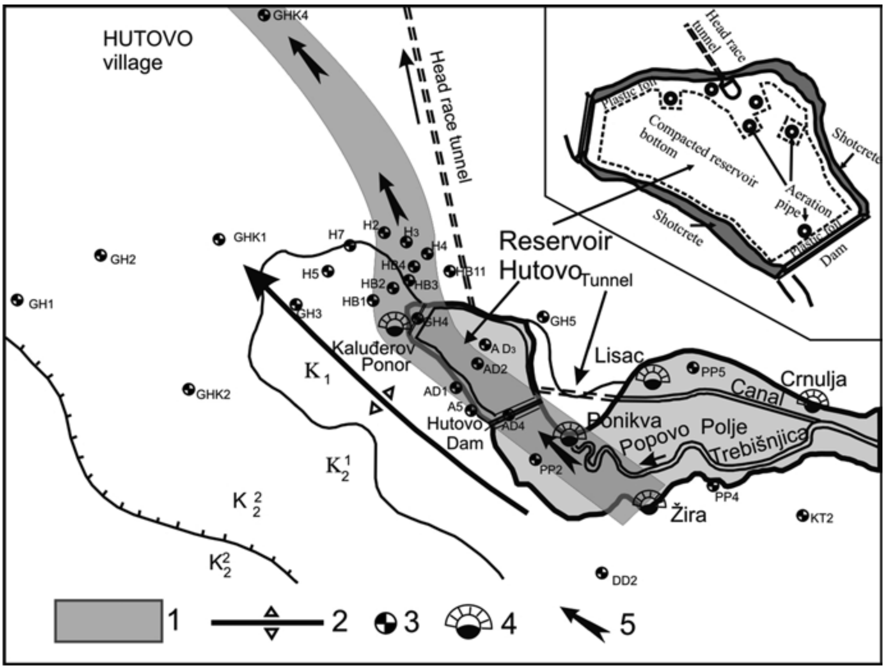

Fig. 3.5 Hutovo Reservoir (B-H). *1* Zone with concentrated underground flows, *2* Anticline axis, *3* Piezometers, *4* Large ponors (swallowholes), and *5* Main direction of underground water flows

Slivlje (diameter 50 m) and estavelles, Opačica and Misor, (Montenegro, Nikšićko Polje). One way to solve the problems of estavelles in storage reservoirs is by closing the opening with plugs equipped with nonreturned valves. Cylindrical dams and nonreturned valves were used in many projects in China. However, experience with nonreturned valves in Vatic Reservoir (Montenegro) has not been totally successful because after heavy precipitation, the extremely strong upward pressure opened a number of new estavelles at the reservoir bottom.

3.6.2 Underground Treatment

3.6.2.1 Grout Curtain – Continual Watertight Structures

Construction of grout curtains in karst requires special approaches and technologies. The design work is only finished when curtain construction is completed. Modifications during construction are therefore the rule and not the exception due mainly to the presence of huge caverns (filled with sediment or empty). Grout curtains in karst are more complex and much larger than curtains in other geological formations (Table 3.2). Common modifications to curtains are rerouting of the curtain, increasing of curtain length or depth, increasing the number of grouting galleries, increasing of grouting rows and cavern plugging.

Four different types of continual watertight structures (curtains) are:

- Suspended (hanging) grout curtain
- Grout curtain connected with impervious structures (positive cut-off)
- Cut-off diaphragm wall (constructed by trench or overlapped piles)
- But-tab structure (completely closed watertight structure)

The most common materials for grouting in karst are cement, clay, asphalt, and hot bitumen. Cement-based grout mixes are commonly applied in recent grouting practice. The cement component usually consists of >95% of the grout mix, and additional components are bentonite, different chemical additives, polyurethane, and artificial sponges. Clay-cement stable grout mix uses clay as its base component with cement and bentonite as additional components. This grout mix was used in many projects in Dinaric karst region: Peruča Dam (Croatia), 75% clay;

Table 3.2 Examples of large grout curtains in karst geologic formations

Location	Dimensions
Attar (Turkey)	1,200,000 m^2, length 5.5 km, depth 300 m
El Cajon (Honduras)	610,000 m^2
Berke (Turkey)	533,000 m^2, depth up to 235 m
Dokan (Iraq)	471,000 m^2
Khao Laem (Thailand)	437,000 m^2
Slano (Montenegro)	404,224 m^2, length 7.011 km

Buško Blato Reservoir (B-H), 55–75% clay; Grančarevo Dam (B-H), 66% clay; Rama Dam (B-H), 45–57% clay and Slano Reservoir (Montenegro), 50–65% clay. Hot asphalt has been used in the USA for sealing leaks at the Hales Bar site (1944) and for sealing Great Falls Reservoir where water losses were reduced to 2% (Milanović 2004).

The grout mix consumption in karst is completely different than in nonkarstified rocks. Based on the experience in nonkarstified rocks, Deere (1976) proposed a range of medium-low to medium-high consumption between 25 and 200 kg/m. According to Heitfeld (1965), average consumption is between 60 and 110 kg/m. The extreme nonhomogeneity of the karstified rocks leads to great variability of grout mix consumption. For instance, at one section of grout curtain at Salman Farsi Dam site (Iran), grout mix consumption varies between 6 kg/m and 234 t/m (average 79 kg/m). Consumption of the one borehole in the grout curtain situated along the Slano Reservoir (Nikšić Polje, Montenegro) was 1,600 t of dry component of grout mix and 1,841 m^3 of aggregate. The only registered rod-fall in this borehole was 0.3 m at a depth of about 100 m. The most frequent (medium or average) value of consumption in karstified rock varies between 100 and 600 kg/m. Almost 70% of the analyzed cases (74 curtains in karstified rock) belong to that range. Consumption <100 kg/m was recorded in 17% of the cases and >600 kg/m at the remaining 13%. This analysis does not include the consumption of grout mix used for filling and plugging the large karst conduits and caverns, which usually takes >1,500 kg/m of grout (Milanović 2000).

The common rule for grout curtain depth recommended by the U.S. Bureau of Reclamation is not applicable to karst: $D = 1/3\ H + C$ (where D is the depth of curtain, H is the depth of reservoir, and C is the variable constant). According to the results from a number of completed curtains, the relationship between depth of curtain (D) and maximum water depth in reservoirs (H) located in karst ranges as follows: $D = 0.3–8.0\ H$. For instance, depth of grout curtain beneath the 24.75 m high Župica Dam (Bosnia) is 185 m. The length of curtain is 692 m and its surface is 127,777 m^2.

From the engineering experiences at many projects in karst, the vertical distance of grouting galleries should not exceed 30 m to intersect as many of the karst conduits as possible. This distance allows easy access to the cavernous space between galleries by auxiliary shafts or adits.

One of the world's most complex grout curtains in the karstified rocks was constructed as part of the Berke Dam project (Turkey). Berke Dam is a 201 m high arch dam on the Ceyhan River. The deepest part of the suspended curtain is 235 m and the curtain surface is 533,000 m^2. The aperture of solution channels, chimneys, and voids range from 20 to 200 cm. The deepest section of the curtain went down 225 m, which needed 33 rigs and 53 grout pumps to aid in its completion (Altug and Saticioglu 2001).

Sizeable caverns and channels have to be plugged. However, if the cavern is too large for curtains, then its rerouting (bypass) is the only technical and economical solution. Detailed speleological investigations of cavernous space are a key prerequisite in order to select the proper and lowest-risk modification for

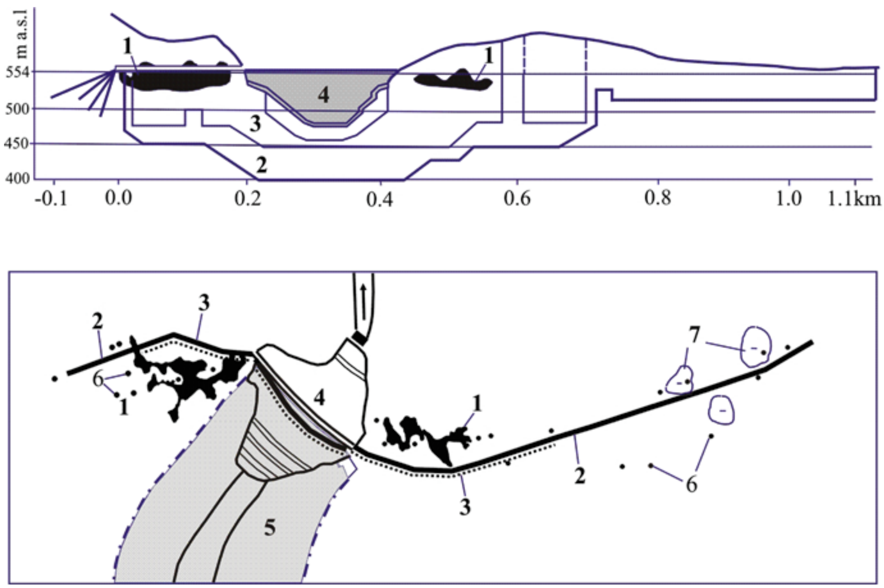

Fig. 3.6 Sklope dam site. Grout curtain bypass around the caverns. *1* Cavern, *2* One row grout curtain, *3* Double row grout curtain, *4* Dam, *5* Reservoir, *6* Boreholes, *7* Large sinkholes (Simplified, from Pavlin 1970)

grout curtains. To bypass a huge cavern, one of two general modification solutions are possible:

1. The alignment of the *downstream* bypass means the cavern is left upstream of curtain and has to be saturated with water after the reservoir has been filled. At the Sklope Dam site in Croatia, caverns were discovered at both abutments. The large cavern on the left bank of the dam site was discovered during the process of constructing the grout curtain. The length of cavern passages were about 500 m and included a large hall about 40 m long, 20–30 m wide and 1–20 m high (Milanović 2004). To address this discovery, the grout curtain route on the left bank was modified to bypass the cave on the downstream end. On the right bank, the grout curtain route bypass was done on the upstream side to avoid another cavern (Fig. 3.6).
2. The alignment of an *upstream* bypass means a cavern is left downstream of the curtain plane and has to be empty and accessible after reservoir filling. At the Salman Farsi Dam in Iran, many caverns along the grout curtain route were detected and speleologically investigated. The largest cavern in the right bank consisted of different but connected levels. The investigated cave was 130 m long, more than 75 m high and between 15 and 25 m wide. On the basis of the speleological data, the curtain route was modified to bypass the cavern on the upstream side (Fig. 3.7). Due to this modification, the length of grout curtain in the right bank was extended by 130 m (Dolder et al. 2002).

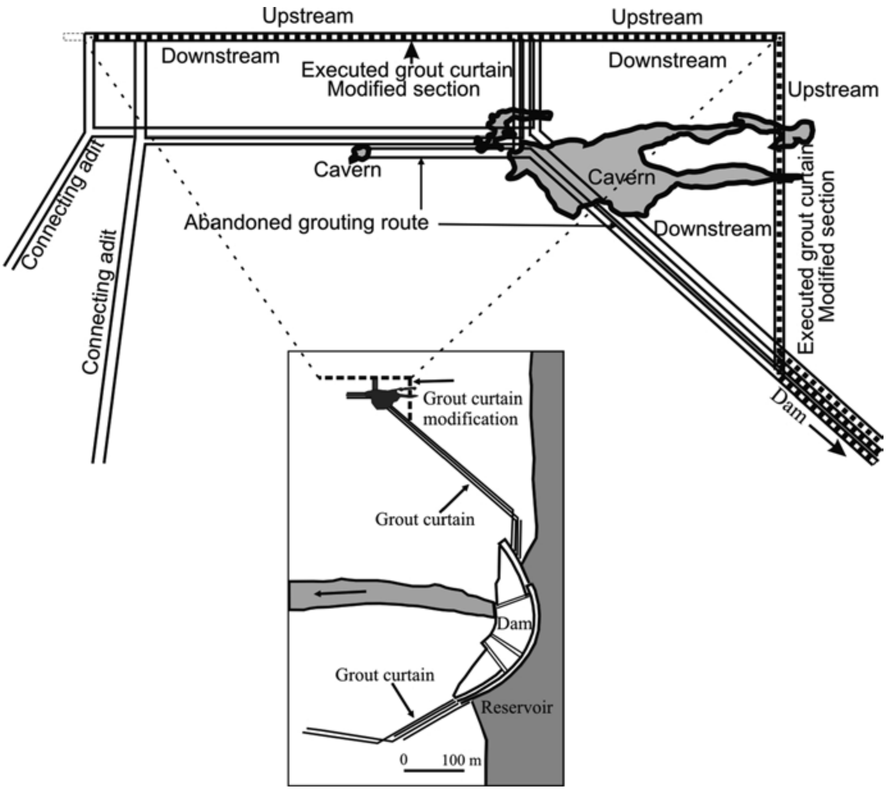

Fig. 3.7 Salman Farsi Dam, Iran. Modification of grout curtain route due to large cavern at curtain route (Dolder et al. 2002)

3.6.2.2 Cut-Off (Diaphragm) Walls

In the case of empty or sediment-filled caverns and cavernous zones, with volumes of tens up to hundreds of cubic meters, the efficiency of conventional grouting is questionable. With these caverns, a cut-off (diaphragm) wall is the most effective means of creating a watertight structure. The most common types of cut-off technologies are:

1. Mining method of an open-pit (trench) excavation between galleries if the structure is situated above the GWL
2. Overlapping piles method that is very useful if the cut-off structure is below the GWL

The mining method, using a combination of trenches, galleries, and shafts, was used for cavern plugging at the Tarbela Dam in Pakistan. A large reinforced concrete cut-off wall was constructed at the underground Wulichong Dam in China to block two underground rivers, surrounding caverns, and a series of wide fissures.

The concrete cut-off wall is 100.4 m high, 50–30 m long and 2.5 to 2 m thick. Loose and weak rocks behind the wall (28–35 m) was excavated and backfilled with concrete and finally consolidated by high pressure grouting to complete the sealing process (Milanović 2004).

In the case of Karun I Dam in Iran, a clay-filled fault zone allowed hydrogeologic connection between the saturated rock upstream of the grout curtain and a large karst spring (named Big Spring) downstream of dam site. In natural conditions, the average discharge of the Big Spring varied from 3 to 15 m^3/s. The leakage through this zone was blocked by a concrete cut-off, exceeding 100 m in height and about 20–30 m in width. This structure is supported by grout curtain from all sides.

At the Khao Leam Dam, Thailand, solution channels between 0.2 and 10.0 m in diameter posed a problem that was rectified by constructing a cut-off wall of overlapping piles 762 mm in diameter. The piles were drilled and concreted from very close and fully pressure-lined galleries. The vertical distance between galleries was only 14 m. For the treatment of minor karst porosity (opening width of 5–200 mm), 300 mm diameter piles were constructed under water using the same overlapping method. The major karst cavities were plugged by applying the mining method (for more information on this method, see Milanović 2004). The surface area of cut-off at the dam foundation is 77,000 m^2 and about 360,000 m^2 in the right abutment (Bergado et al. 1984).

Different schemes for cut-off construction were performed at the Wolf Creek Dam in USA. Above the GWL, the primary elements (1.29 m diameter) were excavated to a depth of about 21.3 m and a borehole was cased with a 1.19 m diameter temporary steel casing. Excavation continued inside the casing down to a depth of 42.6 m. That section of the hole was cased with a 1.04 m diameter casing. After installation of the permanent casing (0.66 m diameter), the hole was filled with tremie concrete. During removal of the temporary casing, the space between the permanent casing and the wall was filled with cement grout mix (Fetzer 1979).

One of the longest cut-off diaphragm walls was constructed as part of the anti-seepage structure at the Akkopru Reservoir, Turkey. The cut-off consisted of overlapped concrete piles (440 mm diameter) to prevent hydraulic connection between pervious alluvial/conglomerate sediments (reservoir bottom) and the highly karstified limestone which was protected by a blanket of heavily reinforced concrete (Fig. 3.4). Average depth of the cut-off wall is 20–40 m and length is 729 m. In areas with large caverns, a second row of cut-off walls was constructed.

3.6.2.3 Treatment of Karst – Cavern Plugging

The most frequent technical difficulty in karstified rock is the presence of a cavern along the grout curtain route. In this case, the cavern plugging or “treatment of karst” is necessary. In engineering terms, the meaning of “treatment of karst” is the geotechnical operation needed to block or reduce concentrated leakage from reservoir through the ponors and estavelles or to block or reduce the groundwater

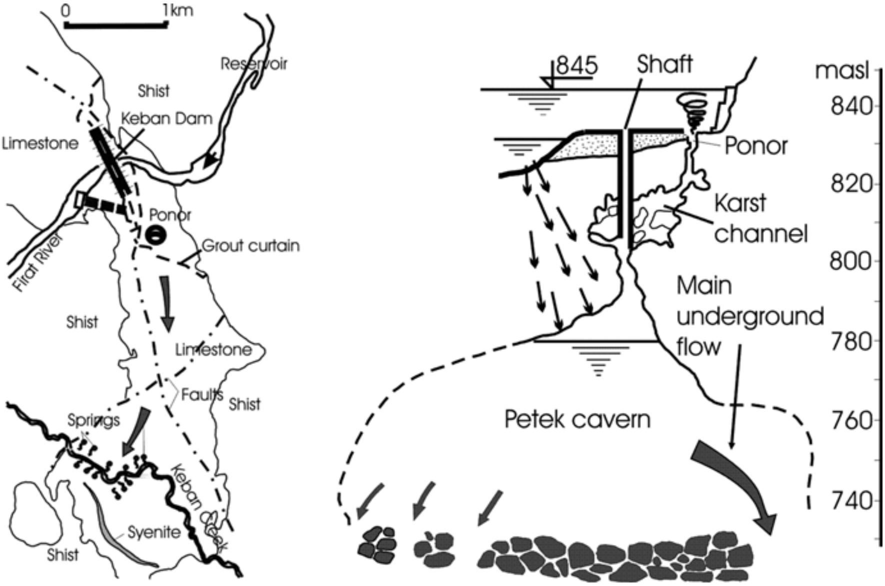

Fig. 3.8 Keban Dam, Turkey. Petek cavern remediation (Božović et al. 1981)

circulation along any karst singularity (channels or caverns) that cannot be treated by conventional grouting technology.

The caverns filled with clay (particularly soft clay) are very questionable for grouting, particularly in the case of caverns below the water table. This kind of cavern deposit is not a groutable media. In the case of Wujiangdu Dam (China), the special technology was applied to treat soft clay (see last paragraph in this section).

Prior to treatment of any accessible cave, speleological investigations are mandatory. Before plugging the cavern, the walls of the cavern should be cleaned and filled using self-compacting concrete (SCC), mortar or thick grout mix. Finally, the contact grouting of the interface between plug and the rock is necessary. During the construction of Keban Dam (Turkey), about 30 caverns were treated with this technique. One cavity, called the Crab Cavity, located 320 m below the crest level, was filled with 64,000 m^3 of concrete and injected solids. However, the largest cavern, called Petek (Fig. 3.8) was discovered during the first reservoir filling. The short subvertical karst channel connected the reservoir with the cave resulting in water losses from the reservoir up to 26 m^3/s. To fill the Petek Cave, one shaft 2.5 m in diameter and 13 boreholes of 14–17 in in diameter were drilled. About 605,000 m^3 of limestone blocks, gravel, sand, and clay were used to fill the cave. After this treatment, the leakage decreased to ~8 m^3/s, a more acceptable level, considering the inflow from the Firat River to be 635 m^3/s (Milanović 2004).

For the treatment of six large cavern systems along the grout curtain of the Salman Farsi Dam site (Iran) (Fig 3.9), 3,125 m^3 of SCC was used. Before filling, all caverns and channels were speleologicaly investigated and auxiliary shafts and access adits were excavated for concrete transport (Dolder et al. 2002).

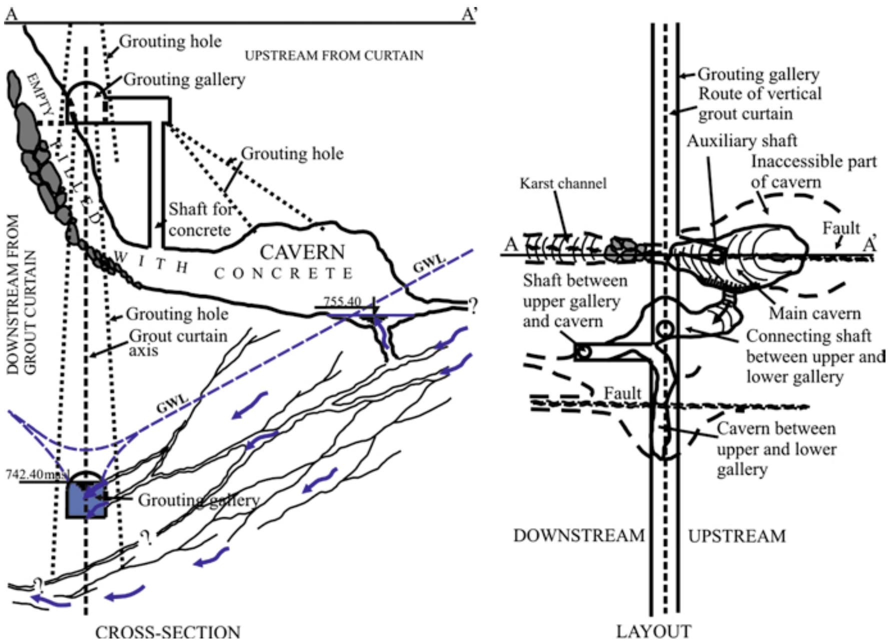

Fig. 3.9 Salman Farsi Dam. Treatment of the large cavernous system at the curtain route between two grouting galleries (From Dolder et al. 2002)

Concrete plugs were constructed to prevent leakage through the channels connected to the reservoir in Buško Blato (B-H). In another example, the channel of Honeycomb Cave, Tennessee River (USA), situated in reservoir upstream from the Guntersvil Dam, was blocked by a concrete plug. A karst channel between Krupac Ponor and Krupac Reservoir (Montenegro) was also successfully plugged. The large cavern was discovered at the Douglas Dam site (USA). The cave was investigated by a mining operation. After cleaning, the cavern was filled with 4,965 t of concrete through the large diameter borehole at the surface. To achieve watertightness of Khaobin Reservoir (Vietnam) 17,600 m^3 of cavities were cleaned for the construction and concrete walls were built for 10.5 km (Skiba et al. 1992).

Treatment of channels below the water table, particularly channels with flowing water under pressure, requires a very complex treatment technology. Even with sophisticated treatment methods, the ability to reduce leakage is not assured. For instance, along the grout curtain route of the Lar Dam in Iran, a large cavern, 27 m high and 68 m wide, was discovered at a depth of 210 m below the riverbed. The volume of the cavern was determined to exceed 90,000 m^3. Through 214 mm diameter boreholes from a gallery, the downstream section of the cavern was filled with about 28,000 m^3 of gravel, with a grading 5–50 mm and 34,000 m^3 of crushed rock. In spite of the extensive grouting and filling of caverns, the reservoir losses are still very high (Djalaly 1988).

Below the El Cajon Dam site in Honduras, several large karst caverns at depth of 176 m or deeper were discovered and had to be grouted under an extremely high pressure head. Some of them were filled with plastic clay. The washing out of the huge amount of clay and consolidation of plastic clay was difficult to control. To plug larger cavities, the following solids were inserted into the cavities using special pipe arrangements and 100 mm diameter boreholes: 8,000 wooden balls (7 cm diameter), 650 mortar balls (6 cm diameter), and 25,000 polyurethane bags (Guifarro et al. 1996).

Prior to plugging the cavernous system at the left bank of Canelles Dam site (Spain), the caves were speleologically investigated and clayey-silty material was removed above the water table. The conduit (17 m^2) was plugged with an 11 m long concrete plug. To fill the cave system, 1,380 t of dry material was used. Deep concentrated flows, down to depths of 200 m, were sealed by using polyurethane foam and acryl asphalt-resin mixes (Milanović 2004).

Cavities 250 m below the Wujiangdu Dam site in China, down to the depth of about 250 m, were filled with soft and very soft clay. To prevent clay washing from caverns, the soft clay in the caverns was subjected to four actions: hydraulic fracturing, extrusion, consolidation, and chemical hardening (Zoumei and Pinshou 1986). For successful hydraulic fracturing, the empty space between the clay deposits and the cavern roof was filled with cement grout mix. As a consequence of the high grout pressure (up to 60 kg/cm^2), the resistance of the clay fillings to water pressure was considerably increased.

3.7 Dams and Reservoirs in Evaporates

A number of dams are situated on evaporates and many of them have been affected by dissolution problems and failures. At least 30 dams in USA were affected by gypsum dissolution, some with catastrophic and tragic consequences. Because of dissolution of gypsum in the foundation of St. Francis Dam (California), the dam collapsed in 1928. The primary cause of failure was a landslide in the schists. However, leakage through the gypsum conglomerate could have contributed to weakening foundations before landslide impact. At the time, the collapse represented the greatest civil engineering failure in that country and killed over 450 people. After 12 years of dam operation, the McMilan Reservoir, (constructed in 1893) dried up. Failure of Quail Creek Dike (Utah) occurred in 1989. The seepage problems, after first filling, have hampered Carter Lake and Horsetooth Reservoirs (Pearson 1999). The proposed Magnum Dam site (Oklahoma) was abandoned because of intensive karstification of gypsum bedrock (Johnson 2008).

Numerous dams in different countries also have gypsum dissolution problems: Kamskaya Dam site and Bratsk Reservoir (Eastern Siberia, Russia); El Isiro (Venezuela); Alloz San Loren, Estremera, and San Juan Dam (Spain); Mosul Dam (Iraq); Huoshipo Reservoir (China); Poechos Dam (Peru); Yangmazhai and Mahuangtian Reservoirs (China); Baypazinsk Dam (Tajikistan); Tange-Duk Reservoir (Iran); and the Yerevan Dam (Armenia). Due to karstified gypsum and problems in its foundation, design modifications were required for the Casa de Piedra Dam (Argentina).

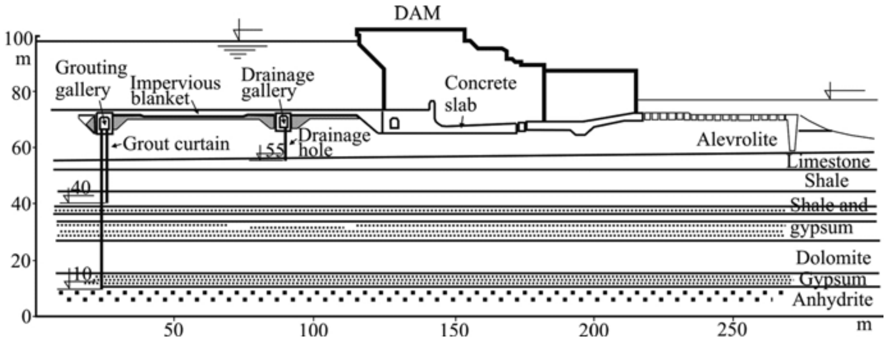

Fig. 3.10 Kamskaya dam site. Geological cross-section perpendicular to the dam axis (Milanović 2006). Alevrolite is a form of siltstone

Salt rock has been detected in the foundation of Rogun and Nurek Dams (Tajikistan) and in the reservoir bank of Gotvand Dam (Iran). Because the salt is 160 times more soluble than gypsum (in flowing water, dissolution rates increase tremendously), this kind of rock will cause leakage problems and pollution of the reservoir water. At the Gotvand Reservoir, deterioration of water quality and slope stability are the key problems. The evaporate block is 2.5 km by 1 km in area and 150 m thick. Remediation work involved recontouring the reservoir bank with added surface protective measures and optimizing the operation of the reservoir. However, dissolution processes cannot be completely eliminated at the Gotvand Reservoir. The main task of remedial measures is to decrease the intensity of solution and to improve bank stability.

The Kamskaya Dam and Reservoir was constructed in 1954 on the Kama River (Russia). The dam is 21 m high and 2.5 km long and is situated on a complex lithology of argillites, sandstone, gypsum, limestone, dolomites, and anhydrites. To prevent leakage below the dam site, a horizontal impervious blanket was constructed with an accompanying vertical grout curtain installed along its upstream border (Fig. 3.10). Immediately after reservoir impounding, leakage through the dam foundation was registered. Due to dissolution and suffusion processes, the permeability greatly increased. During the period from 1956 till 1961, 11 suffusion collapses occurred in the vicinity of the reservoir. To improve the density of the existing cement-based grout mix, a chemical gel-forming solution (oxaloaluminosilicate) was developed and successfully used (Milanović 2004).

The Huoshipo Reservoir (Guizhou Province, China) is situated in the upper gypsum-bearing dolomite and lower dolomite interlayered with 48 strata of gypsum. The gypsum is mostly corroded in a honeycomb shape. During reservoir impounding, the seepage increased slowly to 237 l/s. This water discharges at Sand Spring, 400 m downstream from the dam. As a result of the solution process, collapses formed at the reservoir bed, and laminar filtration was replaced by conduit flow. Antiseepage remedial work consisted of double-liquid grouting to plug the karst conduits, and blanketing all exposed gypsum layers prevented contact of reservoir water with gypsum-bearing strata (Lu and Cooper 1997).

The embankment of the Mosul Dam (Iraq) (110 m high) is situated on Miocene, well-bedded, clayey and marly rocks, gypsum, anhydrite, and limestone. During the first partial filling of the reservoir (1986), the leakage through the dam site increased up to 1,400 l/s. The leakage paths were located at an average depth of 60–70 m. The dissolution intensity of gypsum ranges from 42 to 80 t/day (Guzina et al. 1991). To replace the volume of dissolving minerals, an extensive and permanent grouting procedure was applied, however, without success. Most probable solution will be the construction of the very large cut-off wall.

Specific catastrophic failure of San Juan Earth Dam (Spain) occurred during the first filling of the reservoir in 2001. The San Juan Reservoir, with a capacity of 850,000 m^3, was situated on gypsiferous- mantled pediment deposits overlaying tertiary dispersive clay sediments (Gutierrez et al. 2003). The gypsum component was sand size particles, and due to their intensive dissolution, the pediment structure disintegrated, permeability increased and part of the dam collapsed. A 10 m deep breach in the dam sent a huge flood which covered a large part of the downstream area.

The region of the Bratsk Reservoir (Angara River, Russia) was well known as a karst environment. After the construction of the Bratsk Reservoir, many rapid collapses occurred in the areas with prevailing gypsum-anhydrite rocks. During reservoir filling (1963-1966), up to 200 sinkholes/km^2 developed each year in the reservoir area, with damage to buildings and structures outside of the reservoir area as well (Trzhtsinsky 2002).

Gypsum in the foundations of the weir, locks, and powerhouse of the Hessigheim Dam on the River Neckar (Germany) dissolved and caused settlement problems. Sinkholes have also occurred near the dam, one hole being 8 m in diameter. During the remedial site investigation, cavities up to several meters in height were encountered in the boreholes. The underlying rock has now been grouted in an 8-year project (1986–1994) involving the use of about 10,600 t of cement. Further work still needs to be completed and the expected life of the remedial measures is 30–40 years (Cooper and Calow 1998).

3.8 Conclusions

The nature of karst presents a great variety of risks associated with any kind of human activities, particularly the high-risk nature of construction of large dams and reservoirs on karstified rocks. But dams are costly structures, and at the beginning, designers had little or no experience or knowledge related to karst. Conventional hydrogeological investigation methods and techniques were not successful in the case of karst-type porosity. In some cases, the empty reservoirs are a consequence of incorrect conclusions. Consequently, karst areas were avoided by dam designers.

In many cases, the karst regions are rich with hydro-related resources and their development depends on successful water management. In those regions, reclamation projects and construction of large dams and reservoirs have had a primary role in regional socioeconomic development.

During the past century, existing hydrogeological, hydrological, and geophysical investigation methods have developed or adapted to be efficient in the karst settings. Increasing of geotechnical knowledge and development of sealing technologies became one of key prerequisite for many successful dam construction projects. From the earliest days of dam/reservoir construction till today, finding the position of caverns and karst channels deep below the surface was and is still crucial. A fundamental geological understanding of karst and close cooperation of a wide spectrum of scientists and engineers is the basis of success. The final design of a grout curtain in karst can only be finalized during the execution phase. The curtain needs modifications and adaptations on the basis of the geological exploration of the underground. Newly developed sealing technologies (grouting techniques, underground flow plugging, surface impermeabilization of reservoir bottoms and others) have been successful in many recent projects.

However, the reservoirs in karst may fail to fill despite an extensive investigation program and sealing treatment. The risk cannot be totally eliminated by increasing the investigative programs, but it can be minimized to an acceptable level. In many cases, remedial works are necessary after the first filling of the reservoir. In other cases, progressive erosion of cavern filling and deterioration of grout curtains can take a long time (5-20 years). To control long-term processes, a complex monitoring program is the only way to prevent failure.

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Chapter 4
Experience in Collapse Risk Assessment of Building on Covered Karst Landscapes in Russia

Vladimir Tolmachev and Mikhail Leonenko

Abstract Problems that arise during development of terranes with carbonate and sulfate-covered karst are discussed herein and are based on experiences in Russia, where karst terranes constitute one third of the total territory. Different karst hazards are considered with respect to various types of construction and facilities. Karst hazards caused by sinkholes are classified according to specific sinkhole development intensity (ten categories) and average sinkhole diameter (eight categories). Some examples of accidents causing damage to buildings are presented and the reasons for the accidents are discussed. The main stochastic laws describing sinkhole development are considered. A method of evaluation of karst collapse risk and assessment of the risk level is presented. Application of this method helps to plan an antikarst protection program with both capital and maintenance types of prevention activity.

4.1 Introduction

Information presented herein is based on long-term research into issues involving engineering and construction in karst terranes in Russia (Tolmachev 2006). Russian engineers first encountered serious karst-related problems at the end of the nineteenth century during construction and operation of railways in the Volga River catchment basin and in the Urals region. That was the time when engineering karstology originated as an applied multidisciplinary science combining engineering and construction-related theory, and it later included economics, jurisprudence, and environmental study (Tolmachev 1999). The term engineering karstology was formally adopted in Russia in 1947 at the Molotov Karst Conference (Proceedings 1947). To the best of our knowledge, this term is not used outside Russia, but there

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are some very similar terms, such as applied karst geology (Beck 1993) or engineering geology of karst (Reuter and Tolmachev 1990). Similar to engineering karstology are the trends dealing with geotechnical aspects of construction in karst regions (Sowers 1996; Aderhold 2005).

Russia has nearly 70 years of experience quantitatively assessing hazards for the purpose of development on karst terranes. The main focus was on the karst collapse hazard in covered sulfate-carbonate karst at the depth of 20–80 m. The presence of subsurface karst features is an essential (though not the only) prerequisite for the development of this hazard. In practice, it is difficult and often impossible to locate voids and fissures and to identify their shape and dimensions between these depths. Despite this uncertainty, the karst collapse hazard must be taken into consideration by civil engineers during development. Consequently, Russian researchers, while developing methods of karst collapse hazard assessment, have attempted to both meet the needs of practical engineering and enhance the understanding of surficial karst development mechanisms (e.g., stochastic mechanism of sinkhole development and processes in the overburden). Such attempts can be seen in the evolution of karst hazard and risk assessment methods. However, other aspects of karst hazards exist, and depending on the natural and technogenic situation, some of these may become more important when considering particular economic tasks.

Analysis of karst hazard and risk assessment methods worldwide shows that researchers and engineers follow the same approaches. We assume that the Russian experience described here can be helpful for specialists in other countries. Some important developments in knowledge have only been discussed in Russian publications, which are not easily accessible to foreign researchers.

There exist numerous approaches to karst hazard assessment in Russia. We suggest that the method described below is the most efficient approach available. It presents a solution to the problems of risk assessment for building in karst areas and constitutes the basis of Russian national standards and is also the officially recognized methodology.

As a Russian case study, we will concentrate on work undertaken in that country, and although we recognize there are other hazards and approaches investigated elsewhere, these will not be covered in the chapter. The other aspects of karst hazard and risk assessment are discussed in different chapters of this text. These include:

- Technogenic impacts on karst hazard parameters
- Techniques of zoning of territories according to the level of karst hazard in various natural and technogenic conditions
- Mechanisms of sinkhole development
- Use of geosciences investigation techniques (geomorphological, structural, and lithological mapping, bedrock core drilling, geophysical methods, etc.)

In Russia, engineering karstology evolved mainly from traditional karstology. New research methods for karst study were developed; various forecast techniques for prediction of karst development were created to be incorporated into the construction design in karst regions and even a new specific terminology arose. Engineering karstology deals essentially with the problems of civil engineering in karst regions within the framework of an integral system that is "Karst Engineering" (Tolmachev et al. 1986; Tolmachev and Reuter 1990; Tolmachev and Leonenko 2005). The nature of karst development in Russia, with its subsurface and superficial effects, has been studied within this system. Research has mainly focused on covered karst in carbonate and sulfate rock. In the investigation of subsurface karst features, special attention is paid to the development of voids and deconsolidated areas in the overburden (Tolmachev et al. 1982; Khomenko 1986, 2003). During the investigation of superficial karst features, the emphasis is placed on sinkholes and the conditions of their development (formation mechanisms, spatial and timing stochastic characteristics).

Most Russian engineers and officials perceive general karst hazards and the karst collapse hazard as one and the same, and this simplification often leads to development-related problems on karst territories. The failure to appreciate the distinction between karst risk and karst hazard has often resulted in serious design and engineering mistakes. Nevertheless, it is necessary to recognize that for many areas of Russia with deep karst (over 20 m in depth), the most significant threat of damage to buildings and facilities with shallow foundations is posed by a sudden collapse of foundations. For this reason, most attention will be given to the problem of the collapse (sinkhole) hazard.

One of the crucial issues for construction in karst regions is karst risk assessment. The approach taken in assessment varies depending on the type of structures or facilities, their overall importance, degree of their impact on the environment, their size, and construction characteristics. Designers and contractors stress the importance of karst risk assessment for helping guide the development of structural, building, and operational characteristics of the construction. Their consideration of karst risk assessment is especially important when considering the potential negative impacts of karst development to local economies, societies, and the environment.

Engineering karstology assumes that the results obtained by research should be rendered to engineers through new building codes and specifications. Documentation of this kind first appeared in Russia in 1967, and since that time, a system of standardized requirements including codes of practice, guidelines, and recommendations have been developed. Some of these official documents are adopted throughout Russia while others are valid only for separate regions or departments (Tolmachev and Leonenko 2001). Examples of these documents are:

- Recommendations on Foundation Engineering on Karst Territories (1985)
- Recommendations on the Use of Engineering/Geological Information for Selection of Antikarst Protection Methods (1987)[1]
- Basic Track Maintenance Instructions for Karst Hazardous Terranes (1997)

[1]The term *antikarst protection* is widely used in Russia. It is understood as a system of special engineering and organizational activities, which involves the issues of planning, design, building, technology, geotechnics, hydrogeology, monitoring and operation and which is aimed at prevention or elimination of negative impacts of karst processes during the period of building and operation of constructions. The term is in the name of the author's company.

- The chapter, “Engineering Geological Site Investigations in Karst Terranes,” and the code of practice, “Engineering Geological Site Investigations for Construction” (2000)
- Technical regulation “Engineering, Design, Construction and Operation of Structures in Karst Terranes in Nizhny Novgorod Region” (2010)

We have been instrumental in the development of the above documents. The 2010 document was written in accordance with recent Federal Laws of the Russian Federation, such as “On Technical Regulation,” “Urban Planning Code of the Russian Federation,” “On Environmental Protection,” and “On Safety of Structures and Facilities,” all of which put forward a binding requirement to assess natural risk in order to assure construction does not exceed safe limits.

4.2 Types of Karst Hazard

Negative impacts of karst on economic activity and, above all, on construction work can be described in various ways which are related to specific karst hazards. Table 4.1 describes the types of karst hazard that may be reflected in decisions made in the course of economic development. As a rule, designers of buildings and facilities take into consideration only one type of karst hazard or a combination of two. However, when designing major structures that can cause significant hazard to the health and safety of the population, all of the risk factors outlined in Table 4.1 must be considered.

Karst hazard Type A and B always require a specific approach to the construction and operation of water supply and drainage systems in cities and towns (e.g., appropriate routing of pipelines, pipe material selection, water leakage control). As a general rule, failure to account for karst-suffusion processes in planning water withdrawals increases the frequency of karst development not only at the particular water removal site but also within adjacent areas (Khomenko 1986, 2003). Water leaks usually lead to local increases in karst hazard Type A and B (Figs. 4.1 and 4.2).

Hazard Type A, B, and C are especially important for determining the price of land. All things being equal, the price of land in a karst zone will inevitably be much lower compared to a nonkarst area, especially since the contractor will have to bear considerable additional expenses in order to reduce karst risks. This circumstance is especially important for developers of city planning projects.

Notions of karst hazard and karst risk are closely connected with the insurance of construction in karst territories. The need for insurance may arise for locations with the Type B hazard. Unfortunately, insurance of construction against karst risks is not used in Russia, even though the methodology for probabilistic assessment of karst hazard was proposed long ago. In part, this absence can be explained by general immaturity of insurance in Russia, as well as by a certain exotic character of karst issues to the national insurance companies. This situation is contrasted with the practice in karst areas of the USA (which has sinkhole insurance coverage) (Salomone 1984; Zisman 2005). The American experience should be used in Russia

Table 4.1 Types of karst hazard

Types of karst hazard	Object-specific conditions	Typical structures and facilities causing pollution
A (Fig. 4.1a)	Intensive anthropogenic pollution of the geological environment	– Waste disposal landfills – Chemical plants – Nuclear power stations – Petroleum storage depots and petrol stations – Oil pipelines, delivery ducts – Motorways – Railways – Sewer pipelines
B (Fig. 4.1b)	Probability of great damage or destruction	Building and facilities at the stage of design, construction, or operation (industrial, residential, and public buildings, pipelines, railways, motorways, etc.)
C (Fig. 4.1c)	Unforeseen problems with foundations and underground facilities	– High-rise buildings – Bridges – Tunnels – Subway – Underwater pipelines
D[a]	Excessive leakage from water bodies	– Water-storage reservoirs – Ponds – Canals

[a] This chapter does not consider any particular problems related to hydraulic engineering facilities for karst region, because they lie beyond the professional interests of the authors. Detailed information is given in other publications (Lykoshin 1968; Lykoshin et al. 1992; Daoxian 1991; Milanovich 2000)

as much as possible, especially in terms of interaction between the participants of the insurance process in the following order: geologist, designer, karstologist, insurance agent, and customer. Introduction of insurance procedures will have economic impacts in development of karst regions and will obviously cause some new problems with concepts and methodology. It will be necessary to develop new terms or to correct some of the accepted terminology in order to establish legal precedents that are legally verifiable, clear and comprehensive for customers and experts from insurance companies.

In the process of construction of buildings and engineered facilities in karst terranes, a number of specific aspects of karst hazard of Types A, B, and C should be considered.

4.2.1 Karst Hazard Type A

When a Type A hazard is identified, one must consider the various pathways that pollution may take in entering the geological environment of covered karst.

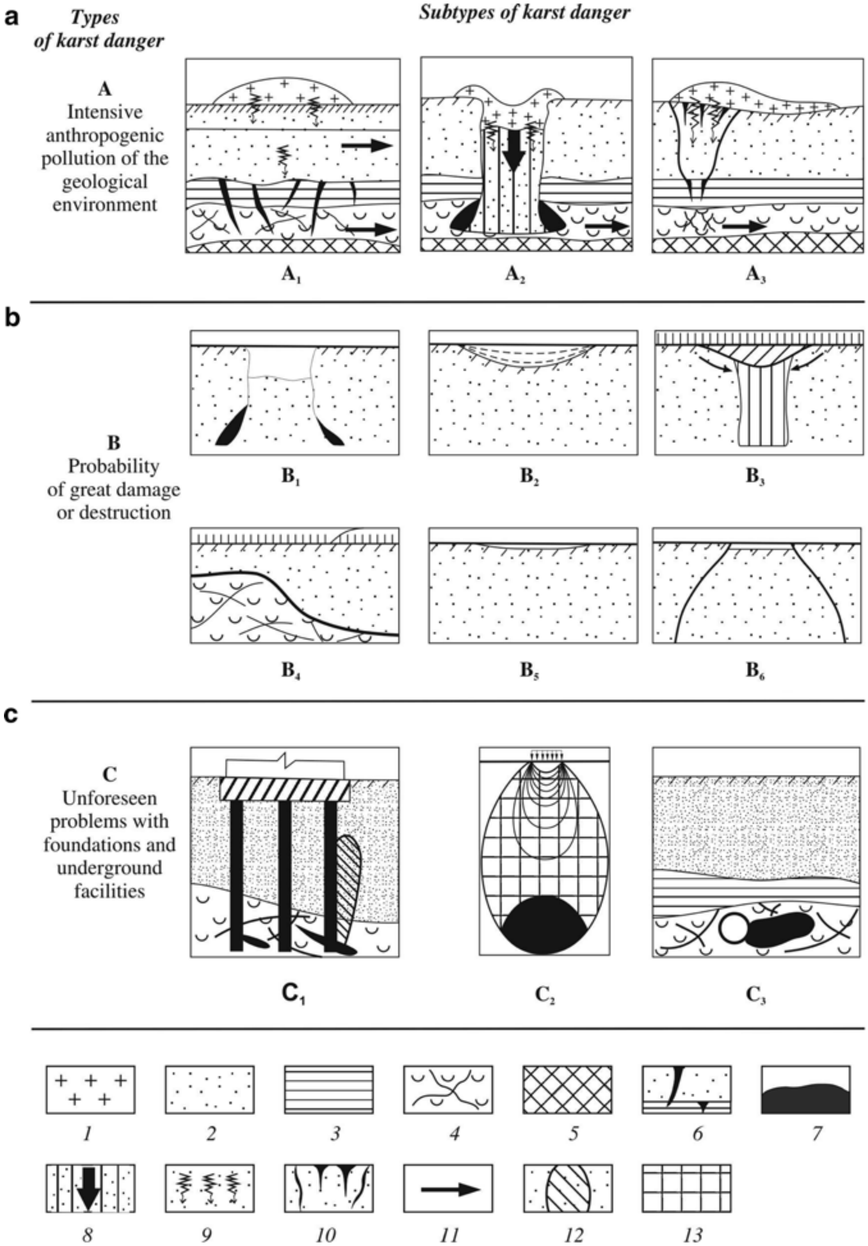


Fig. 4.1 Types and subtypes of karst danger *1* Source of pollution *2* Water-permeable soils *3* Low permeability soils *4* Karstified rock *5* Rock base *6* Karst-induced joints in the soil *7* Karst cavity *8* Friable soil area under a sinkhole *9* Increased infiltration area *10* Disintergrated soils in the rim of the subsidence mold *11*Moving direction of underground water pollutants *12* Subsurface disintergrated area *13* Compressible soil

Fig. 4.2 Development of a karst-suffosion sinkhole induced by a heating main leakage in Dzerzhinsk (2009)

These are described as follows (Mamonova and Tolmachev 1997; Tolmachev et al. 2005):

- The increased rate of pollution of the geological environment is observed in locations of newly developed sinkholes, as well as old sinkholes, in the rims of the subsidence depression, and in the areas of active subsurface karst.
- Water pollutants may penetrate through karst joints to areas many kilometers away from the source of pollution.
- Pollution of underground water can be described as a pulse process dependent on the dynamics of subterranean and superficial karst development.
- Water pollutant penetration rates through karst joints are several times higher in comparison with the values observed in other water-bearing formations.
- Under certain circumstances, pollution traveling through solution pipes in karst terranes may result in a substantial increase of dissolution rate of karst rock.
- The net process may lead to reduction of the soil load-bearing capacity and, therefore, to conditions which facilitate formation of karst features.

In the siting of locations for landfills, the main criterion of Type A in Table 4.1 is to predict a volume of potential pollutant V_p (m^3 per 100 years occurring in an area of 1 ha). This is the potential quantity of pollutant that may penetrate beneath the landfill through existing and newly formed karst features (Tolmachev et al. 2005). Depending on the values of V_p, karst areas can be classified according to their potential environmental vulnerability into a number of conventional subgroups using the units discussed below:

(1) ($V_p < 10$); (2) ($V_p = 10–50$); (3) ($V_p = 50–100$); (4) ($V_p = 100–500$); (5) ($V_p = 500–1,000$); (6) ($V_p = 1,000–5,000$); (7) ($V_p = 5,000–10,000$); etc.

Values of V_p are usually estimated using the results of probability analysis of the features of the developing karst and the distribution of their predicted dimensions. For more details, see Tolmachev et al. (2005).

4.2.2 Karst Hazard Type B

For covered karst areas with Type B karst hazard, risk should be assessed by accounting for specific features and mechanisms that may occur during the life of the facility. For the majority of buildings and facilities, karst features can be grouped in decreasing order of potential risk: (1) soil or rock collapse, (2) local subsidence developed in the vicinity of the construction, (3) old sinkholes located close to the construction, (4) differential foundation settlements caused by karst processes, (5) slow subsidence of soil and (6) karst (karst-suffosion) induced slumps. This arrangement allows further subdivision of Type B karst hazard into subtypes (Fig. 4.1b).

Subtype B_1 (collapse sinkholes) is characterized by the following factors:

- Temporally, collapses are usually immediate events, though occasionally, they are preceded by slumps, concentric fissures on the ground surface, etc.
- Collapse development process has a pronounced probabilistic character (in time and space, i.e., diameter, depth, and volume).
- Often, collapses occur on the same spot or in close vicinity to previous collapses.
- The area around a fresh collapse is characterized by considerably reduced soil load-bearing capacity and increased water permeability.
- The shape of a depression formed by a collapse of the ground surface does not stay the same and changes rather quickly (depending on the kind of soil) with the diameter growing and the depth decreasing, which eventually results in a conical appearance of the sinkhole.

In Russia, the following parameters of the prediction of sinkhole development are used for karst hazard assessment:

- Specific intensity (frequency) of sinkhole development (λ), related to a unit area (as 1 km^2 or 1 ha) per unit time (as 1 year or 1 century) or theoretical intensity of sinkhole development on the area occupied by construction during a given time period (e.g., predicted service life, pre-reconstruction period of operation).
- Average (d_c) and the largest (d_{max}) dimensions of sinkholes. In order to solve many practical design problems, empirical (histograms) and theoretical curves of

Table 4.2 Karst hazard categories according to the predicted specific intensity of sinkhole development (λ, the number of collapses on 1 ha per 100 years)

Category	1	2	3	4	5	6	7	8	9	10
λ	0	<0.001	0.001–0.003	0.003–0.01	0.01–0.05	0.05–0.1	0.1–0.3	0.3–1.0	1–3	>3

Table 4.3 Karst hazard categories according to predicted average diameter of a sinkhole (d_c, *m*)

Category	a	b	c	d	e	f	g	h
d_c	<1	1–3	3–5	5–10	10–15	15–20	20–40	>40

sinkhole diameter distribution may be needed. It is necessary to consider that sinkhole diameter distribution for vast territories (with nonuniform conditions of collapse development) in most cases is described by the lognormal law. In small areas (e.g., construction sites) with practically homogeneous conditions affecting the dimensions of sinkholes, diameter distribution is close to normal (Gaussian distribution).

- Current percentage of the total area of a sinkhole for a given territory and potential vulnerability of this territory during a given period of time (e.g., for 100 years).

As a rule, the assessment of sinkhole development probability includes zoning of the territory based on specific intensity of sinkhole development λ and average sinkhole diameter d_c. For the purpose of zoning, Russian national building specifications recommend a classification with six categories of endangered territories according to the parameter λ, and four categories according to d_c. This classification promotes a much more systematized arrangement of engineering/geological research. However, nearly 40 years of experience revealed a number of weaknesses in use of these categories, especially with respect to their objectivity and applicability for design purposes (Tolmachev and Leonenko 2005; Tolmachev 2009). Recently, a more detailed system of differentiation of sinkhole danger categories was created (Tables 4.2 and 4.3). It has worked well in trial cases and was approved for other karst-endangered territories in Nizhny Novgorod region.

The karst hazard resulting from local subsidence (Subtype B_2) is characterized by the following features:

- Development of local subsidence of the ground surface (and under buildings or other construction) can take from several days to several months.
- Final diameters of local subsidence of the ground surface, as a rule, can extend to several decameters at comparatively small depths (about 1 or 2 m).
- In the zone of local subsidence, a significant horizontal shifting of the soil is observed.
- The rim of the local subsidence is characterized by low soil load-bearing capacity and high water permeability.

Hazard assessment of local subsidence for vast territories should be done together with the karst collapse hazard assessment. However, karst hazard assessment for construction sites should be done separately from karst collapse hazard assessment.

A karst hazard caused by an old sinkhole on construction (Subtype B_3) is characterized as follows:

- The zone beneath the sinkhole and around it retains high probability of another collapse, a new local subsidence or a slump. Anthropogenic effects (due to dynamic and static loads, water leakage from pipelines, etc.) bring the probability value of new collapse very close to one.
- The zone in the immediate vicinity of the sinkhole has low soil load-bearing capacity and high water permeability.

Threat of differential foundation settlement (Subtype B_4) is usually considered under the following conditions:

- Karstified rock with filled sinkholes and joints
- Shallow covered karst overlain by karstified rock of depression, vertical channels, layers of dolomitic lime, and other karst abnormalities
- Deep covered karst with buried karst sinkholes, deconsolidated areas, and other karst (karst-suffusion) deformities in the compressible burden

Karst hazard created by slow subsidence (Subtype B_5) is characterized by the following features:

- Slow depression of the ground surface (several years or decades).
- Rate of subsidence is irregular in different parts of the depression and can vary from several millimeters to several centimeters per year. Revival and dampening periods can be observed.
- Shapes of subsidence depressions are irregular and their diameters can reach several hundred meters.
- On the rims of the subsidence depressions, there are areas of rock with deconsolidated surface layers which facilitate seepage of rain and industrial water into the soil, thereby increasing the probability of new sinkholes in these locations.
- In the subsidence zone, horizontal and vertical deformation can be found in the same area.

Design of construction in areas where karst subsidence is probable requires knowledge of the interdependence between the construction and its foundation with the help of methods that consider mechanisms of subsidence development, their predicted rates and duration. Such methods are common for mines. In this case, the most important design parameter is the subsidence depression slope (i, mm/m). Depending on this parameter, the total area of the subsidence depression can be subdivided into the following sections:

$$(1)\ i<5,\ (2)\ i=5\text{–}7,\ (3)\ i=7\text{–}10,\ (4)\ i=10\text{–}20,\ (5)\ i>20$$

Hazards related to karst (karst-suffosion) soil slumps (Subtype B_6) can be characterized by the following features:

- Like collapses, slumps are formed instantly.
- Slump dimensions seldom exceed 1–2 m and their depth is up to 0.3 m.
- Most often, karst slumps occur after prolonged soaking of soil and due to dynamic and static loads imposed by construction.

- In some situations, karst slumps can be followed by collapses.
- Quantitative assessment of karst slump parameters is difficult and in most cases not necessary. From the practical point of view, designers just need to be aware of the probability of slump formation in the location in which they work. If slumps are the only type of predicted karst features, karst hazard will be determined as Category 1 in Table 4.2 (without the need for separate estimation of slump formation intensity).
- In the course of construction and operation of structures or facilities, it is extremely important to register the exact place and time of this type of depression, as it may be a serious symptom of new karst collapses or local subsidence.

In a karst region, when developers consider the most appropriate sites for large-scale construction, they need to know the results of preliminary zoning of the location according to the proportion of the total area of all karst features at the surface (α, %/km^2). Locations can be classified according to α in the following way: (1) $\alpha<5\%$, (2) $\alpha=5–25\%$, (3) $\alpha=25–50\%$, (4) $\alpha=50–75\%$, (5) $\alpha>75\%$ (Aderhold 2005).

4.2.3 Karst Hazard Type C

Type C can be subdivided into the following subtypes:

- <u>Subtype C_1</u> is created by the additional load from deep foundations that threaten the roofs of karst cavities. In the absence of anthropogenic impacts, such cavities are classified as stable. Serious problems usually arise as early as the stage of foundation building.
- <u>Subtype C_2</u> typically has subterranean karst deformations (voids, disintegrated areas, etc.) in the compressible overburden.
- <u>Subtype C_3</u> is characterized by increased karst water inflow toward underground facilities during construction or service life.

Subterranean karst features are considered potentially hazardous for any structure. These hazards can be determined through identification of probable deformation types and analysis of expected structural loads. Hazard assessment of the subsurface karst features identified by research should also be performed to account for their potential impact on development during the service life of the construction. Karst features in the overburden, especially in sand, demonstrate considerable dynamics. It is also necessary to perform special karstological monitoring with the use of geophysical methods.

4.3 Examples of Structural Damage to Construction in Karst Regions

In the European part of Russia, the proportion of territory where karst presents real danger for buildings and facilities is equal to a quarter of the total area. Karstified rock (predominantly, limestone, dolomite, and gypsum) is found here mainly at the

Fig. 4.3 Collapse of a residential building in Nizhny Novgorod region (1959)

depth of 20–80 m. Generally, it is overlain by clay and/or sandy soil which are often saturated with water. Presence of water makes karst suffosion highly probable. At the surface, karst manifests itself in the form of sinkholes, local subsidence, or slowly developing vast subsidence. Of the karst manifestations mentioned, the highest level of hazard is related to sinkholes due to abruptness of their occurrence.

Sinkholes and local subsidence often cause accidents with damage to residential and industrial buildings, water supply systems, pipelines, railways, and motorways (Figs. 4.3, 4.4, and 4.5). Large-scale accidents happened recently in a number of Russian cities (Dzerzhinsk, Nizhny Novgorod, Pavlovo, Moscow, Bereznyaky, Kungurr, Ufa, Kazan), on the Gorky and Sverdlovsk railways and on the main pipeline in the Perm region. Fortunately, there was no loss of life in any of the accidents.

In 1992, a catastrophic karst sinkhole, more than 10 m deep and 32 m wide (Fig. 4.6), destroyed an industrial facility of a machine-building plant in Dzerzhinsk. It took only 20 min to demolish a 125 m long structure along a row of columns. Direct economic losses were equivalent to ~$30 million, and there were indirect losses as the production shop did not function for approximately 2 months. The dramatic event was found to be a consequence of serious engineering and administrative errors made at various stages from selection of the construction site, research and construction work to the operation of the industrial plant. The building was designed as a frame on isolated foundations. When the plant was being designed in 1963–1964, the specialists involved in the project were under pressure from the administrative authorities who imposed very strict cost demands. The cost was mainly reduced at the expense of antikarst protection during construction.

Fig. 4.4 Collapse of a building in the historical part of Kazan (1977)

Fig. 4.5 Sinkhole in the village of Rastrigino, Vladimir region (1972)

In 1993, local karst subsidence occurred in the form of a sinkhole with a diameter of up to 20 m, threatening a chlorine warehouse for a water supply station in Nizhny Novgorod. The station building did not have any antikarst protection. Subsidence took only several days, during which the building was promptly disassembled to avoid its progressive destruction.

Fig. 4.6 Collapse of an industrial building in Dzerzhinsk (1992)

In 1993, a six-story civil building in Ufa was damaged to the point that it was uninhabitable and had to be demolished. The damage was caused by multiple local subsidences in the zone of buried karst sinkholes which had not been identified by the exploration at the project stage. Destructive deformation continued for 14 years after the building was completed in 1979, despite continuous attempts to prevent the collapse (jacking by sectional piles, securing of the foundation bed, etc.). The lessons learnt from this event are discussed in Mulyukov et al. (2006).

Sinkholes and local subsidence are highly hazardous for railways as they cause not only economic but other serious problems as well. Karst-induced events on the Gorky railway are good illustrative examples. In 1994, a freight train accident took place on a section of a single-way line, Arzamas–Krasny Uzel. The cause of the accident was a comparatively small 2.5 m karst sinkhole which developed under the train. Railway operation in that direction was stopped for several days. Some rail carriages with sulfuric acid were broken in the accident, and it caused local pollution. In 1995, on the 395th km of the two-way railway from Moscow to Nizhny

Novgorod, not far from Dzerzhinsk station, a local karst-suffosion subsidence formed on the surface. Its diameter was 35 m, and although its center was 20 m away from the track, one of the lines sank 15 cm along a length of 25 m. As a result, train operation was interrupted on one track for 12 h, and on the other track, the speed limit of 15 km/h was instituted and remained unchanged for several months until the remedial work was completed. It is interesting to mention that two accidents caused by sinkholes occurred at the same location in 1943 and 1960.

In 2000, on a single track of Kazan-Yoshkar-Ola railway, a large local subsidence damaged more than 100 m of track. The rail track sank 1 m and shifted horizontally toward the center of the sinkhole by up to 0.5 m. The train operation in all directions was stopped and did not start for several days.

The above examples show the high vulnerability of the railway tracks in karst terranes, characterized by high probability of sinkholes. Typically, collapses take place simultaneously with train motion. As antikarst protection during construction is not applicable for rail tracks (unlike structures with foundations), and grouting of karst cavities is not efficient enough, the main safety measures taken are maintenance-related ones (special karst monitoring of the track, arrangement of alarm, and restrictive signalization). New, high-speed traffic programs need to deal with this aspect of safety. In certain cases, karst hazards may present a major obstacle for implementation of the program.

Karst and karst-suffosion processes are extremely sensitive to various anthropogenic effects from construction and operation of industrial plants and facilities which can cause karst deformations. The following examples illustrate this statement.

In 1996, on the property of a chemical plant in Dzerzhinsk, a karst sinkhole appeared with the diameter of 9 m and the depth of 3.5 m. It caused serious damage to an underground water pipeline and brought the operation of some workshops to a halt for several days. The direct cause of the event was leakage from the pipeline which provoked intensification of the karst-suffosion process. In 1998, a 16 m wide and 8 m deep karst sinkhole developed in the center of Pavlovo (a town in Nizhny Novgorod region) and a sewage collector was damaged. The reason for the collapse was long-term leakage of aggressive water penetrating into the soil and karstified rock. Another disaster in 1999 with destruction of a main pipeline section in the karst area of Perm Krai happened because trench work explosions had been used for laying pipes. These explosions greatly increased sinkhole development in the shallow karstified gypsum (Kutepov et al. 2004).

Accidents related to karst development during construction work are often caused by a combination of errors of various types. Nevertheless, the results of studies (Tolmachev 2005; Leonenko and Tolmachev 2006; Mulyukov et al. 2006; Sorochan and Tolmachev 2007) showed the most significant reasons for these events. These are arranged below in ascending percentage of the total number of accidents:

- Unprofessional interference of contractors or administrative bodies in research and engineering activity (10%)
- Inappropriate karstological monitoring during operation of the construction (10%)
- Engineering errors (15%)
- Omission of specialized (karstological) research (20%)

Table 4.4 Distribution of karst deformations in dzerzhinsk district causing damage to construction

Dates	1953–1957	1958–1962	1963–1967	1968–1972	1973–1977	1978–1982	1983–1987	1988–1992	1993–1997	1998–2002	2003–2006	∑*N*
N	3	4	7	6	5	4	2	13	10	12	6	72

- Exploration errors, including lack of knowledge of karst processes (20%)
- Inadequate interaction between researchers and designers (25%). This item was identified outside Russia and in one of the publications described by Bachus (2005)

In the Nizhny Novgorod region, the highest karst risk exists in the city of Dzerzhinsk, which is why in 1952 the Academy of Sciences of the Soviet Union founded a karst station there (at present joint stock company, Antikarst and Shore Protection). Since that time, every karst occurrence has been registered on a regular basis along with data on the damage to construction. The table below presents the distribution of events and damage to construction (N) caused by 72 karst deformations in the territory of Dzerzhinsk between 1953 and 2006 (Table 4.4).

On average, this territory has 1.3 sinkholes annually causing damage to construction. Their total number (72) includes all known instances of damage to buildings, roads, railways, pipelines, etc. It also includes 14 disasters with complete destruction of various industrial sites, which gives the frequency of one disaster every 4 years. The majority of instances of complete destruction (11 out of 14) were the consequences of a sudden karst sinkhole. The distribution of these cases of destruction is close to the law of stochastic events (Poisson law), and the distribution parameter is equal to 0.26. As it was shown earlier (Tolmachev 1968), distribution of independent karst collapses is also described by the Poisson law. For the Dzerzhinsk karst district, the distribution parameter reaches the value of 4.5.

4.4 Stochastic Laws for Sinkhole Development

4.4.1 Probabilistic and Stochastic Properties of Sinkhole Diameters

Sinkhole diameter is one parameter that predetermines the occurrence of a karst hazard, so prediction of probable diameters is one of the most important tasks of the engineering exploration in karst territories. There are a number of approaches to prediction which use various models and methods of forecasting. Theoretical and estimation methods incorporating deterministic geomechanical models are rarely used and only in comparatively simple engineering and geological conditions. In our opinion, forecasting of this kind only gives a rough approximation and other techniques should also be used. The probabilistic statistical method of forecasting based on the statistical analysis of the sizes of sinkholes is the most objectively and widely used (Methodology 1966; Recommendations 1987; Tolmachev et al. 1986). This method, used to predict a sinkhole diameter d, consists of constructing a distribution curve and the estimation of the statistical parameters necessary for further definition of karst failure parameters: arithmetical mean value d_c, standard deviation S, and maximal diameter d_{max}.

The minimum number of karst sinkholes n_d for constructing a distribution curve can be defined by the formula:

$$n_d = (t_d)^2 \cdot K_{var} / (\varepsilon_d)^2, \tag{4.1}$$

where K_{var} – variation ratio, ε_d – admissible error or acceptable relative deviation from arithmetical mean of the limited retrieval from mathematical expectation with a given probability P_t, t_d – normalization factor characterizing probability P_t.

For engineering and geological tasks, it can be assumed that $\varepsilon_d = 0.1$ and $P_t = 0.95$ ($t_d = 2$), and then

$$K_{var} = S / d_c \tag{4.2}$$

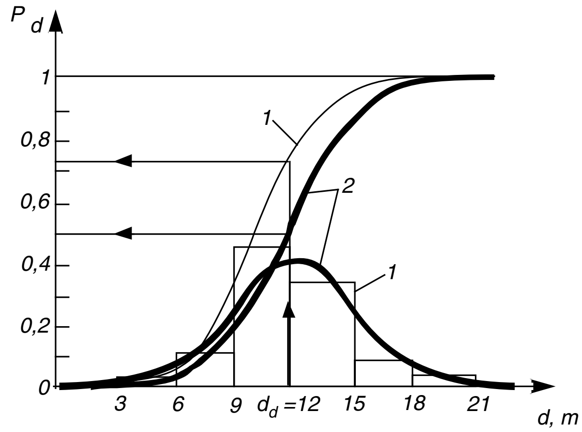
Value of K_{var} can be preliminarily identified by the in situ measurement of the sinkhole diameter. If the number of sinkholes obtained by the formula exceeds the actual number of sinkholes in a certain area, the conclusion is that there was not a large enough representative sample to provide accurate results within error limits. Consequently, results can be improved by simply increasing the number of karst sinkholes included in the study, provided these samples belong to the same general array. However, it is important to realize that increasing the sample size will require a larger area, potentially leading to averaging of nonuniform sites (from the point of view of karst sinkholes dimensions). As a result, the accuracy of the results will be reduced.

To increase the reliability of sinkhole diameter assessment, it is necessary to find theoretical distribution curves corresponding to empirical histograms of sinkhole diameters. Knowledge of the distribution law for karst sinkhole diameters allows us to obtain valid initial data for the structural analysis of karst-proof construction and for the assessment of their efficiency. Figure 4.7 shows one such example of efficiency testing, where the span length is equal to the sinkhole diameter $d_d = 12$ m. Reliability of the construction obtained with the empirical and theoretical distribution curves is shown to be $P_d = 0.73$ and $P_d = 0.5$, respectively. Thus, in this example, the efficiency of the designed construction determined with the use of the histogram is significantly overestimated.

In most cases, the distribution of sinkhole diameter (especially for large areas where natural factors influence sinkhole dimensions) is described by the lognormal law (Fig. 4.8). However, for territories that are homogeneous, in which factors are influencing karst sinkhole diameters, the law of diameter distribution tends toward a normal distribution, which appears to be the case for many small karst areas (Tolmachev 1980).

In the absence of reliable statistical data concerning sinkhole diameters on the site, construction of a distribution curve will be possible if the distribution parameters d_c and $S = (d_{max} - d_c)/3$ are obtained through deterministic models.

Fig. 4.7 The distribution curve of sinkhole diameters *1* empirical; *2* theoretical



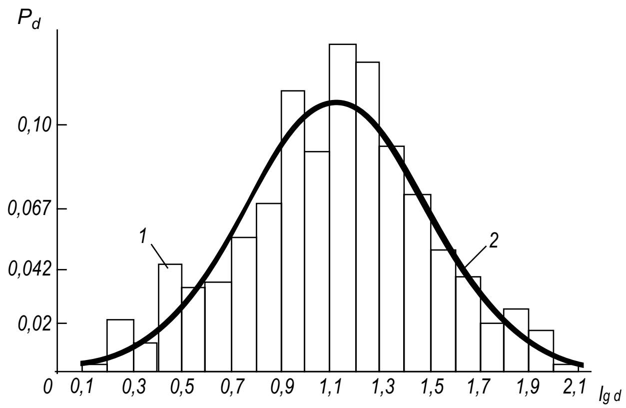


Fig. 4.8 Lognormal distribution curve of sinkhole diameters

Here d_c is estimated for average values of the initial data and d_{max} for the values of the largest sinkhole diameters.

4.4.2 Space and Time Laws for Karst Sinkhole Development

If in a territory with the area *A* during time *t*, the number of new sinkholes is *n* and the average specific frequency (the intensity ratio, λ) of sinkhole development is equal to:

$$\lambda = n / A \cdot t \qquad (4.3)$$

The parameter λ will precisely describe the actual intensity of sinkhole development for large areas when detailed information on the number and the dates of sinkholes is available. In the majority of cases, time span *t* is comparatively short; therefore, the value n should be increased at the cost of increasing A. For separate locations, the objective estimation of the parameter λ by field observation data is possible only in cases of rather intensive sinkhole development. It is frequently necessary to know the value of λ for a small area; however, often it has only been estimated for a much larger region. In this case, λ can be determined using probabilistic and statistical calculation (correlation and dispersive analyses, the theory of qualitative attributes, etc.) methods. These methods are based on the analysis of the engineering/geological situation and the use of maps of natural factors influencing the intensity of karst development. For a detailed description of these, see Tolmachev (1980, 1986).

Presence of an underground karst void is an elemental component of sinkhole development. However, some of the karst voids may never impact the surface throughout a structure's lifespan. For instance, from the results of drilling in Dzerzhinsk karst area, it was found that more than 1,000 karst voids in carbonate and sulfate rock located between 30 and 70 m below the surface; yet, none manifested itself as a sinkhole. Elsewhere in this region, ~4–5 collapses are documented each year. Consequently, there is certain probability that a karst void will manifest itself on the ground surface as a sinkhole (in the engineering sense of time).

Let us consider an area A, where during a given time interval (e.g., one year) a certain number of karst sinkholes appear, and let us divide it into N arbitrary sites with A/N. The probability of karst sinkhole development occurring on any site chosen at random can be presented as:

$$P_s = P_1 \cdot P_2 \tag{4.4}$$

where P_1 – the probability of a karst void existing on the area A/N, P_2 – the probability of the subsequent collapse of the karst void within a given time span. If we increase the number of arbitrary sites and, therefore, reduce their area, probability P_1 will also get lower. Finally, at $N \to \infty$ $P_1 \to 0$ and $P_s \to 0$. We will consider only independent sinkholes, i.e., the situation when the appearance of a sinkhole in one location does not change the probability of a similar event in another location, and karst voids collapse one by one.

The theory of probability requires that the following conditions are satisfied: (1) on the area A in time t, certain points be distributed in a statistically regular way with the average density λ_A; (2) the points occur independently; and (3) points appear one by one, not in pairs, or threes, etc., at $N \to \infty$ and $P_s \to 0$

$$lim NP_s = \lambda_A, \tag{4.5}$$

and the probability of X events for the given time interval is equal to

$$P_{SN}(X) = \exp(-\lambda_A) \cdot \lambda_A{}^X / X! \tag{4.6}$$

The distribution law described by this formula is known as the law of rare events or the Poisson law. This statement appears to be applicable for many karst areas (Tolmachev 1968, 1980). American karst scientists Lilly (1979), Raghu and Tiedeman (1984) also claimed that sinkhole development distribution is close to the

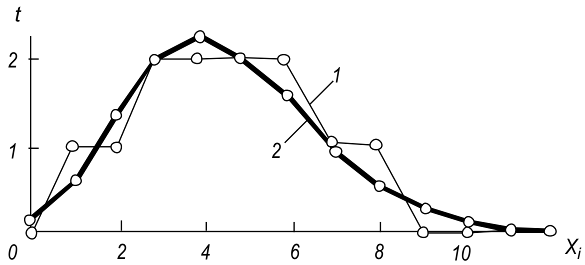


Fig. 4.9 The example of distribution of independent sinkholes development in karstified area of Dzerzhinsk region *1* distribution range; *2* theoretical Poisson`s distribution curve

Poisson law and proved this important statement from the point of view of spatial laws of sinkhole development.

According to a valuable property of this law, mathematical expectation *MX* and dispersion σ^2 are equal to the distribution parameter λ_A, i.e.,

$$MX = \sigma^2 = \lambda_A, \tag{4.7}$$

or, for a separate sample, they are approximately equal to λ_A, i.e.,

$$X_c \approx S \approx \lambda_A, \tag{4.8}$$

where X_c is the arithmetical mean and *S* is standard deviation.

Consequently, we can assume that the distribution of independent karst sinkholes in a region over a particular time interval is regulated by the Poisson law. The distribution parameter λ_A is the mathematical expectation (arithmetical mean) of the number of independent karst sinkholes in the investigated territory that develop during a given time interval.

If we mark value X_i on the X-axis and the corresponding number of years on the Y-axis, we will get an empirical distribution curve for karst sinkholes for the given area (Fig. 4.9). It shows alignment with the Poisson distribution curve and satisfies assumptions of the Pearson's chi-square test.

Known values of λ for the investigated territory with area *A* can give us the probability of the situation when not a single collapse will occur within a given time *t*:

$$P_0 = \exp(-\lambda_A). \tag{4.9}$$

Probability P_{1-n} of at least one karst collapse occurrence equals

$$P_{1-n} = 1 - P_0. \tag{4.10}$$

The probability that during a certain time period the area *A* will be affected by karst sinkholes with the diameters exceeding the estimated sinkhole diameter *d* is found by

$$P_A = 1 - \exp[-\lambda \cdot A \cdot t \cdot (1 - P_d)] \tag{4.11}$$

where, P_d is the probability that the diameter of an appearing sinkhole will not exceed the value *d* (defined by an integrated diameter distribution curve).

4.4.3 Methods of Assessment of Karst Territories Using the Criteria of the Hazard of Karst Collapse

There exist several approaches to determine the level of hazard of karst collapse in karst territories. Analysis of separate aspects of these approaches can be found in some publications (Tolmachev et al. 1986; Tolmachev 2009; Tolmachev and Leonenko 2001). From all the known approaches, separate qualitative and quantitative approaches have been most widely used during the development of karst regions.

The qualitative approach is based on the analysis of the karst environment and the natural factors contributing to void collapse. Standard procedure dictates that the investigated territory is divided into two or three areas (or categories) with different qualitatively described karst hazard levels, e.g., "dangerous area, safe area" or "dangerous area, potentially dangerous area, safe area." While these qualitative characteristics actually reflect comparative hazard, they are often perceived as an absolute definition of karst danger. Their misuse may unreasonably disturb local residents and give the media cause for sensational coverage resulting in contentious public hearings. A preferable situation would be the introduction of neutral description of the land site categories as is done in Germany: Land Niedersachsen now identifies eight digital categories 0, 1,…,7 (Buechner 1991), while Land Hessen identifies eleven categories 1, 2,…,11 (Aderhold 2005). We feel this approach becomes inappropriate when the range of categories widens.

In Russia, a three-stage classification scheme for land areas with respect to their karst hazard was first introduced over 100 years ago and is still often used in spite of recent achievements in karst engineering geology, including a deeper understanding of collapse mechanisms, use of probabilistic methodology for prediction of collapses, GIS-based technologies, and so forth. For the Moscow urban karst territory, this approach was officially adopted some 25 years ago. However, this classification task has not been completed because of insufficient coordination between geological engineers and designers, civil engineers, economists, land-use planners, insurance specialists, and ecologists.

A two-step qualitative classification scheme may be used for general evaluation of vast karst-prone territories in the process of large-scale administrative planning (within the bounds of a whole country or a large region) as has been demonstrated in multiple cases in Russia (Shoigu 2005).

The quantitative approach is to differentiate karst territories by the karst collapse hazard has been known for about 70 years in Russia, but it was not widely used until the Recommendations (1967) were published. Stability categories in karst terranes were supposed to be assigned depending on predicted average frequency (intensity) of karst sinkhole development in a unit area (1 km^2) per a unit time (1 year). In accordance with the range of λ values, territories were subdivided into six stability categories: (1) $\lambda > 1$(very unstable), (2) $\lambda = 0.1-1$ (unstable), (3) $\lambda = 0.05–0.1$ (insufficiently stable), (4) $\lambda = 0.01–0.05$ (slightly unstable), (5) $\lambda < 0.01$ (relatively stable), and (6) $\lambda = 0$ (stable). In view of the above discussion, too many categories would lower the utility and value of the classification (Tolmachev and Leonenko 2001).

Intensity ratio of karst sinkhole development is an important parameter reflecting the probability of collapses. However, the intensity ratio alone (without predicted sinkhole dimensions, particularly diameters) does not fully characterize the karst hazard for constructions. Civil engineers were dissatisfied with this method of karst collapse probability assessment. That was why Methodological Recommendations of 1986 presented a new classification scheme with four classes based on sinkhole diameter *d*: (1) $d=30–20$ m, (2) $d=20–10$ m, (3) $d=10–3$ m, (4) $d=3–0.5$ m. However, this approach failed to consider the intensity of karst sinkhole development with time.

These points of concern were corrected by the building specifications "Engineering Exploration for Construction" developed in 1987. This document and the more recent "Code of Practice 11-105-97," which is now in force, identify the stability categories of karst territories using two predictable parameters: intensity of sinkhole development λ (1–6, no qualitative characteristics added) and average sinkhole diameter d_c: (a) > 20 m, (b) 10-20 m, (c) 3--0 m, (d) < 3 m. Through this approach, engineering exploration became more manageable and focused on the technical aspects. Nevertheless, the practical application of this method over a protracted period revealed further weaknesses:

1. The term "stability of the territory" is not a correct engineering term. Originally, it was adopted from the geographical study of karst. In our opinion, it would be more reasonable to use the term "karst collapse hazard" similar to "landslide hazard" and "seismic hazard." Karst collapse hazard could have a numerical designation in the ascending order (depending on both the intensity of sinkhole development and the average sinkhole diameter).
2. The unit which measures the specific ratio of sinkhole development intensity λ(the number of sinkholes on 1 km^2 per a year) seems difficult for civil engineers to perceive as its origin was again geographical. It would be desirable to modify the unit measure in spatial units more applicable to civil engineering needs. For example, we can use 1 ha (0.01 km^2) as a unit area, which covers most construction and the unit time period of 100 years, which corresponds to the expected life of construction. Interaction with designers shows that the resulting unit of measurement is now better understood by engineers. It should be noted that the numeric value of λ remains the same, even with the new unit measure.

Differentiating karst hazards is important for solving various practical and economic problems (Tolmachev et al. 1986). For instance, it provides data for antikarst protection planning, defines the cost of protecting properties from the negative impacts of karst development, assesses the risk of damage to construction in case of karst sinkhole development, and identifies optimal conditions for insurance of construction against karst-induced risk. Thus, the probability of damage to a property with the area of 1 ha during the time span of 100 years can be estimated by the formula:

$$P_r = 1 - \exp(-\lambda_d) \qquad (4.12)$$

Here λ_d (predicted value of the intensity ratio of sinkhole development) is obtained using the average and maximal sinkhole diameter. It reflects the probability of karst-induced damage to a unit area (1 ha), including the situations when the sinkhole center lies outside the proposed construction site. Therefore, for the purpose of selection of a potential construction site and comprehensive city planning, it is recommended to use only the categories presented in Table 4.2 for $\lambda = \lambda_d$ (Tolmachev 2009).

4.5 Karst Risk Assessment

Karst risk can be understood as the probability of economic, social, and environmental damage, which may be caused by karst collapses, to a territory over time. Using various methods of assessing risk allows for the comparison of construction sites at the selection stage by the value of predicted damage to the structure being designed, as well as antikarst protection planning at the construction and maintenance stages. Damage can also include loss of life and pollution of the environment.

In case of economic damage, karst risk is assessed in the following way:

$$R_e = P_r D \tag{4.13}$$

where P_r is the probability of sinkhole development on an area of 1 ha during 100 years (Formula 12) and D is the economic damage caused by deformation or complete destruction of a building as well as costs for remedial work, technological losses, residents resettlement costs among others.

Estimation of D is a difficult economic task, and it does not need to be calculated exactly for every type of construction. On the contrary, large-scale projects, such as new residential areas of the cities, important industrial plants, nuclear power stations, and so forth, are likely to require knowledge of predicted D values. It is even more difficult to define monetary costs associated with social and environmental damage. In practice, the Russian Scientific Society for Risk Analysis suggested in "The Declaration on Allowable Risk Limits" to identify general types of negative karst impacts for various scenarios based on comparative verbal characterization. Consequently, Table 4.5 takes that recommendation and defines allowable risk levels for various types of damage in karst terranes, by showing the value of specific allowable karst risk for a 1 ha economically developed area during 100 years (R_n).

For practical purposes, each of these three classes of damage is further divided into the following types:

1 Economic Damage

I. Small scale (up to 10 million rubles)
II. Medium scale (from 10 to 100 million rubles)
III. Large scale (from 100 million to 1 billion rubles)

Table 4.5 Allowable karst risk level R_n in different scenarios of negative impacts of karst on future construction and facilities (on 1 ha during 100 years)

	Types of economic damage								
	I			II			III		
	Types of environmental damage								
Types of social damage	1	2	3	1	2	3	1	2	3
a	0.1	0.05	0.01	0.05	0.01	0.005	0.01	0.005	0.001
b	0.05	0.01	0.005	0.01	0.005	0.001	0.005	0.001	0.0005
c	0.01	0.005	0.001	0.005	0.001	0.0005	0.001	0.0005	0.0001

1. For existing buildings and construction never before damaged by any karst features R_n values increase by an order, and for the construction which needs restoration the values increase by half an order
2. Allowable risk values R_n given in Table 4.5 (with the fixed time span of 100 years) are decreased by two orders if the normative time span is 1 year
3. For extremely dangerous and unique construction projects, possible risk types and corresponding allowable karst risk values R_n are assessed by a situation-specific procedure

2 Environmental Damage

1. Improbable pollution
2. Probable local pollution
3. Probable pollution of large areas

3 Social Damage

a. No threat to human life
b. Threat to life of a small group of people (up to ten people)
c. Threat to life of a large group of people (up to 100 people)

Comparison between the values of allowable risk R_n and the values of probability P_r can give us the notion of relative risk level for a certain site of a particular territory and allow appropriate antikarst protection measures to be undertaken. The relative risk level is realistically described by the following expression:

$$LR = P_r / R_n \tag{4.14}$$

Antikarst protection activity of an appropriate type helps reduce P_r and/or increase R_n.

Consider the following example. Designers came to a conclusion that it is necessary to build karst-protected foundations for any construction placed on a given site. Such a preventive measure will exclude economic damage in future, as well as environmental and social damage. Let us assume that prior to the use of antikarst foundation design features, negative impacts of karst were assessed as (II-2-a) in the above table, which corresponds to $R_{n1}=0.01$. It was demonstrated that karst-protected

Table 4.6 Karst collapse risk land adequate antikarst protection measures

LR	Most efficient or economically reasonable antikarst protection activity to reduce karst risk	Antikarst program related to karst collapse risk levels
<0.1	No measures needed	–
0.1–0.3	(A) Prevention of significant anthropogenic impact on the geological environment	A
0.3–1	(B) Refusal from isolated foundations for frame construction	A + B
1–3	(C) Constructional antikarst protection	A + B + C
3–10	(D) Continuous control of the construction state	A + B + C + D
10–30	(E) Special alarm devices	A + B + C+D + E
30–100	(F) Reinforcement of the upper part of the construction	A + B + C + D + E+F
100–300	(G) Reinforcement of karstified rock	A + B + C + D + E + F + G
>300	(H) Construction is not recommended	H

foundation corresponds to the predicted scenario of (I-1-a), where $R_{n2}=0.1$. Let us also assume that the specific risk (probability) of karst feature occurrence on the construction site became $P_{r1}=0.2$, and the risk of unacceptable damage to the construction with karst-proof foundations is lowered by 70%, i.e., $P_{r2}=0.2\cdot 0.7=0.14$. Thus, relative risk values prior to and following the introduction of antikarst protection can be expressed as $LR_1=0.2/0.01=20$ and $LR_2=0.14/0.1=1.4$, correspondingly, i.e., LR_1 values became 14 times lower. Reduction of the risk $P_{r2}=0.14$ below the acceptable level $R_{n2}=0.1$ is now possible due to the maintenance type of antikarst protection activity, including specialized karstological monitoring, raised awareness for construction personnel and other measures. In such cases, the residual risk value P_{r0} may be decreased to a level below, which is allowable ($P_{r0}\leq R_{n2}$), i.e., the relative specific risk level has now become $LR_0<1$.

The above approach encourages the combination of antikarst protection measures. When dealing with designers, investors, developers, and especially administrative authorities, there is a need to render the specificity of the approach in a comprehensible way, and for this reason, relative karst risk values for typical buildings and facilities can be subdivided into several classes. Table 4.6 shows an example.

4.6 Conclusions

The problem of building on karst areas is mainly associated with karst hazard and karst risk assessment. These two notions are interrelated. In real life, in engineering practice and in publications, they are erroneously used as synonyms. What they have in common is the methodology of probabilistic assessment of karst-related events. However, karst hazard assessment involves probability of karst features development (on a given area during a given period of time) which can bring damage to structures, whereas karst risk assessment deals with probability of any negative impacts from exposure (economic, social, and environmental). Differences between these two notions become evident when the karst hazard is realized by sinkholes developing on the ground surface. In addition, karst hazard assessment is usually performed by geological engineers experienced in applied karstology (engineering karstology), but karst risk assessment is performed by a multidisciplinary team (investors, geologists, civil engineers, economists, building maintenance managers, insurance agents, ecologists, etc.). Quantitative karst risk assessment is only meaningful if we have defined safe limits of karst risk. This gives us grounds for further planning of antikarst protection activities during both facilities construction and operation, for evaluating residual risk and defining protection parameters to achieve allowable risk levels.

Involvement in the karst risk assessment process can fulfill our notion of sustainable development of terranes adopted by the UNO in 1987. This concept is declared in the current legislation of the Russian Federation, although our interaction with local authorities, Russian and foreign investors show that they neglect laws in order to reduce costs. To remedy the situation, we have formulated principles of sustainable development on karst terranes (Sorochan et al. 2010) and included them into the regulations for Nizhny Novgorod region as a product of the karst risk assessment methodology.

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Chapter 5
Agriculture and Karst

Catherine Coxon

Abstract This chapter provides a review of the impacts of agriculture on karst terranes, and on management approaches to minimize such impacts. It discusses the range of agricultural activities with potential impacts on soil and water in karst regions, including deforestation, changes in grazing intensity and changes from pasture to tillage, application of fertilizers, and pesticides and storage of farm wastes. Case studies of impacts on soil and on water quantity and quality are presented, with a particular focus on water quality issues including suspended sediment, nitrate, phosphorus, pesticides, and microbial pathogens. The particular vulnerability of karst regions to such impacts is discussed, including the occurrence of point recharge in closed depressions and swallow holes, the thin, patchy soil cover found in many karst areas, the presence of epikarst and the occurrence of conduit flow within karst aquifers. Methods of risk evaluation are reviewed briefly and management strategies to minimize impacts of agriculture are discussed, including the use of Best Management Practices, community-based agri-environmental initiatives, and various legislative controls.

5.1 Introduction

Of all the human activities that have a potential impact on karst terranes, agriculture is perhaps the most ubiquitous. A few karst regions have undisturbed natural vegetation, but the vast majority have some form of agricultural activity. Karst plateaux sometimes have low-intensity agriculture because of the constraints imposed by the rocky terrane, shallow soils, and scarcity of water. However, where higher-intensity agriculture occurs, the risk of problems such as soil erosion and water contamination is generally much greater than in other terranes.

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Agricultural activities in karst regions have wide-ranging implications for soils, water, and landscape, for ecosystems and biodiversity, and for social and economic sustainability. It is not possible within the scope of this chapter to review all of these areas, and so the following discussion is focused specifically on the impact on soils and water, particularly on water quality, and on management approaches to minimize such impacts. However, it is acknowledged that any changes to soil and water quantity and quality will have implications on other aspects of the natural and human environment, and that any management strategies must take these linkages into account.

One of the greatest problems associated with land clearance for agriculture and agricultural intensification in karst terranes is the risk of soil erosion. Karst areas are particularly prone to this, both because limestone soils are typically shallow (as the rock from which they are derived yields little insoluble residue) and because the open joint systems facilitate the washing underground of soil material (Williams 1993). Intensification of land use, including irrigation and drainage schemes, may also bring about hydrological changes to karst aquifers, including changes in timing or amount of aquifer recharge or discharge and flooding problems. Alterations to water quality may arise from land use change, from the use of fertilizers and pesticides, and from point sources of contamination such as badly stored farm wastes. Karst aquifers are particularly vulnerable to chemical and microbial contamination due to the occurrence of point recharge via sinking streams and dolines, the presence of an epikarst zone, and the existence of both conduit and diffuse flow within the aquifer itself (Field 1989; Smith 1993). Changes in water quality may have implications for human health and for ecosystems, including cave communities and surface water ecosystems fed by karst springs.

The range of agricultural activities with potential impacts on soil and water in karst regions is outlined in Sect. 5.2, while case studies of actual impacts are presented in Sect. 5.3. Case examples are mainly drawn from the last 15 years; for additional earlier studies, the reader is referred to the review by Coxon (1999). Methods of risk evaluation and management strategies to minimize impacts of agriculture are reviewed in Sect. 5.4.

5.2 Activities

5.2.1 Land Use Change

Deforestation of karst regions results in a loss of biodiversity; the vegetation changes in turn cause increased soil erosion, and the combination of changes in evapotranspiration and in soil cover will result in hydrological changes. Increases in grazing pressure and the conversion of pastureland to tillage may also increase soil erosion rates and have hydrological impacts. Land use changes are also likely to have impacts on water quality, particularly on suspended sediment and nutrients.

Fig. 5.1 Grazing of recently deforested land in the Vaca Plateau, Belize (Image © M Day)

Prehistoric and historic occurrence of soil erosion due to deforestation has been reported from many karst areas. For example, agricultural development by the Maya people in the Yucatan Peninsula of Mexico, Belize, and Guatemala from 4,000 to 3,000 BP onwards gave rise to soil erosion in karst areas; soil conservation measures, including extensive terracing, appear to have been effective in reducing soil loss, but a further period of soil erosion followed (Beach et al. 2002). Deforestation continues to the present day in the karst of the Caribbean region (Day 1993, 2007; Fig. 5.1). It is also an important issue in many other tropical and subtropical karst areas, notably in a large area of subtropical China (Yuan 1993; Wang et al. 2004). Soil erosion due to deforestation has also been widespread since prehistoric times in Mediterranean karst areas (Gams et al. 1993) and in karsts of cool temperate climatic zones (Drew 1983). Soil erosion problems are discussed in Sect. 5.3.1.2, while hydrologic impacts of deforestation are reviewed in Sect. 5.3.2.1 and suspended sediment is discussed in Sect. 5.3.3.2.

Forest clearance may give rise to other water quality changes besides suspended sediment. Lichon (1993) found that the release and leaching of forest nutrients, following deforestation of Tasmanian karst, resulted in elevated nutrient loading of karst streams and contamination of water resources, while Ellaway et al. (1999) note that springs and cave streams from uncleared native forest catchments in Buchan, Australia, differ in chemistry from those with catchments of cleared agricultural land. Jiang et al. (2006) document changes to major ion concentrations of groundwater in the karst Xiaojiang catchment in Yunnan province, China, between 1982 and 2004, due to deforestation and agricultural intensification.

Intensification of agriculture on existing farmland, such as increased grazing pressure or a change from pasture to tillage, may also provoke soil erosion and hydrological and water quality changes. Problems associated with land clearance and intensification are documented from the Burren karst plateau, Ireland, by Drew and Magee (1994), and from Murgia, Southern Italy, by Canora et al. (2008). In the latter area, a dense network of drystone walls had an important role in reducing soil erosion and retarding runoff, but wall clearance, agricultural mechanization, and a change from grazing to tillage from the 1980s onwards caused changes to the soil and hydrology of the region. Figure 5.2 shows the contrast between the karst landscape unaltered by clearance and the cleared, tilled land.

A decrease in agricultural intensity, often associated with rural depopulation, may also cause environmental problems, albeit of a different nature. In the Burren plateau, Ireland, a decrease in winter livestock grazing in recent years has led to increasing encroachment of hazel scrub vegetation with loss of characteristic world-renowned arctic-alpine flora designated as priority habitats under the E.U. Habitats Directive (Dunford and Feehan 2001; BurrenLIFE 2006). Efforts to tackle this issue are discussed in Sect. 5.4.2.

5.2.2 Irrigation and Drainage

Soil water content is frequently altered to facilitate agriculture, with moisture levels being either increased by irrigation or decreased by land drainage operations. This is likely to have an impact on groundwater resources, with changes in amount and timing of recharge and discharge, and such impacts will be particularly marked in karst areas where surface waters and groundwaters are so closely interlinked.

Irrigation of agricultural land may cause a hydrological impact at the source of the irrigation water or at the irrigation site. In karst aquifers, the lowering of the water table due to irrigation water withdrawals may be very uneven and difficult to predict. The irrigated land may then provide a new source of recharge to the karst aquifer, with potential problems of salinization noted below. Problems may also arise with damming for irrigation purposes, e.g., Gillieson and Thurgate (1999) record damage to the Texas cave system in Australia due to the building of an irrigation dam. Land drainage operations carried out with the aim of decreasing soil moisture levels to improve agricultural productivity may also have significant hydrological impacts. For example, in the carboniferous limestone lowland areas of Western Ireland, channelization to relieve flooding of agricultural land has resulted in a lowering of water tables and a change to the flooding regime of ecologically important seasonal karst lakes (Drew and Coxon 1988) (see Sect. 5.3.2).

Irrigation or drainage of land is generally accompanied by agricultural intensification and increased use of fertilizers and pesticides, resulting in changes to soil water and groundwater quality. Irrigation may also provoke groundwater quality

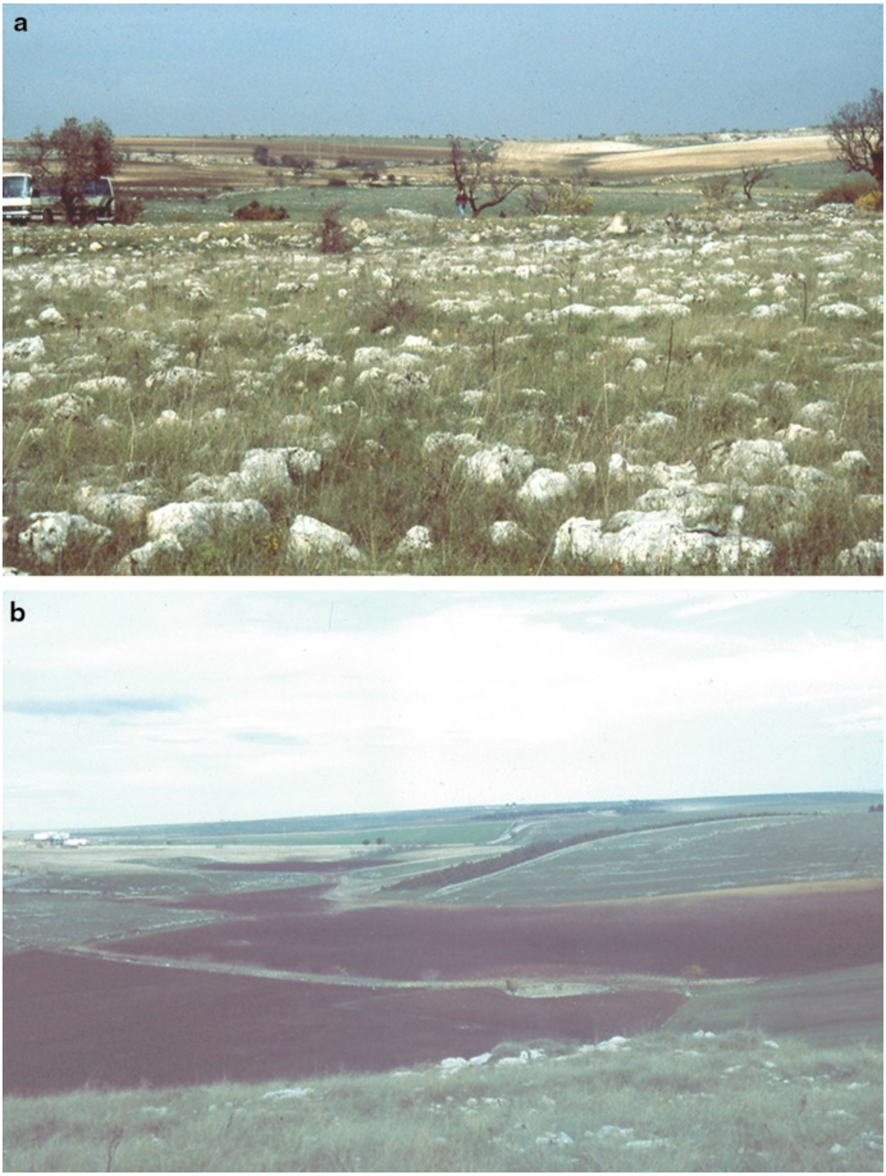

Fig. 5.2 Contrast between (**a**) an unimproved field and (**b**) a reclaimed, tilled doline in Apulia (SE Italy) (Images © D Drew)

changes if it brings about increased leaching of natural or artificial chemical constituents from the soil. Salinization of karst groundwaters due to increased leaching of soluble salts has been documented from several areas, e.g., Puerto Rico (Day 1993). Equally, irrigation with water of a high salinity may have an adverse impact on soil chemistry and productivity, as noted in Southern Italy by Gams et al. (1993).

Drainage operations along river channels may provide entry routes for contaminants to underlying karst aquifers. For instance, in the Clarinbridge catchment in the Western Irish karst lowlands, channel excavation into bedrock resulted in line and point recharge with polluted surface waters, causing a nitrate plume in the karst aquifer (Drew 1984; Fig. 5.3a).

5.2.3 Landspreading of Fertilizers and Pesticides

Over the last few decades, there has been a global increase in the use of inorganic fertilizers, which has led to an impact on groundwater quality, particularly nitrate concentrations. Agricultural land is also landspread with an increasing range of organic material, including agricultural wastes (livestock manure or slurry, silage effluent, farmyard runoff), human wastes (sewage effluent, sewage sludge), and agro-industrial wastes (dairy effluent, blood, offal). Pesticide use has also increased greatly in recent decades in many countries. The resulting water quality problems are widespread throughout both the developed and developing world and are by no means unique to karst areas. However, karst aquifers are particularly vulnerable due to the high aquifer permeability, often combined with thin soil cover. Furthermore, groundwater contamination may not be restricted to the more mobile constituents such as nitrate and chloride; constituents more usually associated with point agricultural sources (e.g., phosphorus, potassium, ammonium, and fecal microorganisms) may also gain entry to vulnerable karst aquifers from diffuse agricultural sources. Similarly, pesticide contamination in karst aquifers may not be restricted to the most mobile compounds, as pesticides adsorbed to colloidal soil particles may gain entry to the aquifer via solutionally widened fissures. Case examples of karst groundwater contamination by nitrate, phosphate, pesticides, and microbial pathogens are given in Sect. 5.3.3.

5.2.4 Rural Point Sources

Agricultural point sources of pollution can range from small-scale inputs of fecal material from groupings of animals at feeding troughs or sheltered/shady locations to larger pollutant plumes originating from badly stored farm wastes such as slurry and silage effluent. These can cause pollution in any vulnerable hydrogeological situation. However, in the case of karst aquifers, there is an added risk at locations of concentrated recharge: contamination is particularly acute where agricultural point sources coincide with karst features such as sinking streams and dolines. Thus, cattle congregating around cave entrances or entering sinking streams can cause severe localized contamination with fecal microorganisms and nutrients (Berryhill 1989). Dumping of animal carcasses into karst-closed depressions is another common source of contamination (Gillieson and Thurgate 1999). Storage of silage on bare limestone pavement in the Burren karst plateau in Ireland has resulted in

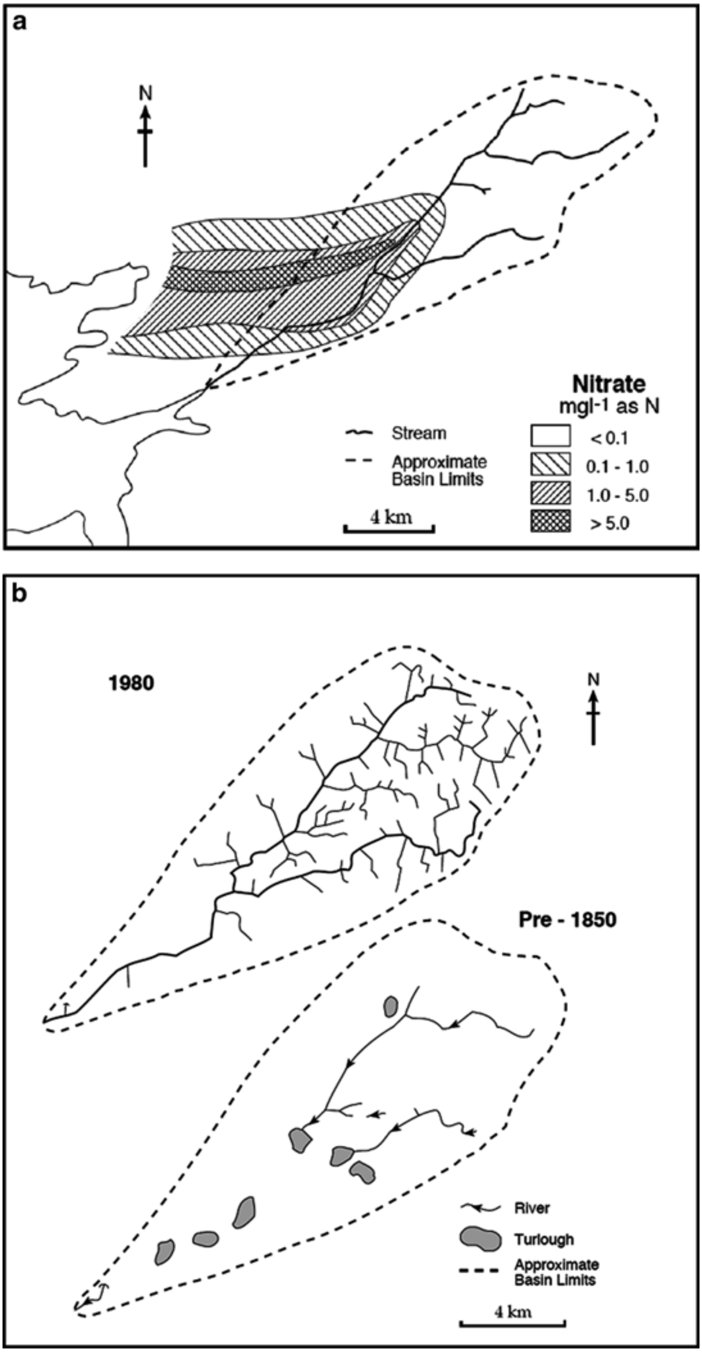

Fig. 5.3 Impacts of agricultural drainage in an Irish lowland karst catchment (Clarin, County Galway), (**a**) Nitrate plume due to line recharge along an artificial river channel, (**b**) Change in drainage density due to agricultural land drainage (After Drew 1984)

Fig. 5.4 Silage clamp on bare limestone pavement on the Burren karst plateau, Ireland, posing a threat to groundwater quality (Image © D Drew)

contamination of karst springs in summer, at times of maximum water demand (Drew 1996; Fig. 5.4).

Another rural point source of contamination is septic tank effluent from rural housing not served by city sewerage systems. While not strictly agricultural, this contaminant source often occurs in close association with agricultural point sources; thus, rural groundwater contamination by fecal microorganisms may be due to a combination of human and animal waste. The presence of thin soils in many karst areas, providing insufficient purification in the percolation area, combined with the rapid transfer of effluent through solutionally widened fractures in the unsaturated zone, means that fecal contamination from septic tank effluent is particularly common in karst regions (Panno et al. 1997).

5.3 Impacts

5.3.1 Impacts on Soil

5.3.1.1 Introduction to Agricultural Impacts on Soil

As noted in the introduction, karst areas are particularly prone to soil erosion due to a combination of shallow, erodible soils and solutionally widened fractures into which soil particles are easily transported. Such erosion is often triggered by clearance of forested land for agriculture or by increase in grazing density or increased cultivation. Examples of such impacts from karst regions around the world are given in Sect. 5.3.1.2 below.

The mechanisms of soil erosion in karst areas are discussed by Hardwick and Gunn (1990). The greatest sediment inputs are associated with sinking streams, particularly where these originate on noncarbonate rocks. Soils may be eroded into karst aquifers by autogenic recharge, particularly where macropores are present and where dolines provide routes of sediment entry. Hardwick and Gunn (1990) also consider that sediment transport through the epikarst or subcutaneous zone is highly likely; they suggest that it is probably very slow but should not be neglected, as they note studies in the Dinaric karst which show suspended load in cave trickles to be of the same order of magnitude as dissolved load. Suspended sediment in karst waters is discussed further in Sect. 5.3.3.2.

In addition to soil erosion, agriculture can also have a major impact on soil chemistry. Jiang (2006) documents the changes in soil organic matter content and chemical properties due to land use change in a karst agricultural region in Southwest China and notes that the modifications in soil properties were greater in soils developed from carbonate rocks than in soils developed from sandstone. Soil carbon dioxide levels will also vary as a result of landuse change. For example, Day (1999) documents changes in soil carbon dioxide levels arising from “slash and burn” agriculture in the Hummingbird karst of Belize, with a drastic reduction on the day after burning and gradual recovery in subsequent days, and he notes that such changes are relevant to limestone dissolution.

5.3.1.2 Soil Erosion Associated with Land Use Change

As noted in Sect. 5.2.1, deforestation of many karst regions has given rise to soil erosion since prehistoric times, and continues to the present day. One region where soil erosion is particularly severe is in Guizhou Province, Guangxi Zhuang Autonomous Region and Yunnan Province in Southwestern China, where it has been termed rocky desertification (Huang et al. 2008; Fig. 5.5). In this region, land is being lost by the transformation of vegetation – and soil-covered karst landscapes - into exposed rock at a rate of 25,000 km^2 per year; about 40% of the land area is affected by soil erosion, and in addition to causing severe impacts in the eroded areas, this has caused problems of sedimentation of river courses and reservoirs (Wang et al. 2004). Silt transport rates for rivers in this region subject to deforestation and rocky desertification are 208–1,980 tonnes/km^2/year (Yuan 1993).

Soil erosion has occurred in many Mediterranean karst regions since prehistoric times (Gams et al. 1993). Different phases of land exploitation in the karst Venetian Fore-Alps (Northern Italy) are reviewed by Sauro (1993), who notes that forest clearance and cattle and sheep grazing have been responsible for significant soil loss into subsoil karren cavities. Bou Kheir et al. (2008) note that karst landscapes which comprise 70% of Lebanon have thin soils which are prone to erosion due to deforestation, burning, and overgrazing, and they readily succumb to desertification. Gillieson and Thurgate (1999), reviewing karst and agriculture in Australia,

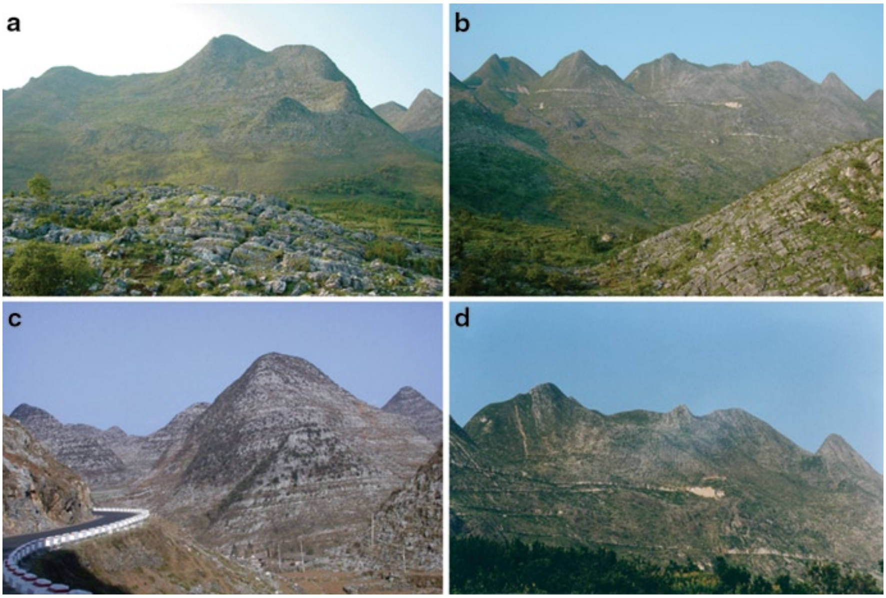

Fig. 5.5 Examples of karst rocky desertification in South-West China (From Huang et al. 2008, p.391, © Royal Swedish Academy of Sciences)

comment that there is a crucial link between landscape stability and vegetation cover in Australian karst; they note that clear-cutting in the Florentine Valley in Tasmania caused the accumulation of 1 m of cave sediment, and they also record evidence of sediment accumulation due to deforestation in the karst of New South Wales. An increase in grazing pressure, particularly in arid and semi-arid areas, may trigger increased soil loss; this is documented for the example in the Nullarbor Plain in Australia (Gillieson et al. 1994). Poor tillage practices may also trigger erosion in karst regions (Berryhill 1989). Intensive vine cultivation in the Entre-deux-Mers karst plateau in Southern France, involving field leveling by bulldozers, has resulted in significant soil erosion, with clogging of drainage channels and development of suffusion dolines (Audra 1999).

5.3.2 Impacts on Water Quantity

5.3.2.1 Changes in Groundwater Recharge

Changes in land use such as deforestation, reforestation, and conversion of grassland to tillage will all have implications for groundwater recharge due to the change in evapotranspiration rates. Lerner et al. (1990) document several case studies of carbonate aquifers where groundwater recharge is related to vegetation cover. Alteration to groundwater recharge due to vegetation changes and resultant changes in evapotranspiration are not, of course, unique to karst areas. However, the recharge mechanisms specific to karst areas may accentuate the change.

Huntoon (1992) noted that in the stone forest karst aquifers of South China, massive deforestation since 1958 has resulted in a major impact on the magnitude and duration of the seasonal recharge pulse. Water that was formerly retained in the forested uplands and gradually released to recharge the aquifers on the lowland now passes rapidly through the system, so that the decline in water level in the aquifers during the dry season has been accelerated. Water shortages due to karst rocky desertification in Southwestern China are also noted by Wang et al. (2004), who comment on a reduction in the retention of surface water and drinking water shortages due to drying up of springs and wells. Similarly, deforestation associated with increasingly intensive slash-and-burn agriculture in the karst area of Batuan on the Island of Bohol in the Philippines is regarded by Urich (1993) as the primary cause of a decline in spring discharges by 40% in a 20-year period. Chandler and Bisogni (1999) also note that forest clearance in karst areas of the Philippines has resulted in an increased frequency of water shortages: in the Leyte uplands, a comparison was made between sites with forest cover, slash-and-burn cultivation, plouwed land, and pastureland. The latter two land uses had reduced infiltration and increased runoff, and it was proposed that disturbance of the soil surface results in progressive plugging of the epikarst. Deforestation may also trigger geomorphological changes with implications for recharge. Kiernan (1989) notes that forest clearance for pasture in Tasmania has resulted in accelerated sinkhole development.

Modification and intensification of existing agricultural land may also result in changes to groundwater recharge. For example, Canora et al. (2008) modeled the hydrological impacts of agricultural intensification on the Alta Murgia karst plateau in Southern Italy (Sect. 5.2.1) and found that cereal cultivation on the reclaimed “shattered stone land” resulted in a significant decrease in recharge to the karst aquifer, which provides an important regional water resource.

Drainage of agricultural land in karst regions will also have an impact on recharge. In the Western Irish carboniferous limestone lowland, channelization carried out from the mid-nineteenth century onwards to relieve flooding of agricultural land has resulted in a decrease in aquifer recharge and lowering of water tables. For example, in the Kilcolgan-Lavally catchment in East Galway, summer water tables have been lowered by 2–3 m, causing previously perennial springs to become ephemeral (Drew and Coxon 1988). In the neighboring Clarinbridge catchment, the drainage density has been increased from 0.2 to 4 km/km^2, and in the lower catchment, an artificial river has been excavated into bedrock (Fig. 5.3b). As a result, surface runoff from the basin has been increased from 0 to 40% of effective precipitation and aquifer recharge has been reduced accordingly. Spatial patterns of recharge and discharge have been altered, with the artificial stretches of channel providing line and point recharge and discharge at different times of year (Drew 1984).

5.3.2.2 Flooding

Flooding problems may sometimes result from deforestation and associated soil erosion, due to increased runoff and blockage of the karst drainage system by the eroded soil and sediment. For example, in a karst region of Kentucky, U.S.A., removal of oak-maple forest cover and cultivation of tobacco and corn in the 1930s resulted in disastrous valley floods known locally as "valley tides." Runoff was increased, and the increased sediment load blocked the already insufficient underground drainage channels, resulting in backing up of runoff and flooding of the valleys upstream of river sinks (Dougherty 1981). Forest clearance in Mole Creek, Tasmania, caused cave conduits to become choked by sediments, resulting in flooding of pastures during the winter months (Gillieson and Thurgate 1999).

Some agricultural changes may cause a decrease rather than an increase in flooding. The drainage operations in the Western Irish limestone lowlands referred to in Sect. 5.3.2.1 have also resulted in the draining of turloughs (seasonal karst lakes; Fig. 5.6); approximately, a third of turloughs have been drained since the nineteenth century (Drew and Coxon 1988). The cessation of seasonal flooding has serious ecological implications (Sheehy Skeffington et al. 2006). Karst poljes, which provide areas of flat, fertile land within rocky Mediterranean karst landscapes, have also been subject to drainage schemes by various means and with varying degrees of success. In recent decades, polje water regulation schemes have been multi-purpose, for hydroelectric power generation and water supply as well as agriculture, and have involved major tunnel construction (Milanovic 2002).

5.3.3 Impacts on Water Quality

5.3.3.1 Vulnerability of Karst Aquifers to Agricultural Contamination

The existence of point recharge to karst aquifers makes it particularly easy for agricultural contaminants to gain access. Swallow holes provide direct access points to the aquifer, with little or no attenuation, so contaminants more frequently associated with surface waters, which would not normally enter by diffuse recharge (e.g., phosphate or pesticides adsorbed to suspended sediment), may enter karst conduits by point recharge. Furthermore, many karst areas have a mosaic of bare rock and thin rendzina soils, and the lack of protective cover combined with solutionally widened fissures in the limestone creates extreme vulnerability to pollution from agricultural sources. The epikarst or subcutaneous zone may allow rapid lateral movement of diffuse contamination to vadose shafts. It can also provide significant temporary storage for contaminants, which may then be released from this zone by flood pulses (Field 1989).

The presence of conduit flow in karst aquifers allows rapid transfer of contaminants through the aquifer, with minimal opportunity for attenuation by adsorption, ion exchange, chemical breakdown, or microbial die-off. The short underground residence time also means that very little time is available for remedial action to avoid contamination of drinking water supplies. In addition, the lack of attenuation

Fig. 5.6 Kilglassan turlough, Co. Mayo, Ireland, a karst seasonal lake in winter, spring, and summer (Many such features in Western Ireland no longer flood regularly due to agricultural land drainage schemes) (Images © P Coxon)

in the karst aquifer can result in groundwater contaminants emerging at springs and having an ecological impact on surface waters to a greater degree than in other aquifer types. However, it should be noted that karst aquifers demonstrate a spectrum of behavior, often reflecting the age of the limestone. In older limestones with secondary permeability only, contaminants in recharge may move through the unsaturated zone extremely rapidly through solutionally widened fissures, while in dual porosity aquifers such as the Cretaceous Chalk, there may also be a very slow recharge component in the primary pore space. In the saturated zone, pollutants may move rapidly along cave conduits, or they may form a more conventional plume where there is a significant proportion of diffuse fissure flow.

In the following sections, some of the most significant groups of agricultural contaminants of karst groundwater are discussed, with case examples from many different regions.

5.3.3.2 Suspended Sediment

The presence of solutionally enlarged joints and sinking streams allows sediment derived from soil erosion to enter karst aquifers to a greater extent than in other aquifers. Suspended sediment may cause problems of turbidity in drinking water supplies, but it is particularly important because it can provide a method of entry for a range of adsorbed contaminants including phosphorus, pesticides, and viruses.

Suspended sediment loads show a large degree of temporal variation. For example, in the Big Spring Basin (Iowa, U.S.A.), an agricultural karst catchment with a rotation of corn/pasture/hay suspended sediment loads in the spring increase during flood events from negligible values to concentrations over 4,000 mg l^{-1}, corresponding to a load of over 87,000 kg h^{-1} (Hallberg et al. 1985). Figure 5.7 illustrates the chemical

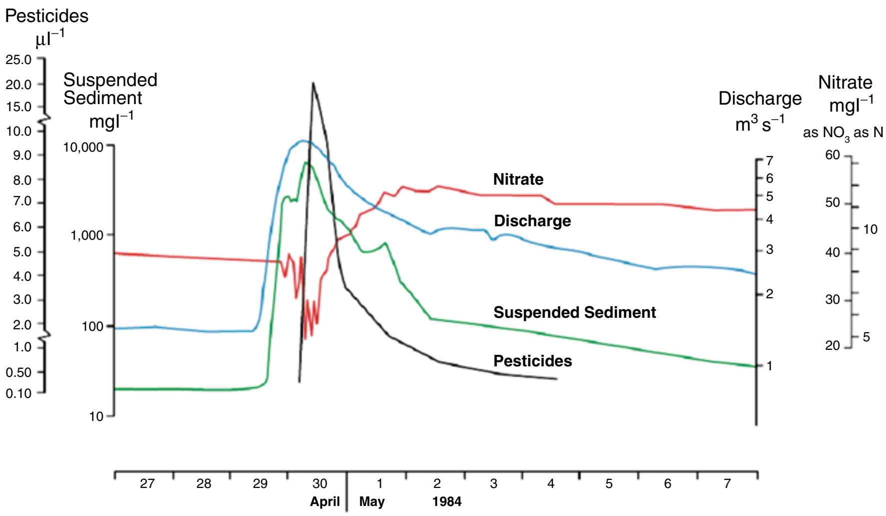

Fig. 5.7 Changes in water quality during a summer discharge event at Big Spring, Iowa, USA (After Libra et al. 1986)

changes associated with summer discharge events at Big Spring; it can be seen that the suspended sediment concentrations mirror the variation in discharge, and the pesticide peak corresponds to the suspended sediment peak. Similarly, Nebbache et al. (2001) note that turbidity peaks in springs, fed by the Brionne Basin karst system in Normandy, France, are short-term events coinciding with heavy rain episodes.

Pronk et al. (2007) studied sediment transport through karst flow systems draining agricultural land in the Yverdon karst system in Switzerland. Continuous monitoring of particle size distribution was undertaken during storm events (Fig. 5.8); the first turbidity peak corresponded to a mixture of coarser and finer particles remobilized within the karst conduit by the flood pulse, while the arrival of the second turbidity peak, consisting of finer particles and coinciding with an increase in total

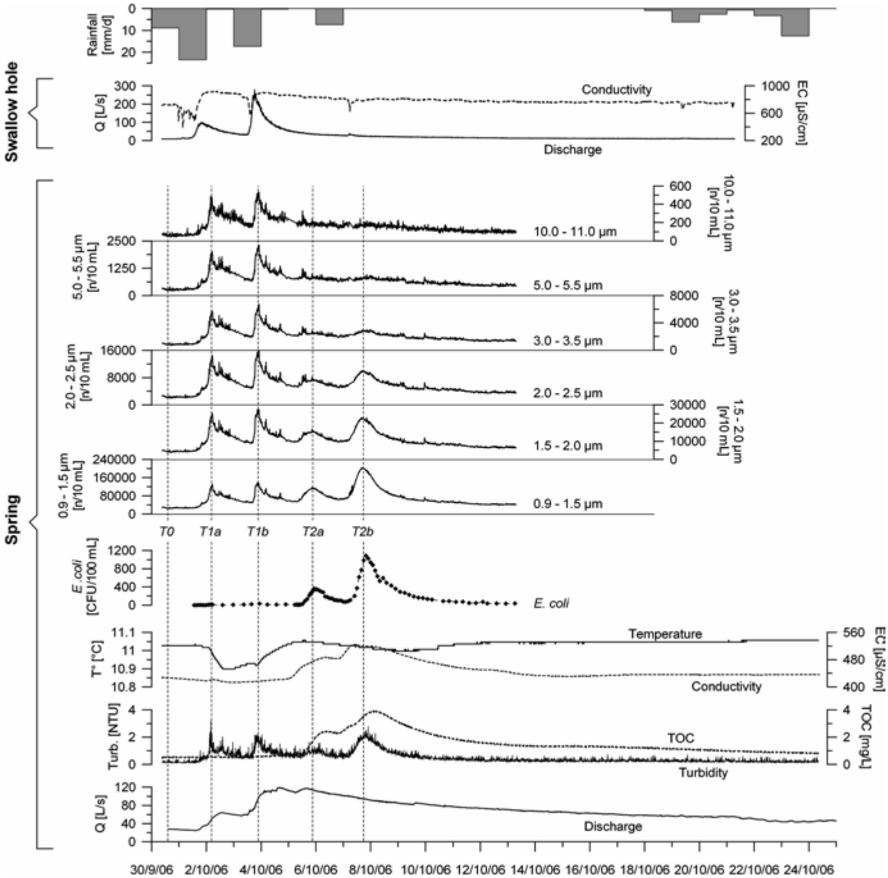

Fig. 5.8 Variation in turbidity and other parameters during a multiple flood event at the Feurtille swallow hole and Moulinet spring, Yverdon karst aquifer, Switzerland. T0 = pre-storm conditions, T1a/b = autochthonous turbidity signals of the first/second flood event, T2a/b = allochthonous turbidity signals of the first/second flood event (From Pronk et al. 2007)

organic carbon, indicated the arrival of swallow hole water at the springs (with larger particles removed by sedimentation within the aquifer).

5.3.3.3 Nitrate

Nitrate contamination of karst aquifers in rural areas can arise from many sources, both diffuse (spreading of inorganic and organic fertilizers and release of soil nitrogen due to land use change) and point (e.g., badly stored farm wastes and septic tank effluent). The nitrate ion is highly soluble and mobile, so nitrate pollution is found in many free-draining hydrogeological situations, but the characteristics of karst regions outlined in Sect. 5.3.3.1 make karst aquifers particularly vulnerable. The shallow, patchy rendzina soil cover overlying some karst aquifers increases the risk of leaching. Where a thicker soil cover is present, nitrate may move slowly through the soil matrix, or macropore flow may provide opportunities for rapid transfer (Iqbal and Krothe 1995; Peterson et al. 2002). The presence of point recharge via swallow holes and dolines may allow nitrate to enter the aquifer with little residence time in the soil. For example, in the Brionne Basin in Normandy, Northern France, nitrate reaches the karst springs both by rapid transfer of point recharge (with short-lived nitrate peaks occurring during heavy rainfall, coinciding with turbidity peaks) and by leaching of diffuse recharge (providing a longer-term sustained nitrate input) (Nebbache et al. 2001). Where the aquifer has secondary porosity and permeability only, nitrate will pass rapidly through the unsaturated and saturated zones (e.g., in the carboniferous limestone of Ireland; Richards et al. 2005), while, if the limestone has dual porosity, there is a possibility of retention in the unsaturated zone for considerable time periods (as in the Cretaceous Chalk; Jackson et al. 2008).

Elevated nitrate is found in many karst groundwaters around the world, including Australia (Gillieson and Thurgate 1999), China (Guo and Jiang 2009), Turkey (Davraz et al. 2009), and Morocco (Laftouhi et al. 2003). Nitrate levels are problematic in many European carbonate aquifers. For example, elevated nitrate in the Cretaceous Chalk of Eastern England has given rise to concern since the 1980s, breaching the European Union drinking water standard of 50 mg l^{-1} NO_3 (11.3 mg l^{-1} as N) and creating a challenge for meeting improvement deadlines under the EU Water Framework Directive (2000/60/EC) (Jackson et al. 2008). High nitrate is also found in karst aquifers in the Franconian Alb of South Germany (Einsiedl and Mayer 2006). Such problems were a contributing factor to the introduction in 1991 of the European Union Nitrates Directive (91/676/EEC) (see Sect. 5.4). However, not all European karst regions have such nitrate problems, as in some instances the difficult nature of the karst terrane has meant that agriculture has remained less intensive than elsewhere. In Ireland, the synclinal carboniferous limestone valleys in the south of the country have intensive dairying agriculture, and as a result, there are nitrate problems from both diffuse and point sources (Bartley and Johnston 2006), but the Western Irish limestone lowlands and the Burren plateau have less intensive agriculture, and as a result, nitrate concentrations are significantly lower, as seen from Irish EPA monitoring data in Clabby et al. (2008). A similar contrast can be seen in French karst regions: the Brionne Basin in Central Normandy has undergone agricultural intensification, with increased nitrogen inputs and increased area of arable land, and shows a trend of increasing groundwater nitrate concentrations over the last few decades (Nebbache et al. 2001), but Plagnes and Bakalowicz (2001) note that many French karst areas have a lower intensity of human activity and therefore have groundwater of generally good chemical quality. For example, the Larzac plateau in Southern France has patchy soils and is mainly used for low-density sheep grazing. However, they note that even in this area, agriculture is the main source of nitrate, with a relationship between nitrate flux and amount of cultivation, and they suggest that measures are needed to prevent further increases in nitrate concentration.

In the U.S.A., many papers over the last three decades have documented concerns about nitrate in karst groundwaters. Breaches of drinking water standards for nitrate were recorded in karst groundwaters in Minnesota, Pennsylvania, and Iowa (Berryhill 1989). Nitrate from diffuse agricultural sources is especially well documented for the Big Spring groundwater basin in Iowa (Hallberg et al. 1985; Libra et al. 1986; 1999), where the nitrate problems are linked to nitrogen fertilizer application to corn (maize). Boyer and Pasquarell (1995) found that nitrate concentrations in karst springs in Southeastern West Virginia showed a strong linear relationship with percent agricultural land, with the land being used primarily as pasture for cow-calf and dairying operations. A further study of cave streams in this region (Boyer and Pasquarell 1996) showed that nitrate concentrations were highest in cave streams draining a dairy farm and in a cave stream draining an area of pasture where cattle congregated for shade and water. Management approaches to tackle these problems are discussed in Sect. 5.4.2. More recently, Panno et al. (2001) have used stable isotopes (δ^{15}N and δ^{18}O of the nitrate ion) to determine the sources of nitrate in karst groundwater in the sinkhole plain of Southwestern Illinois and to investigate denitrification in the aquifer. Monitoring of nitrate loads from two large karst springs draining this aquifer indicated a loss of ~27 kg N/ha/year, with approximately half coming from background sources and most of the remainder coming from fertilizer (Panno and Kelly 2004).

Temporal variations in nitrate concentration in karst groundwaters will depend on the source of nitrate and the pathway it takes through the aquifer. In many instances, high nitrate concentrations are associated with diffuse recharge, while lower concentrations coincide with major point recharge inputs, when a major input of surface water dilutes the nitrate. For example, in the Big Spring basin in Iowa, nitrate reaches maximum levels during discharge recession when infiltration recharge dominates (Fig. 5.7). Mahler et al. (2008) noted that despite the contrasting hydrogeological characteristics of the Chalk aquifer of Normandy, France, and the Edwards aquifer, Texas, U.S.A., in both aquifers, nitrate was a diagnostic tracer of resident groundwater, decreasing in concentration during storm events, whereas potassium and turbidity were effective tracers of infiltrating storm runoff. The analysis by Guo and Jiang (2009) of temporal variations in the rising of a subterranean river in a peak cluster karst area of China showed that there was a nitrate peak at the start of the rainy season, which was attributed to release of nitrogen which had accumulated in the soil during the dry season from fertilizers, animal waste, and general village waste. Analysis of shorter-term variations during three rainfall events showed that higher nitrate was associated with piston flow from the soil and vadose zone and with arrival of recharge from these zones.

5.3.3.4 Phosphorus

Inputs of phosphorus to surface freshwaters via surface or near-surface pathways have been a concern for many years because this is often the limiting nutrient to eutrophication of rivers and lakes. However, over the last decade, there has been a growing awareness that in some instances groundwater can provide a pathway of phosphorus transfer to ecologically sensitive surface waters, and this is particularly likely to occur in vulnerable karst situations.

Calcareous soils retain significant quantities of phosphorus, due to both adsorption and precipitation reactions. However, leaching may occur where the soils are highly saturated with P or where it has been mobilized by the addition of manure (von Wandruszka 2006). Leaching is particularly likely in karst areas where thin, organic rendzina soils are present, but the greatest reason for concern about phosphorus in karst areas is the occurrence of point recharge bypassing the protective soil cover, combined with rapid passage flow through the aquifer via conduits and discharge to springs which may feed surface water bodies susceptible to eutrophication (Kilroy et al. 2001). Initial lack of evidence for phosphorus in karst springs from studies in the 1980s was at least partly due to poor detection limits in many groundwater phosphorus analyses, reflecting nonexistent or high drinking water limits for P (of the order of mg l^{-1}). Ecological thresholds are much lower, e.g., the OECD phosphorus threshold for eutrophic lakes is a total phosphorus concentration of 35 μg l^{-1} (Vollenweider 1982).

Hardwick (1995) found elevated concentrations of phosphorus in cave waters in a karst aquifer in Derbyshire, U.K., which increased after application of sewage sludge to the overlying agricultural land. Alloush et al. (2003) noted a strong positive correlation between total dissolved phosphorus concentrations in rivers in the Appalachian region of the U.S.A. and the percentage of their catchment areas classified as karst landscape. They found that the total dissolved P concentration and the proportion of dissolved nonreactive P in soil samples increased with the amount of cattle grazing in karst sinkholes in this region. Runoff to the sinkholes contained very high concentrations of dissolved P (several mg l^{-1}), which was dominated by inorganic P, whereas the cave stream contained dissolved P concentrations of the order of 0.2 mg l^{-1} (200 μg l^{-1}), which was dominated by nonreactive P (i.e., organic or colloidal P fractions). These concentrations significantly exceeded U.S. EPA guidelines of 0.1 and 0.05 mg l^{-1} for streams and lakes, respectively.

The western karst lowlands of Ireland contain ecologically sensitive surface water bodies, including rivers, lakes, and turloughs which have close interactions with karst groundwater (Coxon and Drew 2000). Investigations of phosphorus in karst groundwaters in this region (Kilroy and Coxon 2005) showed that mean total phosphorus (TP) concentrations in both springs and boreholes were greater than the

20 μg l^{-1} threshold for eutrophic conditions in Irish lakes. Monitoring of temporal variations in P in eight karst springs showed a peak in P concentrations in response to the first autumnal rains, attributed to release of P accumulated in the soil during the summer following inorganic fertilizer and manure applications. Dissolved reactive phosphorus (DRP) was the dominant P component, but particulate P and dissolved nonreactive P increased to a greater degree than DRP during periods of high rainfall (Fig. 5.9a). This study also provided a case example of the passage of a contaminant plume attributed to the release of silage effluent, resulting in an increase in TP concentration in the down-gradient spring from 42 to 1,814 μg l^{-1} within 24 h (Fig. 5.9b). Such localized pollution incidents may be of particular significance if they impact surface waters in the summer months when groundwater constitutes a high proportion of river flow.

The presence of phosphorus in karst groundwaters contributing to sensitive surface waters can have important management implications. While evaluating the status of Irish groundwater bodies under the E.U. Water Framework Directive (2000/60/EC), one of the factors taken into account was the assessment of adverse impacts of chemical inputs from groundwater on associated surface water bodies and the combination of ecologically significant groundwater phosphorus concentrations. High contributions of groundwater flow to surface waters in Irish karst regions resulted in 101 groundwater bodies occupying 13.3% of the area of Ireland being designated as poor qualitative status. Programs of measures to restore good status are required under the Water Framework Directive, and reducing phosphorus inputs from agriculture to these vulnerable karst systems is likely to have significant social and economic costs (Daly 2009).

5.3.3.5 Pesticides and Other Synthetic Organics

Pesticides vary greatly in their toxicity, mobility, and persistence. However, many have health effects such as carcinogenicity at very low concentrations; therefore, leaching of only a small proportion of applied pesticide can result in violation of drinking water standards. Easily leached pesticides such as atrazine may be found in many aquifer types, but the thin soils and subsoils associated with many karst aquifers together with the potential for rapid movement through solutionally widened fissures will make contamination more likely than in other hydrogeological situations. Less mobile pesticides are readily adsorbed on to soil particles and have a lower risk of entering aquifers but may reach karst groundwater because of the possibility of colloidal particles entering via sinking streams or solutionally widened fissures.

Atrazine, a herbicide used widely in maize (corn) cultivation and as a general broad spectrum weed killer, has been the most widely reported pesticide in karst groundwater over the last two decades. Karst aquifers in the American mid-west in which atrazine has been recorded include the Big Spring basin, Iowa, where it is the dominant pesticide in the groundwater (Libra and Hallberg 1999; Rowden et al. 2001); two karst catchments in West Virginia, where atrazine and its metabolite desethylatrazine were detected in more than 50% of samples (Pasquarell and Boyer 1996); the Green

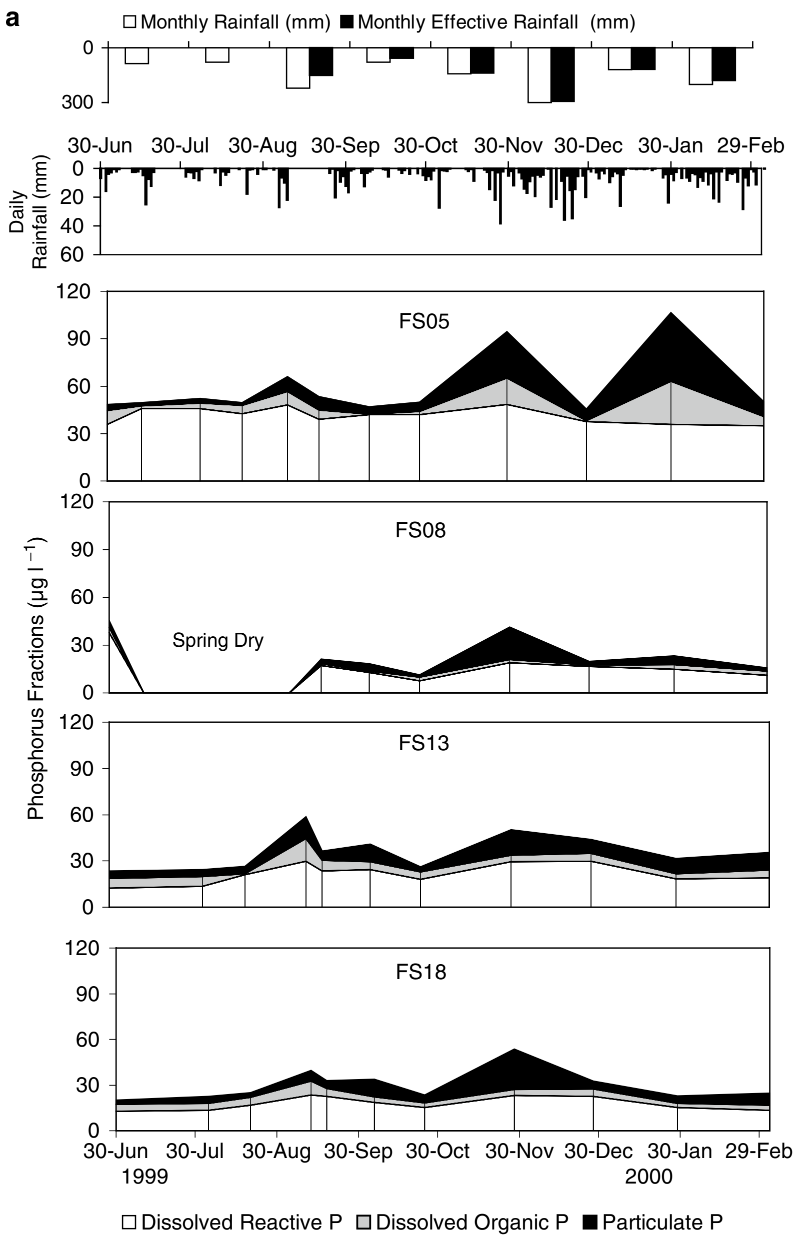

Fig. 5.9 Phosphorus in Irish karst springs (**a**) Temporal variation in different phosphorus fractions at four springs in the Fergus catchment, County Clare (**b**) Short-term variation in total phosphorus at a spring in the Robe catchment, County Mayo (From Kilroy and Coxon 2005)

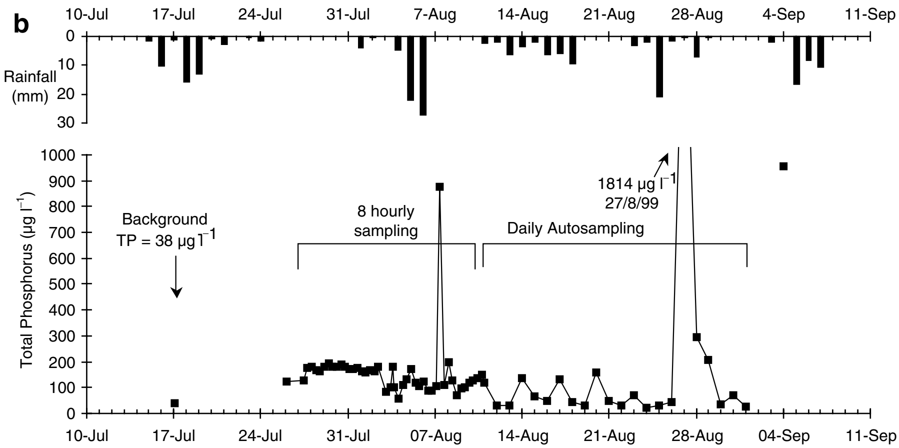

Fig. 5.9 (continued)

River Basin in Kentucky, where it was detected in 100% of karst spring water samples (Crain 2002); the Illinois sinkhole plain, where concentrations ranged from <0.01 to 34 μg l^{-1} (Panno and Kelly 2004); and two karst springs in Northern Alabama (Kingsbury 2008). The drinking water limit for atrazine in the U.S.A. is 3 μg l^{-1} as a yearly average (with higher concentrations permissible in the shorter term), while in the European Union, the limit is 0.1 μg l^{-1}. It has been recorded from a range of European karst aquifers including a Jurassic karst aquifer in Germany (Milde et al. 1988) and a weakly karstified Cretaceous Chalk aquifer in France, where it was present in 83% of samples at concentrations up to 5.3 μg l^{-1} (Baran et al. 2008).

The presence of atrazine continued to be recorded for several years after its use was banned, both in Slovenian groundwater (Gotvajn et al. 2001) and in the French Chalk aquifer mentioned above, where it was recorded 3 years after the ban in 2003 (Baran et al. 2008). Other herbicides recorded in karst groundwaters include other triazines such as simazine (Crain 2002; Debrewer et al. 2008); alachlor, a widely used herbicide particularly in maize and peanut cultivation (Panno and Kelly 2004; Dalton and Frick 2008); and fluometuron, used in cotton cultivation (Dalton and Frick 2008; Kingsbury 2008).

Pesticides which are readily adsorbed on to colloidal particles may enter karst aquifers via sinking streams or solutionally widened fissures. Simmleit and Herrmann (1987) examined the passage of lindane through a karstified Jurassic limestone and dolomite aquifer in Franconia, Germany, and found that transient rises in lindane concentration and loading coincided with increases in suspended solids and in dissolved humic material. Libra et al. (1986) also noted the coincidence between peaks in pesticide concentration and suspended sediment peaks, at Big Spring in Iowa, as shown in Fig. 5.7. Ekmekci (2005) noted that different pesticides of varying mobilities were found in different hydrologic zones of the

Kestel-Kirkgoz karst system in Turkey: lindane and hepta epoxide characterized surface water input to the aquifer via swallow holes, while aldrin and dieldrin characterized shallow groundwater in the polje, and the metabolites of DDT were found in deep groundwater with a longer residence time.

The importance of tracking pesticide metabolites in addition to the primary substance was demonstrated by Pasquarell and Boyer (1996). These authors found that prolonged storage of atrazine in the soil results in loss of its metabolite desethylatrazine (DEA) from the soil to karst groundwater, but atrazine may also be transported more directly to groundwater through dolines and conduits, bypassing the soil desethylation process. Baran et al. (2008) also found DEA occurring as frequently as atrazine in a French chalk aquifer. Similarly, Kingsbury (2008) noted that degradates of the herbicides atrazine and fluometuron were detected at concentrations comparable to or greater than the parent pesticides. In the Floridan limestones of Southwest Georgia, Dalton and Frick (2008) noted that degradates of alachlor and metoalachlor were generally found at higher concentrations than their parent compounds.

Antibiotics are another group of synthetic organic compounds which are a potential cause of concern in karst groundwaters. Landspreading of animal manures in vulnerable karst situations may not only cause problems of nutrient loss and microbial contamination, but may also contaminate water supplies with antibiotics, giving rise to concern about the spread of antibiotic resistance. Dolliver and Gupta (2008) documented a 3-year study of leaching and runoff losses of antibiotics from land application of hog and beef manures in a karst area of Wisconsin, U.S.A.: chlortetracycline was detected in runoff while monensin and tylosin were detected in both runoff and leachate, with detections occurring mainly during the nongrowing season (November to April) following autumn application of manures.

5.3.3.6 Microbial Pathogens

Microbial pathogens are a particular problem of karst aquifers because the lack of filtration within the aquifer and the short underground residence times mean that if organisms manage to pass through or bypass the unconsolidated material overlying the aquifer, they are almost certain to appear in water supplies. The presence of conduit flow within the karst aquifer can allow viable organisms to travel for hundreds of meters or even several kilometers from the point of entry. The microorganisms involved include bacteria, viruses, and protozoan parasites.

Fecal bacteria have been reported from karst aquifers for several decades. The large numbers of bacteria present in human and animal waste, combined with the fact that pathogenic bacteria and indicator organisms such as fecal coliforms and fecal streptococci must be absent from drinking water supplies, mean that the problem is not solved by dilution. Kelly et al. (2009), reporting on fecal bacterial contamination of karst groundwater in Southwestern Illinois from domestic wastewater and livestock manure, noted that there was chemical evidence of substantial dilution of the wastewater, but that this did not lower bacterial concentrations sufficiently to meet drinking water limits. In Ireland, fecal bacterial contamination of groundwater supplies from karst aquifers has been reported since the 1980s (Thorn and Coxon 1992) and continues to the present day (Clabby et al. 2008). Celico et al. (2004) record bacterial contamination of karst springs in Southern Italy resulting from manure spreading, with the highest bacterial numbers found when intense rainfall produced concentrated infiltration of runoff in a swallow hole. Fecal bacterial contamination is also well documented from karst aquifers in North America. Boyer and Pasquarell (1999) compared bacterial contamination in cave streams in a beef cattle area and a dairying area and found that fecal coliforms and fecal streptocci were present in much greater numbers in the dairying area. However, bacterial numbers were much lower where best management practices were in place (Sect. 5.4.2). Kozar and Mathes (2001) found that 32% of wells in a karst limestone and dolomite aquifer in West Virginia contained *E. coli*, with contamination rates being higher where there was nearby agricultural activity.

A current serious concern with fecal coliform contamination is the possible presence of verotoxin-producing *E. coli* (VTEC) such as *E. coli* 0157, which causes dysentery and hemolytic uremic syndrome, which can be fatal (Percival et al. 2004). The presence of VTEC in a karst spring in an agricultural catchment in the Swiss Jura was correlated with high *E. coli* concentrations and with rainfall events: contamination was attributed to local infiltration of polluted surface waters and rapid passage through karst conduits (Auckenthaler et al. 2002). The most serious recorded case of karst groundwater contamination by *E coli* 0157:H7, combined with *Campylobacter jejuni*, took place in Walkerton, Ontario, Canada, in May 2000, when 2,300 people became ill and seven people died. The contamination appears to have come from cattle feces which entered the karst groundwater following heavy rainfall. Tracing experiments demonstrated a significant degree of karstification, with flow velocities 80 times faster than predicted in the initial modeling which had treated the aquifer as an equivalent porous medium (Worthington et al. 2002).

Many viruses are retained in soils by adsorption to soil particles, particularly where the soil has a high clay content (Gerba et al. 1991), but they may gain entry to karst aquifers while adsorbed to such particles. Enteric viruses are recorded in karst groundwaters in the U.S.A. by Berger (2008). Viral transport through karst groundwater has been studied using bacteriophage tracers (i.e., virus infecting bacteria and harmless to humans). For instance, Auckenthaler et al. (2002) carried out tracing experiments in a karst spring in Switzerland using marine bacteriophages H4 and H40 and found a similar breakthrough curve for these as for *E. coli* and enterococci bacteria occurring naturally in the spring.

A recent and growing concern is contamination by protozoan parasites, particularly *Cryptosporidium parvum*, which causes acute gastroenteritis and persistent and potentially fatal disease in immune-compromised individuals. This organism has caused disease outbreaks even where water supplies are treated by conventional chlorination, because it forms an oocyst which is resistant to chlorination; successful removal requires physical barrier treatment, e.g., flocculation and filtration or ozonation (Percival et al. 2004). The first outbreak of cryptosporidiosis linked with karst groundwater occurred in Braun Station, San Antonio, Texas, in 1984, when more than 200 people became ill due to contamination in the Edwards aquifer (D'Antonio et al. 1985). *Cryptosporidium* has been detected in many karst groundwater supplies in the last decade, including springs in West Virginia, U.S.A. (Boyer and Kuczynska 2003), a karst spring in Switzerland (Auckenthaler et al. 2002) and the karst springs which provide the water supply for the town of Ennis in Ireland (Page et al. 2006, p.64).

Microbial contamination in karst aquifers is often ephemeral and not easily detected by routine monitoring at regular wide intervals (e.g., monthly or quarterly). Where even brief exposure to a pathogenic microorganism in a water supply could have serious consequences, the need to predict temporal variations is particularly acute. Soil moisture levels may play a role in controlling temporal variations in fecal coliform numbers, with bacteria stored in the soil zone being released once soil moisture increases and groundwater recharge occurs (Pasquarell and Boyer 1995).

Several authors have noted that peak bacterial numbers often coincide with flow peaks (Thorn and Coxon 1992; Auckenthaler et al. 2002) and with turbidity and sediment peaks (Dussart-Baptista et al. 2003; Boyer and Kuczynska 2003; Pronk et al. 2006; 2007). In Fig. 5.8, it can be seen that the peaks in *E. coli* numbers coincide with the second turbidity peak corresponding to the arrival of allochthonous sediment from the swallow hole.

5.4 Management

5.4.1 Risk Assessment

The first step in implementing management measures to minimize the problems discussed above is to evaluate the degree of risk. This enables appropriate controls to be taken, with the most stringent measures and most rigorous monitoring being applied in the highest-risk situations. The approaches used will differ depending on the nature of the problem, but in many instances, the source-pathway-receptor model of risk assessment is applicable. The source term relates to the agricultural pressure (e.g., animal stocking densities, fertilizer application rates), while the pathway term relates to the transfer route (i.e., the geological pathway through the karst system), and the receptor will vary depending on the nature of the impact being considered (e.g., a drinking water supply or an ecosystem).

While soil erosion risk assessments in most terranes focus on downslope sediment movement, risk of gullying, etc., in karst terranes, the risk of vertical movement into solutionally widened joints and closed depressions must also be taken into account. Nevertheless, Yue-Qing et al. (2008) found that the revised universal soil loss equation (RUSLE) integrated in a Geographic Information System was of value in predicting soil erosion risk in a rural karst catchment in Guizhou Province, China. A remote-sensing and GIS-based model has also been used to assess soil erosion in the Lebanese karst (Bou Kheir et al. 2008).

Risk of groundwater contamination from agricultural sources is commonly evaluated in the context of groundwater protection schemes. These are now widely used around the world, but the extent to which karst is taken into account varies considerably. Groundwater vulnerability assessment methodologies, which take account of karst, include the EPIK method (Doerfliger et al. 1999), the PI method (Goldscheider 2003) and the pan-European method developed in COST Action 620 (Daly et al. 2002). These methods are general purpose assessments of intrinsic vulnerability, while some approaches (Sinreich and Zwahlen 2002) evaluate specific vulnerability to particular types of contaminant. Risk assessments relating to particular substances have also been undertaken in the delineation of nitrate vulnerable zones for the EU Nitrates Directive and in risk assessments for particular groups of chemical parameters for the EU Water Framework Directive (WFD). The Irish WFD groundwater body risk assessments for diffuse source pollutants including nitrate and phosphorus involved an evaluation of agricultural pressures, pathway susceptibility, and receptor sensitivity; the pathway susceptibility took karst aquifers into account, and in the case of phosphorus, the presence of swallow holes was also included in the risk assessment (Working Group on Groundwater 2005).

5.4.2 Management Strategies and Planning Controls

Controls on particular agricultural activities (discussed further below) often form part of an overall land management plan or a groundwater protection policy for the karst region. Groundwater protection policies in karst aquifers incorporate the vulnerability and risk assessment procedures discussed in Sect. 5.4.1, with more stringent planning controls being implemented in the higher-risk zones.

The impact of deforestation can be minimized by good management practices. Planning requirements for timber harvesting in karst areas outlined by Kiernan (1987a) include an inventory of karst features and the designation of karst reserves within the overall karst area where felling is prohibited, while operational measures (Kiernan 1987b) include a prohibition of logging on steep limestone slopes or in the vicinity of sinkholes and cave entrances, and the provision of silt traps in situations where there is a risk of karst stream siltation. Where damage has already occurred due to deforestation, management strategies are required to restore and rehabilitate the landscape. Measures to reverse karst rocky desertification in Southwestern China include programs of reforestation, the planting of economically useful woodland plants, and the development of ecologically sensitive agriculture (Wang et al. 2004).

A major difficulty in implementing planning controls in karst groundwater protection zones is that the nature of karst flow systems means that such zones are much more extensive than in most other aquifer types. Plagnes and Bakalowicz (2001), reviewing groundwater protection in the Larzac plateau in Southern France, note that whereas in nonkarst regions, protection zones typically extend over a few square kilometers, the two springs acting as water supplies in this area have recharge areas of 100 and 110 km^2. Furthermore, karst spring catchments may have large partial contributing areas, where sinking streams contribute a varying proportion of their flow to the spring, as seen in the Western Irish karst lowlands (Coxon and Drew 2000).

Diffuse or nonpoint source pollution is often tackled by a combination of "carrot and stick" approaches: in some instances, farmers are encouraged to implement good land management strategies on a voluntary basis and may be grant-aided or provided with free management advice (as in implementation of Best Management Practices [BMP] in the U.S.A.), while in others, there is an increasing degree of legislative control (such as the European Union Nitrates Directive). Agricultural point sources are somewhat easier to deal with than diffuse sources, given that in many instances they can be eliminated by simple pollution control measures such as constructing adequate storage tanks, rather than requiring fundamental changes to the agricultural system. Point sources have also been addressed in some instances by advice and grant aid, and in others by legal controls.

Initially, agricultural BMPs in the U.S.A. were not specifically geared to karst areas: Berryhill (1989) reviewed BMPs for controlling diffuse pollution in tillage areas (e.g., conservation tillage, crop rotation, reduced input agriculture) and in grazing areas (e.g., rotation of pastures with rest periods to allow regeneration, and fencing animals away from water bodies and areas subject to erosion), and he commented on their relevance to karst areas. He also assessed BMPs used to control pollution from agricultural point sources (e.g., leak-proof feed and manure storage facilities, runoff control structures, and vegetative filter strips for erosion and nutrient control). More recently, BMPs more specific to karst areas have been implemented and have met with a varying degree of success. In some cases, they have been of value in minimizing bacterial contamination of karst groundwaters: Boyer and Pasquarell (1999) found that while a karst stream in a dairying area in Central Appalachia without BMP had more than 4,000 fecal coliforms per 100 ml, a dairying area with BMP for control of animal and milking shed waste was not contributing significant amounts of fecal bacteria to the karst aquifer. However, Currens (2002) found that BMPs implemented in a karst groundwater basin in Kentucky were only partially successful, and Boyer (2005) noted a lack of consistent water quality improvement in two karst study areas in Southeastern West Virginia following several years of implementation of BMPs. He suggested that BMPs should be targeted at well-defined contributing areas that significantly impact water quality (e.g., excluding cattle from particularly vulnerable sinkholes). BMPs subsequently implemented include the use of vegetative buffer strips around sinkholes (Petersen and Vondracek 2006). Boyer (2008) described a sinkhole filter involving filter fabric sandwiched between layers of crushed rock, which was not effective in reducing nitrate concentrations but achieved a considerable degree of success in reducing fecal coliform concentrations; he proposed that it would be a valuable tool in some situations when used in combination with land management measures such as buffer strips.

While catchment controls involving agricultural BMPs may improve the microbial quality of karst waters, they are unlikely to succeed in eliminating microbial contamination. Shutting down of raw water intakes at times of maximum risk, during the passage of flood waves at karst springs, may also be of value. However, reliable prediction of contamination incidents can be problematic. Because analyses of fecal microorganisms take hours or days, they cannot be used for instant monitoring of karst groundwater supplies. As noted in Sect. 5.3.3.6, turbidity is often highly correlated with microbial pathogens, and monitoring a combination of turbidity and total organic carbon, or monitoring turbid particle size distribution, may enable autochthonous turbidity (from remobilization of sediments within the karst conduit) to be distinguished from allochthonous turbidity (representing arrival of swallow hole waters and potential pulses of microbial contamination) (Pronk et al. 2006, 2007; Fig. 5.8). However, Auckenthaler et al. (2002) warn that in some karst systems, microbial numbers may rise several hours before turbidity, so they suggest that spring discharge may be a safer warning parameter. Because of the difficulty of prediction and potentially serious public health consequences, adequate treatment, including treatment to remove microorganisms such as *Cryptosporidium* that are resistant to chlorination, remains of considerable importance.

In the European Union, the Nitrates Directive is implemented by means of mandatory action programs within nitrate vulnerable zones and voluntary codes of practice outside these zones; these are drawn up by individual member states, so the extent to which karst is taken into account varies. The Irish legislation, giving effect to the directive, includes a ban on landspreading of manure within 15 m of karst features such as swallow holes and collapses and a ban on manure storage within 50 m of such features, while spreading of soiled water is strictly limited in karst regions where the depth to bedrock is less than a meter (Stationery Office Dublin 2009). Management measures to reduce nitrate contamination may also involve limits on nitrogen fertilizer application, such as the livestock manure limit of 170 kg N/ha/year imposed in the E.U. Nitrates Directive. However, the time lag between a reduction in fertilizer inputs and a reduction in groundwater nitrate levels can vary greatly; as noted in Sect. 5.3.3.3, time lags are greatest in dual porosity chalk aquifers. Thus, Nebbache et al. (2001) comment that while short-term peaks in nitrate concentration in the Brionne Basin due to point recharge may be addressed on a short-term, local basis, the longer-term trend of rising nitrate over the last few decades will require a longer-term approach, with solutions applied today potentially taking decades to have a tangible effect in this Chalk system.

While nitrate pollution is being tackled by a series of measures including a reduction in fertilizer inputs, in the case of pollution by some pesticides, a complete elimination of inputs is being recommended or enforced. For example, Milde et al. (1988), working on pesticides in German karst aquifers, suggested that substances such as atrazine should not be used in highly vulnerable karst catchments. Atrazine was subsequently banned throughout the European Union, but in parts of the world, where a general ban is not currently in place, a ban on its use in vulnerable karst situations may be justifiable.

In areas where the rocky karst terrane has resulted in low-intensity agricultural systems and where nitrate and pesticides are not currently at problem levels (e.g., the Larzac plateau in France, mentioned above, and some of the Slovenian karst plateaus discussed by Kovačič and Ravbar (2005)), a useful management approach

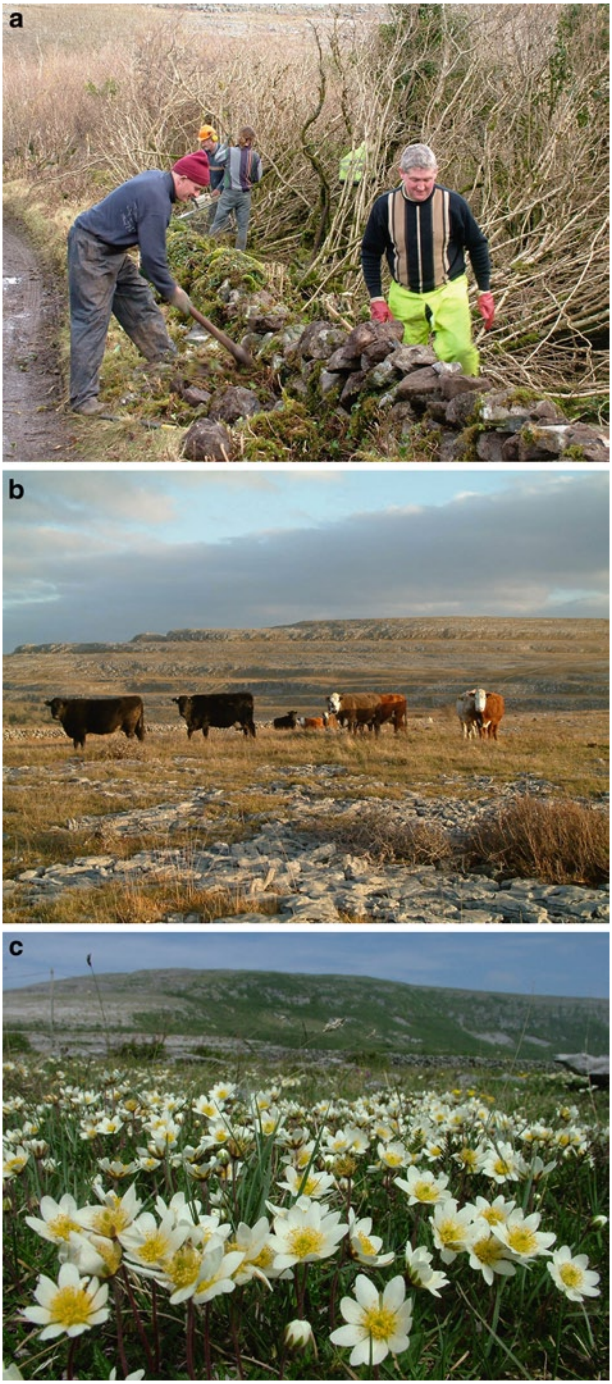

Fig. 5.10 Farming for conservation in the Burren karst plateau, Ireland (**a**) Hazel scrub removal (**b**) traditional winter cattle grazing (**c**) Arctic-alpine flora (*Dryas octopetala*) (Images © B Dunford, BurrenLIFE)

may be to combine catchment controls such as groundwater source protection zones with a positive promotion of the values of such regions. In the karst areas of Croatia, organic sheep breeding involving indigenous breeds of sheep, adapted to the karst environment, is being promoted as a means of economic growth while preserving the traditional way of life and protecting the environment (Radin et al. 2008). In the European Union, whereas earlier schemes funded by the Common Agricultural Policy sometimes exacerbated environmental problems in karst regions (Drew and Magee (1994) and Canora et al. (2008), discussed in Sect. 5.2.1), more recent community-based E.U. projects have had a more positive influence. In the Burren plateau in Western Ireland, the BurrenLIFE project was initiated in 2005 with funding from the European Commission LIFE Nature Fund, combined with national and local sponsorship, in recognition of the importance of farming in protecting internationally important habitats such as limestone pavements and orchid-rich grasslands, which are subject to scrub encroachment as noted in Sect. 5.2.1. This project aims to develop a model for sustainable agriculture, bringing together farmers, scientists, conservationists, and others to develop farming systems and supports to protect the Burren karst plateau (BurrenLIFE 2006, 2009; Fig. 5.10). Another EU LIFE-funded project, the Limestone Country Project, which ran in the upland karst of the Yorkshire Dales, U.K. from 2002 to 2008, also sought to promote sustainable land management and restore limestone pavement and limestone grassland habitats by encouraging a return to mixed farming using hardy upland cattle breeds (Yorkshire Dales National Park Authority 2009).

5.5 Conclusions

From the wide range of research studies carried out over the last few decades, it is clear that agricultural activities can have a wide range of impacts on karst landscapes and karst waters. Clearance of forest vegetation for agriculture gives rise to problems of soil erosion, impacts on groundwater recharge and degradation of water quality. Increases in grazing intensity or a change from pasture to tillage may trigger further soil erosion and impacts on water quality. Irrigation and drainage operations associated with agricultural intensification may have both hydrological and water quality impacts. Landspreading with fertilizers and pesticides can result in water quality problems in drinking water supplies and groundwater-fed ecosystems. Animal wastes, if stored inappropriately or if landspread in vulnerable situations, may give rise to contamination with a range of constituents, with fecal microorganisms posing particular risk to human health.

While such environmental problems associated with agriculture are by no means unique to karst areas, they may occur with particular severity because of the peculiar characteristics of karst: the occurrence of concentrated recharge in closed depressions and swallow holes, combined with the presence of conduit flow and flow in solutionally widened fractures in the aquifer, render karst regions particularly susceptible to soil erosion and entry of contaminants to groundwater. The thin, patchy soil cover found in many karst areas may act as a check on agricultural intensification, but it can further increase the risk of adverse impacts of any agricultural activities that do take place.

Appropriate management measures will vary depending both on the nature of the agricultural systems and also on the nature of the karst region in question. Karst aquifers overlain by significant thicknesses of soil and subsoil are more likely to have intensive agricultural operations such as tillage or intensive animal rearing; in such regions, a combination of approaches may be desirable. This might include a program of education for farmers about the vulnerability of karst systems and on the use of Best Management Practices to avoid problems, combined with appropriate legal controls on application of fertilizers and pesticides and on storage of farm wastes. National programs required to meet national or international legislation, such as the EU Nitrates Directive and Water Framework Directive, may need to be modified to suit the particular needs of karst regions.

Management measures to minimize adverse impacts of agriculture must strike a difficult balance between the need for environmental protection and the need to maintain agricultural activities. In rocky karst plateau regions, maintenance of traditional farming practices may be of importance in preserving distinctive karst landscapes and ecosystems. Measures such as the promotion of indigenous organic sheep production in the Croatian karst and initiatives such as the BurrenLIFE project in Ireland may be of value in preserving distinctive karst flora and fauna and in preventing problems of rural depopulation, while minimizing any adverse impacts on the environment.

Although the quest for an environmentally sustainable solution to the development of agriculture in a particular karst region must take local geological, hydrological, ecological, and socioeconomic factors into account, in many cases, there are valuable opportunities to benefit from work in other similar karst regions around the world, sharing scientific research on environmental processes and impacts and sharing experience of management approaches.

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Part II
Management of Subterranean Karst

Chapter 6
Management of Caves

David Shaw Gillieson

Abstract People have used caves in many ways for tens of thousands of years and only recently recognized their recreational, aesthetic, and scientific value. However, this has not prevented their degradation and some suggest the carrying capacity of a cave is effectively zero. Caving results in a variety of impacts on the physical cave environment, although not equally for all caves or every part of the cave, which is then a challenge for management is to correctly evaluate the relative vulnerability of cave passages. These impacts can arise because tourist caves require physical alteration of natural passages, installation of lighting, pathways, platforms, and associated infrastructure. Cave fauna are impacted by alteration of cave hydrology, temperatures, lighting conditions, and carbon dioxide levels. Resulting invasive plants, desiccation of cave formations, and localized sedimentation highlight the need for effective ongoing monitoring of the cave atmosphere, water quality, and particulate deposition. Even scientific researches have impact; therefore, proposed research projects must minimize damage and maximize benefit for all cave stakeholders. Cave inventories are important for documenting valuable cave features, and they also allow for inter-cave comparisons and help with management classification and/or zoning. More enlightened management regimes consider good relations with park neighbors as essential and parks are run using principles of adaptive management. Cave managers should embrace the new management paradigms whilst conserving what are essentially nonrenewable resources.

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6.1 Introduction

Caves have been used by people in many ways over tens of thousands of years. They are used for a wide variety of purposes, apart from water supply, recreational caving, and tourism. Recorded industrial and agricultural uses include fish breeding, mushroom growing, rope making, cheese production, harvesting of birds' nests, extraction of guano for fertilizer and therapy (hot springs and sanatoria). Caves and other limestone landforms are widely regarded as sacred sites by indigenous peoples and are used as temples, especially in Asia.

The recreational use of caves in a modern sense dates from the early seventeenth century, when the Vilenica Cave in Slovenia was open for visits by paying tourists. By 1816, a number of caves worldwide were being regularly visited (Postojna, Wookey Hole, Mammoth Cave). A rapid expansion in the number of show caves occurred in the second half of the nineteenth century. Today, there are more than 600 show caves open worldwide, with some receiving several million visitors each year (Gillieson 1996).

The IUCN Guidelines for Cave and Karst Protection (Watson et al. 1997) provides a general list of the impacts which may result from human activities in caves:

- Alteration of the physical structure of the cave
- Alteration of water chemistry
- Alteration of cave hydrology
- Alteration of air currents and microclimate
- Introduction of artificial light
- Compaction or liquefaction of floors
- Erosion or disturbance to cave sediments or their contents
- Destruction of speleothems
- Destruction of fauna
- Introduction of alien organisms or materials (e.g., concrete, climbing aids), pollutants, nutrients, animal species, algae and fungi
- Surface impacts such as erosion, siltation, vegetation change

It should be said that any consideration of human impacts in caves should also take into account activities in the catchments overlying the cave. These activities are covered in other chapters. In this chapter, I consider the impacts of both recreational caving and show cave development. I also review some methodologies for assessing the values and vulnerability of caves, including the impacts of scientific research. Finally, I comment on the changing paradigms for protected area management which have implications for the way in which caves will be managed in the future.

6.2 Recreational Caving and Its Impacts

The aesthetic and scientific values of wild caves (caves not modified for tourist development) are being degraded as a result of increased recreational use (Spate and Hamilton-Smith 1991). Aley (1976) stated that the carrying capacity of a cave is

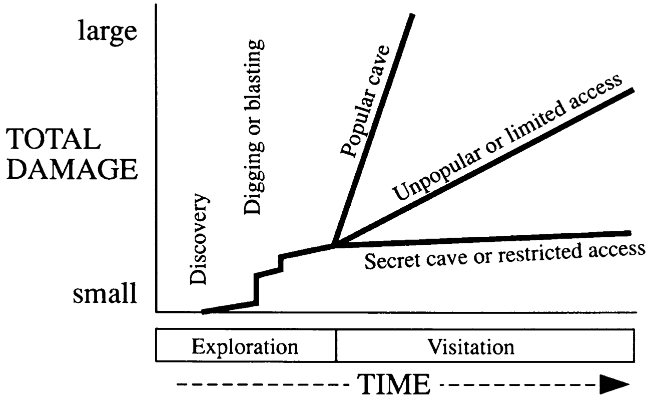

Fig. 6.1 Damage vs. time during the exploration and visitation phases of a hypothetical cave. Total damage will vary widely depending on popularity, knowledge, limitations on access, experience of visitors, etc. (From Ganter 1989)

effectively zero. That is, the capacity of a damaged cave system to regenerate in anything like human generational timescales is very limited or nonexistent. This is because natural rehabilitation processes in caves operate very slowly in the comparatively low-energy cave environment. It is therefore important to attempt to quantify both the extent and severity of actual or potential impacts to establish appropriate management regimes for wild caves and to determine the acceptable limits of environmental change (Wilde and Williams 1988). Coupled with this is the need to establish some monitoring to provide baseline data, to assess the direction and rate of change, and to identify the causes of change. It is unusual to have absolute baseline data as many caves have been entered before; we therefore often start with an existing level of damage and must mitigate further damage. Various strategies exist to achieve this (Fig. 6.1), for example by limiting access and reducing the number and frequency of visitors, permit systems and trail marking (Ganter 1989).

Recreational caving results in a variety of impacts on the physical cave environment (Gillieson 1996; Bunting 1998). In the first instance, there is a direct contact between the caver and the floor, walls and ceiling of the cave. Cavers moving through a cave cause direct impacts to the physical cave environment such as disturbances to cave sediments and cave breakdown deposits, erosion of cave rock surfaces, damage caused by bolting and rigging, modification of cave entrances and passages, speleothem breakage, and disturbances to fossil deposits (Gillieson 1996). In addition, there are impacts associated with sediment transfer to previously clean areas of cave, carbide dumping, carbide staining on cave walls and ceilings and the introduction of energy sources from mud and food residues and sometimes deposition of feces and urine.

The impacts listed above may not occur in every cave or in every part of one cave system. Not all parts of caves are equally vulnerable to disturbance, and the challenge for management is to correctly evaluate the relative vulnerability of cave passages. One approach that is valuable takes account of the relative energy status of the cave passage (New Zealand Department of Conservation 1999:10–11) in evaluating potential visitor impacts.

High-energy cave passages are subject to high-energy events, such as flooding or rockfall, on a regular basis. These cause the regular modification of the passage and may involve rapid sedimentation as well. Speleothem formation is rare because they are quickly scoured away or broken off, unless they are in elevated or secluded alcoves. The effects of visitors on such passages will be minimal, and they may cope with high visitor numbers. Examples include the large river caves of Southern China, Sarawak, and Vietnam.

In medium-energy cave passages, forces such as running water, air currents, or animal activities operate at a somewhat lower magnitude. These caves often contain the most abundant active speleothem formations, reflecting inflow of abundant saturated water. Cave pools may have abundant life with periodic influx of organic matter providing an energy source (Tercafs 1993). The effects of visitors may be more evident than in high-energy caves, although they may be masked by occasional flooding and sediment reworking. Many tourist caves fall into this category.

For low-energy cave passages, a major event may be a single falling droplet of water. Speleothems in a low-energy cave are characterized by small and delicate formations resulting from the slow rate of crystal growth. Sediment deposits may have been in place for tens or hundreds of millennia. The influx of energy may be measured on decadal timescales. The presence of visitors in a low-energy cave may have a serious cumulative effect on the cave environment, as the amount of energy released by them in even a short visit may be more than what the cave has experienced in hundreds of years.

In most cases, individual caves are likely to contain components of all three different types of energy levels. Many caves are medium- or low-energy environments, with essentially little input of energy on a human timescale. The entry of a single caver can change the energy balance by affecting the heat, light, and nutrients therein. One factor that is only now being realized is the potential introduction of microflora and microfauna by cavers (Cunningham et al. 1995). The effects of visitors to caves are generally cumulative and quite possibly synergistic.

Damage to bone deposits in caves has been well covered by Griffiths and Ramsey (2005). Significant paleontological/archeological assemblages are less likely to occur in high-energy caves or cave passages, since regular flooding or rockfalls are liable to redistribute or cover them. Such assemblages are far more likely to be found in medium- or low-energy passages. The same stable environmental conditions which would tend to facilitate the preservation of paleontological assemblages and their contexts are those which are most vulnerable to disturbance. Excavations in such passages may entail significant changes to the energy regime, with corresponding impacts on the underground environment. In contrast to disturbances to surface sites, traces or effects of human activities in medium- or low-energy underground environments may persist for hundreds or even thousands of years – consider what is believed to be a Cro-Magnon footprint discovered on the surface of a sediment deposit in Chauvet Cave, France (Tattersall and Schwartz 2001)

Documented attempts at quantifying recreational impacts in caves have been limited (Bodenhamer 1995; Bunting 1998; Bunting et al. 2001) and may indicate difficulties in quantifying and, subsequently, documenting recreational impacts in the cave environment. Cave photomonitoring is one method that can be used to assess and monitor the effects of recreational use of caves. This involves the collection of precise photographs of selected points within the cave, taken on regular basis, appropriate to the management cycle (Uhl 1981). The main problem with photomonitoring is the difficulty in accurately and efficiently replicating the image view (Bunting 1998).

Many of the problems listed above can be avoided or minimized by adoption of a minimal impact code for caving (Table 6.1; Webb 1995)

6.3 Impacts of Visitors and Infrastructure on Show Caves

The development of caves for mass tourism requires physical alteration of natural passages, installation of lighting, pathways, platforms, and associated infrastructure. Under such conditions, the cave biology is the first to suffer, and heavily used areas are generally depauperate of cave fauna (Culver and Pipan 2009:202). The cave hydrology may also be altered, and there may be pollution from car park and road runoff, gray water and sewage in extreme cases. The organic pollution of Hidden River (Horse) Cave, Kentucky, was both catastrophic and long lasting. The cave was commercialized in 1916, and at that time, its underground river had a rich fauna including fish and crayfish. Contamination by sewage and creamery waste led to the extinction of the cave fauna and closure of the cave by 1943. Since the 1980s, the pollution has been stopped, and the cave is now recovering as fauna recolonizes from more pristine upstream sections of the cave. It has now reopened to visitors (Lewis 1996).

Cave entrance modification is widespread in show caves but can also occur in wild caves. This action can have a profound effect on terrestrial fauna. Infilling or gating can restrict or stop the movement of animals, especially bats. Enlarging an entrance or creating a new artificial entrance can alter air flows, changing the microclimate. At Mammoth Cave, Kentucky, the Historic Entrance was blocked to stop cold winter air from entering (Elliott 2000); bats abandoned the cave as a result. Cave entrance gates can be designed to allow free passage of bats (Fig. 6.2), though some species will avoid any gate and alternative solutions like fencing must be found.

Large numbers of visitors in a cave can significantly raise the air temperature. A single person releases heat energy at 80–120 W (Villar et al. 1986), about the same as a single incandescent light bulb. Thus, a party of 50 or 60 people on a cave tour can locally raise temperatures by 1–2°C. The passage of tourists through Altamira Cave, Spain, raised air temperature by 2°C, CO_2 concentration from 400 to 1,200 ppm and decreased relative humidity from 90% to 75% (De Freitas and Littlejohn 1987). The main effect of the reduction in humidity is drying and flaking of flowstone surfaces. According to Cigna (1993), management needs to ensure that

Table 6.1 Minimal impact code for caving (Adopted by the Australian Speleological Federation (Webb 1995))

1. Remember every caving trip has an impact. Is this trip into this cave necessary? If it is just for recreation, is there another cave that is less vulnerable to damage that can be visited? Make this assessment depending on the purpose of your visit, the size and experience of the proposed party, and if the trip is likely to damage the cave
2. Where possible the party leader should have visited the cave previously and hence should be aware of sensitive features of the cave, the best anchor points, and generally reduce the need for unnecessary exploration
3. Cave slowly. You will see and enjoy more, and there will be less chance of damage to the cave and to yourself. This especially applies when you are tired and exiting a cave
4. If there are beginners on a trip, make sure that they are close to an experienced caver, so that the experienced caver can help then when required, e.g. in difficult sections. Ensure that the party caves at the pace of the slowest caver
5. Keep your party size small – four is a good party size
6. Cave as a team – help each other through the cave. Don't split up unless impact is reduced by doing so
7. Constantly watch your head placement and that of your party members. Let them know before they are likely to do any damage
8. Keep caving packs as small as possible and don't use them in sensitive caves or extensions
9. Ensure that party members don't wander about the cave unnecessarily
10. Stay on all marked or obvious paths. If no paths are marked or none is obvious – define one!
11. Learn to recognise cave deposits or features that may be damaged by walking or crawling on them. Examples are: Drip Holes, Stream Sediments, Paleo soils, Soil Cones, Crusts, Flowstone, Cave Pearls, Asphodilites, Bone materials, Potential Archaeological sites, Cave Fauna, Coffee & Cream, Tree Roots
12. Take care in the placement of hands and feet throughout a cave
13. Wash your caving overalls and boots regularly so that the spread of bacteria and fungi are minimized
14. If a site is obviously being degraded, examine the site carefully to determine if an alternative route is possible. Any alternative route must not cause the same or greater degradation than the currently used route. If an alternative is available suggest the alternative route to the appropriate management authority and report the degradation
15. Carry in-cave marking materials while caving and restore any missing markers. Tape off sensitive areas you believe are being damaged and report the damage to the appropriate management authority
16. If it is necessary to walk on flowstone in a cave remove any muddied boots and or clothing before proceeding or don't proceed! Sometimes it is better to assess the situation and return at a later date with the appropriate equipment
17. Treat the cave biota with respect, watch out for them, and avoid damaging them and their "traps", webs, etc. Also avoid directly lighting cave biota if possible
18. If bone material is found on existing or proposed trails it should be moved off the track to a safer location if at all possible. Collection should only be undertaken with appropriate permission
19. If you eat food in a cave ensure that small food fragments are not dropped as this may impact the cave biota. One way is to carry a plastic bag to eat over and catch the food fragments. This can then be folded up and removed from the cave
20. Ensure that all foreign matter is removed from caves. This includes human waste. If long trips are to be made into a cave, ensure that containers for the removal of liquid and solid waste are included on the trip inventory
21. When rigging caves with artificial anchors, e.g. traces, tapes, rope etc., ensure that minimal damage occurs to the anchor site by protecting the site. For example protect frequently used anchors, e.g. trees, with carpets, packs, cloth, etc. Bolts should only be used where natural anchors are inappropriate
22. Cave softly!

Fig. 6.2 Construction of the Tumbling Creek Cave chute gate, March 2004. The open chute allows pregnant gray bats to use the entrance freely, but excludes human intruders. Bats have increased in numbers since the gate was built (From Elliott and Aley 2006)

these fluctuations lie within the range of natural variation for the cave, and that they return to normal levels in a short period of time (Fig. 6.3). Calaforra et al. (2003) provide a good example of determining visitor thresholds in such cases (Fig. 6.4).

Increases in CO_2 concentration due to visitor respiration can range from 1,500 to 2,000 ppm, at which point people start to be distressed. At such concentrations, speleothems will start to redissolve. A threshold for this corrosion is reached at 2,500 ppm in the Glow-Worm Cave, New Zealand, while at Jenolan Caves, the threshold is at 2,700–2,800 ppm. Managing carbon dioxide levels requires effective monitoring, limiting the party size and frequency of tours, and modifying doors to improve air circulation. Studies at Jenolan Caves have shown that well-ventilated sites reach background levels in a few hours, while poorly ventilated sites can take days (James 2004).

The continuous lighting of cave features provides an opportunity for the establishment and growth of green plants (blue-green and filamentous algae, mosses, and ferns) in a concentric zone around the light. This is known as *lampenflora* and has been the subject of considerable research (Aley 2004). Reduction in light intensity below the threshold for photosynthesis, movement activated switches, and C-Bus technology controlling lights can all help to eliminate this problem. C-Bus is a

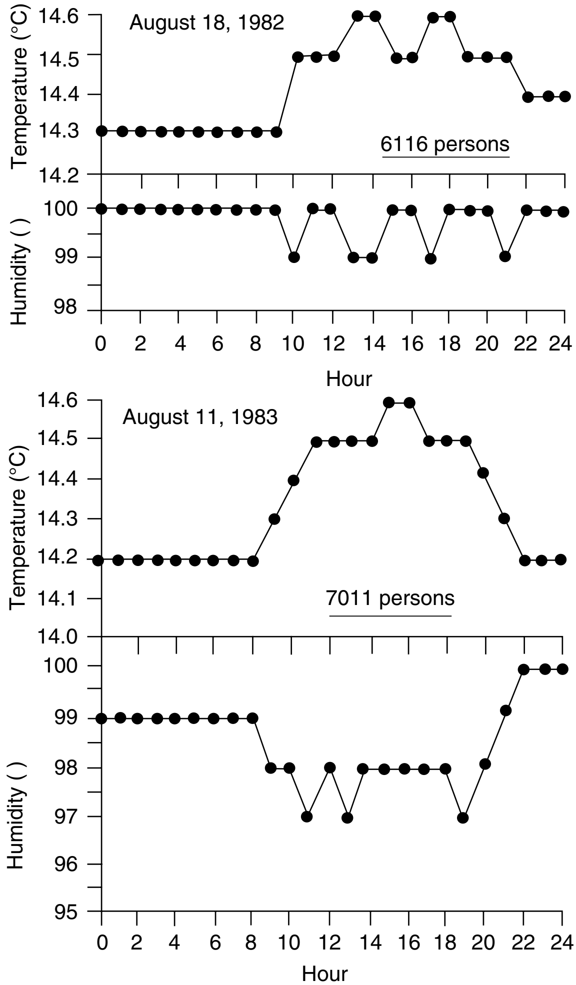

Fig. 6.3 Sample 24 h records of air temperature and relative humidity in Ancona Hall, Grotta Grande del Vento, during the peak of the tourist seasons in 1982 and 1983 (From Cigna (1993))

microprocessor-based control and management system for cave lighting. It is used to control lighting and other electrical services such as audio-visual devices, pumps, motors, etc. A twisted pair cable network operates at 36 V and allows installation in wet places where conventional mains power would be dangerous. A lighting or audio-visual sequence can be preprogrammed or can be interrupted or changed at any location by a ranger or tour guide. The technology has now been employed in many caves in Australasia, Europe, and North America.

The introduction of microflora and microfauna into caves is an ongoing problem. In the Lascaux Cave, the first problem that attracted management attention was the "maladie verte," due to algal development. Later on, fungal colonies appearing as white and/or black spots created the main conservation problem. Only recently, a research project has been funded which aims at studying the ecology of the cave,

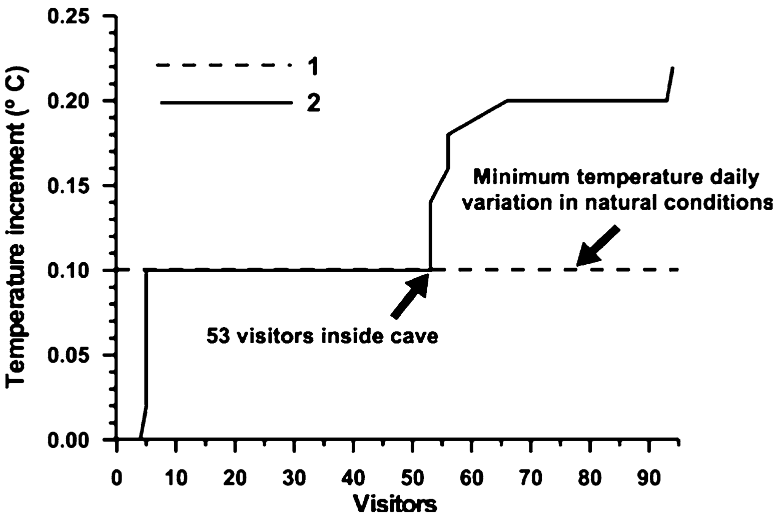

Fig. 6.4 Number of visitors producing an increase in temperature of more than 0.1 °C: *1* maximum mean daily variation of temperature under natural conditions; *2* mean variation caused by visitors (From Calaforra et al. (2003))

including interactions between microorganisms (bacteria and fungi), other organisms (protozoa, and arthropods) and human presence. Currently, the most important point of interest in Lascaux is the development of "black spots" corresponding to the growth of melanized fungi (Bastian and Alabouvette 2009). Introduced microbiota can also be a problem in more pristine caves; in Lechuguilla Cave, New Mexico, biofilms associated with water siphoning tubes serve as a substrate for coliform bacteria (Hunter et al. 2004). Many apparently pure pools have significant bacterial colonies as a result.

Within caves, pathways and stairs may concentrate the flow of drip water away from flowstones or stream channels, causing desiccation of cave formations and localized sedimentation. Leachates from concrete can also form deposits mimicking natural speleothems. Construction debris, including wire clippings, can leach toxins into cave streams. Galvanized steel railings and steps have been shown to leach various metallic ions, including cadmium, which can harm freshwater fauna (Buecher 1995). Today, there is increasing use of stable materials such as stainless steel, plastic decking made from recycled PET bottles, plastic rails, and similar products (Fig. 6.5). In Australia and in Europe, there is now a widespread use of recycled materials to produce inert resin products for guiderails, decking, and other outdoor infrastructure. The materials derive from post-consumer plastics, principally HDPTE, and wood waste. These recycled products do not leach any chemicals, require low energy for production and have almost zero carbon emissions. See http://www.advancedplasticrecycling.com.au/index.php for further details.

Fig. 6.5 Re-lighting of the Donna Cave, Chillagoe Queensland. Main lighting sequence is controlled by c-bus programming and can be modified by a guide. Tracklights are low energy use LEDs. Note use of inert materials – plastics and stainless steel – for all stairs and railings (Photo by David Gillieson)

In many caves, speleothems and pathways are cleaned on a regular basis due to the deposition of dust, hair, and lint from visitors and of algae and fungi. High pressure water jets are commonly used, often with external mains water supply. Steam cleaning and use of surfactants have also been used. All of these methods have some impact on the surface being cleaned. Spate and Moses (1994) studied the impact of cleaning at Jenolan Caves, New South Wales. They found that repeated cleaning with

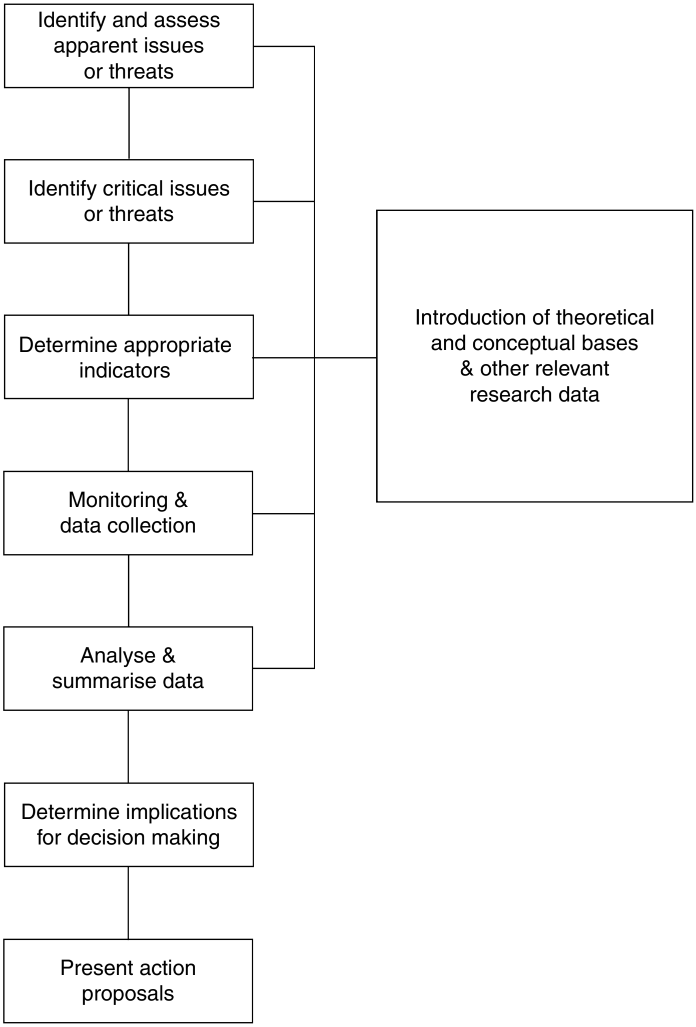

Fig. 6.6 Outline of Visitor Impact Management (VIM) process implemented at Jenolan Caves, New South Wales (From Jenolan Caves Reserve Trust (1995))

high pressure jets damaged crystal facets and recommended other strategies such as protective clothing for visitors and mesh entrance walkways to limit dust tracking.

These impacts highlight the need for effective ongoing monitoring of the cave atmosphere, water quality, and particulate deposition. A set of biophysical indicators can be defined and their state reviewed periodically. Coupled with this is the need for a set of social indicators that address the issue of the level of satisfaction of both visitors and staff (Hamilton-Smith 2004; Davidson and Black 2007). These should form part of an ongoing process of adaptive management (Fig. 6.6) that takes account of monitoring results and is informed by the latest research.

6.4 Cave Lighting

Lighting of show caves has tended in the past to over-illuminate the cave passages and chambers, as if they were offices or shopping malls. A more enlightened view would light the cave as a cave with deliberate use of darkness and sequencing of illumination on selected cave features. There are two important principles to be borne in mind when designing the lighting for a show cave: access and atmosphere.

Lighting for access should be at the minimum level consistent with safe movement of all cave visitors. Effective lighting can be used to create safe access through an unfamiliar environment, a zone of familiarity that relaxes the visitors. The use of LED strip lights, 12 V downlights and other low-energy technology can all achieve this aim. These can be attached to railings or path edges, with necessary inverters or batteries well hidden below. In general, all fixtures and cabling should be well hidden from visitors but accessible for maintenance without further damage to the cave and its contents. Reduced power consumption has benefits beyond reduction of CO_2 emissions: lower power requirements facilitate the use of local uninterruptible power supply when there is a mains power failure. Less heat is produced as well. There are many technologies available – remote controls, c-bus controlled electrical systems, high lumen per watt output lighting, batteries/inverters, optical fibers, etc. – but they should be used as tools to achieve an end, not as an end in themselves.

The second principle is that of atmosphere. There should be an underlying philosophy to the lighting scheme. A theme should be established which illustrates aspects of cave development or history. The lighting should be sequential, with visitors led from one scene to the next. This avoids the massed illumination of a whole chamber. The manager needs to be very selective about what to light and what not to light. Any light in a dark environment will have a dramatic effect, and sometimes, a very distant light will enhance the illusion of depth and mystery we are trying to foster. Lighting of water features can be very effective (Fig. 6.7). In all of these, the fragility of the cave contents needs to be considered, with some areas being out of bounds for any installation of lighting.

A final principle is that of creating a performance, with analogy to an orchestral performance (Kell 2002). All too often, a show cave tour proceeds from the entrance to the rear of the cave over half an hour or so, then there is a "bolt and run" back to the entrance. Clever use of lighting and c-bus sequencing allows for a different experience on the return journey to the entrance at a leisurely pace. This provides a more satisfying experience and may allow for a different theme to be explored.

6.5 Research in Caves and Its Impacts

As stated before, all human activities in caves have some impact. Thus the dilemma for cave management is to determine whether the net gain in knowledge from a research project justifies the damage done to the cave. This concept may be difficult

Fig. 6.7 Effective lighting of the Lake Cave, Margaret River, Western Australia. Minimal path lights and c-bus technology allow for a varied experience with illusions of depth and darkness. The water table in the cave has lowered significantly in recent years due to extraction for irrigated viticulture (Photo by David Gillieson)

for some researchers to grasp, used as they are to free access and elevated social status as scientists. Thus, it is important that scientists and managers work together to evaluate proposed research projects and modify them to minimize damage and maximize benefit for all cave stakeholders.

One method of evaluating any project is to use a matrix developed by Griffiths and Ramsey (2005) for paleontological projects in Canadian caves. Any project can be evaluated against several criteria:

- Direction – does the work have beneficial effects on cave resources; is it neutral or does it have adverse effects? In most cases, the effects will be adverse.
- Scope – is the effect limited to a small area of the cave, to the immediate area of the action, or does it extend throughout the cave system?
- Duration – effects may be significant for less than 1 year or less than one generation of cave biota, may be significant for 1–10 years or one generation of biota, may be significant for more than 10 years or more than one generation of biota.
- Frequency – effect occurs once only or rarely and irregularly or on a regular basis and at regular intervals.
- Magnitude – minimal impairment of the cave system's function or processes; measurable impacts on functions and processes but recovery to preaction level,

or serious measurable impairment of function and processes that is not recoverable and leads to serious habitat loss or degradation.
- Confidence – how robust are the conclusions? Can we have confidence in the general applicability of the results?

6.6 Cave Inventories and Classification

Caves have values that relate to their aesthetics, their geology and geomorphology, their biology, their archeology and paleontology, and their history, to name but a few. Cave inventories provide a means of documenting all of the values of an individual cave. It also allows for comparison between caves and therefore underpins management classification and/or zoning. Detailed inventories can also provide a valuable snapshot of baseline conditions in caves, against which subsequent degradation of cave values may be measured. Many recreational cavers produce basic inventories as part of mapping and documentation activities. These provide very valuable, but sometimes unacknowledged, sources of data for management agencies. Maps produced by cavers are especially valuable, as a wealth of detail is usually recorded. In caves with exceptional values, a more detailed multidisciplinary approach may be needed. This can include geomorphology and ecology, archeology and paleontology, groundwater hydrology and ecology, microbiology, tourism, and cultural heritage.

Caves should be carefully evaluated on an individual basis for the significance of each category of values and the vulnerability of the cave to disturbance. The significance of each category of values can vary from cave to cave. One cave might have high recreational and hydrological values but demonstrate low biological, archeological, and geological values. Another might only be significant in terms of its historical associations.

Kiernan (1988: 41) points out

> … There is a need for cave managers to recognise that each cave has a limiting factor on usage (i.e., the value most at risk). Each site needs to be managed on the basis of the particular limiting factor for that site.

The limiting factor for some caves may be biological, mineralogical or any of the other values listed above. Management authorities need to establish what that limiting factor is, prior to making any decisions about a cave's use, either by researchers or the general public.

This provides an alternative view to more conventional recreational planning concepts and tools such as Limits to Acceptable Change, Recreation Opportunity Spectrum, and Visitor Impact Management. All of these are well entrenched in the outdoor recreation planning literature. They are all based on the premise that the system in question has some capacity to regenerate over a relatively short timescale. This is simply inappropriate for most caves. They are also based on the premise that visitor needs should be more important than natural or cultural heritage considerations.

In Western Canada, parks are preparing to adopt cave management guidelines using a three-tier classification system to manage access (Horne 2005). Class 1 caves are "access by application" only – they have the highest resource value and are not for recreation. Each visit must add significant knowledge or give nett benefit to the cave. Class 2 caves are "access by permit" – recreational use is allowed, and there are some management concerns. Entry for education/orientation is possible under the permit. Class 3 caves are "unrestricted public access" – there are few or no management concerns, and no permit is required. In order to determine which class a cave will fall into, three sets of factors are considered: (a) cave resources, (b) surface resources, and (c) accident and rescue potential. Other countries have similar systems of cave classification in place or under development.

6.7 Trends in Cave Management

Over recent years, many cave sites worldwide have been listed as World Heritage, either in their own right or as part of larger nominations. There are now 45 cave and karst properties inscribed on the World Heritage register, with a further 30 listed as being worthy of nomination (Williams 2008). A National Geographic survey of 415 World Heritage sites, undertaken by over 400 independent, suitably qualified people, found that the standard of management across these sites had declined significantly since 2004. Presumably, World Heritage sites should be the best managed, as the sites with outstanding universal values to be presented to the world. Identified causes for this decline were mass tourism, inappropriate tourism products and rampant commercial and industrial development. There is a strong conflict between tourism and heritage management on one hand and a focus on economic return on the other. These issues also apply to other caves being managed by state or federal agencies in many countries.

There are a number of common issues which are raised by cave managers. Funding is usually dispensed on an annual basis with little chance of carryover into the next financial year. Long-term plans are difficult if not impossible to implement under this model, and so many activities, especially monitoring, are compromised. Funding is more available for tourism development than for scientific studies aimed at managing the resource. Staff training to build capacity and enable them to deliver professional outcome has suffered in quality and availability. Cave guide exchange schemes, a valuable source of cross-fertilization of ideas, have been virtually abandoned. Many organizations are preoccupied with occupational health and safety issues to the exclusion of all else. Clear lines of communication between agencies are not maintained and thus a holistic approach to management is made more difficult.

For many governments, the environment is now low on the political agenda and is being overshadowed by industries such as logging and mining. There is a recent proposal to allow mining in the National Parks of New Zealand – including its karst areas. Geodiversity conservation is also very low on the political agenda. Environmental concerns and conservation planning are dominated by biodiversity

Table 6.2 Contrasting Paradigms for Protected Areas (From Phillips 2003)

As it was: protected areas were…	As it is becoming: protected areas are…
Planned and managed against people	Run with, for, and in some cases by local people
Run by central government	Run by many partners
Set aside for conservation	Run also with social and economic objectives
Paid for by taxpayer	Paid for from many sources
Managed by scientists and natural resource experts	Managed by multi-skilled individuals
Managed without regard to local community	Managed to help meet needs of local people
Developed separately	Planned as part of national, regional and international systems
Managed as "islands"	Developed as "networks" (strictly protected areas, buffered and linked by green corridors)
Established mainly for scenic protection	Often set up for scientific, economic and cultural reasons
Managed mainly for visitors and tourists	Managed with local people more in mind
Managed reactively within short timescale	Managed adaptively in long term perspective
About protection	Also about restoration and rehabilitation
Viewed primarily as a national asset	Viewed also as a community asset
Viewed only as a national concern	Viewed also as an international concern
Managed in a technocratic way	Managed with political considerations

issues and fail to recognize the importance of geological heritage in integrated landscape management. There is a new paradigm emerging of public vs. contracted management or private ownership of cave and karst areas. While in many cases outsourcing of park management can inject new ideas and funding, safeguards need to be in place to ensure that nature conservation values are not compromised in favor of accelerated tourism development.

On a more positive note, there has been a quantum shift globally in the underlying philosophy of protected area management. Previous management regimes about protection were exclusionary and restrictive and took little regard of public opinion. We are now moving to more enlightened management regimes, where good relations with park neighbors are seen as critical, and parks are run using principles of adaptive management (Table 6.2: Phillips 2003). The challenge for cave managers will be to embrace the new paradigms whilst conserving what are essentially nonrenewable resources.

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Chapter 7
Some Considerations on Show Cave Management Issues in Southern Italy

Mario Parise

Abstract Show caves represent an important tourist attraction, especially when located in rural territories where not many sites of interest, except those naturalistic, are present. For people working on karst and cave science, they are the main way to allow great number of people to visit a cave, experience safely the underground world, transfer information to raise public awareness about karst environments, and understand the need to protect and develop them in a sustainable way. Some considerations about management of show caves in peninsular Southern Italy are presented through description of lessons learned from direct and indirect experience in show caves in Campania and Apulia. Overall, many problems have to be faced, starting from the lighting system (often quite old and promoting the lampenflora growth), the quality in the guides' explanations as well as updating safety measures. In addition, the high number of tourists allowed, regardless of the visitor capacity of each cave, has also to be mentioned, since it determines degradation in the cave atmosphere and the overall underground environment.

7.1 Introduction

Show caves represent an important tourist attraction and a possibility for exploitation in karst, especially when located in rural territories where there are not many sites of interest, except those naturalistic. Show caves are also the main contact between the general public and the karst environment and are the main way to allow high numbers of people to visit a cave and experience safely the underground world. A one-day experience may become, especially for children and young people, a fundamental tool to transfer information to raise in the public an environmental

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awareness about karst ecosystems and resources, the need to protect them and develop in a sustainable way.

It has been known for a long time how opening a cave to the public may completely transform the life of nearby towns and villages, bringing great number of visitors in the area, and strongly contributing to its tourist development. On the other hand, the inevitable infrastructure needed to allow untrained persons to safely visit the cave irreversibly change its characteristics, with serious consequences for the karst ecosystems and several negative effects, among which one of the most common is the unwanted growth of vegetation (lampenflora) due to installation of lights along the tourist trail (Aley 2004; Mulec and Kosi 2009).

Visitor capacity is defined as "that flow of visitors into a defined cave that confines the changes in its main environmental parameters within the natural ranges of their fluctuation" (Cigna 1987; Cigna and Forti 1988). It represents a powerful concept for cave environmental impact assessment, useful to reach a sustainable compromise between maximum number of visitors allowed and protection of the karst ecosystem. Identification of the visitor capacity for each single cave should ideally be derived from a specific monitoring program (lasting not less than 1 year, possibly 2; Cigna 1993), while results obtained in a cave should never be taken as transferable to another site, since each cave has its own features and characteristics, depending upon a great number of variables, including size, depth, presence of water, air circulation, etc. (Huppert et al. 1993). Further, given the increasing variability of the climatic regime, it would be preferable to adopt monitoring programs for longer timeframes, at least 3–5 years. This will allow controlling the response of the karst system even on the occasion of particular events, from the occurrence of extreme rainfall, to drought, to other local situations related to anthropogenic activities.

7.2 Case Studies

To focus on some of the aforementioned issues, show caves from Southern Italy are briefly dealt with in this section. The considerations presented here derive from direct experience of the author, integrated by interviews with cave managers, cavers, local inhabitants, and tourists, and scrutiny of the existing documentation and publications. The analyzed caves are located in peninsular Southern Italy, and specifically in Apulia (Castellana Caves, Zinzulusa Cave) and Campania (Castelcivita Cave, Pertosa Cave; Carucci 1907; Boegan and Anelli 1930).

The Castellana Caves were discovered in 1938, and soon after it became a tourist cave in 1939, the access tunnel to the first room (the largest cavern of the karst system, named Grave; see Fig. 7.1) was dug by miners from Sardinia, and the cave was opened to the public, even though for a short trip. Since then, it has always been a great attraction for tourists, and in 1950s, the town changed its name, becoming the present Castellana-Grotte, to acknowledge the importance of the caves in the development of this small Apulian town. During the years, several different phases occurred in the management, with the number of visits progressively increasing, reaching over 450,000 in 1982. After that peak, and realizing that such numbers

Fig. 7.1 Castellana Caves: *left*, the Grave (photo: G. Campanella), the largest cavern in the karst system, produced by fall of the vault of the underground cave; from here the tourist visit starts. Note the caver ascending the 55 m deep shaft. *Right*, descent in the deepest shaft of the system, reaching the maximum depth at −122 m from the ground surface

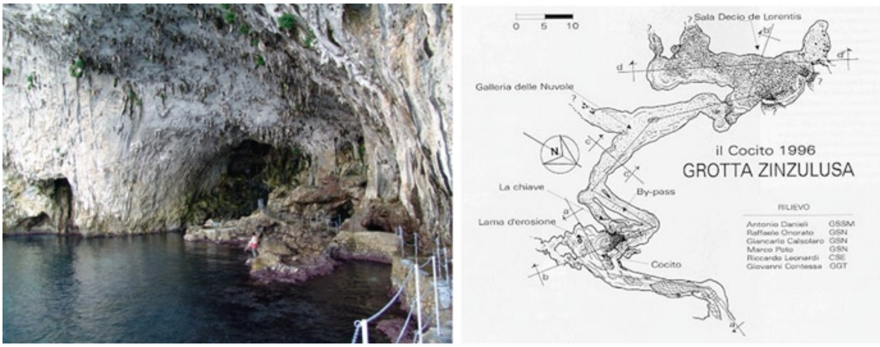

Fig. 7.2 Zinzulusa Cave: *left*, the cave entrance (photo: S. Inguscio); *right*, plan of the cave (After Cadastry of FSP, the Apulian Speleological Federation)

were producing severe damage to the cave system, a decrease in the visitors number had to be attained until the present average of about 250,000 visitors per year. Discovery and exploitation of the Castellana caves played an important role for the rest of the region, and many attempts were carried out to establish other show caves from the several hundreds of karst caves in Apulia.

Among these, Zinzulusa Cave was opened to the public in 1950s. Originally discovered in 1793, this cave is a site of great importance for biodiversity, as testified by the presence of many aquatic species, and one of the most famous anchialine caves in Southern Italy (Fig. 7.2). Located along the Adriatic coast, in a sector of

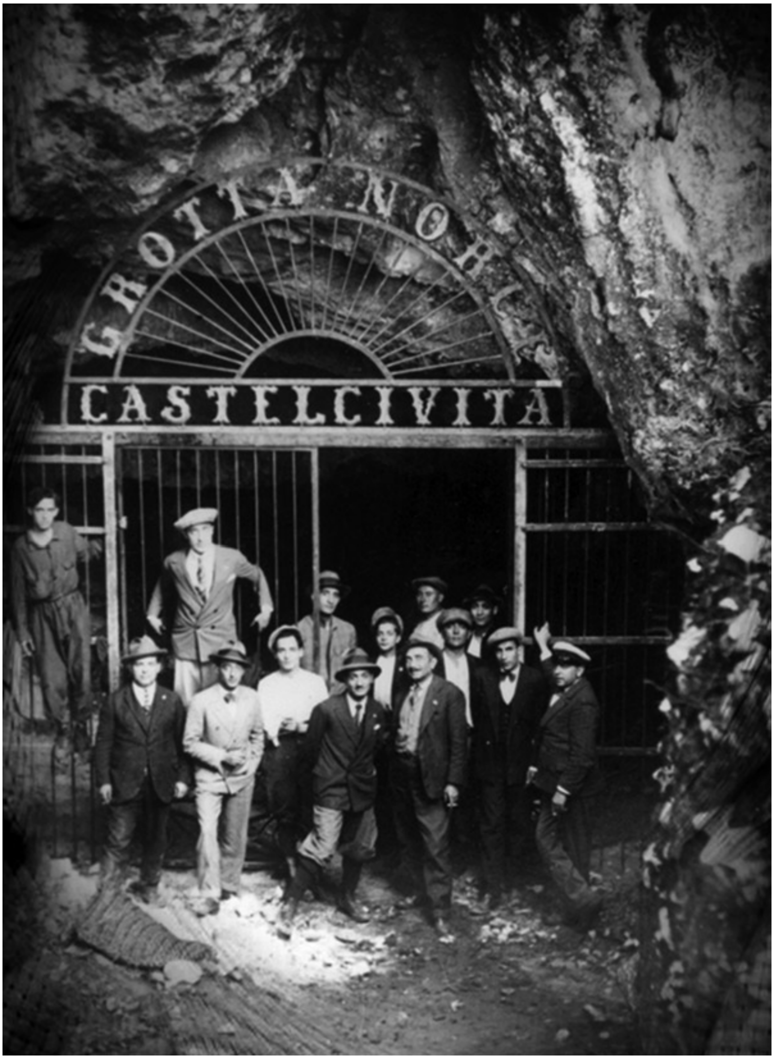

Fig. 7.3 Photo taken at Castelcivita in August 1930, at the time of realization of the first gate for the show cave (After Trotta 1931)

high naturalistic value, it is intensely exploited during the summer season, due to the great amount of tourists in this area. With an average of 100,000 tourists per year (peak of 3,500 visitors per day), it has a tourist section 150 m long (out of a 260 m total length), while the remaining part of the cave, in part flooded, is closed to visitors due to its remarkable importance as a biodiversity hot-spot (Pesce 2001).

In the Campania region, the Castelcivita and Pertosa caves are located on opposite foothills (respectively, SW and NE) of the Alburni Massifs, which is the most important karst area in Southern Italy, hosting several hundred caves (Bellucci et al. 1995). Castelcivita became a show cave in 1930 (Fig. 7.3), and Pertosa in 1932 (even though the first lighting was installed only 30 years later, due to a dispute between the municipalities of Pertosa and Auletta; Russo et al. 2005). The first exploration of Castelcivita cave was tragic (Boegan and Anelli 1930). In 1889, two brothers from a nearby town entered the cave using oil lamps. Carbonic acid from a lateral branch of the cave system shut off the lamps after the two brothers had entered 300 m into the cave. They were not able to find their way out, and only 8 days later were rescued. One died soon after, and the other went insane. With a total length of 5,400 m, Castelcivita is the longest cave in Southern Italy.

Without any doubt, Pertosa Cave (Fig. 7.4) represents the best example so far regarding exploitation: today, the cave is managed through a foundation (Mida) that also is in charge of two museums in the area. A number of activities were recently started in order to improve the quality of the site and increase the touristic experience. For instance, taking advantage of the peculiar underground environment, further enriched by the presence of water, theater shows are scheduled every week, such as a presentation of Dante's "Inferno." These shows have been improved by the recent change in the light system: light emitted diode (LED) lamps were installed in the cave, which resulted in significant energy saving (>80%) and better scenography (due to the use of LED with different colors). Following the success of "Inferno" theater show at Pertosa in 2009, a new show has been started at the nearby Castelcivita Cave: Orpheus and Euridice, once again a drama whose best set is in an underground environment.

7.3 Discussion

One of the worst aspects of the management of show caves in Southern Italy is the quality of the cave guides. Obviously, the great majority of visitors are not experts and their only aim is the experience of a short visit to the underground world, and therefore they are not very interested in scientific or technical issues. However, this does not imply that the guide talks should not touch on any science at all. A balance should be pursued between human interest topics and scientific sound information, in order to reach, on average, a good level of satisfaction for the tourists.

However, it commonly happens that most of the talk is about the cave discovery, and while moving through rooms and caverns, the tourists are simply invited to look at the main speleothems, named after daily objects or animals (i.e., ham or bacon slice, the camel, the owl, etc.). This may be interesting to listen and look at, but should not represent the only information offered to visitors. In many caves, even passing through points of high interest regarding geology, speleogenesis or geomorphology, nothing is said about the processes involved in the cave genesis, development, and evolution. In addition, it has to be noticed that most of the guides are not young people, while, on the other hand, involvement of specifically educated youngsters, especially if linked in some ways to the caving world (cavers, students in earth sciences, etc.), might contribute to raising professionalism in the field. Simply put, it appears that at present the guide explanations are not based on scientific knowledge, and it is very common that, when specific questions are posed by the tourists,

Fig. 7.4 Map of Pertosa cave: the entrance is to the *left* (W). The *pale blue* marks the flooded sectors, where tourists are transported by means of boats moved by the guides

the answers may strongly differ, depending upon the level of knowledge of the individual guide. That is, there is no uniformity in the product that is offered to the public, and the tourist satisfaction is essentially dependent upon personality and approach of the accompanying guide.

This problem was clearly displayed at Castellana Caves, where in 2004, a training course was organized for the guides. During this course, there was a strong effort in presenting scientifically based information about karst, cave formation, speleogenesis, from both a general point of view and in the specific case of Castellana. The guides were not very open to include in their explanation new facts and information. In particular, it was very difficult to convince them that some of the most common beliefs that they narrate tourists every day were wrong and not based on any science. Overall, the course was a very stimulating experience, but, sadly, the outcomes were not so satisfactory, since in many cases, the guides preferred to keep working with the previous "knowledge." Of course, this was permitted by the lack of control of the managers, who did not seem to be interested in any feedback coming from the tourists at the end of the visit.

A further, crucial problem is monitoring of the cave parameters, especially with regard to changes over time once the cave is open to the public. Discussing cave monitoring priorities in Central America and the Caribbean, Day and Koenig (2002, p. 131) concluded their study stating that "cave monitoring is poorly developed and is hampered by a general lack of awareness of its importance and utility". In addition, they also listed, as further impediments, limited funding, absence of requisite equipment, and scarcity of qualified personnel. Of course, the situation is very different in Italy, one of the countries where knowledge about cave and karst started, and qualified scientists are working in this field, including that of show caves, over several decades. Nevertheless, the experience in Southern Italy has shown that cave monitoring (Cigna 2002; Osborne 2002) is rarely carried out properly, following a detailed time schedule and especially using the outcomes to improve the quality of the cave and the offerings to tourists. Therefore, it is not the case, in Italy, of any lack of knowledge or equipment or personnel or lack of funding: in most of the cases, it is a conscious choice.

Why should the cave managers put money into monitoring? It is something that needs to be done (theoretically) at the beginning of the activity, but then, once the show cave is open to public, it is rarely done. Actually, it is from that very moment of the cave opening to the public that assessment and monitoring of changes become extremely important. Up to that moment, we only have a partial understanding of how the cave works, but nothing is yet known as regards the effects of tourists on it: their impact, the negative changes they are going to produce. Monitoring is essential at this stage, since it is the main tool to capture timely changes in the cave atmosphere and ecosystem and to intervene accordingly. It has to be stressed that monitoring means not only the collection of data but also (as a fundamental part) their analysis and the evaluation of the observed changes to address the following questions: why was the change produced? Does it represent a problem to the cave? What are the factors causing it? How can we solve the problem (if any)?

Lack of awareness of the importance and utility of cave monitoring, and even more of karst fragility, is probably the main issue. Owners and managers of show caves have a wide range of objectives, many of which have a purely financial motivation (Hamilton Smith 2004). In many cases, they are more interested in spending the money coming from the cave on other activities, able to have a rapid feedback in terms of notoriety and gratefulness from the locals, rather than using these funds to improve the quality and safety of the touristic offering. This is often a consequence of the fact that no specialist or cave scientist or caver is involved in cave management, and in rare occasions when this happens, they are generally limited to act as counselors, while the final decisions are always taken by other people, who, in most of the cases, are not competent in cave management and are motivated by political-economical rather than scientific or environmental reasons. Therefore, it is very clear that this type of management does not move toward creation of a sustainable exploitation of show caves or raising an environmental awareness about karst, which is, on the other hand, crucial for a proper management, in both the social and economic terms (LaMoreaux et al. 1997; Hamilton Smith 2002).

Such an approach can be quite dangerous to the natural environment, since people, being unaware of the high fragility of karst and its extreme vulnerability to different types of hazards (Parise and Pascali 2003; Parise and Gunn 2007), may carry out actions that have the potential to greatly degrade or destroy karst ecosystems. Application of a recently developed index (van Beynen and Townsend 2005) to evaluate the disturbance induced to karst by human activities in Apulia has already shown, for instance, many problems in the management of these territories (Calò and Parise 2006; North et al. 2009), in particular as regards the stewardship of the karst region. It must therefore be concluded that, even though Italy has a long history of cave explorations and development of show caves too, there is still a long way to go in the attempt to improve the tourist experience and to safeguard as much as possible the cave ecosystem. On the other hand, something is slowly moving: for instance, the Apulia Region recently (December 2009) updated the existing law on safeguard of the geological and karst heritage. The newly approved legislation permits opening of show caves only after specific steps are carried out to ensure feasibility of the work and guarantee didactic and tourist interest of the site and safety of the cave. Simply put, this type of environmental legislation should encourage better compliance in the near future.

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Chapter 8
Geoarchaeology and Karst: A New Perspective

Philip Reeder

Abstract In the context of karst-related research, the multidisciplinary approach is necessary and the paradigms of the emerging field of geoarchaeology provide a new perspective for completing studies that contains the human-element. Research completed at the Cave of Letters (COL) and the Qumran Archaeological Site in Israel and on the Vaca Plateau in Belize, utilizes the multidisciplinary approach endemic to geoarchaeology. By creating a series of digital, updatable maps for the COL and Qumran, spatial trends in and relationships between the physical and cultural landscapes become apparent. Additionally, through the use of geophysics (ground penetrating radar (GPR) and electro-resistivity tomography (ERT)), an ancient living surface (the Bar Kokhba layer) was delineated in the COL, and potentially collapsed caves, that may contain archaeological remains, were located at Qumran. GPR also delineated possible grave sites at the cemeteries of Qumran. In Belize, petrographic analysis of rock samples determined that the physical landscape is dominated by limestone breccias, which are mostly depositional in origin. Comparison of these results, with data collected related to quarried and cut stones used to face structures at the Ix Chel Archaeological Site, suggested some stones were quarried locally but, due to the sheer number of stones required to build the site, dictates that other regional sources were required. The studies detailed in this chapter point to the need for continued karst-based research within the multidisciplinary realm of geoarchaeology, because this marriage only enhances the quest for new knowledge and understanding.

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8.1 Introduction

Multidisciplinary and cross-disciplinary research is becoming the norm rather than the exception in many disciplines, including karst-based research. By pulling together the elements of several disciplines into one research design, a new, fresh perspective can be gained as new information is added to the existing base of knowledge. With respect to karst-related research, it has always drawn from the basic paradigms of many disciplines (e.g., geography, geology, biology, geochemistry, geomorphology, geophysics, hydrology), which were often melded together under the banner of undertaking a "karst-based" research project. This is still the case, but the scope has been further broadened to include other disciplines and sub-disciplines such as history, anthropology, archaeology, human ecology, climate and paleoclimate, environment and paleoenvironment, resource conservation and management, and the use of emerging technologies such as remote sensing, geographic information system science, and new approaches in geophysics.

Over the last 20 years the numerous karst-based projects I have been involved in have utilized multidisciplinary approaches. Some of these projects fall into the emerging cross-disciplinary field of geoarchaeology, which combines archaeological research with methods and concepts of the earth sciences (Butzer 1982). As stated by Fouache (2007), geoarchaeology can be more precisely defined as "the use of methods borrowed from geography and geosciences to reconstitute paleoenvironments and landscape dynamics from an archaeological perspective." The archaeological perspective is a logical fit with the geosciences in that archaeology offers a deep time perspective on historical patterns and process that allows researchers to examine the intersection of long- and short-term sociological and natural phenomena, and to compare them across different spatial scales.

The research presented in this chapter utilizes the "tools" of disciplines often grouped together as the geosciences, which individually or collectively, within the framework of geoarchaeology can be applied to archaeological studies. A small body of literature merges methodologies and technology from archaeology and the geosciences to complete research that falls within the realm of geoarchaeology and karst studies. Many of these studies involved the use of geophysical techniques such as electrical resistivity tomography (ERT) (Gautam et al. 2000; Zhou et al. 2000; van Schoor 2002; Roth et al. 2002) and geographic information systems (GIS) to study karst features (Szukalski 2002; Lyew-Ayee et al. 2006).

Geography (both physical and human), geology, geomorphology, and geophysics, can be combined with archaeological methodologies to develop a multidisciplinary research design, within which new and innovative research can be conducted. The examples used in this chapter come from studies conducted at the Cave of Letters and the Qumran Archaeological Site in Israel (Reeder and Jol 2006; Reeder et al. 2004a, b; Jol et al. 2002, 2000) and on the Vaca Plateau in West-Central Belize, Central America (Colas et al. 1999, 2003, 2006; Reeder et al. 1996, 1998; Reeder 2003, 2009; Webster 2000; Webster et al. 2007; Polk et al. 2006, 2007).

By conducting these projects within the multidisciplinary framework of geoarchaeology, the full range of earth/geosciences was combined with archaeological pursuits to infer past processes and events (Rapp Jr. and Hill 1998). Collecting and understanding physical and cultural data in a cross-disciplinary framework are major components within these project's research designs, as was understanding the intrinsic relationships that exist between the physical and cultural landscapes, and natural resources in these areas. It is the intent of this chapter to build upon the previous studies by further illuminating these relationships within the framework of a karst-based inquiry. First, the background of each project will be reviewed. This is followed by a discussion of the various research designs and methodologies. Then the salient results from the different projects will be presented and discussed, as will the conclusions drawn from the analysis of the data. Additionally, the contributions that these studies have made with regard to expanding the base of knowledge related to the karst-geoarchaeology of the Dead Sea area of Israel and the Vaca Plateau in Belize will be addressed.

8.2 Background

8.2.1 The Cave of Letters

In 132 CE, the legendary Shimeon Bar Kokhba led the Second Revolt of the Jews against Roman rule. The First Revolt, which occurred 62 years earlier, ended with the famous resistance at Masada in the land of Israel. During the Second Revolt, Bar Kokhba's troops captured Jerusalem, and restored the Jewish state, but they were eventually defeated in 135 CE by the Roman general Julius Severus. Events associated with the First Revolt, recorded by Josephus Flavius, are part of the historical record for this period, but no such historian existed for the Second Revolt; so for nearly 2,000 years, Shimeon Bar Kokhba remained a mythical figure known mostly through Jewish folklore. All of this changed in 1960 and 1961 when archaeological expeditions headed by famed Israeli archeologist Yagael Yadin explored a Judean Desert cave in the Nahal Hever near the village of En Gedi (Aharoni and Rothenberg 1960; Yadin 1963) (Fig. 8.1). Rebel commanders, and their families, sought refuge in the cave near the end of the Second Jewish Revolt against the Romans (~135 C.E.). Research at the Cave of the Letters (COL) has yielded a priceless collection of artifacts.

Hall "A" (see Fig. 8.3), the first large chamber in the cave, contained a large cache of bronze objects. Excavations in Hall "B" (the second large chamber in the cave) led to the discovery of a fragment of a scroll that contained a rendering of an old psalm. In Hall "C" (the final large chamber in the cave), Yadin and his team discovered a bundle of leather, which later proved to be a goat waterskin that contained beads, perfume flasks, cosmetic tools, a hand mirror, and a bundle of papyri tied with string. Among the papyri were four wooden slats that were covered with writing, which were later determined to be letters from Shimeon Bar Kokhba to military commanders stationed at En Gedi. The first wooden slat contained the heading "Shimeon Bar Kokhba President over Israel". The goatskin belonged to

Fig. 8.1 Location of the Cave of Letters and the Qumran Archaeological Site in Israel

Babatha, a young woman from a remote village in the Dead Sea area, and the wife of Yehonatan bar Be'ayan, one of Bar Kokhba's military commanders. When she fled to the cave, she had taken these items with her as part of her household belongings (Aharoni and Rothenberg 1960; Yadin 1963). The bundle of documents she left chronicles what life was like for a Jewish family at this important time in history. In all, approximately 70 documents written in Hebrew, Aramaic, Nabatean, and Greek were discovered in the cave, hence the name, Cave of Letters. About a dozen documents bore the name of Simeon Ben Koseva, the historical figure known as Bar-Kokhba.

No sanctioned research was conducted in the cave between 1961 and 1999, although it was postulated that a substantial amount of new information about this unique period in history remained to be discovered. Research expeditions to the Cave of Letters in July 1999 and July 2000 (the John and Carol Merrill Cave of Letters Expeditions) utilized state-of-the-art technology (ground penetrating radar (GPR), electrical resistivity tomography (ERT), a gradiometer, a high-resolution transient EM metal detector, and an endoscope), as well as traditional geologic, archaeologic, and surveying techniques. Their purpose was to add a substantial amount of new information to the existing bases of knowledge about the Second Jewish Revolt, as well as the viability of geophysical research in caves. Because the COL is located in the tectonically active Dead Sea Rift Zone, and local limestone layers are being wedged apart by the growth of gypsum crystals, the cave floor is covered with roof fall that obscures the underlying archaeological deposits.

8.2.2 Qumran

The Qumran Archaeological Site, also in Israel, is located along the western shore of the Dead Sea (Fig. 8.1). This site is most famous for the caves located in the cliffs west of the site, where the Dead Sea Scrolls were discovered. In 1947, Arab shepherds found a cave whose contents were soon hailed as the greatest archaeological discovery of the twentieth century (VanderKam 1994). Approximately 800 manuscripts have been found in the 11 caves at Qumran (VanderKam 1994).

Data compiled by Roland de Vaux (1973), based on his excavations from 1953 to 1956 assert that Qumran was occupied by a group engaged in communal activities and religious rites (Schiffman 1995). In an attempt to understand the historical context of the Dead Sea Scrolls, scholars have tried to identify the group responsible for these documents (VanderKam and Flint 2002). Schiffman (1995) feels that the "Qumran Sect" was intrinsically linked to the scrolls found in the caves. The most widely adopted view of the "Qumran Sect" is that they were a small branch of the larger Essene movement (Sukenik 1955; VanderKam and Flint 2002), and that this sectarian group was responsible for gathering together, copying (mostly between 150 B.C.E and 68 C.E.) and depositing documents in area caves. After modern discovery, these documents came to be called the Dead Sea Scrolls (Schiffman 1995).

Another important facet of Qumran is the cemeteries located at the site. There are three cemeteries associated with Qumran, with the largest one located just east of the site, and smaller cemeteries found to the north and south (VanderKam 1994). In the main cemetery, de Vaux excavated 37 tombs out of the estimated 1,100 graves at the site, in the north cemetery two out of 12, and in the south four out of 30. Therefore, based upon de Vaux's estimates, there are a total of 1,142 graves in the three cemeteries at Qumran.

Past and present research efforts at Qumran have focused on the caves, the site, and the cemetery. Nine earlier reports, dating back as far as 1850 and continuing through 1947, described various aspects of the Qumran Site, but no one had subjected the ruins to a thorough examination (VanderKam and Flint 2002). After the discovery of scroll material in cave one in early 1947, the site became of great archaeological importance. It was not until February 1949, because of political instability and hostilities that the first scholars began to work at Qumran. The 1949 excavation at cave one was directed by de Vaux and G. Lankester Harding. During this excavation, they also visited the ruins of Qumran and conducted a quick surface examination (VanderKam and Flint 2002). They returned in late 1951 and began to excavate portions of the surface ruins and cemetery. They returned again to work in newly found caves and at the surface ruins and cemetery in 1953. Additional expeditions were also staged in 1954, 1955, and 1956. After the final de Vaux-Harding expedition in 1956, Qumran received very limited archaeological attention. Little work was done with the archaeological remains at Qumran between the end of the de Vaux-Harding digs and the mid-1980s. Since then, several studies have been completed, in part supporting de Vaux's work and in part revising or refining his conclusions (VanderKam and Flint 2002). In 1995–1996, Magen Broshi (former curator of the Shrine of the Book at the Israel Museum in Jerusalem) and Hanan Eshel (Bar Ilan University) conducted a six-week season of excavation in an area of collapsed caves just north of Qumran. This was the last organized research effort at Qumran, until the John and Carol Merrill Excavations, which I was a part of, began at the site in July 2001.

8.2.3 The Vaca Plateau in Belize

Since 1990, the Northern Vaca Plateau Geoarchaeological Project (NVPGAP) has conducted 21 seasons of field research on the Northern Vaca Plateau in Belize, Central America (Fig. 8.2). The 25 km^2 study area is made up of mostly hilly, rugged terrain that exhibits landform features indicative of fluvio-karst topography, with the suite of landforms including an integrated system of dry valleys separated by residual hills and interfluves, single inlet and compound sinkholes, isolated cockpits, cutters, solution fissures and corridors, and caves (Reeder et al. 1996; Colas et al. 2008).

Petrographic analysis completed on rock samples collected in the study area concluded that the Campur Formation, the predominant geologic formation in the area, is a limestone breccia. Specifically, the study area is dominated by depositional breccias that formed in materials eroded off the Mountain Pine Ridge area of Belize just east of the Vaca Plateau, that were deposited and re-cemented in a shallow sea environment, and that now form the geologic materials we see on the Vaca Plateau today (Reeder et al. 1996). Geomorphic analysis in the study area has focused on relationships between structural elements of the areas bedrock, and the formation and evolution of area caves and the karst landscape. It was determined that planes of structural weakness formed in the Campur Limestone have similar orientations to contemporary karst landform features such as solution valleys, the long axis of sinkholes, and cave passages. These relationships suggest an important structural

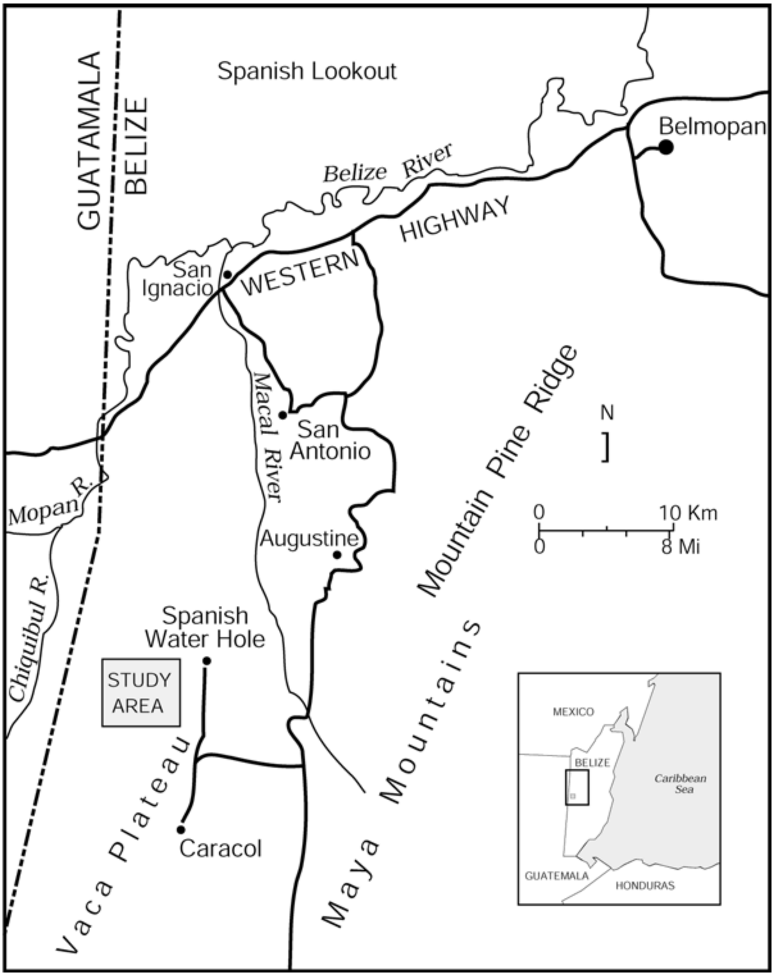

Fig. 8.2 Location of the Northern Vaca Plateau study area in Belize, Central America

control on the formation and evolution of area caves and the karst landscape. Furthermore, the dry-valleys and stair-step cave profiles indicate that the lowering of base level through time was interspersed with relatively stable periods when horizontal cave passages developed (Reeder et al. 1996).

The multidisciplinary research completed in the study area has provided a wealth of geologic, geomorphic, and speleologic data, as well as archaeological information about Late Classic Maya society and their usage of caves (Reeder et al. 1998; Colas et al. 2000, 2008), which are common in the rugged karst terrain of the Northern Vaca Plateau. As part of the cave-based component of the research, over 200 caves have been entered and explored, with maps created of the larger and/or more geologic or archaeologic important caves. Although most of the research in the study area has concentrated on caves, a large surface site, which was discovered in 1993, has been investigated as well (Colas 2001; Colas et al. 2006). The archaeological site of Ix Chel was discovered situated at the top of one of the many isolated hilltops in the study area. A sketch map of the Ix Chel Site was created in the mid-1990s, and in 2006, a detailed map of the site's core was produced (Fig. 8.12). Collected surface ceramics from Ix Chel suggest a Late Classic occupation, as do the artifacts in many of the caves that have been investigated thus far. Because these caves lie relatively close to Ix Chel, they may have been used by Ix Chel's inhabitants as ritual places (Colas et al. 2008).

8.3 Research Designs and Methodologies

8.3.1 Cave of Letters

The research design used at the Cave of Letters was cross-disciplinary and involved aspects of Geography, Geology, Geophysics, Archaeology, History, and Biblical Studies. The overall objective for the project was to better clarify some of the uncertainties associated with the Second Jewish Revolt, and the use of the cave by associates of the legendary Shimeon Bar Kokhba, who led the revolt against Roman rule. The research was conducted within the multidisciplinary framework of the emerging discipline of Geoarchaeology, and specifically it sought to: (1) Quantify the specifics of the area's geology and geomorphology, and to link it to the formation of the cave, the cave's setting in the Dead Sea Fault Zone, and the patterns of cave use by Bar Kokhba's followers; (2) Produce the most up-to-date and detailed maps of the cave that are digital and thus easily updatable; (3) Use geophysics to locate and then study the Bar Kokhba living surface layer in the cave; (4) Study the spatial and temporal nature of the microclimatic variations in the cave environment, and relate these variations to cave geology, geomorphology, and the patterns of cave use; and (5) Complete archaeological excavations in the cave to study the Bar Kokhba era living surface and the associated artifacts.

Much of the research conducted at the Cave of Letters and Qumran sites in Israel involved the collection of data to produce maps, and the collection of geophysical data to assess the nature of the near surface materials at these sites, and to designate the optimal sites for archaeological excavations. In order to create new, detailed maps for the Cave of Letters, surveys were completed using the traditional methods utilized in cave surveying, which included the use of the following hand-held survey instruments: (1) An optical compass, (2) an optical inclinometer, and (3) a nylon survey tape. More technologically advanced instruments, such as laser surveying devices (Lerma et al. 2010), were not available for use by the survey team; hence the traditional methods were used. A total of 82 survey stations were established within the cave. Data collected between each station includes azimuth, inclination, and distance. At each survey station, a sketch of that segment of cave passage was also produced. The survey data was plotted using the CAVEPLOT computer program, and the plots were exported to Adobe Illustrator for map production. Plan view and cross-sectional maps were produced, as well as maps that depict the locations where geophysical and archaeological analyses were completed. A portable digital pulseEKKO™ 100 and 1,000 GPR system was used to obtain the GPR profiles. Four antennae frequencies, 100, 200, 225, and 450 MHz, were tested. To reduce data collection time in the rugged cave environment, a backpack transport system was employed. The digital profiles were processed and plotted using pulseEKKO™ software. The application of radar stratigraphic analysis, an approach for interpreting sedimentary environments (Beres and Haeni 1991; Jol and Smith 1991), provided the framework to investigate both lateral and vertical geometry of the reflection patterns. After processing, printing, and interpreting the GPR profiles while in the cave, archaeological probes were completed at selected locations using an endoscope, metal detector, and/or traditional archaeological excavation techniques.

The two-dimensional electrical resistivity and tomography (ERT) analysis in the cave involved introducing an electrical current into the ground with two electrodes, and measuring the voltage drop across the cave-floor with two other electrodes. Because electrical flow disperses throughout the surface of the geologic materials that make up the floor of the COL, these measurements provided information about the electrical character of materials below the surface of the cave floor.

ERT is a surface geoelectric technique for mapping the distribution of subsurface electrical resistivity in a cross-sectional format. Data are collected through a linear array of electrodes coupled to a DC resistivity transmitter/receiver and an electronic switching box. The collection process is driven by a computer that is also used for data recording. The entire dataset is then inverted using a two-dimensional (2-D) finite difference, smooth inversion routine. The final product is a 2-D geoelectrical cross-section, plotting “true” resistivity (in ohm-m) versus “true” depth. The acquisition hardware used in this program was the ABEM Lund Imaging System.

The locations of two of the ERT sections surveyed are presented in Fig. 8.4. For line # 1, a minimum electrode spacing of 1 m was used, providing a maximum depth of investigation of approximately 12 m below ground surface (mbgs). This line was 80 m in length and ran from Hall A, through the AB connection, through Hall B, and into passage BB (Fig. 8.4). ERT Line 2 was a 40 m line running from the northeast corner of Hall B, north through the Hall C Connection, and across the southwest corner of Hall C. The length of Line 2 was constrained by the geometry of the cave. A minimum electrode spacing of 0.5 m was used, providing a maximum depth of investigation of approximately 6 mbgs. While smaller minimum electrode spacing decreased the depth of investigation of Line 2, as compared to line 1, it increased the spatial resolution. In order to facilitate good electrode contacts (i.e., lower the contact resistance), approximately 200 ml of water was poured around each electrode placement. It is believed that the large amount of halite present on the surface, when saturated with water, significantly assisted in decreasing the contact resistance, making the ERT survey practicable in this extremely arid cave environment. Each of the electrodes used in each ERT spread were surveyed for relative relief along the line. The inverted (modeled) geoelectric sections account for any changes of relief along the lines.

Profiles were produced by modeling the data from a series of measurements with different depths and locations along a survey line (Reynolds 1997). In the COL, two electrical resistivity and tomography transect lines were established. A gradiometer and a high-resolution transient EM metal detector were also used in the COL, with limited success, to locate artifacts in and below the rubble.

8.3.2 Qumran

The multidisciplinary research project completed at the Qumran Archaeological Site was focused on efforts to uncover new information about the site by (1) finding new caves using geophysics, (2) expanding the base of knowledge about Qumran by studying the cemetery, and (3) producing maps that depict the site, caves, cemeteries, and the spatial relationships between these features. My main area of focus during this 2 year project (2001 and 2002) was to complete the most detailed maps to date of the Qumran Cemeteries and surrounding areas, from which we began to assess the spatial relationships between the cemeteries, caves, the Qumran site, and the physical and cultural landscapes of the area. One physical/cultural landscape feature that received special attention was the aqueduct system at Qumran. The sectarians that occupied Qumran spent a large amount of time engaging in activities associated with ritual purity (Schiffman 1995). Among the most striking features at the Qumran ruins are the cisterns and baths at the site. A growing population made it necessary to provide a plentiful and constant supply of water for the settlement; so, an aqueduct was constructed to carry water provided by winter rains (de Vaux 1973). This segment of the research sought to determine (1) how the Qumran Sectarians manipulated their water resources, and (2) what role the local geologic conditions played in the manipulation of area water resources.

It has been previously noted that accurate maps of the Qumran cemeteries are pivotal in understanding the archaeological evidence collected thus far at Qumran (Schiffman 1995). The detailed maps produced as part of this research allowed the spatial aspects of the databases developed for Qumran to be assessed, compared, and contrasted. Past mapping efforts by de Vaux and others did not produce a complete, accurate depiction of the site and surrounding area. At Qumran, a Total Station Surveying instrument was used to map the cemeteries, as well as the Qumran Aqueduct system, the Qumran Archaeological Site, and the location of ERT lines, and GPR lines and grids. A Total Station is a surveying instrument that utilizes a laser to measure distance, and x and y coordinates are collected relative to a know point of reference (a benchmark), so that a map can be created.

Most graves in the cemeteries were located visually, but additional graves, or what are suspected to be graves, were located using ground penetrating radar (GPR). Location and elevation data were collected for each grave using the total station, then the data was entered into spread sheets, and transferred to a plotting program (CAVEPLOT), and the plots were then exported into a graphics program (Adobe Illustrator 10.0) for map production.

A Noggin GPR system mounted on a cart for increased mobility was used to explore the cemeteries at Qumran. The system emits radio waves into the ground and then collects these waves as they reflect back from the underlying geologic materials. In a known cemetery, GPR can look for locations where the materials had been disturbed, indicating a grave location with no surface expression. GPR surveys in some parts of the cemetery indicated undisturbed flat-lying layers of geologic materials while other places had obviously been disturbed. The GPR plots for these locations indicated a v-shaped pattern indicative of a site that had been dug and then refilled with the same material. Suspected graves, located using GPR, were identified in all of the cemeteries at Qumran. Additionally, 2-D resistivity, and EM were used to search for subsurface voids at Qumran with the intention being to better understand the burial practices of the people of Qumran, and to locate potentially collapsed caves that may or may not contain written materials.

8.3.3 The Vaca Plateau in Belize

The multidisciplinary research design implemented for the Vaca Plateau in Belize includes (1) exploration and mapping of caves and surface ruins in the study area, (2) studying area geology, geomorphology, hydrology, and speleology to better understand the study area's physical landscape, (3) mapping, collecting, and analyzing soils from archaeological sites and terraces, (4) collecting sediment and speleothems from caves for physical, chemical, and paleo-climate/paleo-environmental analysis, (5) collecting rock samples from outcrops, caves, archaeological sites, and possible quarry sites, (6) determining the usage patterns of caves via archaeological excavation and interpretation, and (7) determining relationships between cave formations (speleothems) and long-term changes in climate, vegetation, and land use patterns. This manuscript will focus on two subtopics within the projects' multidisciplinary research design. These subtopics revolve around the theme, how aspects of the physical landscape affect the cultural landscape. Examples will be presented and discussed regarding how the area's geology has affected and influenced the Maya cultural landscape that developed on the Northern Vaca Plateau. Specifically, local geology will be quantified to develop an overall understanding of the areas physical landscape, and this knowledge will be compared with geologic evidence related to area quarrying activities and the stones used in monumental construction, thus establishing a linkage between the physical and cultural landscapes.

Data regarding the petrology of the geologic formations in the study area were obtained by analyzing thin sections prepared from 25 rock samples. Rock specimens were collected at five general landscape positions and were grouped as follows: (1) Residual hilltops (7 samples), (2) residual hillside slopes (9 samples), (3) dry valley bottoms (2 samples), (4) cave entrances (4 samples), and (5) cave walls (3 samples). Three of the cave entrance samples were collected in dry valley bottoms, and one was from a residual hillside slope. The cave passages from which samples were collected have entrances located on a residual hilltop (1 sample) and on a residual hillside slope (2 samples). Thin section analysis was used to identify rock constituents. Initial investigation indicated a large degree of heterogeneity, making the point count method of analysis (Folk 1962) inadequate. On brecciated rocks, the point count method may be misleading because of variations in lithology of the clasts, and the type and amount of cement. The relative abundance of sparite, micrite, fossils, or other characteristics becomes meaningless in these rocks, and it is more appropriate to classify the rock by using field relationships, stratigraphy, and petrographic analysis. The samples were therefore classified first using systems described by Pettijohn (1975), and then by methods described by Blount and Moore (1969).

Additionally, 32 rock samples were collected in and around the Ix Chel, with these samples coming from the surface of ruined buildings at the site, suspected quarry sites, and area outcrops. The purpose of this inquiry was to determine similarities and differences between stones used to face the buildings at Ix Chel, and area rocks from outcrops and suspected quarries. The determinations that were made, based upon this research, assisted in establishing a better understanding of the use of local resources versus using resources, in this case quarried stones, from the broader region. Analysis of the samples allowed a determination to be made regarding whether the sample was a breccia or non-breccia (Pettijohn 1975), and non-breccias samples were further analyzed using methodology utilized by Folk (1962), and breccia samples were described using the criteria outlined by Blount and Moore (1969). The brecciated rocks in the area cannot be quarried and carved because of their physical structure (large clasts embedded in a matrix of sparite or micrite), and extreme hardness. Once identified, the non-brecciated building stone samples were compared with non-brecciated samples from the suspected quarry sites to determine if the quarries were indeed the source for the building stones used at Ix Chel.

8.4 Results and Discussion

8.4.1 Cave of Letters

The mapping of the Cave of Letters (Fig. 8.1) was a major component of the project's overall research design because (1) it facilitated the creation of a new base map of the cave, and this map could be stored in a digital format and was thus easily updated, (2) layers of data could be added to the map in real-time, (3) the mapping process in the cave facilitated a through exploration of all passages, and (4) detailed maps could be created which highlighted the various components of the research (i.e., geophysics, geology, and archaeology). The collection of survey data, and the eventual production of a series of maps related to the 1999 and 2000 research completed in the cave, took place as a series of steps that included (1) data collection and acquisition, (2) data entry, storage, and manipulation, (3) plotting, (4) data export to a graphics program and de-construction of data plots created in the plotting program using this graphics program, and (5) map production using the graphics program. By combining the

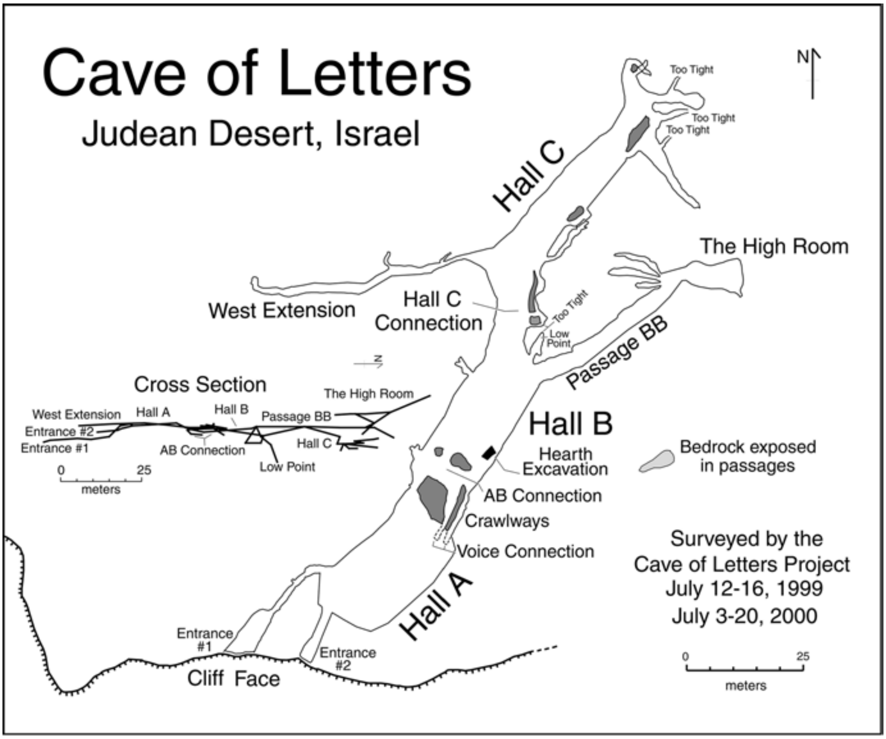

Fig. 8.3 The 2002 base map from the Cave of Letters, Israel

plotting program output that plots the cave walls, and the map sketch that was produced during the survey of the cave, a general base map of the Cave of Letters was produced in 1999, and updated after the 2000 expedition (Fig. 8.3). Based on the 1999 base map, the length of the Cave of Letters, based upon the most direct route through the cave, was estimated to be 335 m. The 474 m surveyed length of the cave reflects the distance between the 66 survey stations which were used to produce the map. In the three large chambers in the cave (Halls A, B, and C), the layout of survey stations meandered through chambers, not taking the most direct route. Hence, the 474 m distance value is an over-estimation, although it does reflect the surveyed length of the cave. The addition of the 16 survey stations from the year 2000 survey added 65 m to the surveyed length of the cave.

Using the base map created after the 1999 and 2000 surveys, more detailed, and sometimes topic specific maps were created. One map generated provides details related to the location of roof fall on the cave floor, holes in the cave floor, the topography of the cave floor, and features in the cave ceiling. A line plot of the cross-section of the cave was also created which could be added to maps, as were 25 individual cross-sections from throughout the cave, hence allowing the maps to depict both the plan view and cross section view of the cave on the same map sheet. Data related to archaeological finds in the cave were plotted on a version of the map

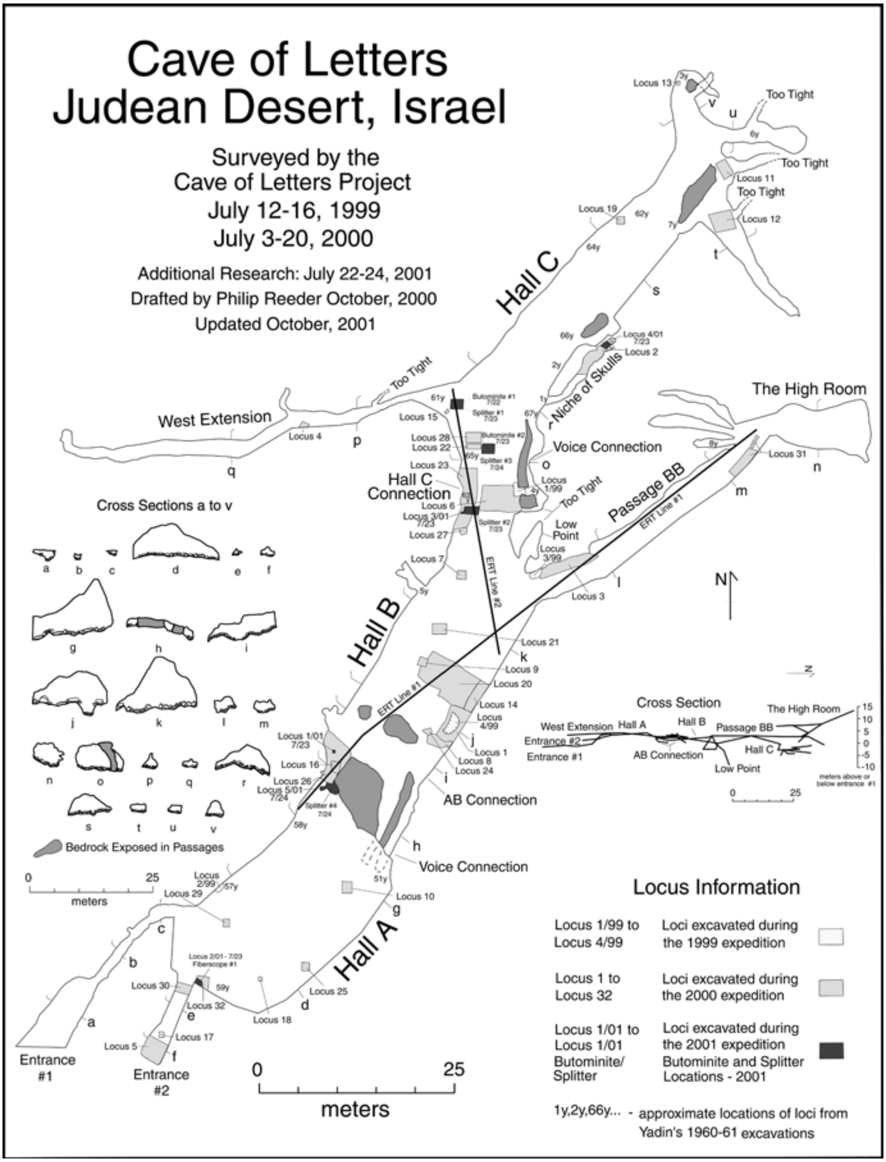

Fig. 8.4 A detailed 2001 map of the Cave of Letters that depicts cave cross-sections, the location of archaeological excavations and selected geophysics transects in the cave

as well (Fig. 8.4). Because the map data was in digital format, it could be stored in a hand-held touch screen computer and information related to the archaeological loci and associated baskets could be added to the map database in real-time. This process greatly facilitated updating the archaeology research map of the cave. In addition, utilizing the same base map and the detailed physical and archaeology maps, maps were created that depict the location of Ground Penetrating Radar or ERT survey lines, as well as the locations where rock splitting efforts were concentrated in 2001.

The set of maps that were produced as a result of this research provide a mechanism for understanding the spatial complexities/inter-relationships of the research, as well as a means of visually conveying this information. Very few researchers, or members of the general public, have been privileged to visit the Cave of Letters, but the set of maps produced as part of this research have contributed to establishing a better understanding of the geography of the Cave of Letters.

With regard to the use of GPR in the Cave of Letters, parallel transects were collected in each of the three rooms in the cave, as well as all the passageways that connect the rooms. In all, over 50 GPR transects were completed in the cave over the two field seasons (1999 and 2000). The lowest GPR antennae frequency used in the Cave of Letters was 100 MHz. A 27 m long 100 MHz profile was collected in Hall B, with the antennae separation of 1.0 m and a step size of 0.25 m. The upper area of the profile is similar in appearance to the underlying area, but it is separated by a near continuous, undulating reflection. The interpretation for this assemblage is that the upper area of the profile is the most recent roof fall (dislodged by the frequent earthquakes that occur in the area) which has accumulated on the hypothesized Bar Kokhba habitation layer.

Additional GPR transects were completed to further corroborate the existence of this layer. A 19 m long transect using 200 MHz antennae, with a separation of 0.5 m and a step size of 0.1 m, was completed in Hall B. This transect was at a 45° angle to the 100 MHz transect and crossed that transect in the southwestern part of the cave room. The reflection patterns in this transect were very similar to the first transect, with the upper levels of the profile in more detail because of the use of a higher resolution 200 MHz antennae and a closer step size (0.1 m). Again, the nearly continuous, undulating reflection that separates the two layers in the upper profile is interpreted as the Bar Kokhba floor. Additionally, above these reflection patterns, which became apparent using the higher resolution 200 MHz antennae, are several reflection patterns which were interpreted as additional material from more recent roof fall events that occurred since the cave was abandoned during Bar Kokhba times. Other 200 MHz survey transects were completed in various parts of the cave and they were able to image the undulating bedrock surface (original cave floor) and the hypothesized Bar Kokhba habitation layer. In addition, the first 4 m of the 19 m long transect discussed above was examined using an even higher frequency antennae (450 MHz) with a separation of 0.17 m and a step size of 0.05 m. With the increase in frequency to 450 MHz, the profile shows a decrease in depth of penetration (to approximately 3 m), but an increase in the resolution of the upper layers, with more details of the roof fall material apparent including the internal stratigraphy of the materials that the survey crossed.

A three-dimensional (3D) dataset was also developed for the Cave of Letters (Fig. 8.5). These type of datasets are useful for interpreting the framework of the subsurface materials and they provide a more detailed view of the geometry of individual units within the stratigraphy. In the Cave of Letters, three-dimensional datasets were collected in each large room in the cave to assist in the detailed

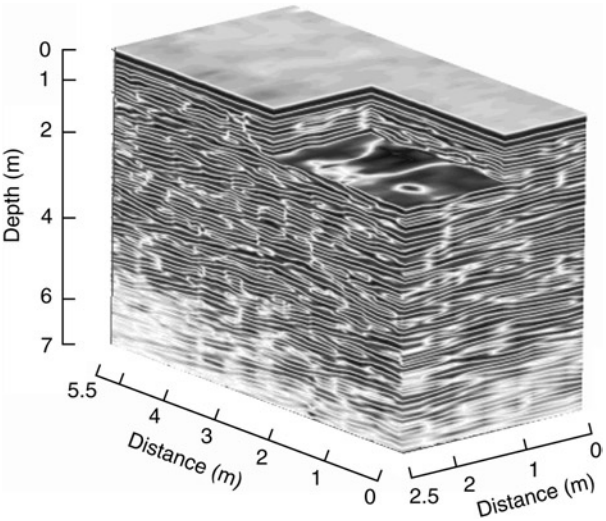

Fig. 8.5 A three-dimensional GPR depiction cut away to the suspected Bar Kokhba habitation layer

interpretation of the cave deposits, and to possibly indicate optimum locations for archaeological excavation. A dataset for eventual three-dimensional depiction was collected in Hall B with the 200 MHz antennae with an antennae separation of 0.5 m and a step size of 0.1 m. The grid, the data was collected from, was 5.5 by 2.5 m. The reflections discussed in the previously cited two-dimensional examples are also visible in a 3-D perspective, wherein the three-dimensional cube created by the software is sliced and the Bar Kokhba habitation surface is exposed. The more continuous reflections in the cube below the Bar Kokhba layer may be former cave floors that pre-date the Bar Kokhba layer. The success in locating this surface beneath the roof fall materials provided locations for further exploration beneath the rubble using an endoscope, and pinpointed locales for possible excavation.

Interpretation of the data collected along ERT Transect 1 identified two distinct layers in the profile. An upper layer is thought to be composed of various sized roof fall material. The deeper and thicker layer is believed to be limestone bedrock. There is no evidence of internal layering within the roof fall materials. If a packed earth floor exists, as was interpreted using the GPR data, this layer should appear as a less resistive layer within the roof collapse debris. One explanation for the absence of this horizon is that it is too thin to be detected using ERT.

Similar to ERT 1, ERT 2 has two prominent layers, consisting of a highly resistive layer of roof collapse debris, which overlies a moderately resistive layer interpreted to be limestone bedrock (Fig. 8.6). Different from Transect 1, ERT 2 contains a mostly continuous, lower resistivity layer that cuts almost completely across Hall B and partially through the floor materials in the BB Passage. This layer varies from just below the cave floor surface to approximately 3 m below the cave floor. Similar to the interpretations made based upon the GPR data, this layer is hypothesized to be the remains of the Bar Kokhba period surface. This layer was detected

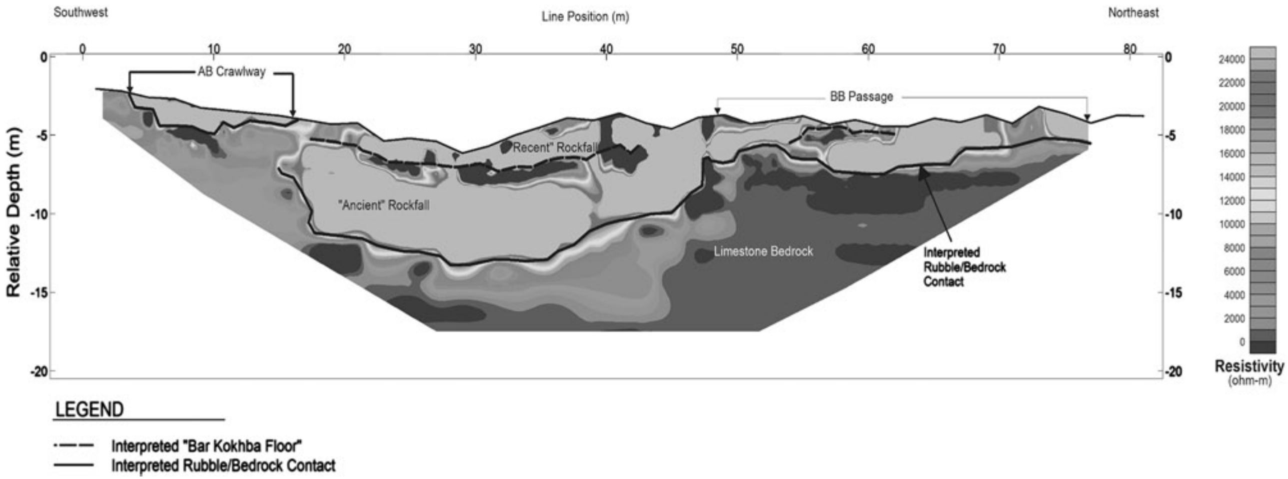

Fig. 8.6 An ERT cross-section from the AB passage, though Hall B and down the BB passage, which highlights the Bar Kokhba habitation surface, locations of ancient roof fall materials, as well as recent rock fall

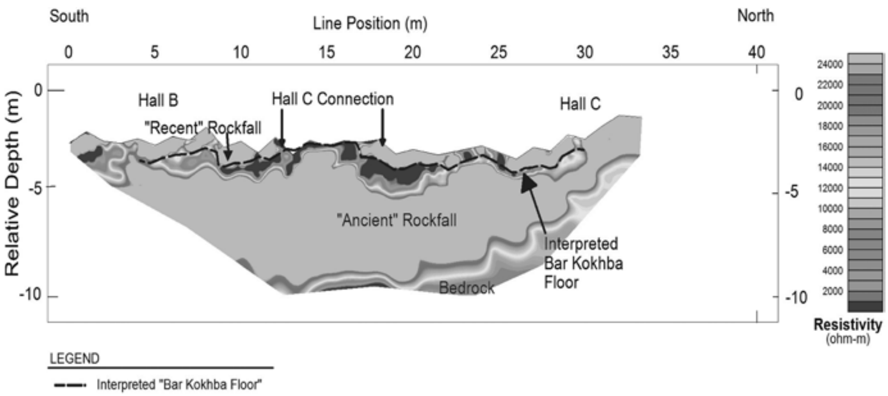

Fig. 8.7 An ERT cross-section from Hall B, through the BC passage and into Hall C, which *highlights* the Bar Kokhba habitation surface, the location of bedrock, locations of ancient roof fall materials, as well as recent rock fall

in the ERT 2 Transect and not ERT 1, because ERT 2 crossed the center of the room, and ERT 1 traversed along the wall. Most of the activities in the cave would have taken place more in the open areas of the cave toward the center of the rooms and not along the walls.

As with ERT Line 1 and 2, Line 3 contains two layers, including a highly resistive (>20,000 ohm-m) layer of roof collapse rubble overlying a moderately resistive (1,000–9,000 ohm-m) layer interpreted to be limestone bedrock. Only a relatively small thickness of the limestone bedrock is imaged as the depth of investigation of the 40 m long section is only 6 m below the cave floor. The roof collapse rubble reaches a thickness of about 6 m in Hall B and in the Hall C Connection. The rubble reaches at least 5 m below the cave floor in Hall C.

Similar to Transect 2, ERT 3 contains a continuous, lower resistivity layer that exists for almost the entire extent of the 40 m line (Fig. 8.7). The depth of this layer varies from just below the cave floor surface to approximately 1.5 m below the cave floor. This interpretation corroborates interpretations based on the GPR data that this layer is the Bar Kokhba habitation surface. In the C Connection Passage, excavation revealed a densely packed surface of fine grained material which required a digging tool to penetrate. Excavation of this layer revealed a Vespasian coin (in conjunction with metal detection surveys), 72 pieces of Roman period pottery, and a pointed wooden stick that was possibly a writing instrument.

8.4.2 Qumran

The Dead Sea Scrolls are approximately 900 different manuscripts discovered in eleven caves in the vicinity of Qumran between 1947 and 1956 (Fig. 8.1). The scrolls contain every book of the Hebrew Old Testament except the Book of Esther, with the scrolls predating any other version of the Bible by more than 1,000 years. Thus, the Dead Sea Scrolls are often referred to as the most important archaeological find of the last century, and Qumran is perhaps the most important archaeological site in the world from the perspective of the development of Judeo-Christian civilization.

An intriguing aspect of the Qumran Site, along with the ruins, caves, and aqueduct system, is the cemeteries (Fig. 8.8). Qumran is arguably one of the premiere sites from

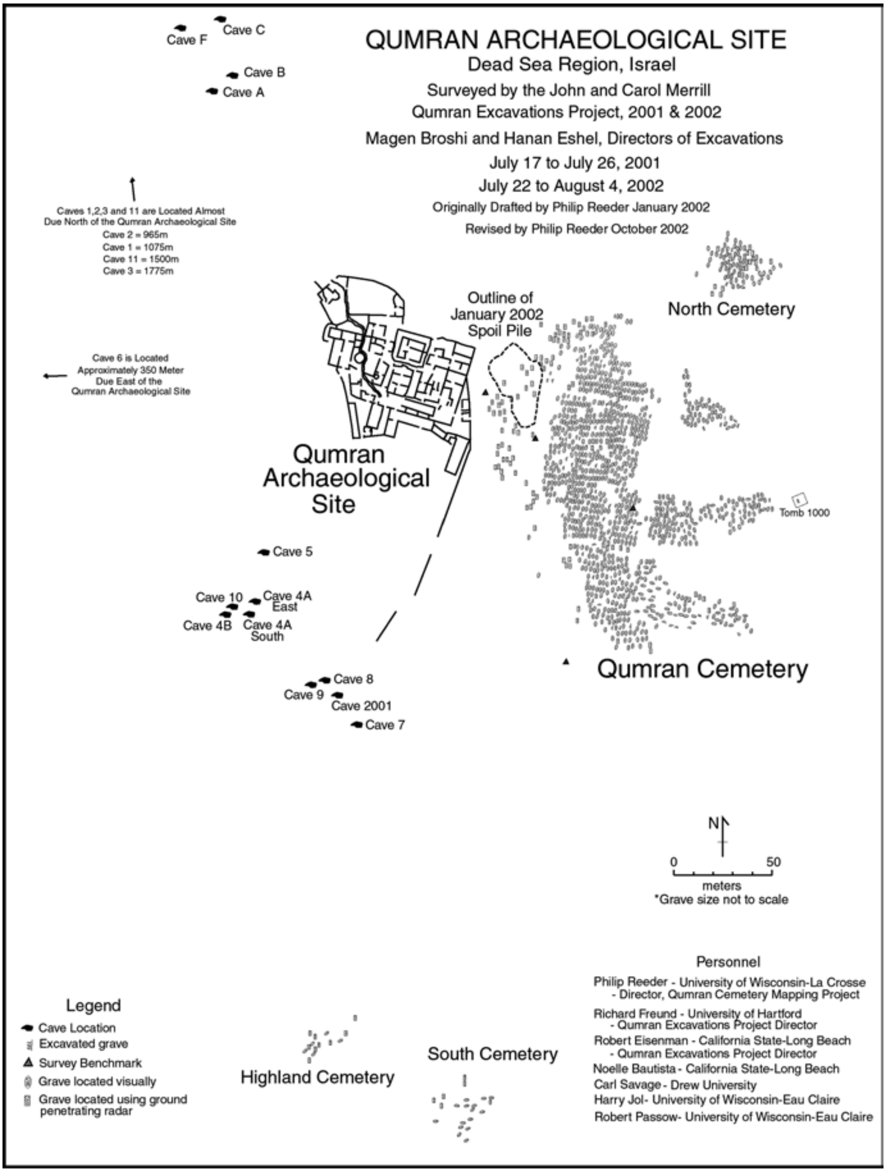

Fig. 8.8 A map of the Qumran area depicting the spatial relationships between the caves, the archaeological site, and the cemeteries, with tomb 1,000 *highlighted*

antiquity in Israel, but the cemetery had never been thoroughly studied and systematically mapped. The 2001 and 2002 surveys of the cemeteries at Qumran found 1,056 graves with surface expression in the main cemetery, fingers and North Cemetery (978 were located visually). Seventy-eight of these graves had been previously excavated. Records indicate that there are 46 legally excavated graves in the cemeteries, so it can be assumed that the other 32 are the result of illegal excavations. If the South and Highland Cemeteries are included, four additional excavated graves (for a total of 82) and 17 additional visual graves (for a total of 995) are added, producing a total of 1,077 graves in all of the cemeteries that have some visual expression.

To non-intrusively assess the subsurface of the cemeteries at Qumran, a Noggin GPR system mounted on a cart for increased mobility was used to explore the cemeteries. In a known cemetery, GPR can look for locations where the materials had been disturbed but have no surface expression. GPR surveys in some parts of the cemetery indicated undisturbed flat-lying layers of geologic materials, while in other locations v-shaped patterns indicative of a site that had been dug and then refilled with the same material were located. Suspected graves, located using GPR, were identified in all of the cemeteries at Qumran, with 84 located in the main cemetery, one in the Middle Finger, six in the South Finger, 22 in the North Cemetery, five in the South Cemetery, and nine in the Highland Cemetery. A total of 122 GPR anomalies were found.

The total number of graves in all the cemeteries at Qumran, including suspected graves found using GPR, is 1,199. Of the 995 graves located visually in all the cemeteries (not including excavated graves), 14 (1.4%) were in excellent condition, 164 (16.5%) were in good condition, 424 (42.6%) were fair, 301 (30.3%) were poor, and 92 (9.2%) were in very poor condition.

Two graves located on the middle finger of the east extension of the main cemetery took on a special significance (Figs. 8.8 and 8.9). In 2002, a skeleton was discovered in a grave that has been designated Tomb 1,000, the same site where the remains of two women from the first century AD were found during the summer of 2001. Prior to the discovery of the two women in 2001, an anomaly was found at the site using GPR. Excavation revealed a building that was eventually determined to be a mourning enclosure, and the skeletal remains of the two women. In 2002, the floor of the mourning enclosure was again surveyed using GPR and another anomaly was located which proved to be the location of a skeleton. This skeleton was discovered 1.5 m below the surface, and approximately 1.0 m below the remains of the two women. This building (mourning enclosure) is situated in a prominent elevated position on the periphery of the cemetery. The positioning of this burial chamber may indicate that a person of some importance was buried in this location, and a ceramic dated to the first century CE was found alongside the skeletal remains (Jacobson 2002). The skeleton was found facing east and the first rays of the rising sun would strike the burial chamber. This burial chamber is one of the most elaborate in what is otherwise a very simple place (Jacobson 2002). The east–west orientation is generally thought to coincide with Muslim burials that have taken place in the cemetery over the last several hundred years, but the presence of the first century pot confuses this issue. Scholars generally agree that the other east–west burials in the

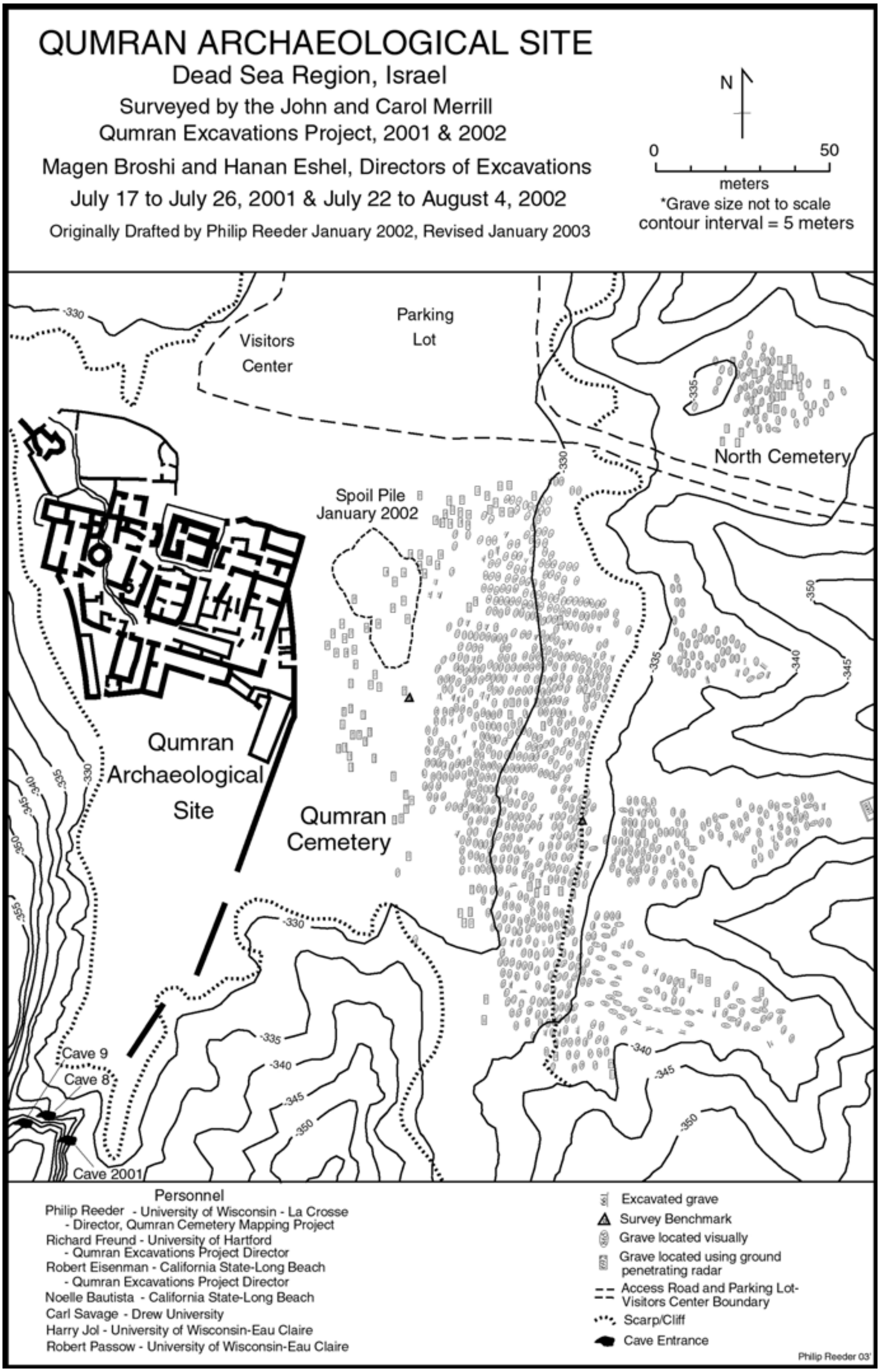

Fig. 8.9 A more detailed map of the Qumran Archaeological Site, with the caves and cemeteries close to the site included, as well as the areas topography

cemeteries are either Christian or Muslim (Bedouin) dating to the last few centuries (Zias 2000; Eshel et al. 2002), but the Tomb 1,000 burial remains a mystery.

Another mystery in the cemeteries at Qumran is grave 978, which contains the remains of a zinc coffin. This grave was likely excavated by looters, and portions of the zinc coffin were damaged or removed. This grave is oriented north–south, which is interpreted as a burial from the era of the Qumran Sect (Schiffman 1995; VanderKam and Flint 2002). The zinc coffin may have been used to transport a body from another location for burial at Qumran.

A map of the aqueduct in the vicinity of the Qumran Site was also completed. A growing population made it necessary to provide a constant supply of water for the settlement (de Vaux 1973). A narrow canyon extends from the mountains west of Qumran, connecting with the upper reaches of Wadi Qumran. Structures were created in the lower portions of the canyon to move water toward the site, rather than down the wadi into the Dead Sea. At some points, the aqueduct going through tunnels cut into the rock, and in other places the water flowing through channels excavated into surface exposures of bedrock. Once out of the rocky canyon, the aqueduct was dug into the marl terrace that slants toward the settlement (Schultz 1960). Upon reaching the settlement, the channel was coated with plaster and, for some part of its winding course between buildings it was covered with stone slabs (de Vaux 1973). The difficult and elaborate construction of the aqueduct is a testimonial to the importance of water to the Qumran Sect.

In addition to the use of GPR at Qumran, other geophysical techniques, namely two-dimensional electrical resistivity and tomography (ERT), were used as well. ERT can detect cavities in the subsurface that have no surface expression. The previously discovered caves that contained scroll material are in areas of rugged, exposed limestone cliffs, with many of the caves adjacent to the Qumran Site and others up to 1.8 km away. This limestone topography is very common in and around Qumran, the area is tectonically active, and there is a distinct possibility that earthquakes caused caves containing artifacts to collapse. ERT surveys in the vicinity of the Qumran Site were completed to pinpoint possible locations for excavation. The ERT surveys delineated several locations where possible voids (collapsed caves) existed (Fig. 8.10). These areas were probed with an auger (a portable hand-held drilling device), but no cavities were found. The original research design for this phase of the project called for the use of a power auger to drill into the voids, but this request was not approved, and only the use of a hand auger was allowed. No further research permits were submitted to continue this work at Qumran; so, we will never know if a more sophisticated drilling device would have been able to probe the suspected voids.

8.4.3 The Vaca Plateau in Belize

Geologic, geomorphic, speleological, and archaeological research has been conducted for the past 20 years within a 25 km^2 area of the Northern Vaca Plateau centered 6 km east of the border between Guatemala and Belize, 15 km south-southeast of

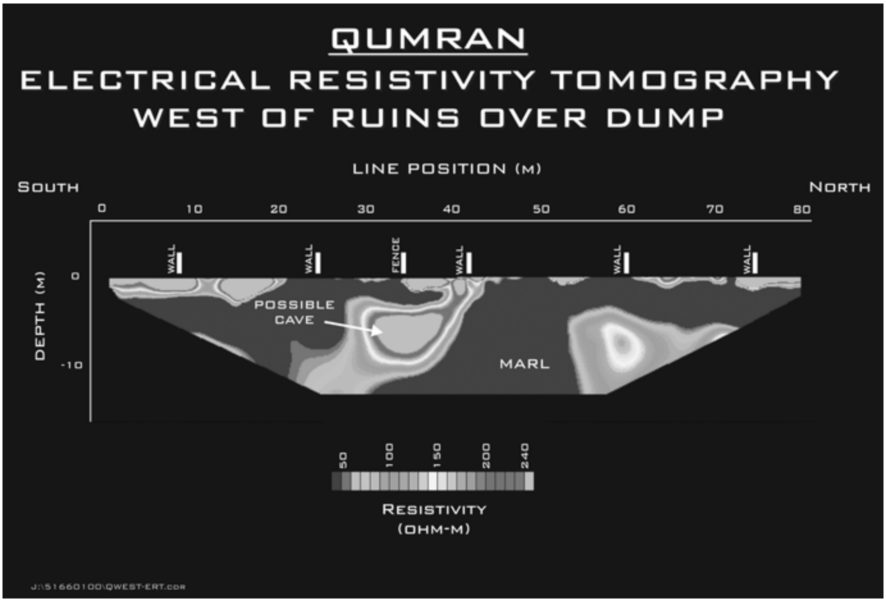

Fig. 8.10 An ERT cross-section from Qumran from near the archaeological ruins to an area called the dump site, with the location of a possible cavity (cave) included, as well as some subsurface geological features

the Augustine Forestry Station, and 8 km north of the Caracol Archaeological Site, the largest archaeological site in Belize (Fig. 8.2). One component of this research was to quantify the physical landscape characteristics of the Northern Vaca Plateau (i.e., limestone petrology, structure, geomorphology, and hydrology) and to relate these parameters to landscape and cave formation and evolution, and the development and evolution of the Maya cultural landscape. A beginning point in this study was a detailed analysis of the area's geology. Specific research regarding the physical landscape in this portion of Belize has not been conducted prior to the onset of our (the Northern Vaca Plateau Geoarchaeology Project) work which began in 1990. The only sources for physical geography and geology information were very general country-wide or regional assessments, citations in publications regarding the Mountain Pine Ridge and Maya Mountain section of Belize, or detailed studies in other areas with similar geologic characteristics.

What follows is a small segment of the research completed on the Vaca Plateau that deals with quantifying the study area's geology. Once a firm understanding of the area's geology was obtained, an additional study was completed that assessed the petrology of the building stones used at Ix Chel, and the relationship between these stones and rocks from suspected quarry sites in the area.

The petrology of 25 samples collected from outcrops in the study area was analyzed. Twenty-one samples were classified as breccias, and four were classified as non-breccias. Using Pettijohn's (1975) system, the breccias were classified into

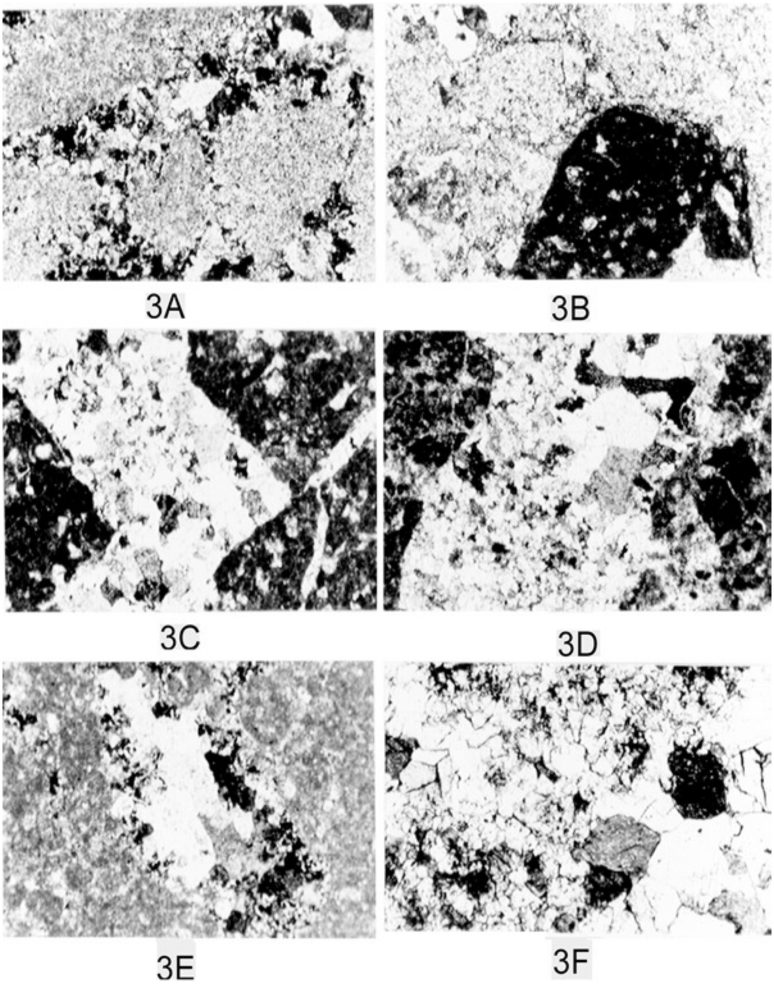

Fig. 8.11 Thin sections depicting six different types of rocks found on the Vaca Plateau in Belize

four types: (1) 12 samples were micrite clasts dominate, sparite cement (Fig. 8.11a); (2) 3 samples of sparite clasts dominate, sparite cement (Fig. 8.11b); (3) 3 samples were fossiliferous micrite clasts dominate, sparite cement (Fig. 8.11c); and (4) 3 samples of pelletic micrite clasts dominate, sparite cement (Fig. 8.11d). The non-breccias were classified as follows: (1) 2 samples of micrite dominates with some pellets (Fig. 8.11e); and (2) 2 samples were sparite (Fig. 8.11f). The four breccia types were further classified using Blount and Moore's (1969) system, which is based upon the origin of the breccias as determined from field relationships, stratigraphy, and petrographic analysis. All 21 breccia samples are lithoclastic (reworked fragments of an older lithified limestone). They consist primarily of pre-existing limestone fragments with some samples containing rudistid (a bivalve mollusk) fossil fragments and/or pellets (probably mollusk feces). The clasts are considered lithoclasts, rather than intraclasts (penecontemporaneous, usually weakly consolidated carbonate sediment that eroded from adjoining parts of the sea floor) (Folk 1962), because the lithoclastic interval is over 200 m, based upon the elevation difference between breccias found deep in vertical caves and on the highest hilltops.

In 12 samples, micrite clasts dominate and the matrix is sparite. The lithology of the lithoclasts is similar to non-lithoclastic limestones from the same formation, indicating they are intraformational (from the same geologic formation). Based upon these characteristics, and criteria outlined by Blount and Moore (1969), these samples are designated depositional breccias. In three other breccia samples, sparite clasts are embedded in a secondary matrix of sparry calcite cement and these specimens were classified as tectonic breccias (Blount and Moore 1969). In three samples, fossiliferous micrite clasts dominate within a sparite cement. The fossils appear to be broken rudistid fragments and the lithoclasts are intraformational. These specimens were classified as depositional breccias as well. In three samples, pelletic micrite fragments are cemented by sparite, and these specimens were classified as depositional breccias. Two samples classified as non-breccias are probably homogeneous fragments of the breccia. Two other samples were composed entirely of sparite. Based upon their homogeneous carbonate mineral composition, they were classified as non-breccias, but they are probably directly related to area breccia formation.

The analysis of these samples assisted in establishing a basic understand of the geology of the study area. Equipped with this knowledge, an assessment of the nature and source of the building stones used in the construction of Ix Chel was completed. The Ix Chel site is comprises three distinct groups, namely the main plaza (Group A), a possible palace complex (Group B), and the acropolis (Group C) (Fig. 8.12). These groups extend roughly along a north–south axis. In the periphery of Ix Chel, agricultural terraces, too numerous to be mapped, were observed. At present, only a relative chronology for Ix Chel exists, and absolute dating remains difficult. Collected surface ceramics suggest a Late Classic occupation, as do the many caves that have been investigated thus far. Because these caves lie relatively close to Ix Chel, they may have been used by Ix Chel's inhabitants as ritual places.

Thirty-two rock samples were collected with these samples coming from the surface of ruined buildings at the site, suspected quarry sites, and area outcrops. The purpose of this inquiry was to determine similarities and differences between stones used to face the buildings at Ix Chel (Fig. 8.13) and area rocks from outcrops and suspected quarry sites. The analysis of the samples was blind, in that they were collected in the field and thin sections were prepared from the collected samples, and sample id numbers were coded to thin section id numbers; however, this information was not made available to the researchers completing the analysis. Hence, it was unknown to these researchers which samples were from building stones, which were from quarry sites and which were from outcrops. In this way, any bias introduced because of prior knowledge was kept at a minimum.

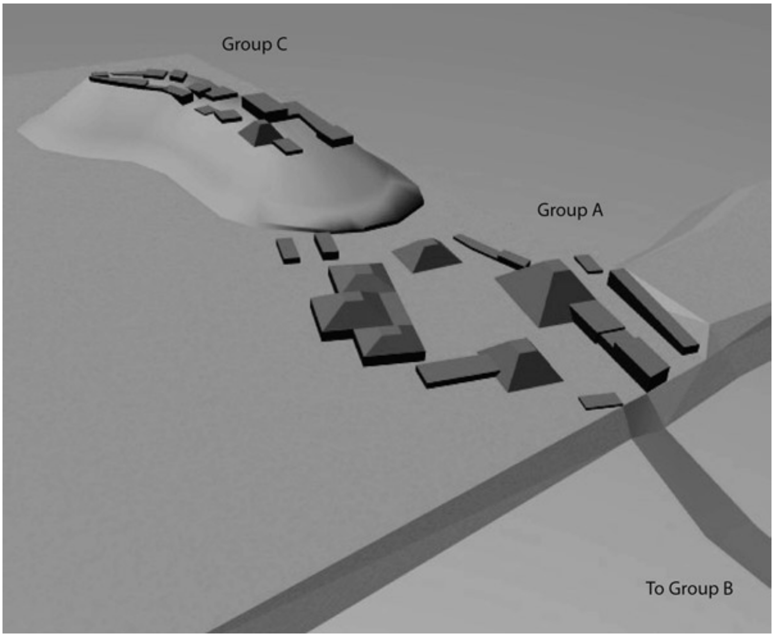

Fig. 8.12 A map of the Ix Chel Archaeological site on the Vaca Plateau in Belize

Fig. 8.13 A quarried and shaped building stone from the Ix Chel Archaeological Site in Belize

Samples	Similarities
1, 2, 3, 6, 10, 19, 30	Classified as Fossiliferous Micrite, Pelletiferous Micrite, or contained fossils or pelletal remains
11, 27, 31, 32	Classified as Biosparites, and contained >40% Sparite/Microsparite;
11, 15, 27, 28, 29, 30, 31, 32	Conglomerates
1, 2, 7, 8, 9, 10, 13, 14, 19-21, 24-27, 29-32	Porous Samples
2, 7, 8, 10, 13, 14, 16, 17, 19, 21, 22, 23	Non-Conglomerates with >3% Sparite/Micrite
1, 3-7, 9, 12-14, 16-26	Building Stones

Fig. 8.14 Determinations based upon the analysis of thin sections with respect to the relationship between know building stones and other rock samples collected in the study area

Analysis of the sample thin sections determined whether they were breccia or non-breccia (Pettijohn 1975), and non-breccias samples were further analyzed (Folk 1962), and breccia samples were described using criteria outlined by Blount and Moore (1969). The brecciated rocks in the area are not used as stones to face the exterior of buildings at Ix Chel. The buildings are faced with softer, more easily formed and shaped stones. The various samples (building stones versus suspected quarry versus area outcrops) were compared to determine if they were petrographically similar.

Samples were analyzed by clast and matrix, and the calcite crystals were determined based on their measurement and translucence. Using criteria outlined by Folk (1962), the samples were classified in terms of lithology for the clasts, and matrix for the breccia's cement. Examination of the thin sections revealed that of the 32 samples, 22 (68%) were micrites, although 21 of these samples contained some microsparite and sparite clasts. Two of the samples were classified as fossiliferous micrite (6.25%), while three were pelletiferous micrites (9.4%). In four samples all clasts were sparite (12.5%).

Based on the modal percentages, and clast angularity, the samples were divided into three catagories: Building stones, non-building stones, and conglomerates. Figure 8.14 provides the summation of which samples originate from what source. From a mineralogical standpoint, several of the non-conglomerates had >3% sparite/microsparite, which may be indicative of the same source, or may include samples near the transition zone in the rock outcrop between the conglomerate/breccias common in the area, and limestone (probably secondary depositional deposits) used for building stones. Of the non-conglomarates, samples 2, 8, and 10 were brecciated on a portion of the sample. Based on the brecciation in those samples and in the samples classified as conglomerates, the following were probably non-building stones: 2, 8, 10, 11, 15, 27, 28, 29, 30, 31, and 32. Of these, the following are conglomerates: 11, 15, and 27–32. Thus, samples 1, 3–7, 9, 12–14, and 16–26 are likely to be building stones (Fig. 8.14).

The building stones were collected directly from ruined structures in and around Ix Chel, and they were obviously shaped for their function. Quarry site 1 is located behind the B Group at Ix Chel and it is an outcropping of rock that is obviously different than most of the breccias/conglomerate rocks that outcrop in the area. The outcrop also appears to be extensively modified, possibly by quarrying. This rock is much softer, and more porous. Samples 29 and 30 were collected from this suspected quarried area, but at points where the softer, more porous rocks transition to the harder breccias. Samples 31 and 32 were collected from a site near Ix Chel that appeared to have been modified (excavated), but the rocks were brecciated. Below is the list of samples and where they were collected.

Building stones: 1, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26,
Quarry Site 1 (Soft Rock): 8, 9, 10
Quarry Site 1 (near transition to Breccia): 11, 29, 30
Quarry Site 2: 31, 32

If the list above is compared to the determinations for sample source in Fig. 8.14, the determination for building stones, based on modal percentages and clast angularity, matches precisely with the list of collected building stone samples. One of the soft Quarry Site 1 samples (#9) was classified as a building stone, and samples 8 and 10 were classified as non-conglomerates with >3% sparite/micrite. The other suspected quarry samples were classified as conglomerates (although they were more porous than the normal conglomerates in the study area) and showed very little similarity to the building stones or other suspected quarry sites. Although not exactly similar to the building stones collected at Ix Chel, samples 8, 9, and 10 from the suspected quarry were similar enough to conclude that they could have been carved into building stones and they were similar enough to have been from the same source as the building stones at Ix Chel. Although the volume of material that appeared to have been removed from suspected quarry site # 1 was substantial, it was not near the volume that was required to construct the buildings at Ix Chel. Therefore, the suspected quarry site was a source for building materials for Ix Chel, but other sources must exist as well, and these sources have yet to be determined.

8.5 Conclusions

The multidisciplinary framework of geoarchaeology allows the full range of related disciplines such as geography, geology, archaeology, and religious studies (and when working in karst areas speleology) to be melded and applied to pursue new avenues of research and add to existing bases of knowledge. Understanding the cultural implications of physical data within a multidisciplinary framework were major components of the research discussed in this chapter. Such an approach enhances the understanding of the intrinsic relationships that exist between physical and cultural landscapes, and in some cases the utilization and exploitation of natural resources in these areas. It was the intent of this chapter to take previous studies conducted in Israel at Cave of Letters and Qumran, and in Belize at the Ix Chel

Archaeological Site on the Vaca Plateau, and stress the utility and importance of conducting karst-based, multidisciplinary research within the framework of the emerging discipline of Geoarchaeology.

The 1999 and 2000 John and Carol Merrill Cave of Letters Projects, and the 2001 and 2002 John and Carol Merrill Qumran Excavations Projects have added to the base of knowledge about both of these important locations, with the completion of detailed and accurate maps depicting multiple aspects of the site. These maps not only detail the spatial and temporal relationships at the sites, but the relationships between the physical landscape and the cultural landscape are highlighted. The use of geophysical applications also played a prominent role in this research. Ground penetrating radar at COL indicated the location and depth of the Bar Kokhba habitation surface, as did ERT, which aided in pinpointing the most advantageous locations for excavation. At Qumran, these technologies proved useful as well, indicating the possible locations of burials that have no surface expression and pinpointing a location where eight buried jars were discovered. GPR also indicated an area of disturbance that may be the location of the latrines for the city. ERT discovered new cavities beneath the Qumran site, and provided important information about the nature of the subsurface geologic materials in the area. Working within the multidisciplinary framework of geoarchaeology, we were able to apply various aspects of the geosciences to interpret past processes and events at the Cave of Letters and Qumran, providing new insights into the physical and cultural landscapes of these locations.

The same can be said for the research conducted in Belize. Analysis of lithologic and geomorphic features within the 25 km^2 study area revealed that the karst landscape is greatly influenced by the lithology and structure of the bedrock. The majority of limestone in the study area formed adjacent to a structurally emergent area, as a depositional breccia consisting mostly of lithoclasts of micrite with a sparry calcite cement. Variations in composition of the lithoclasts reflect local variations in the depositional environment. Geologic structures including faults, joints, and fractures formed during periods of uplift in and adjacent to the study area. These periods of uplift account for the existence of some tectonic breccias in the study area. By studying the petrology of the area and related features, it was possible to gain a limited understanding of the formation and evolution of the northern Vaca Plateau's karst landscape. It also aided in understanding the relationships that exist between the physical landscape and the cultural landscape developed by the ancient Maya. They were very much guided by the nature of the physical landscape in their daily lives, be it ritual activities in caves, extensive terracing of the poor quality, clay rich soils that exist on the karst landscape, or the source of the building materials used to built their cities. A study of the building stones at Ix Chel, and comparison to the rocks at a nearby suspected quarry site, indicated that some of the building materials did indeed come from very near Ix Chel. However, it also indicated that there was another, yet unknown source, which leaves yet another avenue for future research to be added to the already extensive list.

Karst research has drawn from the basic paradigms of many disciplines (e.g., geography, geology, biology, geochemistry, geomorphology, geophysics, hydrology), which were often amalgamated under the zeitgeist of a “karst-based” research project. This is still the case, but the scope has been furthered broadened to include other disciplines and sub-disciplines such as history, anthropology, archaeology, human ecology, climate and paleoclimate, environment and paleoenvironment, and resource conservation and management. Karst-based research needs to continue this evolution, for it only makes it a more viable pursuit in the quest for new knowledge and understanding.

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Chapter 9
Management of Subterranean Fauna in Karst*

Daniel W. Fong

Abstract Ensuring the appropriate quantity and quality of energy flow from the surface to the subterranean environment is a universal challenge of managing subterranean fauna in karst. This chapter covers four major issues central to an understanding of the energy connections between the surface and the subsurface ecosystems. The first issue is that there needs to be a greater focus on species that are not restricted to subterranean habitats because some of these species act as major vectors of energy into subsurface ecosystems. The second issue is that a greater understanding of the paths of allochthonous energy into the subterranean ecosystem is necessary to ensure the long-term health of the subterranean fauna. Percolating water delivered from the epikarst appears to be more important than organic matter transported by sinking streams in supporting the biofilm that serves as the base of the aquatic food web. Energy transported by active movement of organisms from the surface is essential in supporting the terrestrial food web and possibly some aquatic species as well. The importance of many potential sources of energy, such as the organic matter left on the riparian zones of subterranean streams, has not been studied. The third issue is that management practices need to focus on factors that threaten the energy flow from the surface to the subsurface because, unlike many other threats to subterranean ecosystems, disruptions of such paths of energy are usually not overt and easily recognizable. The fourth issue is that the metabolic adaptation of many subterranean species to the underground environment may increase their resilience to disruptions of energy flow from the surface. Thus, management practices that recognize threats to such energy paths may allow for a higher probability of successful interventions leading to restoration of the health of subterranean ecosystems.

* "When we try to pick out anything by itself, we find it hitched to everything else in the universe" – John Muir

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9.1 Introduction

Globally, there is growing awareness of a need for protection of organisms dwelling in subterranean habitats in karst regions. Subterranean organisms appear to be especially at risk because most species exhibit a suite of characteristics that increase their vulnerability to anthropogenic disturbance. These characteristics include limited geographic range (Barr and Holsinger 1985; Christman et al. 2005), poor vagility (Verovnik et al. 2004; Hoslinger 2005) and low reproductive potential, long life span and small population size (Culver et al. 1995). These life history characteristics are excellent adaptations to the subterranean environment, but they also lead to a slow population growth rate, and, in concert with the high degree of endemism and low dispersal ability, greatly reduce the ability of these organisms to rapidly recover from a reduction in population size for any reason. The vulnerability of the subterranean fauna is underscored by the fact that, a decade ago, over 20 subterranean invertebrate species were listed as federally threatened or endangered and about 600 were listed as critically imperiled in the United States alone (Culver et al. 2000), and the numbers are likely much higher now.

The identification of subterranean species at risk and the development of effective strategies for their management face a set of unique challenges. First, most of the physical space in the subterranean environment is too small to be accessible to humans. Cave passages, wells and even submerged caverns represent only small windows into vast expanses of unreachable space. Basic information on the ecology and life history of most subterranean species are unknown because gaining entry to their habitats is often technically challenging and because their lengthy life span and low population density render ecological studies difficult. Aquatic subterranean species pose additional problems because of conflict between management practices and demand for ground water from expanding urban and agricultural development, and these problems are especially acute in karst regions.

A large number of human activities pose threats to the subterranean fauna (Culver and Pipan 2009; Romero 2009; Tercafs 2001). It is impossible to provide an in-depth discussion on managing subterranean fauna in karst areas to deal with all threats in one chapter in a collected volume. Instead, this chapter stresses the importance of surface-subsurface connections and develops the central theme that ensuring the appropriate quantity and quality of energy flow from the surface to the subterranean environment is a universal challenge of managing subterranean fauna in karst. This is the general conclusion drawn by many researchers who have examined this issue (Elliott 2000; Hamilton-Smith and Eberhard 2000; Humphreys 2000; Tercafs 2001; Culver and Pipan 2009). Although this volume and chapter focus on karst, subterranean fauna also exist in nonkarst habitats, especially habitats associated with groundwater such as wetlands and the hyporheic zone (Hancock and Boulton 2008; Humphreys 2009; Hahn 2009). The importance of surface-subsurface connections in terms of energy flow discussed in this chapter should apply in general to these nonkarst habitats as well, although the specific details may be more complicated in nonkarst habitats (Gibert and Culver 2009).

This chapter begins with the example of Robber Baron Cave and the management issues that arise, focusing on the path of energy from the surface to the underground. It then details the different ways that energy is transferred from the surface to the subterranean ecosystems, following the theme that a thorough understanding of the connections between the surface and the subterranean environments in terms of energy flow is the key to effective management and protection of the subterranean fauna. The chapter concludes with a discussion on management of the subterranean fauna in light of the different paths of energy flow from the surface to the underground.

9.2 The Case of Robber Baron Cave

Robber Baron Cave is located in the City of San Antonio in the State of Texas, USA (Veni 1988). It was a commercialized show cave, drawing 300,000 visitors from 1926 to 1933. The owner had even physically modified the cave by erecting false cave walls to hide some passages from tourists. Because of its urban location, the cave has experienced much vandalism and associated human activities. A gate installed at the entrance was frequently tampered with and had to be replaced periodically, at times requiring physical rearrangement of the entrance area with heavy machinery. In spite of such intense anthropogenic impact, the cave still boasts a rich fauna. It houses at least ten troglobionts, species that occur only in subterranean habitats and are never found above ground. Two of the species, the Robber Baron Cave Spider, *Cicurina baronia* (Fig. 9.1), and the Robber Baron Cave Harvestman, *Texella cokendolpheri*, exist only in this one cave, and both are listed as federally endangered by the US Fish and Wildlife Service. A number of other species that are not troglobionts are also found in the cave. Some are occasional visitors but many are residents that move between the cave and the surface on a seasonal or daily basis, such as the cave cricket *Ceuthophilus secretus* (Fig. 9.2). Robber Baron Cave has been protected and managed according to a management plan since it was acquired by the Texas Cave Management Association in 1995. However, many populations of its fauna still appear to be in decline since. The cause was encroachment by urban development toward the cave entrance, which severely limited the foraging area of the cave crickets when they left the cave at night to feed on the surface (Taylor et al. 2005). Consequently, the amount of energy the crickets brought back to the cave, in the forms of guano, eggs and newly hatched nymphs when they reproduced and biomass when they died, was insufficient to sustain the food web within the cave.

The situation at Robber Baron Cave illustrates some of the major issues in the management of subterranean fauna in karst areas. The first issue concerns the meaning of subterranean fauna itself in light of a historically biased research and management focus on only a subset of the subterranean fauna. The second issue concerns the importance of energy flow from the surface to subterranean ecosystems, the central theme of this chapter. The third issue concerns the apparency of different

Fig. 9.1 A *Cicurina* cave spider, displaying the troglomorphic features of reductions in eyes and in body pigmentation as well as elongated appendages. Photograph by Dr. Jean Krejca, Zara Environmental LLC. Used with permission

Fig. 9.2 The cave cricket *Ceuthophilus secretus*. Photograph by Dr. Jean Krejca, Zara Environmental LLC. Used with permission

types of threats to the subterranean fauna and that threats to the paths of energy flow to the underground are usually less apparent than other threats, such as those that directly affect the physical integrity of the subterranean habitats. The last issue illustrated by Robber Baron Cave is the potential resiliency of the subterranean fauna to disruptions of energy flow from the surface because of the metabolic adaptations of many subterranean species. These issues are discussed in turn below.

9.2.1 The Subterranean Fauna

In general, when considering subterranean fauna, most often species that are not adapted exclusively for the subterranean environment come to mind. These adaptations include a suite of features termed troglomorphy by Christiansen (1962), including reduced-to-complete loss of eyes and body pigment, elaborated extra-optic sensory structures, elongated appendages and more slender body forms compared to related surface-dwelling taxa. The endangered harvestman and spider in Robber Baron Cave both exhibit this classic troglomorphic phenotype. Research on and management practices concerning subterranean fauna have and are mainly focused on troglomorphic troglobionts. Less emphasis is placed on non-troglomorphic troglobionts, such as *Spelobia tenebrarum*, a small fly found only in caves over a wide geographic area but exhibits no obvious troglomorphic feature. Other than bats, and, more recently, cave crickets, species that are not troglobionts, ones that also occur in but are not limited to subterranean habitats, have received the least attention. This bias is understandable in light of our long history of fascination with the often bizarre appearance of troglomorphic species, such as the European Cave Salamander, *Proteus anguinus* (Sweet 1986), and the tremendous academic interest in elucidating the mechanisms of the evolution of troglomorphy, dating back to Darwin (Culver et al. 1995; Culver and Wilkens 2000; Culver and Pipan 2009). In addition, the study of troglomorphy may also provide information on the mechanisms of evolutionary loss of features in general, a common phenomenon not exclusive to members of the subterranean fauna; the loss of hearing in moths on islands without bats is just one of many examples (Fong et al. 1995).

The lack of emphasis on non-troglomorphic species in the study and management of subterranean fauna may also partially follow from the tradition of ecological classification of the subterranean fauna into troglobites: obligate cave-dwelling species, troglophiles: facultative-cave dwelling species and trogloxenes: surface species that are occasionally found in caves. According to this scheme, troglobites, rather than troglophiles and trogloxenes, are the more interesting species, with the mindset that trogloxenes and troglophiles are merely troglobites in training and have not yet arrived at their destinations on their evolutionary paths. But as Culver (1982) pointed out, many troglophilic species are very successful in caves, and that many species are often assigned to one of these ecological categories based on morphology instead of ecology, circular reasoning at its most basic. Furthermore, inherent in these designations is that evolution of subterranean organisms is a linear process, from trogloxene to troglophile to troglobite. However, adaptations to the subterranean environment surely follow multiple paths, with different species evolving different solutions at any one moment, thus what are designated as troglophiles or even some trogloxenes are no more but certainly no less adapted to the subterranean environment than are troglobites; some troglophiles may evolve into troglobites but many may not. Even entire subterranean communities without a troglobitic species may be severely constrained by the subterranean environment (Gunn et al. 2000). The utility of these designations is in doubt (Sket 2008), and they are not used further in this chapter.

The lack of emphasis on non-troglomorphic species may also result from inadequate resource for species identification. Colonization of, and adaptation to, subterranean habitats by surface species are continuous, ongoing processes. Therefore, at any time, the subterranean fauna must consist of a variety of species, many that have successfully adapted to the subterranean environment in different ways but also many more that are recent arrivals. Therefore, the subterranean fauna consists of many more species that are not troglomorphic or are not troglobionts, or both, than species that are troglomorphic troglobionts. Thus identification of both troglomorphic and non-troglomorphic species from any subterranean ecosystem would require a greater commitment of time by more taxonomic specialists than identification of only the troglomorphic species. In addition, troglomorphic species generally exhibit high degrees of endemism (Culver and Pipan 2009). Troglomorphic specimens from different subterranean systems are more likely to constitute new taxa than non-troglomorphic specimens and may enjoy a higher priority for identification by taxonomic specialists. Constraints in money and time are real impediments to a full description of the entire fauna in a subterranean ecosystem. For example, in a 3-year survey of the invertebrate cave fauna of West Virginia, Fong et al. (1994) documented only troglobionts, most of them troglomorphic, because it would have been too expensive and too time consuming to obtain complete taxonomic information on all the species collected.

The lack of emphasis on non-troglomorphic species is unfortunate. Although the traditional view of the pinnacle of adaptation to the subterranean environment is that of troglomorphic species, such as the Robber Baron Cave Spider, many more non-troglomorphic species are also well adapted to this environment and are integral components of subterranean ecosystems. Some of these non-troglomorphic species, such as the cave cricket in Robber Baron Cave, are keystone species that play a critical role in supporting the entire subterranean fauna, including the endangered troglomorphic spider and harvestman, and they do so by serving as biological vectors bringing energy from the surface, or allochthonous energy, into the subterranean ecosystem. Indeed, most of the troglomorphic taxa are effectively energy sinks, while many non-troglobionts, by serving as vectors of allochthonous energy, are effectively proximate energy sources of subterranean ecosystems. Therefore, management practices need to consider all of the taxa in addition to the troglomorphic species and especially their ecological roles in the subterranean ecosystem.

9.2.2 The Importance of Allochthonous Energy

The hallmark feature of the subterranean environment is constant darkness and thus the absence of primary production through photosynthesis. In most underground ecosystems, the base of the food web depends on input of allochthonous energy derived ultimately from photosynthesis on the surface. There simply is no other source of energy for the fauna in subterranean ecosystems except for systems based on chemoautotrophy (see below). As the situation at Robber Baron Cave illustrates, protecting the subterranean fauna requires management practices that maintain the ecological integrity of not only the subterranean system itself but also that of the surface terrane, which is the ultimate source of energy, as well as that of the natural paths of energy flow from the surface into the subterranean system. Management of energy flow in situations similar to that of Robber Baron Cave means ensuring sufficient energy input into the cave to support the underground trophic structure by biological vectors, such as the cave cricket, and by other means.

Management of energy flow also means preventing excessive energy input, particularly in the form of organic pollution. This problem is especially acute in karst areas experiencing heightened intensity of agricultural activity or housing and industrial development. Pollutants, both organic and inorganic, may be toxic by themselves or may alter the chemistry of the subterranean environment so as to pose a direct threat to the fauna (Pasquarell and Boyer 1993; Elliott 2000). For example, Culver et al. (1992) documented the near extirpation of one of only four known populations of an endangered troglomorphic aquatic isopod crustacean, *Lirceus usdagalun*, due to illegal dumping of sawdust into a cave entrance sinkhole in Virginia, USA. Organic pollution may also indirectly affect the cave fauna through excessive nutrient enrichment of the subterranean habitat, which then promotes invasion by surface species that may out-compete and displace resident species (Sket 1999). Of course, such point sources of organic pollution are easier to identify than the nonpoint sources, such as the slow accumulation of pesticides and fertilizers from agriculture runoff that then drain into subterranean systems.

Another form of excessive energy input, affecting mainly caves developed for commercial tourism, is from lighting used to illuminate passages and especially rock formations. Prolonged illumination promotes growth of a lampenflora, plants and algae associated with electrical lighting (Aley 2004). Development of a lampenflora destroys the aesthetic value of the cave itself at best and may enable establishment of invasive surface species and subsequent displacement of the native cave fauna at worst. In large systems where commercialized trails comprise a small percentage of the total passages, lampenflora may not be a major issue, but even then, affected passages are known to have fewer cave species compared to unaffected passages (Culver and Pipan 2009). In small systems, lampenflora may, in concert with other effects of physical alteration of the passages for and from tourism, have a large adverse effect on the cave fauna. Installation of low wattage lighting of appropriate spectra may address this issue but requires a large initial monetary investment.

Frequently, one management practice to protect a subterranean system and its fauna is gating cave entrances to minimize human activity. The assumption is that human activity inside a cave will have a negative impact on the cave fauna. However, Robber Baron Cave still harbors a diverse cave fauna in spite of a long history of high- impact human visitation. The fauna in Robber Baron Cave was in decline because of curtailment of energy flow into the cave due to urban development on the surface, not because of disturbance from human visitation inside the cave. A cave gate is effective in curbing incidences of vandalism, theft of speleothems and outright malicious attacks on large aggregations of animals such as roosts of bats (Elliott 2000). A cave gate is also an attractive management tool because the gate is a visible, physical evidence that something has been done. It is becoming clear, however, that gating a cave by itself is not an effective tool to protect the fauna in the cave, especially the invertebrates. The design of cave gates has evolved from early ones that actually hindered to modern ones that allow for the movement of vectors of allochthonous energy, such as bats and other small mammals as well as crickets and other insects, between the surface environments and the caves (Elliott 2000). However, as the scenario at Robber Baron Cave shows, if the integrity of the surface ecosystem is compromised and its ability to generate and provide allochthonous energy to support the subterranean ecosystem is diminished, even a perfectly designed gate is ineffective in protecting the community of organisms in the cave. Thus, a thorough understanding of the connections between the surface and the subterranean environments in terms of energy flow is one crucial key to effective management and protection of the fauna.

In some subterranean systems, the trophic structure is supported by energy produced within the system from chemoautotrophy and is independent of allochthonous energy derived from photosynthesis. The best documented type of chemoautotrophy is based on the oxidation of hydrogen sulfide, such as in Moville Cave in Romania (Sarbu et al. 1996), which supports a large number of troglomorphic species. Engel (2007) detailed other such chemoautotrophic subterranean systems. The two types of energy sources are not mutually exclusive. For example, Grotta di Frasassi in Italy shows two distinct food webs, one based on allochthonous energy input in the form of bat guano and the other based on energy from chemoautotrophy (Sarbu et al. 2000). Chemoautotrophic systems are largely driven by microbial activity. The topic of management of the subterranean microbial fauna and flora in karst is discussed elsewhere in this volume.

9.2.3 Apparency of Threats

A host of human activities unrelated to the energy base of the subterranean ecosystem in karst areas also affect the underground fauna. Much of these activities causes physical disturbance of the karst terrane. Examples include limestone quarrying, flooding of cave systems as a result of water impoundment behind dams, mining of groundwater aquifers and road building, among others. These activities have severe consequences for the subterranean fauna because they physically alter the landform at best and can completely obliterate a cave system at worst. The relative intensity and impact of these activities differ in different locations. For example, on a global scale, limestone quarrying is growing at the highest rate in Southeast Asia (Clements et al. 2006). This region is considered a biodiversity hotspot for both surface and subterranean fauna and flora, because the limestone karst in the area is relatively untouched by other human activities and the fragmented nature of the karst terrane in the region promotes endemism. Quarrying activities there have probably resulted in extirpation of numerous species before the species were discovered (Culver and Pipan 2009). Quarrying activities also threaten the cave fauna in much of Australia, especially the Cape Range (Hamilton-Smith and Eberhard 2000; Humphreys 2004), but it is of concern in only some parts of the U.S. (Dasher 2001; Jones et al. 2003). There are many additional threats to the subterranean fauna. Tercafs (2001) gave a detailed discussion of a long list of potential threats to the subterranean ecosystems and the subterranean fauna. Some of the issues raised are especially intractable. For example, Culver and Pipan (2009) reasonably suggested that global warming is a universal threat to subterranean fauna.

Effects of such human activities that pose direct physical threats to subterranean systems and the activities themselves have high apparency because they are usually overt, visible and some may even be well understood. Likewise, point sources of pollution can be identified. This is not to minimize the complex issue of managing karst resources and the subterranean fauna in face of such overt threats. Local, regional and national laws protecting karst resources, especially caves and associated fauna with threatened or endangered status, exist in many parts of the world. Application and enforcement of such laws, however, are often tempered by social and economic realities at the local scale. But clearly all these threats have high apparency, and at the emotional level, at least, people are motivated to action for protecting a subterranean system or its fauna or both when the threats are identifiable and apparent. A good example is recounted by Elliott (2000), who led a 3-month project in 1976 to relocate all 30 species of the entire fauna along with as much cave soil, rocks and woody debris as could be carried from a cave to a nearby abandoned mine because the cave was to be completely inundated from rising water behind a newly constructed dam, and the cave was one of the only two known sites at the time of the rare cave harvestman, *Banksula melones*.

In contrast, how allochthonous energy is made available and delivered to the subterranean fauna is generally not immediately obvious, and disruptions to the delivery of this vital resource to the underground are not readily apparent. As illustrated by the situation at Robber Baron Cave, an understanding of how cave crickets act as the main vector of allochthonous energy revealed the major mechanism by which urban development affected the cave fauna. In this instance, the cause of degradation was not disturbance by increased human visitation or the increased potential of pollution. When the threat has low apparency, such as when cave crickets return less and consistently less energy to Robber Baron Cave as their foraging area becomes smaller and smaller, it may be difficult to understand the issue at hand to begin with, and once it is understood, it may be difficult to garner support to address the problem than when the threats are highly apparent. This is understandable, because in the first case, support means well-defined action, such as helping to stop quarrying activity toward a certain direction or to reroute a road being built or even to relocate an entire fauna of a cave, but in the second case, it is unclear what support means in terms of specific action for each potential supporter involved. One inherent challenge to management practices for protecting subterranean fauna is first to recognize such threats with low apparency and then to motivate public support to deal with such threats.

9.2.4 Potential Resilience of the Subterranean Fauna

Although not universal, many subterranean species have lower metabolic rates and longer life spans compared to surface counterparts (Huppop 2000), and some may also be adapted to ramp up reproduction during infrequent episodes of increased influx of energy resources (Turquin and Barthelemy 1985). Low metabolic rates and long life spans may allow such species to persist for some period even when the normal paths of energy input have been disrupted or curtailed for a duration. This may be the situation with many of the species in Robber Baron Cave. Encroachment of urban development toward the cave entrance in San Antonio leading to the reduction in energy input from cave crickets has been an ongoing process for a lengthy period, yet the fauna in the cave has persisted, and their persistence may be possible because of this metabolic adaptation. Recognition of this resilience means that recovery of the subterranean fauna is a real possibility, provided that the route of energy input is understood. The documented decline of the fauna in Robber Baron Cave has probably resulted from natural attrition of individuals over time coupled with the lack of recruitment of new individuals from reproduction due to insufficient food. However, now that the critical role of the crickets in this system is understood, increasing the energy flow into the cave by restoring the surface ecosystem to enable expansion of the foraging area of cave crickets should be a long-term management goal. Reversing urban development may even be achievable in light of the number of small dams that have been removed since the severe ecological consequences of such dams are understood and widely publicized. In the meanwhile, management practices that emphasize a gradual increase coupled with periodic jumps in input of energy into the cave system in the future may allow the fauna to recover. Such energy may be artificially augmented, e.g., by establishing protected night time feeding stations for *Ceuthophilus secretus* near the cave entrance.

9.3 Paths of Allochthonous Energy

Allochthonous energy enters subterranean systems via four main paths (Tercafs 2001; Culver and Pipan 2009). The first and most obvious is transport by water. The second is transport by active movement of organisms into caves. Energy also enters via passive input from gravity or by wind. A less common path is by tree roots projecting into cave passages. The relative importance of these paths differs in different regions and for terrestrial and aquatic habitats.

9.3.1 Transport by Water

The most obvious path of energy from the surface to the underground is via water, as dissolution is how caves are created in limestone karst. Water enters subterranean systems via sinking streams or as percolating water infiltrating vertically through the soil. The quantity and the quality of the energy delivered via these two routes differ in significant ways.

9.3.1.1 Sinking Streams

Surface streams usually sink and become part of a karst subterranean drainage at the contacts between water impermeable rock and soluble limestone. Sinking streams vary greatly in size, from intermittent rills to permanent rivers. The volume of water carried by a sinking stream may vary seasonally by several orders of magnitude. In forested, temperate regions, sinking streams can transport underground a large amount of organic matter in the form of leaves, twigs, branches and even entire tree trunks, known as coarse particulate organic matter (CPOM). However, the energy quality of this CPOM input appears very low. Generally, the CPOM is rapidly processed by shredders, such as some crustaceans and larvae of aquatic insect, into fine particulate organic matter (FPOM) and quickly becomes unimportant in the metabolism of the cave stream organisms (Simon and Benfield 2001, 2002). Furthermore, the aquatic subterranean fauna, such as snails and amphipod and isopod crustaceans, actually depends on energy from the biofilm coating rocks and sediment in the cave stream (Simon et al. 2003). The biofilm consists of a variety of microorganisms as well as organic and inorganic particles embedded within a polysaccharide matrix (Boston 2004), and the biofilm is limited by carbon in dissolved organic matter (DOM), not FPOM (Simon et al. 2003). The importance of sinking streams as an allochthonous energy source therefore depends on the quantity of DOM they transport underground. The quantity of DOM in the surface stream is positively correlated with the duration of processing of CPOM and FPOM by biological agents and mechanical breakdown by physical disturbance of the substratum (Allen and Castillo 2007). However, this duration is also positively correlated with the size of the stream and therefore the velocity or scouring power of the water current. Therefore, a larger sinking stream will bring in more DOM to support the biofilm but will cause physical disturbance of the substratum where biofilms are located, while a smaller sinking stream will have little DOM. Thus, in temperate regions, although sinking streams are the source of a large quantity of particulate organic matter in cave streams, the quality of this organic matter is such that they do not constitute an important source of allochthonous energy for subterranean aquatic fauna.

The large quantity of particulate organic matter delivered underground by sinking streams, however, may not be inert for the subterranean ecosystem. Sinking streams frequently deposit CPOM and FPOM on banks of cave streams, and organic matter is quickly colonized by fungi and possibly bacteria. Although these deposits are spatially and temporally highly heterogeneous within a cave system, most cave organisms are adapted to rapidly seek out and utilize ephemeral resources as they become available (Culver and Pipan 2009). In fact, when searching for terrestrial cave invertebrates, speleobiologists commonly focus their attention first on any available leaves and wood debris left behind by flood water if other organic matter such as guano is absent. Whether these deposits of organic matter and their associated fungal or bacterial colonies constitute a significant allochthonous energy base for terrestrial cave organisms such as springtails, millipeds and beetles that patrol the riparian zone is yet to be quantified. Clearly, this resource is utilized by the terrestrial cave fauna. The unanswered question is whether the absence or reduction of this resource will adversely affect the diversity or the carrying capacity, or both, of the terrestrial cave fauna.

Sinking streams also inject more than particulate organic matter into subterranean habitats. It is common, especially after spring thaws and storm events, to find washed into cave streams numerous individuals of the surface aquatic fauna, such as larvae of aquatic insects, especially of mayflies, caddisflies and stoneflies and even some surface vertebrates such as amphibians and fish. Their biomass, when consumed by resident subterranean species immediately as prey or later when they die, certainly represents a spatially and temporally unpredictable energy resource of high quality directly or indirectly through increased microbial activity similar to fungal colonies on particulate organic matter left on cave stream banks. Possibly, some of the subterranean fauna are stimulated to initiate reproduction by such an influx of high-quality energy, but there is no direct evidence to support this. The relative importance of this resource for the diversity and abundance of the aquatic cave fauna has not been quantified.

9.3.1.2 Percolating Water

Precipitation reaching the ground surface and not utilized by plants can move laterally and form streams or lakes, or infiltrate vertically through the soil. Water percolating through the soil will accumulate dissolved material, and more importantly, dissolved organic carbon (DOC) resulting from decay of vegetation and metabolism of soil organisms, as well as microbes and other organic compounds adsorbed onto soil particles. In karst areas, the transition zone between the soil and the underlying limestone is a potentially vast network of minute cavities and channels, termed the epikarst, which can retain a large volume of water (Williams 2008). Epikarst water percolating further downward through fractures in the limestone can intersect cave passages, forming water drips from cave ceilings. The epikarst has a tremendous storage capacity. Thus, it is common to find water dripping from cave ceilings even if the local surface terrane has experienced a prolonged dry period. Indeed, water in the majority of small headwater streams in a subterranean drainage basin likely originates from the epikarst rather than from sinking streams.

Drip water from the epikarst contributes DOC to cave streams (Simon et al. 2007). Although the concentration of DOC in drip water is usually low, it may be the only source of organic carbon available to support the biofilm, which in turn, is the foundation of the aquatic food web in cave streams (Simon et al. 2003). Furthermore, the large number of water drips in cave passages point to the delivery of a potentially vast quantity of DOC over time from the epikarst to cave streams. Epikarst water is potentially a highly significant source of allochthonous energy for the aquatic subterranean fauna, especially at small, upper level headwater cave streams.

Examination of drip water also reveals a diverse assemblage of organisms, including bacteria, small crustaceans, microarthropods and even archaeannelids (Pipan 2005; Pipan and Culver 2005), indicating that the epikarst is the primary habitat for many species and is likely an ecosystem in itself. Fong and Culver (1994) show that in a large subterranean drainage basin, diversity of aquatic crustacean species is highest at smaller, upper-level headwater streams and decreases towards larger, lower-level streams. They attributed the higher diversity of headwater streams in part to a higher rate of influx of epikarst species, because the upper-level headwater streams are closer to the epikarst and because there are more upper-level headwater streams than larger streams in any drainage basin. Recent biological surveys in caves with an emphasis on water of epikarst origin have yielded many new species of copepod and amphipod crustaceans (Fong et al. 2007, Holsinger JR pers. comm.). The scenario is thus one of a constant rain of epikarst water delivering not just DOC but also animals into cave streams. Knapp and Fong (1999) and Fong (2003) examined the temporal variation in the population size of an amphipod crustacean, *Stygobromus emarginatus,* in a headwater cave stream and suggest that movement of organisms between the epikarst and the uppermost reaches of some cave streams is an active, dynamic process in addition to the passive downward rain of animals trapped in ceiling drips. Whether these animals of epikarst origin constitute a significant input of allochthonous energy to cave streams in the form of biomass is unclear. Simon et al. (2007) and Culver and Pipan (2009) conclude that the energy input in terms of numbers of organisms from ceiling drips, consisting mostly of copepod crustaceans of 1 mm or less in body size, is insignificant compared to the quantity of DOC in drips. This conclusion does not take into account the possibility of active movement of potentially large numbers of organisms of large body size, up to 10 mm in body length for *S. emarginatus* in the Knapp and Fong (1999) study, between the epikarst and the cave stream via means other than drips. My experience from collecting live amphipods from cave streams is that *S. emarginatus* must be separated immediately from *Gammarus minus*, another amphipod of about the same body size whose primary habitat is the cave stream, because most specimens of *S. emarginatus* would be quickly eaten by *G. minus* if both are left in the same container. Thus, it is reasonable to assume that *S. emarginatus*, which likely originates from the epikarst, is a high-quality energy source for *G. minus* in the cave stream habitat itself. In general, whether the biomass of organisms of epikarst origin is or is not a significant component of the allochthonous energy input in addition to DOC from the epikarst, the importance of epikarst water as a source of energy for the aquatic cave fauna cannot be overemphasized.

9.3.1.3 Humidity

Although the previous sections emphasize the role of water as a vector of energy into subterranean systems, the presence of water itself is obviously vital to the cave fauna. This is self-evident for the aquatic cave fauna. Many terrestrial cave species show a reduction in the thickness of the cuticle. The interesting question of whether this is an adaptation to the high humidity of caves or an adaptation to metabolic economy or simply a result of relaxed selection is not yet settled. In any case, a thinner cuticle clearly results in increased water permeability and thus a heightened sensitivity to desiccation (Howarth 1980). Some cave beetles in both North America and Europe have elaborated, specialized organs functioning as humidity detectors (Peck 1977; Accordi and Sbordoni 1978), ensuring that they can seek out areas of high humidity and suffer low rate of water loss. Thus, water entering subterranean systems either from sinking streams or the epikarst also serve to maintain a high humidity in cave passages, which is vital to the survival of some, if not most, of the terrestrial cave fauna. Again, it is common experience among speleobiologists that both the diversity and abundance of the terrestrial fauna are lower in drier than in moister cave passages.

9.3.2 Transport by Movement of Animals

A variety of animals actively move in and out of caves from the surface environment. Some are accidental or occasional visitors to caves, such as snakes, raccoons and wood rats, while others migrate between the cave and the surface on a daily or seasonal basis, such as the cave crickets, in Robber Baron Cave, and bats. To different extents, all these animals bring energy resources from surface habitats into caves, but, clearly, bats and crickets are major vectors. The quantity and type of resources brought into caves differ among different groups of organisms.

Guano deposited by animals in caves after foraging outside is a major mechanism of energy delivery. In Mammoth Cave, for example, sources of guano range from animals such as unpredictable raccoons to highly predictable cave crickets, and each type of guano is associated with different specialized communities adapted to differences in ease of physical processing and assimilation of the guano (Poulson 2005).

In addition to guano, another important mechanism of energy delivery into caves by cave crickets is the laying of eggs in caves. As detailed below, some beetles have become specialized cricket egg predators, relying only on cricket eggs during parts of the year.

9.3.2.1 Bats

Many bat species forage outside at night and return to caves during the day, often forming large roosts, both in the tropics and the temperate regions. Many species also form large seasonal aggregations in caves, either as maternity colonies or winter hibernation colonies. The dominant form of resource they produce inside caves is guano. Caves harboring large bat colonies can receive an impressive amount of guano. About 20 million Mexican free-tailed bats, *Tardarida brasiliensis*, deposit 5×10^4 kg of guano per year in Bracken Cave in Texas (Barbour and Davis 1969). Even smaller colonies, such as the 3,000 gray bats, *Myotis grisescens*, forming a maternity colony in Cave Springs Cave in Arkansas produce 9 kg of guano each year (Graening and Brown 2003). The importance of bat guano as a high-quality energy resource for cave invertebrates, especially in the tropics, is underscored by the existence of whole communities specializing in bat guano with complex trophic structures and many species showing different degrees of troglomorphy (Deharveng and Bedos 2000). The importance of bat guano as an energy source for the fauna in a temperate zone cave is illustrated by an inadvertent experiment in Shelta Cave in the City of Huntsville, Alabama, as described by Elliott (2000). The cave harbored a large colony of the gray bat, *M. grisescens*, as well as a rich and abundant aquatic invertebrate fauna including three species of crayfish and a shrimp along with amphipod and isopod crustaceans. Because of potential threats from encroaching urban development, the National Speleological Society bought the property around the cave entrance, and the entrance itself was gated in 1968 to protect the cave and its fauna. Unfortunately, the bats abandoned the cave within 2 years, partially because the gate was ill-designed for transit by bats and because of accelerated urban development, and did not return even after a bat-appropriate gate was installed in 1981. The subsequent demise of the aquatic cave invertebrate fauna was well documented in a series of studies (see Summary in McGregor et al. 1997). It is impossible to tease apart the specific effect of the absence of bats and the diffuse effects of increasing urban development, such as nonpoint source pollution, on the decline of the cave fauna; but the sudden cessation of a once reliable influx of a high-quality energy resource in large quantity in the form of bat guano is very likely a major contributing factor. Recently, Fenolio and Graening (2009) documented a large congregation of the aquatic isopod crustacean *Caecidotea macropropoda* in a cave in Oklahoma. They estimated 10,000–15,000 individuals forming a mat in a pool that was 3 m in diameter and less than 10 cm at the deepest point. The cave has accumulated much guano deposited by a seasonal maternity colony of the gray bat, *M. grisecens*, and the pool bottom was covered with decaying bat guano. They also cited previous work indicating this isopod was extremely abundant back in 1982 in this cave, and that tens of thousands of the cave flatworm, *Dendrocoelopsis americana*, were observed in the same cave in 1950. Clearly, the bat guano in this temperate zone cave has supported highly abundant populations of at least two aquatic troglomorphic species for a long time.

In situations where bat guano is scattered rather than concentrated, no specialized guano community exists and the guano is certainly utilized by the usual cave fauna. The importance of this scattered resource, similar to particulate organic matter on cave stream banks, however, has not been quantified.

Bats, of course, leave more than just guano in caves. Bodies of dead bats and some newborn bats fall onto cave floors, and underneath large bat roosts especially in the tropics, they are quickly consumed by scavengers that are part of the guano communities (Deharveng and Bedos 2000). Where bats do not form concentrated colonies and specialized guano communities are absent, it is assumed that dead bats represent a spatially and temporally unpredictable, high-quality energy resource utilized by the subterranean fauna.

9.3.2.2 Bats and White-Nose Syndrome

Since it was first noticed in early 2006 in a cave in Northern New York, a fungus has devastated winter hibernation colonies of several bat species in the Northeastern U.S. (Blehert et al. 2009) and has subsequently spread to other states. This disease is termed bat white-nose syndrome (WNS) because the white fungus appears most prominently on the noses of infected bats. The fungus is identified as *Geomyces destructans*, a new species genetically related to but is morphologically distinct from other species of the wide-spread genus *Geomyces* (Gargas et al. 2009). Although the origin of WNS is unknown, its effect is dramatic, killing up to 75% of bats in infected sites (Blehert et al. 2009). Appropriately, there are much ongoing research and management concerns targeting WNS. Management practices are focused primarily on monitoring of unaffected sites to detect the spread of WNS, and on prevention of the spread of WNS to new sites via restriction of human traffic, although there is no evidence indicating any new WNS infestation directly resulting from movement of humans (Aley 2010). Management of WNS is reasonably concentrated mainly on bats in caves. However, Aley (2010) indicates that the other members of the cave fauna must not be neglected. Because bats are important vectors bringing in allocththouous energy into caves, the drastic reduction in bat population sizes means that the invertebrate cave fauna in infected caves will probably also suffer from the effects of WNS well into the future. Management of WNS should include practices that recognize the fauna of the entire subterranean ecosystem in addition to the bats. A possible management practice to buffer the invertebrate cave fauna in infected caves may involve artificially supplying energy into these caves in the form of guano harvested from laboratory colonies of small mammalian insectivores such as shrews.

9.3.2.3 Crickets

Large aggregates of cave crickets of the family Rhaphidophoridae are commonly encountered just inside cave entrances, especially during the warmer months, in many parts of the world (Culver and Pipan 2009). They move out at night to forage on the surface under appropriate temperature and humidity conditions and may range up to 100 m from the cave entrance, return before dawn and stay in caves during the day (Taylor et al. 2005; Lavoie et al. 2007). These crickets are omnivorous, feeding on a variety of foods and bring energy resources into subterranean systems in two main forms: guano and eggs. Poulson (1992) shows that cricket guano is the major energy base for many terrestrial cave invertebrates in Mammoth Cave, Kentucky. Cricket guano is likely the critical energy base for the invertebrate community in Robber Baron Cave. In particular, cricket eggs are extremely important resources for a number of cave beetles in the U.S. During the reproductive season, cave crickets insert their eggs with their ovipositors in holes up to 10 mm deep in sandy substrate. Several species of cave beetles, including *Rhadine subterranea* (Mitchell 1968), *Darlingtonea kentuckensis* (Marsh 1968) and *Neaphaenops tellkampfi* (Kane et al. 1975), are specialized predators equipped to dig up the cricket eggs and consume the contents. The importance of eggs of the cave cricket, *Hadenoecus subterraneus*, as an energy source for *N. tellkampfi* is illustrated by the following: Firstly, the average dry weight of a cricket egg, at 2.26 g, is about 67% of the average dry weight of an entire beetle (Studier 1996); secondly, after consuming a single cricket egg, it takes about 50 days for a beetle to return to its prefeeding weight (Griffith and Poulson 1993); lastly, cricket eggs are the only food available to the beetle during the cricket egg-laying season (Kane and Poulson 1976). Without doubt, in this situation, any reduction in egg production by *H. subterraneus* will have a detrimental effect on the abundance of *N. tellkampfi*.

The crickets leave more than just guano and eggs in caves. It is not uncommon to encounter dead crickets covered in fungi within cave passages. Certainly, these are utilized by other cave organisms, although the quantitative importance of this resource to the cave fauna is unknown. In addition, the newly hatched and very young cricket nymphs may be important prey for predators such as cave spiders and adults and larvae of other cave beetle species as well as cricket egg specialists. There is no evidence that any of the subterranean species in Robber Baron Cave specialize on cricket eggs. It is very likely, however, that newly hatched and very young cricket nymphs are important prey for the endangered harvestman and spider in the cave.

9.3.3 Passive Transport by Gravity or Wind

Some openings to subterranean systems, such as open air pits, sinkholes and cave entrances located at the base of steep slopes, can receive large amounts of leaves and other plant material or aerially dispersing arthropods by gravity and wind. Most of this fallout usually accumulates near the openings, but depending on the geometry of the opening, some of this fallout may be blown deep into the subterranean system. There has been little research to quantify or to determine the quality of this potential resource for the terrestrial subterranean fauna. The quality of the plant matter as an energy source will depend on how rapidly it is colonized by fungal and bacterial decomposers, which, for any given temperature, should be positively correlated with the moisture content of the fallout material. In temperate regions with ample precipitation, a high rate of colonization is expected, but the high moisture content and, thus, the tendency to form clumps and the heavy weight of this material should reduce the distance it can be blown further underground. Thus, the delivery of this material deeper into the subterranean system in temperate regions will depend more on actions of other agents, such as flowing water or active movement of organisms that have initially utilized this resource near the opening. In arid regions, this relatively dry and light-weight material may be blown far underground by wind but a low rate of colonization by decomposers and thus low energy quality is expected.

Aerially dispersing arthropods may be a better source of high-quality energy fallout in arid regions. Ashmole and Ashmole (2000) estimated 40 mg in dry weight of arthropods per m^2 per day falling on a volcanic field underlain by a vast expanse of mesocaverns. They suggest that terrestrial species occupying mesocaverns, including many with troglomorphic features, actively forage for such fallout on the surface when physical conditions are favorable, such as lower temperature and thus higher relative humidity during the night than during the day.

Although some animals labeled as accidentals become trapped after having actively moved into caves, many do fall into caves due to real accidents. It is not uncommon to find at the base of vertical cave entrances emaciated but living, decomposing carcasses, and bones of small vertebrates such as frogs and snakes to large ones such as foxes or deer or even cattle. These are temporally unpredictable, high-quality energy resource in large quantity, but there is no published study examining their relative importance in the energy budget of the subterranean fauna.

9.3.3.1 Fallout and Phreatic Habitats

There is indirect evidence supporting the importance of fallout for a population of the cirolanid isopod crustacean, *Antrolana lira*. This species inhabits phreatic waters under the Shenandoah Valley in the Eastern U.S.A. (Holsinger et al. 1994) and may be captured with baited traps placed in wells or in caves with access to the water table. The population sizes are small, with ten or usually fewer individuals captured per sampling attempt at most of the 19 sites where it has been collected, including several sites where only one specimen has ever been collected in spite of repeated sampling attempts (Hutchins and Orndorff 2009; Hutchins et al. 2010). The exception is at Steger's Fissure, where the estimated population size is two to three orders of magnitude higher than at other sites (Fong in prep.). The Steger's Fissure site is also the only site where the water table is open to the surface, with two vertical, 1 m diameter openings at the base of a rock outcrop next to a steep hillside allowing leaves and other organic material to fall in. The surface of the water table is about 5 m below the opening and is usually obscured by a mat of plant material, including tree branches. This isopod seems an opportunistic predator preying on any organism that falls in rather than utilizing the copious amount of plant fallout material. Collins and Holsinger (1981) found remains of insect cuticles in the gut contents of several specimens. Raw shrimp is the usual bait used to trap *A. lira*, and my experience at this site is that two shrimp abdomens, each about 8 cm in length and 2 cm in diameter, may attract about 200–300 specimens, and the bait pieces are usually completely consumed after 2 h. There is no other prey for *A. lira* as it coexists in this system with only one other crustacean, the amphipod *Stygobromus stegerorum*, which is only 3 mm in length compared to up to 15 mm for *A. lira*. The large population size of *A. lira* at this site, and only at this site, is probably a result of occasional fallout of high-quality energy resource in the form of surface organisms, effectively raising the carrying capacity at this site by orders of magnitude compared to other sites where fallout is absent. Because phreatic waters are extremely nutrient-poor (Culver and Pipan 2009), fallout, when available, may be a critical source of energy for organisms inhabiting this habitat.

9.3.4 Tree Roots

Tree roots commonly penetrate into shallow caves, usually in the form of long strands of aerial roots hanging from cave ceilings. Condensation forming on the roots from the highly humid cave air is a source of water for the trees, and this is especially important in arid regions. In some situations, such as lava tube caves, tree roots are the only stable source of high-quality energy for cave organisms (Howarth 1983). A variety of cave invertebrate specialists feeding on these aerial roots, including planthoppers, terrestrial isopods and even a moth have been described from lava tube caves in Hawaii, the Cape Verde Islands and the Canary Islands (Howarth 1972; Oromi and Martin 1992; Hoch et al. 1999). These specialists are in turn preyed upon by other cave organisms. Thus tree roots form the critical energy base supporting a whole ecosystem of diverse organisms in many lava tube caves (Stone et al. 2005).

In some shallow caves in parts of Australia, with low air humidity and little soil moisture, cave streams are an important source of water for some trees. Aquatic roots of these trees penetrate into the cave stream, forming dense, compact mats of fine rootlets. A diverse assemblage of organisms depend on the energy supplied by these root mats, including amphipods, isopods, leeches, and even fish (Jasinska and Knott 2000). Root mat communities generally support more species with higher abundances than communities based on aerial roots (Jasinska et al. 1996).

9.4 Conclusions

It is unsurprising that, except for those based on chemoautotrophy, subterranean ecosystems are ultimately dependent on the surface ecosystem for energy. That they are intimately connected to surface ecosystems in myriad ways is less obvious. Effective management of the subterranean fauna thus requires holistic approaches that emphasize these continuities between the surface and the subsurface. Maintenance and protection of the physical integrity of the subterranean environment is obviously an important management practice, yet this must go hand in hand with the same for the surface environment and the paths that connect them.

The extent of the surface environment that must be comanaged with the subterranean environment will depend on the nature of the regional setting. In situations where sinking streams provide the main input of organic material into the subsurface, the scale of focus must be at the level of the drainage basin. It is uncommon, however, that an entire surface drainage basin in a karst area is protected and extremely rare that one is protected as part of a plan to manage the associated subsurface ecosystem. Curiously, as pointed out above, maintaining the integrity of a surface drainage basin may be less important for the aquatic subterranean fauna but more so for the terrestrial subterranean fauna that patrol the riparian zone for organic matter carried in by sinking streams.

In situations where the main input into the subterranean ecosystem is via vertical movement of water, the focus of protection must be at the scale of the recharge area of the epikarst. The epikarst is beginning to be recognized as a subterranean ecosystem in itself with a community of endogenous species. It is also documented to be the major source of dissolved organic carbon needed to support the biofilm which is the base of the food web for the aquatic subterranean fauna, especially in small, upper-level cave streams. The physical extent of the recharge area of an epikarst zone is difficult to delineate; however, at the very least, one or more epikarst zones must map onto the subterranean drainage basin as indicated by surveyed cave passages underneath. Fortunately, extensive archives of such information exist and should be available to resource managers.

In arid to semi-arid regions, animals, such as bats and crickets as discussed above, are the major vectors of energy to the underground. The importance of bats is well recognized, especially for tropical and semiarid subterranean ecosystems. There is evidence indicating bat guano may also be an important energy source in some temperate zone caves. The importance of crickets is beginning to be documented. More studies similar to that of Taylor et al. (2005) are needed to understand the foraging areas of crickets and fully appreciate their role in supporting subterranean ecosystems. Clearly, many organisms may serve similar roles in different settings, and the physical extent of the connected surface environment will differ. The one constant is the integrity of the entrance to the subterranean systems, such as cave entrances. Cave entrances are also potential points of conflict among different management goals, such as ones focused on protecting archeological, geological, historical or other resources by keeping humans out with a gate ill designed for transit by energy vectors.

Of course, the mechanisms of energy transfer, as discussed, for any one setting are not exclusive to each. All the different paths of energy transfer linking the surface and the subsurface likely occur in any one setting but differ in relative importance. Because some of these paths often have low apparency, recognizing the important links that may be impaired for a given situation is critical to the creation of management plans to protect subterranean fauna at risk. Repairing any such impacted energy links may be extremely effective management practices in light of the metabolic adaptation of the subterranean fauna. Their low metabolic rates may allow some of them to persist for a period of interrupted energy input and slowly recover upon restoration of the normal energy flow. Once a subterranean system has been quarried away or drowned behind an impoundment, it is gone and unrecoverable. However, the potential resilience of some subterranean fauna to restricted energy input means that many of the impacted communities have a likelihood of recovery. Karst resource managers just need to recognize the situation and make it apparent.

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Chapter 10
Managing Microbial Communities in Caves

Diana E. Northup

Abstract Microbial communities in caves vary from striking microbial mats observed in many lava tubes worldwide, to occasional colonies on the wall, to invisible biofilms on rock walls and ceilings of caves, to microbial end products, such as manganese oxides. The investigations of the last decade, using culture-independent techniques in which we extract DNA from environmental samples and sequence clones to identify organisms present based on their genetic sequence, have revealed a wealth of microbial species never before described. These microorganisms represent a minimally explored treasure trove of organisms that can be impacted by the actions of humans living above caves and exploring within caves. The degree to which we impact cave microbial communities depends on the nature of the cave. Mammoth Cave in Kentucky, USA, and other similar caves, have rivers or streams running through major portions of the cave. Water flowing into caves may either bring plumes of pollutants to many parts of the cave and/or may help to wash away some impact caused by human visitation. Arid-land caves, such as Lechuguilla Cave in New Mexico, USA, that lack much in the way of flowing water, may be subjected to other kinds of impacts. Several strategies have been suggested to lower the impact that we explorers, scientists, and people living above caves have on cave microbial communities in order to preserve them for future study. Cave microbial communities can represent an extremely valuable resource that is worth protecting by modifying our behavior in visiting and living above caves.

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10.1 Introduction

Microorganisms in caves range from completely invisible to highly colorful microbial mats (Fig. 10.1) that line the walls of lava tubes to microbial waste products, such as iron oxides. It is hard to appreciate and value something that you cannot even see (Fig. 10.2), but there are many compelling reasons to protect and conserve cave microorganisms and their habitat, including the immense amount of novel diversity that we are finding, the roles that microorganisms play in the formation of speleothems in caves, and the potential compounds of biomedical and biotechnological use that cave microorganisms may produce.

In the last two decades, we have seen a major increase in research concerning the role that microorganisms play in the dissolution of bedrock and other surfaces and the precipitation of secondary mineral deposits (Barton and Northup 2007; Northup and Lavoie 2001). New discoveries of sulfur oxidizing bacteria in caves are revealing microbial roles in cycling sulfur in caves (Fig. 10.3) and enlargement of cave passages through sulfuric acid dissolution, as well as a possible role in sulfuric acid driven speleogenesis (Engel et al. 2004; Hose et al. 2000; Macalady et al. 2007).

Fig. 10.1 Colorful microbial mats adorn the walls of many Azorean lava tubes. The photo on the left gives an overview of a yellow microbial mat, while the photo on the right shows a closeup of yellow microbial colonies growing on organic ooze on a basalt formation. Photos courtesy of Kenneth Ingham

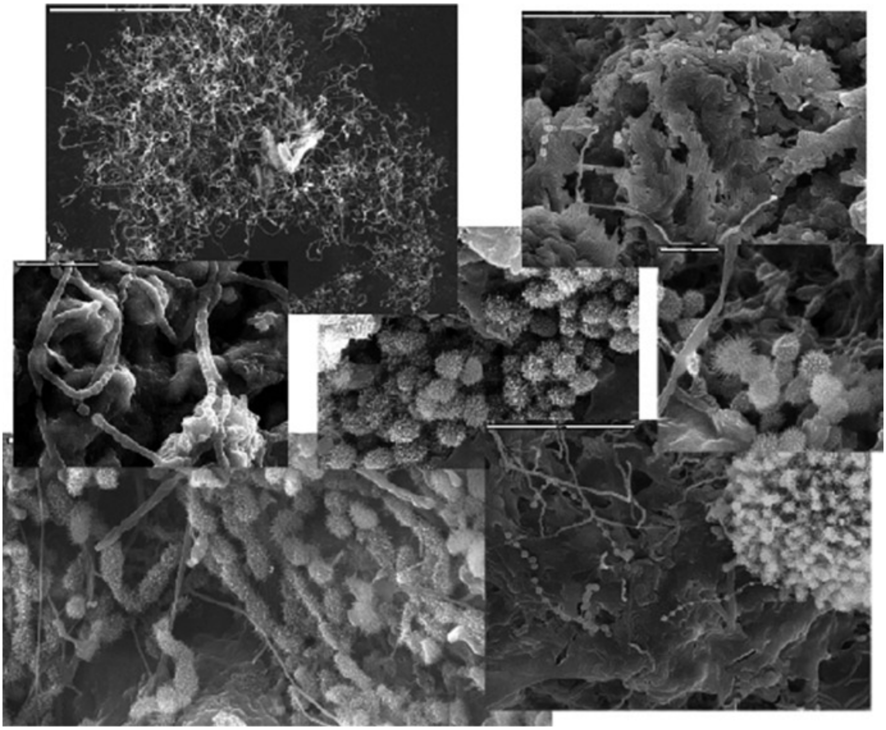

Fig. 10.2 Microscopic organisms that live on cave walls in limestone caves and lava tubes present an amazing array of shapes when viewed with a scanning electron microscope. (**a**) Putative bacterial filamentous morphology was found in a gold mineral-like deposit from Four Windows Cave, El Malpais National Monument, New Mexico, USA. (**b**, **c**) Rods, filaments, beads-on-a-string, and fuzzy coccoid morphologies were observed in white microbial mats from an Azorean lava tube on the island of Terceira, Portugal. (**d**) Fuzzy cocci and segmented filaments were revealed in a sample from a Cape Verde lava tube. Photomicrographs by Michael Spilde, Penelope Boston, and Diana Northup

Spilde et al. (2005) have shown a microbial role in the production of ferromanganese deposits in arid-land caves, where little organic carbon exists to fuel microbial processes (Fig. 10.4). These and other studies are showing key geomicrobiological roles for microorganisms in caves. Although much remains to be learned about the microbial role in energy transfer and elemental cycling, some evidence suggests that microorganisms facilitate the transfer of energy between cave life and organic carbon and serve as food for the cave life (Simon et al. 2007). Perhaps, most exciting is the amount of novel biodiversity that culture-independent molecular studies are revealing in caves (e.g., Barton et al. 2004; Gonzalez et al. 2006; Northup et al. 2003). Some of these novel (and not so novel) species may produce chemical compounds that are very useful to humans, such as new antibiotics to replace those to which bacteria are now resistant (Dapkevicius, Terrazas and Northup, unpub. data). The geomicrobiological studies (Barton and Northup 2007) and those of novel

Fig. 10.3 Pendant acidic microbial structures, termed snottites, hang from the walls of sulfur caves such as Cueva de Villa Luz in Tabasco, Mexico. Photo courtesy of Kenneth Ingham

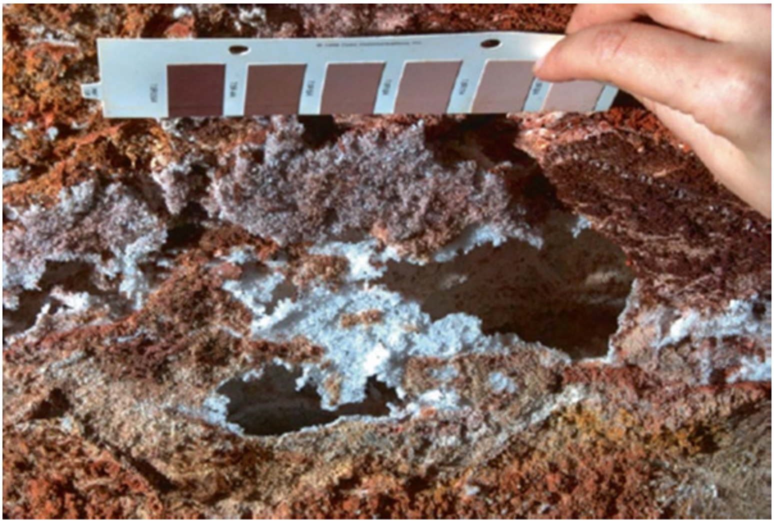

Fig. 10.4 Red, brown, and pink ferromanganese deposits, which contain varied microbial communities, adorn the walls of Spider Cave, Carlsbad Caverns National Park, New Mexico. Photo courtesy of Kenneth Ingham

microbial biodiversity also serve to aid our understanding of how to detect life on other planets, such as Mars, where life is likely to shelter from harsh surface conditions in the subsurface (Boston et al. 2001). Thus, our research emphasizes the critical nature of cave microbial communities and suggests that their conservation is vital. However, several threats to cave microbial populations exist.

10.2 Threats to Microbial Populations

Cave microorganisms are susceptible to a variety of threats, including human visitation, soil compaction, pollutant spills, cave restoration, habitation above caves, and organic carbon enrichment. Whether microorganisms reside in arid-land caves, or those in areas with more rainfall, affects the degree to which these threats are an issue for microbial populations. Rivers and streams running through caves can carry away pollutants and dampen the effects of various threats; however, rivers and streams can also be the vehicle for introducing pollutants. Such pollutants can have a major impact of aquatic microbial communities within caves with potential subsequent impacts on the invertebrate communities that feed on these microbial communities. Some threats are common across this spectrum, while others are more problematic in arid-land caves.

10.2.1 Organic Carbon and Other Nutrient Enrichment from Human Visitation

Arid-land and caves are much more subject to the effects of organic carbon enrichment and other impacts that result from human visitation of caves due to their oligotrophic nature. When we visit caves, we shed tens of thousands of skin cells, many of which are life rafts for our own microbial inhabitants, as well as hair and fibers and mud from our clothing. If we are sick and vomit in the cave, we greatly enrich organic carbon in the habitat. Longer cave trips may bring the issues of urine and feces deposition (Fig. 10.5). While cricket and beetle feces are a natural part of the ecosystem, human feces are not. Humans obviously deposit much more feces than a cricket and human feces has almost 50% microorganisms. Urine can lead to the buildup of harmful compounds that change the microbial ecosystem (Lavoie 1995). Most cave visits are several hours in duration and often involve eating. Dropping crumbs of food in the cave may not seem much of an impact, but to the microbial communities it represents a large infusion of organic carbon, which may, over time, fuel the growth of “weedy” heterotrophic organisms such as the fungus pictured in Fig. 10.6. These microorganisms, which may be transplants from the surface, may then outcompete the resident microorganisms, if organic carbon levels throughout the cave have increased. Where native microbial populations reside in oligotrophic habitats within caves, we may see the most profound effects.

Fig. 10.5 A sign warns against depositing feces in the cave

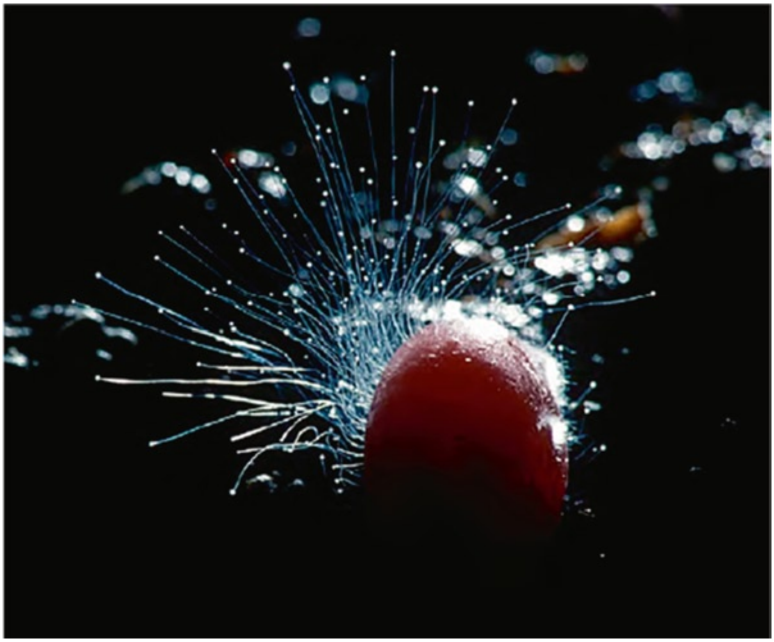

Fig. 10.6 Human visitors dropped a jelly bean, which fueled the growth of microorganisms in this lava tube. Photo courtesy of Kenneth Ingham

Oligotrophic microorganisms do not simply get “fatter” when you feed them more; they often die off, allowing more surface-adapted microorganisms to take their place. Koch (1997) suggests that organisms in low nutrient environments grow at very slow rates and that cultivation studies using standard amounts of nutrients simply provoke death, which suggests that carbon enrichment of the cave, may prove harmful to the native micro biota. Thus, human visitation can introduce new organic matter and exotic microorganisms into caves, which may harm native microbial populations.

Some organic carbon enrichment originates from the surface in a variety of ways (Fig. 10.7). Sinkholes have long been a favorite place for the dumping of trash.

Fig. 10.7 Sinkholes are convenient trash dumps; sewage pipes occasionally penetrate caves; and land use above caves, such as grazing, can provide higher levels of nutrients entering caves. Photos courtesy of Kenneth Ingham

Besides being a source of organic carbon enrichment into caves, some trash brings toxic chemicals which may harm microbial communities, or in some cases may stimulate the growth of microorganisms that can utilize chemical substances that are toxic to most life forms.

Sewage leakage into caves can be a major source of organic carbon and other nutrient enrichment. In some rural communities, sewage pipes have been known to penetrate caves (Fig. 10.7), dumping raw sewage into the cave. In other instances, cave visitor centers have had inadvertent sewage leaks into the caves when the aging sewer system cracked and failed without being detected for a prolonged period of time. This led to the growth of bracket fungi in one case. Leaks such as this, invariably test positive for fecal coliforms and pose a health hazard to cave visitors.

10.2.2 Physical Threats

As we walk through areas of the cave with soil or detrital material, we cause compaction of the soil, which decreases the available oxygen. Some organisms may be killed outright by this physical compaction. Because of the lack of substantial weathering in caves, such compaction takes a very long time to reverse. Some visitors draw their names and dates in microbial mats (Fig. 10.8), eliminating microorganisms in the path of their finger and leaving behind their own microorganisms and skin oils (Varela 2009). Some of the names and dates that we have observed in lava tubes have only minimal microbial re-growth after two decades.

10.2.3 Threats from Imported Exotic Microorganisms

Human visitors to caves shed many of their associated bacteria and fungi as they walk, climb, and crawl through caves. Our studies (Lavoie and Northup 2006; unpublished data) suggest that human associated bacteria (e.g., Staphylococcus aureus) are preferentially found in areas with more human impact (Fig. 10.9). Because fungi produce copious numbers of spores that travel easily through the air, they are often found in equal measure in low and high impact of more open caves. If the cave is given time to "rest" (i.e., no human visitation), and we limit the amount of organic carbon buildup, these exotic populations generally die off. However, some exotic populations of bacteria and fungi, brought in by humans and arthropods, can persist and damage cultural artworks, such as those found in the caves of France and Spain (Dupont et al. 2007; Jurado et al. 2008; Bastian et al. 2010 and references therein). Recently, a newly described fungus, Geomyces destructans (Gargas et al. 2009), has been hypothesized to contribute to the death of more than a million bats in the eastern United States. It is currently unknown whether the fungus is native to caves or whether humans have transported the fungus into the cave; research is ongoing to determine the cause of the massive die-off and

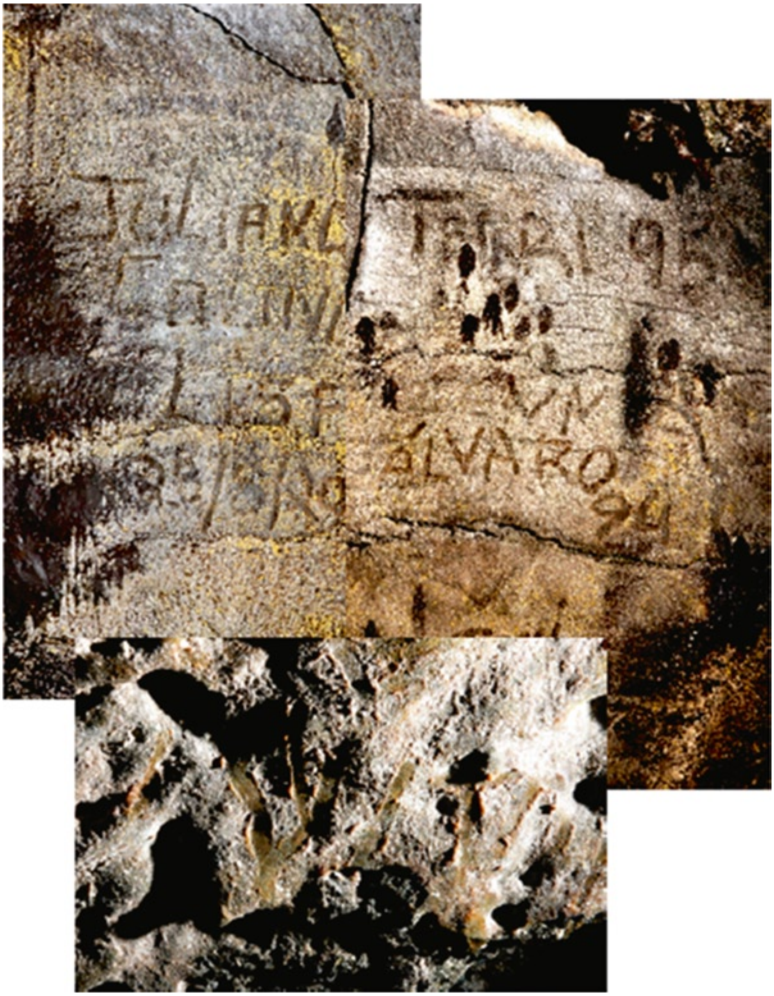

Fig. 10.8 Human visitors write their names (*top image*) in the microbial communities of these Azorean lava tubes, or leave finger smear marks behind when touching the walls (*bottom image*). Photos courtesy of Kenneth Ingham

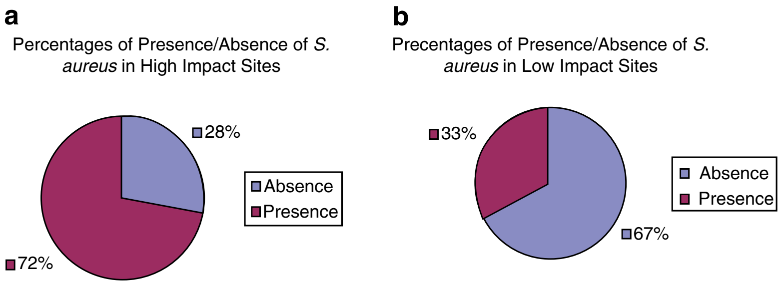

Fig. 10.9 (**a, b**) Relative proportion of Staphlococcus aureus in high (**a**) and low (**b**) human impact areas of Carlsbad Cavern, Carlsbad Caverns National Park, New Mexico, USA. Graphs courtesy of Jessica Snider

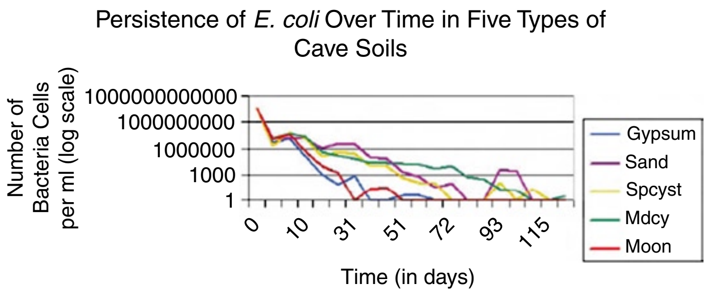

Fig. 10.10 E. coli inoculated into five different soil types form Carlsbad Cavern and Spider Cave in New Mexico, show different patterns of persistence over time. Graph courtesy of Amaka Nwagbologu

illustrates how little we actually know about the role that humans play in changing the makeup of microbial populations in caves.

One conservation technique, designed to protect the pristine pools of Lechuguilla Cave in Carlsbad Caverns National Park, did not have the desired outcome. Explorers and land managers introduced plastic tubing into pools designated as drinking water sources in order to circumvent the need to dip water bottles in the pools, thereby hopefully preventing the contamination of the pools. However, the tubing used contained plasticizers that leaked into the pool, promoting the growth of native bacteria that grew to visible streamers within the tubing, putatively due to the enrichment of organic carbon from the plasticizers. This population explosion of a native bacterial population may have supported or introduced E. coli population growth in the pool (Hunter et al. 2004). In response to our study, Barton and Pace (2005) raised the issue of whether E. coli would persist in the cave environment. We believed that it would (Hunter et al. 2005), and subsequently conducted experiments with cave soils inoculated with E. coli. These studies demonstrate that E. coli can persist in a variety of cave soils at cave temperatures for extended periods of time (Fig. 10.10). E. coli appears to persist in clay soils, in particular. More research is needed into how human associated microorganisms affect microbial populations in caves and the extent to which they persist in the cave environment.

10.2.4 Threats from Cave Restoration Efforts

Our well intended efforts to restore and clean caves can lead to many problems for microbial communities as detailed in Boston et al. (2005). Some restoration efforts use chemicals that can harm cave macro- and microbiota. Chlorine bleach is one of the major hazardous chemicals that is often used in restoration work. The problem with chlorine bleach comes from its nature as a strong oxidant, which can lead to a major decimation of organic matter and the death of invertebrates and microorganisms. Techniques such as pressure water sprays also can be harmful from two perspectives.

The high pressure water can remove and kill biofilms. Secondly, depending on the source and nature of the water, it can introduce non-native microorganisms into the cave and may be acidic in nature. Another consideration in cave restoration is how to clean cave pearl nests. There is some evidence that microorganisms may play a role in cave pearl formation, or at least be associated with cave pearls. Removing the water from around them, or handling the pearls themselves, may either remove needed nutrients or may damage biofilms on the pearls. Extreme care should be taken in cleaning cave pearl areas until we know more about their formation. Thus, careful consideration of what techniques can be used in restoration, without major harm to microbial communities, is essential.

A major target of restoration work is algae and other organisms whose growth is associated with lights in show caves. This growth, which can be from algae, cyanobacteria, or other microbial partners, is often quite luxuriant (Fig. 10.11). Olson (2005) has recommended the use of lighting that employs wavelengths that are utilized extensively by the photosynthetic organisms growing in lampenflora.

Fig. 10.11 Show caves, such as this lava tube in Hawai'i, utilize lights to guide visitors to the caves. These lights result in the growth of lampenflora. Photo courtesy of Kenneth Ingham

Both Olsen (2005) and Mulec and Kosi (2009) offer additional strategies for controlling the growth of lampenflora, while lessening harm to native microbiota.

10.3 Is Protection Possible During Active Exploration and Scientific Investigation?

Should microbial communities in caves be protected at the expense of human access to some caves? Should we entertain the idea of creating "microbial preserves" that protect critical microbial populations within certain areas of caves? At one end of the spectrum is the case of Lascaux Cave in France, which houses some of the world's most fabulous cave paintings. Microbial damage to the paintings, caused in part because of human visitation, led to the closure of the cave in order to protect the paintings and many investigations and mitigation strategies have ensued (reviewed in Bastian et al. 2010). The seriousness of the deterioration led to the formation of the International Committee for the Preservation of Lascaux and the passage of resolutions by UNESCO's World Heritage Committee to work toward more effective means to save these paintings whose value is beyond measure. In the case of Lascaux, there is little doubt that extreme preservation is warranted. But what about less well-known caves, where what is threatened are microbial communities that are invisible to the unaided eye. Additionally, because the research is just beginning into how much of an effect that humans have on microbial populations, it is often hard to make a strong case for making some areas off limits to human visitation in order to protect microorganisms. What is clear is that we need to advance the study of microorganisms in caves and the effect that humans have on cave microbial populations.

In the meantime, there are some relatively simple things that can be done to protect microbial communities in caves. The success of recommendations for protecting cave microbial populations rests in the acceptance of the value of these microbial populations by cavers, scientists, and other visitors to caves. It is hard to think about and protect things that you cannot even see. If cave microorganisms are perceived to be a key component of the cave ecosystem, or an effective treatment for cancer or a new antibiotic that could save a life someday could come from a cave microorganism, then people may be more willing to go the extra mile for the microbes. To provide the information to increase motivation for microbial conservation in caves, we will need to conduct more research into what harms and what protects microbial communities in caves, in conjunction with using that information to educate cave visitors about the problems and solutions. One of the payoffs is that educational programs about cave microorganisms often excite and engage cave visitors – the microbes have wonderful stories to tell. We have begun efforts to share our scanning electron micrographs of cave microbes through the IDEC (Imagery Data Extraction Collaborative) website (http://idec.aisti.org). This site allows viewers of all backgrounds to comment on images and the features contained in them and allows teachers to download images that they can use in their curriculum.

10.4 Recommendations

To protect a subject of interest, you need to understand it. Our knowledge of cave microbial communities is rudimentary, limiting our ability to know precisely what efforts will protect microbial communities in caves. Several laboratories around the world are conducting outstanding culture-independent molecular studies of cave microbial communities to identify novel biodiversity, while others are culturing cave microorganisms to shed light on their physiology and biochemistry, but we need more scientists involved. The first molecular study of microbial diversity was published in 1997, and while many others have followed it, much remains to be learned. Microbial inventories across gradients of depth, nutrient richness, distance from entrances, human impact, etc. are needed to compile a more complete picture of cave microbial communities. Many interesting ecological and evolutionary questions about cave microorganisms await researchers (e.g., Snider et al. 2009). Thus, research and inventory are key steps in our efforts to protect cave microorganisms.

Several research questions concerning the impact of humans on microbial communities in caves require additional research. These include, but are not limited to:

- How do we differentiate native microorganisms from non-natives?
- What human associated microorganisms can be used as tracers of human impact?
- Do human associated microorganisms persist in cave soils and surfaces? Are they metabolically active?
- To what extent does human visitation in caves contribute to organic matter buildup?
- Does organic matter and other nutrient enrichment harm native microbial communities?
- What effects do surface land use practices in karst areas, such as grazing and other human activities, have on cave microbial communities? Do these activities result in increased nutrients entering the cave?
- What techniques can we employ to decrease organic matter enrichment from cave visitation and surface activities?
- We also need to identify critical microbial habitats within cave and karst areas that need additional protection. Different kinds of caves are going to vary in their microbial community makeup and vulnerability. We know little about these differences as yet.
- The following recommendations to conserve microbial habitat and microorganisms are based on our preliminary investigations and insights into microbial communities in arid-land caves, but their effectiveness remains to be tested:
- *Establish trails for movement through the cave*. When you establish trails, use inert markers that do not enrich organic carbon in the cave and do not degrade. Some forms of flagging have proven to be "tasty" to microorganisms and invertebrates, such as camel crickets. If there are no marked trails, always walk where the "elephant tracks" are.
- For caves in which camping is necessary for exploration, *establish camps to concentrate human impact*. If at all possible, carry out all human waste.

- *Eat over bags to catch all crumbs*. What is a crumb to you is a supermarket to a microorganism.
- *Clean your clothes and boots between cave trips to prevent cross contamination of microorganisms between caves*.
- *Brush your hair and beard to remove loose hairs before going caving*.
- *Find ways around pristine pools and avoid dipping anything, including yourself, in the pool*. Establish a clean pitcher for obtaining water. If you use plastic tubing to siphon water, make sure that the tubing does not leak plasticizers that can support microbial growth (Hunter et al. 2004).
- Educate new cavers about cave microbial communities and the ways to preserve and protect microbial communities.

Scientists, cavers, and cave managers who find unusual deposits that may be microbial should consider establishing a microbial preserve to allow investigation before visitation occurs to any extent. If you see something really intriguing, send a photo to one of the microbiologists around the world who studies these communities in caves. Scientists often study a few areas very intensively and may miss key discoveries. Cavers and scientists should collaborate on microbial discoveries for mutual benefit. Scientists can excite cavers and visitors by providing engaging information about their findings through public talks, articles, and other media that bring the science to the public.

10.5 Conclusions

Our knowledge of microbial diversity in caves is growing rapidly and revealing a wonderland of microorganisms that participate in precipitation and dissolution of cave mineral deposits that have roles in nutrient cycling within the cave ecosystem, that may produce chemical substances of great use to humans, and that serve as an analog for possible life on other planets. These important communities are, however, threatened by some of our actions when we visit or live and work above caves. By being conscious of the ways in which we may enrich organic carbon in caves, explorers, scientists, and landowners can do much to protect microbial habitats and microorganisms in caves. Are cave microorganisms threatened? In 1997, Jim Staley wrote the following concerning microorganisms in general:

> Our knowledge of microbial diversity, particularly bacterial diversity, is so meager that we do not yet know if and when most species are threatened.

This is particularly true of cave microorganisms and enhanced efforts to study and understand cave microbial communities are essential to our being able to truly answer the question of whether these populations are threatened. Through a variety of ways, we provide challenges to subterranean microbial populations, but you are not yet fully informed about what these challenges are and the best ways in which to mitigate them.

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Part III
Management of Karst Aquifers

Chapter 11
Management of Carbonate Aquifers

Stephen R.H. Worthington

Abstract Carbonate aquifers are common globally and are widely utilized due to their high permeability. Advances in recent decades in understanding dissolution kinetics have facilitated the numerical modeling of dissolutional enhancement of permeability. This has shown how the dissolution results in an interconnected network of channels that not only results in high permeability but also in rapid groundwater velocities. The high permeability often results in a lack of surface water and thick unsaturated zones, so utilization of groundwater is often from low-elevation springs, especially in mountainous areas. Groundwater divides may not coincide with surface-water divides, sometimes resulting in jurisdictional issues over exploitation of the groundwater. Contaminant transport in carbonates is more complicated than in porous medium aquifers. Transport through the channels may be several orders of magnitude faster than transport through the matrix of the rock. This results in complicated contaminant plumes and makes carbonate aquifers more susceptible to bacterial contamination than other aquifer types.

11.1 Introduction

The approach to managing aquifers in carbonate rocks is (or should be) somewhat different from that used with porous medium aquifers such as sand due to the different permeability structure. In carbonate aquifers, dissolution produces a network of solutionally-enlarged pathways that enhance the permeability. These aquifers are sometimes called karst aquifers.

There is no widely agreed definition of what constitutes a karst aquifer. A narrow definition includes only the small fraction of carbonate (limestone and dolostone)

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aquifers that have known caves, demonstrable turbulent flow in conduits with diameters >1 cm, or a surficial karst landscape. A broad definition focuses on the permeability structure of the aquifer, defining a karst aquifer as having "self-organized, high-permeability channel networks formed by positive feedback between dissolution and flow" (Worthington and Ford 2009, p. 334). However, it is less important to classify carbonate aquifers than to recognize the dissolution-enhanced permeability structure of these aquifers which results in high permeability and rapid groundwater velocities.

Infiltrating precipitation will usually dissolve 100–400 mg/L of calcite or dolomite in a carbonate aquifer. The combination of the high permeability that results from this dissolution combined with the widespread distribution of carbonate rocks result in these aquifers being important globally. It has been suggested that at least 20% of the world's population depends largely or entirely on groundwater obtained from carbonate aquifers (Ford and Williams 2007).

This chapter will describe how dissolution enhances permeability in carbonates and the permeability and porosity characteristics of these aquifers, and then will address the management issues specific to these aquifers.

11.2 Dissolution Processes in Carbonates

There are two aspects to the dissolution of carbonate rocks. These are equilibrium solubility and kinetic solubility effects.

11.2.1 Equilibrium Solubility Effects

Equilibrium solubility refers to the concentration at which a mineral species is at equilibrium when dissolved in a solute, which in a carbonate aquifer is the groundwater. At lower concentrations, the solution is under-saturated with respect to that mineral and so dissolution will occur. At higher concentrations, the solution is supersaturated with respect to that mineral and so precipitation of the mineral will occur.

The solubility of calcite in pure water at 25°C is 14 mg/L. However, its solubility increases substantially with increased carbon dioxide partial pressure. Concentrations of CO_2 in soil air are typically one to two orders of magnitude greater than in the atmosphere. This results in groundwater in limestone aquifers typically having dissolved $CaCO_3$ concentrations of 100–400 mg/L. Variations in carbon dioxide partial pressure are usually the most important factor in determining dissolved $CaCO_3$ concentrations, but there are several other factors. Calcite solubility decreases as a function of temperature and the common ion effect. It increases as a function of pressure, the ionic strength effect, open rather than closed system conditions and the presence of organic complexes (Ford and Williams 2007, pp. 45–62).

While the dissolution potential of $CaCO_3$ is greater for cold than warm environments, tropical regions typically have more productive soils which produce more dissolved CO_2 and also have higher precipitation amounts, leading to greater amounts of $CaCO_3$ being dissolved.

11.2.2 Kinetic Solubility Effects

Kinetic solubility effects refer to the rate at which reactions occur. It has commonly been assumed that reaction rates of carbonate and evaporate mineral dissolution are rapid with respect to groundwater flow. The implication for dissolution is that the water would come to equilibrium on first coming into contact with a soluble mineral near the ground surface or shallow in the bedrock, and that no dissolution would subsequently occur as the water flows through the deeper bedrock, assuming that the equilibrium solubility does not change. Limited experimental data supported this conclusion for limestone (Weyl 1958).

This conclusion posed a problem as it appeared that karst aquifers could not develop. If the groundwater solution comes to full equilibrium on first contact with the carbonate rock, then there is no further dissolution potential further along groundwater flow paths. However, karst aquifers clearly do exist and sometimes have deep flow paths extending to great distances from the infiltration site where water first comes into contact with the carbonate bedrock. It was therefore clear that there was an incomplete understanding of dissolution processes.

Further laboratory experiments on the dissolution of calcite provided a resolution to this conundrum. It was found that dissolution rates diminish precipitously as chemical equilibrium is approached for calcite and dolomite and so only slowly reach full equilibrium (Berner and Morse 1974; Morse and Arvidson 2002). Consequently, most groundwater is slightly undersaturated with respects to calcite and so dissolution is able to proceed throughout most carbonate aquifers even deep within the aquifer and distant from the site of infiltration. Dissolution rates can be expressed as

$$F = k\left(1 - c / c_{eq}\right)^{n} \tag{11.1}$$

where F is the dissolution rate, k is the reaction coefficient, c is the solute concentration, c_{eq} is the equilibrium solute concentration, and n is the reaction order (Dreybrodt 1996). The reaction order far from equilibrium is one, but it increases to between 4 and 11 where c/c_{eq} exceeds 0.6–0.8 (Eisenlohr et al. 1999).

These results turned conventional wisdom on its head. Rather than karst aquifers being rather rare, it now became clear that the majority of, if not all, carbonate aquifers should be karstic, at least in their upper parts where most flow is likely to be concentrated. This theoretical evidence provided an explanation for the high permeability that is common in carbonate aquifers. These findings have been supported by the results from the many numerical simulations of the development of karst aquifers, which are described in the following section.

11.2.3 Reactive Transport Numerical Models of Karst Aquifer Development

Reactive transport numerical modeling of karst aquifers commenced with one-dimensional models (Dreybrodt 1990; Palmer 1991). These early models showed how karstification leads to increases in permeability of several orders of magnitude over periods of 10^3–10^6 years. Early two-dimensional models with small grids (i.e., a small number of large dimension cells) showed how preferential flow would result in most of the flow becoming focused on one main channel. Many of the early papers had simulated recharge at sinking streams, where the water is often significantly under-saturated with respect to calcite. However, Dreybrodt (1996) showed that karstification occurs even where there is just percolation recharge to a carbonate aquifer. In the late 1990s, larger grids (with a large number of smaller dimension cells) were employed that gave more insights to competition between different pathways.

Dreybrodt et al. (2005) systematically examined many aspects of dissolution of limestone, using percolation networks and networks with log-normal aperture distributions and large grids (10,000 nodes). Liedl et al. (2003) developed a numerical model based on MODFLOW, adding subroutines to simulate dissolution and to simulate turbulent flow. The latter subroutine was subsequently added to the US Geological Survey release of MODFLOW 2005 (Shoemaker et al. 2008; Reimann and Hill 2009).

Evidence from numerical modeling, preferential flow directly observed in wells, and the distribution of caves supports the concept that carbonate aquifers vary between macrokarstic and microkarstic end members (Worthington and Ford 2009). Macrokarstic development commonly occurs where there are sinking streams; recharge is substantially undersaturated with respect to calcite, which results in a small number of large channels and in some instances caves. Microkarstic development is common where there is percolation recharge; most dissolution occurs in the upper few meters of bedrock, resulting in a high-permeability weathered (or epikarst) zone. Infiltrating water below this zone is close to saturation and follows many pathways, resulting in a dense network of many small channels. Other factors promoting macrokarst include sparsely fractured rock and low initial hydraulic gradients. Conversely, densely fractured rock and high hydraulic gradients both promote the development of microkarstic networks.

11.3 The Permeability Structure of Carbonate Aquifers

11.3.1 Local-Scale Characteristics

Measurements in boreholes are important for investigating the local variability of permeability in carbonate aquifers. Pumping tests are commonly used to determine aquifer properties and give average values over the whole depth of the borehole for transmissivity, hydraulic conductivity, and storage. However, flow into boreholes in carbonates is rarely represented by seepage from the whole saturated thickness. Instead, preferential flow from a limited number of horizons is more common (Morin et al. 1988; Schürch and Buckley 2002). Packer testing and measuring flow while pumping from the borehole at a low rate are the most useful methods of determining preferential flow into boreholes. Optical or acoustic televiewer, video, temperature, and conductivity are also helpful for identifying and characterizing preferential flow, and gamma ray logs facilitate comparisons between boreholes to be made (Fig. 11.1).

Ideally, porosity and hydraulic conductivity measurements are made separately for the matrix, fractures, and solutionally-enlarged channels. However, in many cases it is challenging to measure hydraulic conductivity and porosity for these three components. A somewhat simpler approach is to group fracture and channel properties together. Plotting porosity and hydraulic conductivity together shows that matrix and fracture/conduit values plot in two distinct fields (Fig. 11.2). In all the examples shown, the matrix of the rock has high porosity and low hydraulic conductivity. Furthermore, the fractures and channels account for a smaller fraction of total porosity but a much higher fraction of total hydraulic conductivity than the matrix. Consequently, most of the storage is in the matrix but most of the flow is in the channels.

11.3.2 Aquifer-Scale Characteristics

The development by dissolution of interconnected channel networks in carbonate aquifers makes them distinctly different from porous medium aquifers. The most common ways to investigate these differences are tracer tests and spring studies. Tracer tests have been most commonly used where there are sinking streams, and many thousands of such tests have been carried out over distances of up to tens of kilometers (Fig. 11.3). These tests have been used to determine groundwater velocities and the existence of flow paths between the injection and the observation sites. The geometric mean velocity for the 3,015 tracer tests shown in Fig. 11.3 is 1,740 m/day (Worthington and Ford 2009). These tests are all between sinking streams and springs and represent flow along large channels.

Springs in carbonates represent the outlets of channel networks, and heads in large channels are lower (except at high flow) than in the surrounding bedrock. Consequently, mapping of heads in boreholes can help identify the location of large channels and thus the major flow paths in an aquifer. Figure 11.4 shows a number of contrasting characteristics at a scale of kilometers or more. These differences can be used to estimate the nature of karstification in an aquifer, for instance, whether an aquifer is closer to macrokarstic or microkarstic end members.

The specific discharge (L/s/km^2) from an area can be calculated from the gauged discharge of river basins. If the mean discharge for a spring is measured, then the area of the groundwater basin feeding that spring may be determined. The boundaries of that groundwater basin can be determined by a combination of measuring heads in wells together with tracer tests to the spring (Fig. 11.5).

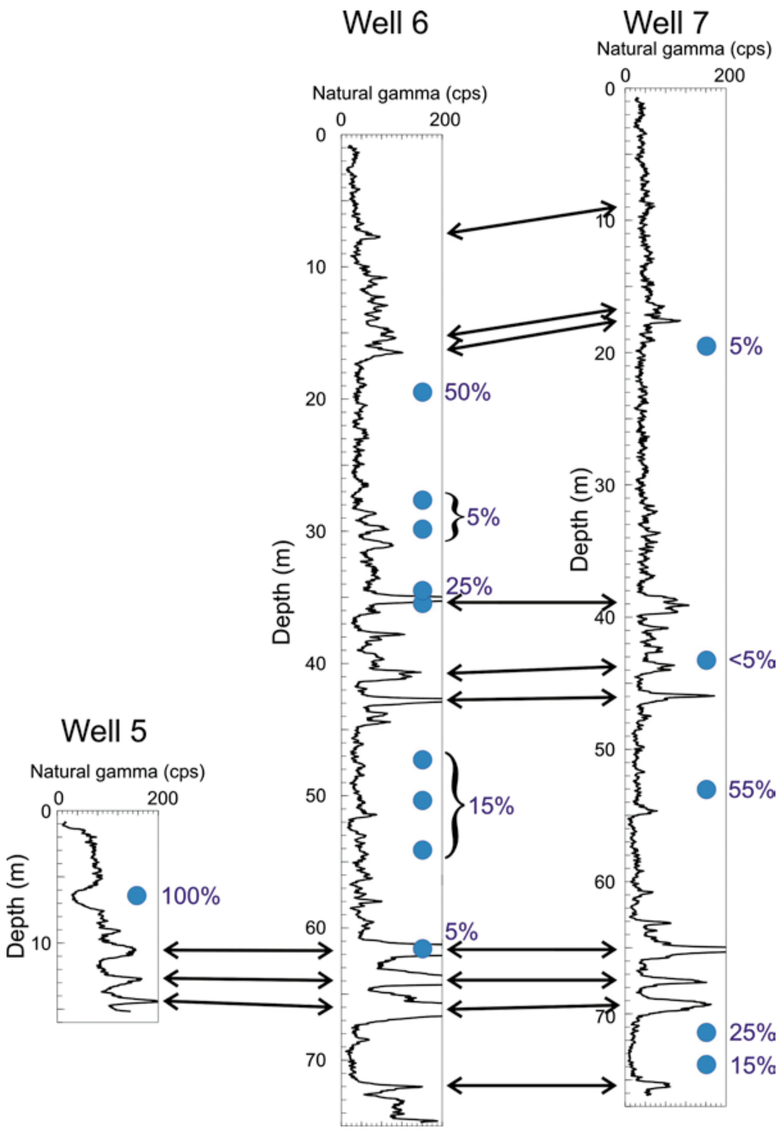

Fig. 11.1 Stratigraphic correlation from gamma ray logs (*black line*) and inflow from flow meter measurements (*blue dots*) at the three municipal wells in use at the time of the Walkerton Tragedy (after Worthington et al. 2002)

11.3.3 Scaling Effects

In carbonate aquifers, most randomly-drilled boreholes are unlikely to intersect major channels. Consequently, localized hydraulic testing such as packer tests will have lower average permeabilities than tests such as pumping tests that sample

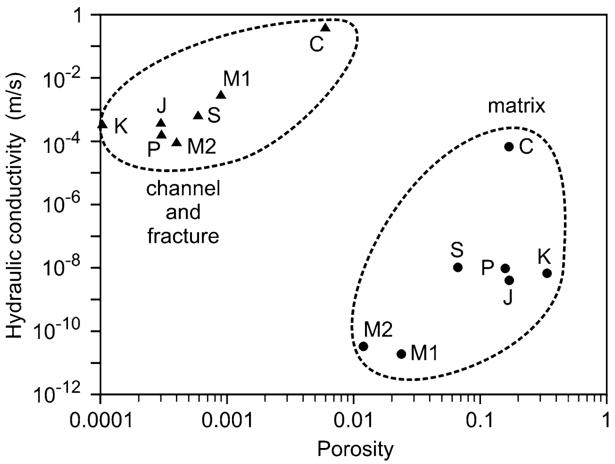

Fig. 11.2 Porosity and hydraulic conductivity values for the matrix and for fractures and channels for Silurian dolostone (Ontario, S), Mississippian limestone (Kentucky, M1; England, M2), Permian limestone (England, P), Jurassic limestone (England, J), Cretaceous limestone (England, K) and Cenozoic limestone (Mexico, C), (after Worthington and Ford 2009)

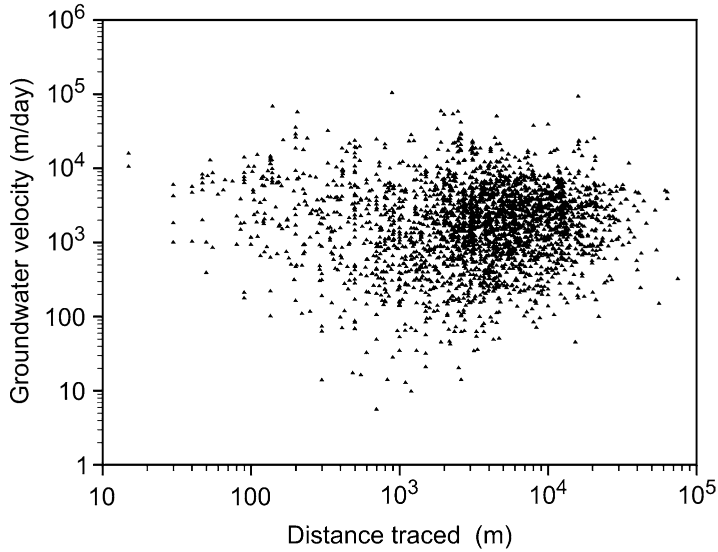

Fig. 11.3 Groundwater velocities for 3,015 tracer tests along channels in carbonate aquifers (after Worthington and Ford 2009)

a larger volume of the aquifer. This property is known as the scaling effect. It was introduced by Kiraly (1975), and his data for limestones in the Jura Mountains in Switzerland are shown in Fig. 11.6, as well as data from several other carbonate aquifers.

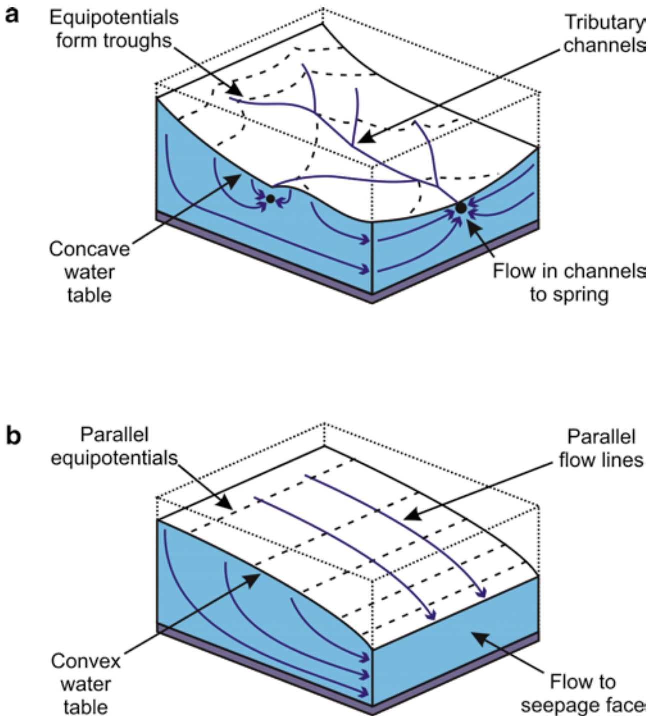

Fig. 11.4 The principal aquifer-scale differences between (**a**) an ideal karst aquifer and (**b**) a homogeneous porous-medium aquifer (after Worthington 2009)

There are large differences in the hydraulic conductivity for tests on core rock samples (effective test radius assumed to be 0.1 m) because the matrix permeability of poorly compacted rocks (e.g., Cenozoic carbonates) is much higher than for highly compacted rocks that were deeply buried (e.g., most Paleozoic carbonates). However, as the test radius increases by moving from fist-sized rock samples to methods like pumping tests that sample ~100 m of the rock surrounding the borehole, the permeability values tend to converge, as all the carbonate aquifers shown have channel networks and thus have broad similarities at the scale of the whole aquifer. Scaling effects are substantial where karstification has occurred. However, where karstification is absent and bulk permeability is very low (e.g. $<1^{-10}$ m/s), then the bulk permeability is likely to be similar to the matrix permeability and scaling effects may be absent. This broad similarity between different carbonate aquifers is also illustrated by Fig. 11.2, where the results are grouped into two well defined areas, irrespective of the age, climate and recharge, folding, or other geological history characteristics

The contrasts between the two distinct fields on Fig. 11.2 can be described as double-porosity behavior. Water moves quickly through the channel network, but slowly through the matrix. This means that the residence time of the groundwater in

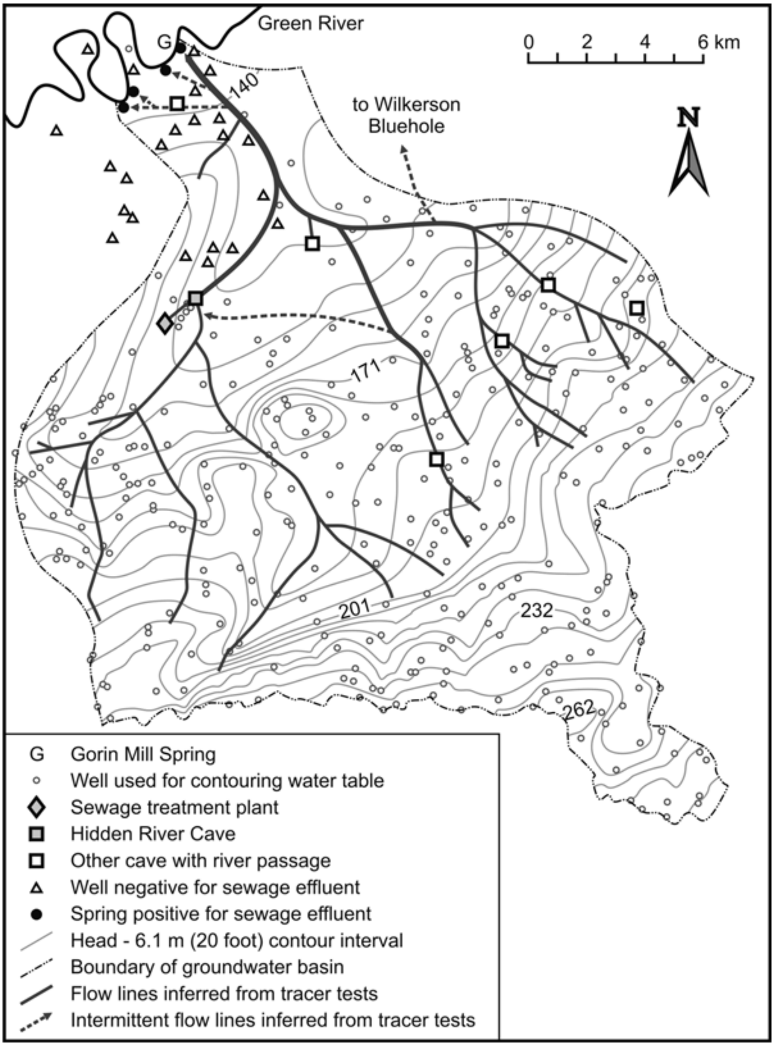

Fig. 11.5 Contour map of water table heads and groundwater flow paths (*black lines*) in the groundwater basin that drains to Gorin Mill Spring, Kentucky. The streams in the southern part of the area (not shown) flow across impure limestones and then sink on reaching purer limestones. Consequently, there is no surface drainage in the northern two-thirds of the drainage basin (compiled from Quinlan and Ray 1989; Quinlan and Ewers 1989; and Ray 1997)

the channels and fractures is likely to be substantially less than the matrix water. Water discharging from the aquifer will be a blend of all these waters and so will have a mixed age. The implication is that age dating using environmental tracers such as tritium, He/H, or CFCs will give much older ages than age dating using tracers that are introduced to the channel network and sampled at a spring in a

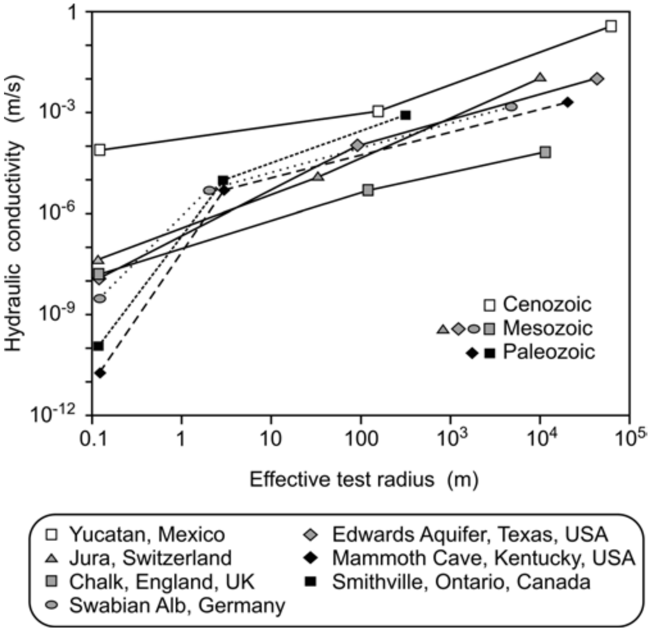

Fig. 11.6 Hydraulic conductivity as a function of testing scale (after Worthington 2009)

natural-gradient test or at a well in a pumping test. There have been a number of case studies where spring water has been dated using both environmental tracers and introduced tracers. The introduced tracers gave average groundwater ages that were about two orders of magnitude less than the environmental tracers (Worthington 2007). For instance, $^3H/^3He$ dating gave a groundwater residence time of 39 years for the discharge at Wakulla Springs (Florida), assuming that the aquifer behaves as a porous medium (Katz 2001). However, subsequent tracing using fluorescent dyes showed that the travel times are of only days to weeks over distances of some 10 km between sinking streams and Wakulla Springs (Loper et al. 2005). The dye tests demonstrated rapid flow along channels whereas the $^3H/^3He$ dating gave an average residence time value that includes the much slower flow through the matrix of the rock. Consequently, the two tracing methods yield complementary information about transport characteristics in these aquifers.

Groundwater velocities through the channel networks can be estimated using Darcy's law, using channel/fracture porosity as the effective porosity (Fig. 11.2). However, direct measurement using introduced tracers has been widely used and is highly recommended where any questions of contaminant transport are being addressed. Tracer test results can also be used to estimate channel apertures (Fig. 11.7). It is notable that channel apertures as small as 1 mm will give groundwater velocities of tens or even hundreds of meters per day. Such velocities are usually much greater than estimates derived from assumptions that an aquifer behaves as an equivalent porous medium.

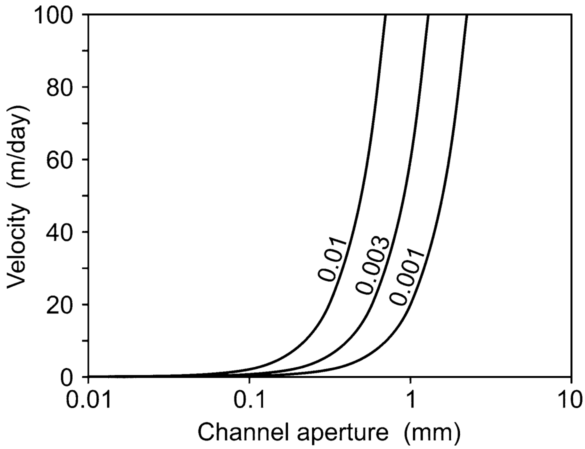

Fig. 11.7 Groundwater velocity along a circular channel, calculated from Poiseuille's Law

11.4 Water Supply Issues

Carbonate rocks outcrop over large areas globally and their high permeability ensures that their use for water supplies is widespread. However, the high permeability has a number of adverse consequences. One is that contamination can move quickly through these aquifers; this will be discussed in Sect. 11.5. A second consequence of the high permeability is that infiltration is high, often resulting in an absence of stream flow on the surface. The high permeability also results in low hydraulic gradients and in mountainous areas, this results in thick unsaturated zones. The lack of surface flow and thick unsaturated zones together mean that it is expensive to access groundwater since deeper wells are required, and the water has to be pumped to a higher relative level. Therefore, communities often rely on springs for their water supplies.

Groundwater divides in carbonates may differ significantly from surface water divides, especially where the unsaturated zone is thick. Administrative boundaries often coincide with surface drainage divides, and aquifers that cross such boundaries may create jurisdictional problems due to competing interests. In carbonate aquifer, tracer tests are often used to define groundwater divides. A further consideration in macrokarstic aquifers is that there is a low probability of a well intersecting the major channels so that most wells have low yields. These conditions make drilling wells in carbonate aquifers often more problematic than in simpler porous medium aquifers. Examples from England and from Texas will be described below to illustrate some of the problems associated with water supply from limestone aquifers.

11.4.1 Limestone Aquifers in England

Contrasts in groundwater abstraction from the Carboniferous Limestone and the Chalk in England exemplify the range of conditions that may occur. The Carboniferous Limestone outcrops in hilly areas such as the Mendip Hills and the Peak District, where the unsaturated zone is up to 200 m thick. Surface flow is absent in the hilly areas but there are streams and rivers in deep valleys that are incised down to the water table. There are many sinking streams and discharge from the aquifer is often from large springs (Atkinson 1977). The geometric mean transmissivity from 59 pumping tests in the Carboniferous Limestone is 22 m^2/day and the standard deviation of log transmissivity is 1.31 (Worthington and Ford 2009). The thick unsaturated zone, low average transmissivity, and high standard deviation mean that using wells to exploit the water supply is expensive and unpredictable. As a result, there are few wells on the limestone that outcrop and water supplies are often drawn instead from springs.

The Cretaceous Chalk outcrops in south-east England in a series of cuestas (Downing et al. 1993). The unsaturated zone is often >50 m thick in areas at higher elevation. There are few major sinking streams and discharge from the Chalk is predominantly from a large number of small springs at the margins of the Chalk outcrop. There are many water-supply wells over the outcrop of the Chalk although springs are also used. The Chalk provides more than half of groundwater abstraction in all of England due to it being the predominant aquifer in the south-east coincident with the highest population densities. The geometric mean transmissivity from 1,257 pumping tests is 440 m^2/day and the standard deviation of log transmissivity is 0.76. The high average transmissivity and low standard deviation are a result of the microkarstic nature of the aquifer, with many small channels (Schürch and Buckley 2002; Maurice et al. 2006). This also means that high-productivity wells can be more reliably drilled in the microkarstic Chalk than in the macrokarstic Carboniferous Limestone aquifers.

11.4.2 Edwards Aquifer, Texas, U.S.A.

The Edwards Aquifer is a Cretaceous limestone aquifer located in a semi-arid area with a growing population. It provides almost the whole water supply for San Antonio, a city with a population of 1.7 million people. The aquifer is about 150 m thick and dips to the south-east at about 1°. Rivers flowing from the north lose much of their recharge to the aquifer when they cross its outcrop (Fig. 11.8). To the south, the confined aquifer extends to depths of more than 1,000 m below the surface. The major natural points of discharge from the aquifer are at Comal Springs and San Marcos Springs, where mean flows are 8.2 and 5.0 m^3/s, respectively. Pumping from wells accounts for about half the total discharge from the aquifer (Hamilton et al. 2009).

Water flowing to Comal Springs comes from as far as 225 km to the west. This results in major inter-watershed transfers of groundwater from the Nueces and San Antonio watersheds to Comal and San Marcos Springs, which are in the Guadalupe watershed (Fig. 11.8). This is a remarkable example of how groundwater divides may differ from surface water divides.

Increases in pumping from the aquifer resulted in some of the springs becoming intermittent and the viability of federally-listed endangered species in Comal and

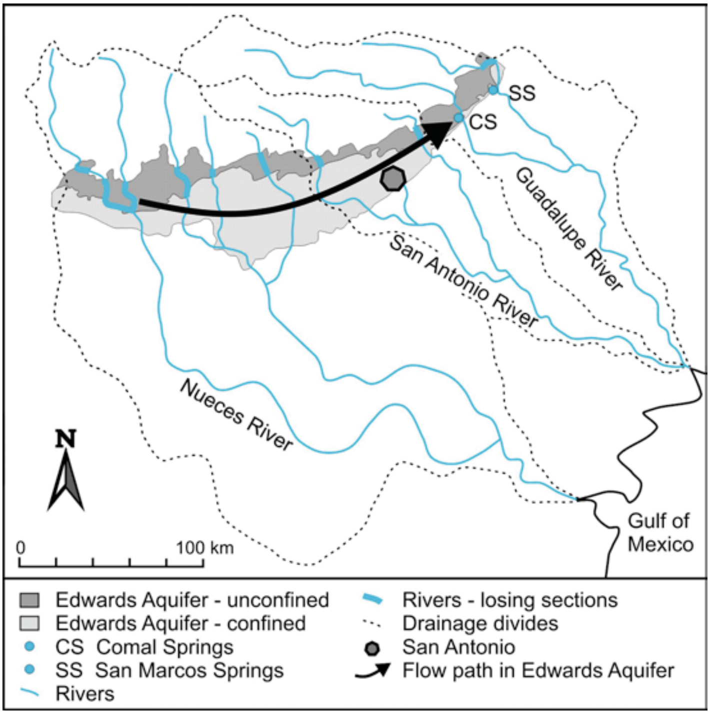

Fig. 11.8 Inter-watershed transfer of groundwater in Texas. Riverbed losses in the Nueces and San Antonio watersheds flow in the Edwards Aquifer to springs in the Guadalupe watershed (modified from Hamilton et al. 2009)

San Marcos Springs was threatened. Following a lawsuit brought by the Sierra Club in the 1990s against the U.S. Fish and Wildlife Service, the Edwards Aquifer Authority was formed to manage the aquifer. A permit system is now in use to limit withdrawals from the aquifer so that flows are maintained at the springs. In addition, a "critical period" plan is in place to reduce aquifer withdrawals when the discharge from Comal Springs or San Marcos Springs or the water levels in index wells in San Antonio or Uvalde falls below trigger levels (www.edwardsaquifer.org).

11.5 Contamination Issues

The presence of interconnected channels networks in carbonate aquifers means that groundwater can move rapidly through them (Figs. 11.3 and 11.4). It also means that contamination can move equally rapidly through them. For instance, a study of water quality was carried out in 1,174 wells in 16 major aquifers in the U.S., six of which were partly or wholly in carbonate rocks (Embrey and Runkle 2006).

Wells in carbonate rocks were more likely to be positive for total coliform bacteria, for *Escherichia coli*, and for coliphage than wells in any other rock type. Given the rapid die-offs of these bacteria in groundwater, this provides evidence of rapid flow of surface waters from a source of contamination through the aquifer system to the wells that were sampled.

Contaminant plumes in carbonates are substantially different from plumes in porous medium aquifers because the contamination will spread quickly along the channel network towards springs. At the same time, contaminant movement into fractures and the matrix of the rock may be several orders of magnitudes slower. Consequently, contaminant plumes in carbonate rocks are much more complicated than the simple oval shapes that are found in homogeneous porous media. Examples from Kentucky and Ontario will be described below to illustrate some of the problems associated with contamination in carbonate aquifers.

11.5.1 Gorin Mill Spring Groundwater Basin, Kentucky, U.S.A.

Detailed water table maps based on well data and using information from tracer tests and cave maps have given many insights on how the flow in carbonate aquifers is organized. The most comprehensive such map covers an area of more than 1,000 km^2 in Kentucky, and is based on more than 400 tracer tests and water levels in 1,500 wells (Quinlan and Ray 1989). Figure 11.5 shows an excerpt from this map. It depicts the 380 km^2 area that drains to Gorin Mill Spring, the largest spring in Kentucky. To the east and west, there are similar, though smaller, groundwater basins and these also drain to large springs on the Green River.

In the southern part of the Gorin Mill Spring catchment area, streams flow across impure limestones and then sink on reaching purer limestones. Consequently, there is no surface drainage in the northern two-thirds of the drainage basin. The flow lines represent the inferred paths of tracer tests. These are located largely along troughs in the water table, though in a few places it is possible to access underground streams. The largest of these is at Hidden River Cave, a show cave in the center of the city of Horse Cave. The tracer injections are at sinking streams, wells, or cave streams. The low heads along the troughs result in flow converging on these troughs, and all the tracer tests flowed to Gorin Mill Spring, a large perennial spring. Tracer tests in high flow demonstrated that there are overflow conduits that allow water to spill over into different parts of the basin. One of these conduits drains to Wilkerson Bluehole, a large spring on the Green River 6 km east of Goring Mill Spring (Ray 1997). There are a number of intermittent springs that discharge some of the flow from the basin during high-flow periods. Flow in the Gorin Mill Spring basin converges on large conduits that have diameters of 5–10 m. These form what is essentially a tributary network of conduits feeding one main spring, though with some distributary conduits.

Until 1912, the town of Horse Cave obtained its water from Hidden River Cave, which is located in the center of the town. Subsequently, municipal water was obtained from wells, and more recently from a spring 26 km away. Waste disposal from residences and industry was by means of septic tanks or directly into wells or dolines. Hidden River Cave was a show cave from 1916 to 1943, when it was forced to close due to pollution. In 1964, a sewage treatment plant went into operation. However, the plant was not capable of adequately purifying the incoming waste stream. This included wastes from a creamery and from a metal-plating plant. The contamination of Hidden River Cave continued and for many years the stench from the polluted water was noticeable through much of the cente of the town. In 1989, a new regional sewage treatment system went into operation and this effectively ended the half century of gross contamination of the aquifer.

Quinlan and Rowe (1977) sampled 23 wells between the sewage treatment plant and the Green River and also a number of springs close to the river. Effluent from the sewage treatment plant in Horse Cave had elevated concentrations of chromium, copper, nickel, and zinc, with chromium concentrations that at times exceeded 10 mg/L. Gorin Mill Spring and the nearby intermittent springs were all positive for these metals, but the 23 wells between the sewage treatment plant and Green River were all found to be negative. Tracer testing convincingly demonstrated why the apparently down-gradient wells situated in between the source and the springs were negative; this showed that flow from the sewage treatment plant was to several springs, but not to any of the 23 wells (Fig. 11.5). Flow in the aquifer converges on the major conduits, which provide pathways with very high permeability through the aquifer and thus occupy troughs where hydraulic gradients are very low. The springs represent the terminal points for the conduits where the groundwater discharges to the surface.

The groundwater studies carried out in this area of Kentucky demonstrate a number of ways in which carbonate aquifers differ from porous medium aquifers. Springs can be effective monitoring points since they may discharge the water recharge over considerable surface areas. Conversely, wells that are apparently down-gradient and even situated very close to a facility may not provide reliable monitoring points unless they can be shown by tracer testing to be on the flow path from that facility. Flow in most of the aquifer is convergent to conduits, but distributaries may be found close to the output point.

It is a common practice in North America to place monitoring wells down-gradient from a contaminated site and to sample them at fixed intervals such as monthly or quarterly. Such a monitoring program is unlikely to provide adequate sampling of contaminant transport where there are substantial conduits as the down-gradient conduit is most unlikely to be intercepted by a randomly-placed well. Furthermore, the rapid flow in conduits means that water quality sampling can be extremely variable in the short term, especially following major recharge events. Quinlan (1990) recommended that springs or wells that have been shown by tracer testing to drain the facility should be monitored, and that there should be frequent sampling through major runoff events. The advent of inexpensive submersible data loggers that measure head, temperature, and electrical conductivity has made this task of monitoring during major events much easier.

11.5.2 Bacterial Contamination at Walkerton, Ontario, Canada

In May 2000, about 2,300 people became ill and seven people died following bacterial contamination of the municipal water supply at Walkerton. Following groundwater and other investigations, a public inquiry, the Walkerton Inquiry, was held to determine the reasons why the water supply became contaminated (O'Connor 2002). It was found that the pathogenic bacteria were derived from cow manure. Such bacteria have rapid die-off in groundwater, implying that the travel time from the surface source to the wells was probably only days or less.

At the inquiry, two conceptual models of flow through the aquifer were presented. The first conceptual model was the one most commonly employed by hydrogeologists, that the aquifer behaves as an equivalent porous medium and that the effective porosity of the aquifer was similar to the total porosity of the aquifer, which in this case was about 5% (Golder 2000). This model also implicitly assumed that any productive horizons found in boreholes were isolated and did not form part of a high-permeability fracture/channel network. Modeling using MODFLOW showed that the 30-day capture zone at Well 7, the most productive municipal well, would extend about 150 m from the well (Fig. 11.1).

A second conceptual model assumed that the aquifer had a network of dissolutional channels. In this case, the relevant effective porosity for the transport of pathogenic bacteria through the aquifer would be closer to 0.1%. This porosity is known as the kinematic porosity (Worthington and Ford 2009). This estimate was based first on the cross-sections of the productive channels and fractures intersected in the wells. In Wells 5, 6, and 7, the number of horizons with measurable flow varied between one and nine and the sum of the cross-sections of these channels and fractures was estimated to be less than 0.1% of the cross-section of the boreholes (Fig 11.1). This indicated that the kinematic porosity of the aquifer would be <0.1%, assuming that the channels formed an interconnected network in the aquifer. The kinematic porosity estimate was also based on experience from many tracer tests (Fig. 11.3). If the kinematic porosity in the aquifer at Walkerton was as low as 0.1%, then groundwater velocities would be 50 times faster than with the first conceptual model and would likely exceed 100 m/day (Worthington 2001).

A post-audit was carried out in October 2001, after the hearings of the Walkerton Inquiry had ended. Tracers were introduced into Wells 6 and 9 and both travelled rapidly to Well 7 (Fig. 11.9). This demonstrated that the kinematic porosity of the aquifer was very low (<0.1%) and showed that the channels encountered in the boreholes formed part of an interconnected network, as is expected from theory (see Sect. 11.2 above). Calculations showed that the hydraulic apertures of the channels between injection wells and Well 7 were at least 3 mm (Worthington et al. 2002).

The tracer testing at Walkerton showed the importance of directly measuring travel times and how uncalibrated estimates based on porous medium assumptions may be extremely poor. The problems with such estimates were noted by Freeze and Cherry (1979, p. 427), who stated "velocity estimates based on the use of these parameters [hydraulic conductivity, hydraulic gradient, and porosity] in Darcy-based

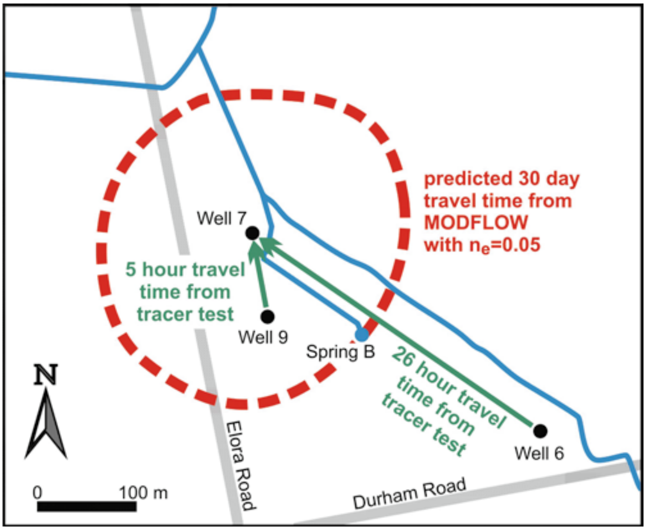

Fig. 11.9 Predicted 150 m diameter 30-day travel time zone to Well 7 at Walkerton, assuming an effective porosity of 0.05, and results from the post-audit introduced tracer tests that measured travel times from Well 6 and Well 9 respectively (from Worthington et al. 2002)

equations have large inherent uncertainties that generally cannot be avoided". The Walkerton Tragedy demonstrates how carbonate aquifers may be susceptible to bacterial contamination because of the presence of interconnected channel networks with concomitant rapid groundwater velocities.

11.6 Conclusions

Carbonate aquifers are common globally and are widely utilized due to their high permeability. Advances in recent decades in understanding dissolution kinetics have facilitated the numerical modeling of dissolutional enhancement of permeability. This has shown how the dissolution results in an interconnected network of channels that not only results in high permeability but also in rapid groundwater velocities.

In mountainous areas, the high permeability results in a lack of surface water and thick unsaturated zones, so utilization of groundwater is commonly from low-elevation springs. Groundwater divides may not coincide with surface-water divides, sometimes resulting in jurisdictional issues over exploitation of the groundwater.

Contamination from point sources travels down-gradient through channel networks to springs, so that springs are useful monitoring locations. Monitoring using wells is challenging as much of the contamination may travel along major channels and bypass wells. Contaminant movement into fractures and the matrix of the rock may be several orders of magnitudes slower than movement through the channels.

Consequently, contaminant plumes are much more complicated than the simple oval shapes that are found in homogeneous porous media. The rapid groundwater velocities in the channel network also make carbonate aquifers more susceptible to bacterial contamination than other aquifer types.

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Chapter 12
Management of Karst Groundwater Resources

Michel Bakalowicz

Abstract Karst aquifers are especially difficult to exploit, manage, and protect because of the extreme variability of their hydraulic properties which are almost impossible to determine at a local scale. Moreover, their functioning may be influenced by non-linearities and threshold effects. Considering long-term aquifer exploitation, karst system complexity does not allow for easy behavioral modeling, such as using the classical isochrone method for determining a protection zone. However, because karst aquifers may offer great storage capacity and high local hydraulic conductivity, high flow rates can be pumped from single sites, allowing for effective management of an aquifer. After outlining the main characteristics of karst aquifers, the management of their groundwater is examined from both quantity and quality viewpoints in order to highlight benefits and problems with this resource. Finally, some new avenues of research are proposed.

12.1 Introduction

Over the centuries, groundwater resources have not been well managed, regardless of whether or not they were karst aquifers. Since the end of the second millennium BCE, karst groundwater withdrawals were made at springs by means of water works and aqueducts as shown by archaeological remains in the Middle East (Bakalowicz et al. 2002). Some examples cited by archaeologists show that groundwater was also exploited from natural pits or from percolation in shallow caves.

Generally, the base flow of a spring is used for a town's water supply; however, when that resource becomes insufficient for the community, a new spring must be tapped. The development of the water supply of the city of Montpellier, France, is a

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good example of this exploitation of karst groundwater in Mediterranean regions. During the eighteenth century, when the town's wells yielded poor quality water, St-Clement Spring was captured and Henri Pitot built a 14-km long aqueduct (Aigrefeuille 1877) from the spring to the town. Initially, a flow rate of 25 L/s was captured but with the growing population, the aqueduct was extended during the nineteenth century to collect outflows from the Lez Spring, one of the most important karst springs in South of France. The total flow rate of the aqueduct was first doubled to 50 L/s, and then increased to 125 L/s in 1882, and to 250 L/s in 1899. The lowest natural base flow rate is approximately 350 L/s, hence not all the outflow is being captured.

For a long time, wells in karst areas were unusual because of the difficulty drilling in limestone which yielded low success rates. However, in areas where the epikarst is well developed and possesses shallow water storage, these waters are within easy reach of wells, and have been used since antiquity, for example, the limestone mountain in the dead cities of north-western Syria (Abdulkarim et al. 2003). The same extraction system was later developed in the karst plateaus of southern France. These examples correspond to what Collin (2004) calls the "gathering economy".

Water capture from karst aquifers changed with new drilling and pumping techniques, making groundwater easily accessible at depth. These techniques were only systematically used in karst since the 1950s, when the water needs considerably increased in western countries due to growing populations and related increased consumption, and the high water demand for agriculture. In addition, the blossoming tourist industry infrastructure demanded more water, especially in Mediterranean regions where often karst aquifers offered the only permanent water resource.

Initially, groundwater was exploited without a management plan, and usually without any knowledge of the functioning of the exploited aquifer. Frequently, an absence of competent management had (has) two serious consequences:

- A lowering of the water table, resulting in a seasonal, even permanent drying of wells, springs, and rivers, as observed in Southern Spain (Pulido Bosch et al. 1989) and in the Poitou – Charente Region in France (de Grissac et al. 1996) ;
- Diffusing pollution of groundwater mainly from agricultural activity or domestic waste water, or occasional salt water intrusion, which in some cases lead to the abandonment of the water resource.

This is what Collin (2004) terms "mining exploitation", i.e., a non-managed exploitation as it was practiced in Spain (Pulido Bosch et al. 1989). Managing karst groundwater should be sustainable and one approach is integrated water resource management (IWRM). Exploitation and protection are parts of an efficient IWRM in karst areas. Because of the distinct characteristics of karst aquifers, their delineation and boundary conditions require specific methodology, which is very different from that usually implemented in alluvium and fissured aquifers. If the correct methodology is not used, the consequences may be disastrous. Examples of drastic groundwater lowering, salt water intrusion, or heavy pollution are well documented (Pulido Bosch et al. 1989).

Aquifers contained with karstified bedrock are known to be problematic because of the considerable heterogeneity of its physical properties. For that reason, karst groundwater as a resource was not targeted while other more simple, predictable, porous, and fissured aquifers were developed and intensely exploited. The push for new water resources has lead to exploitation of karst groundwater, and the consequent need to improve knowledge about their functioning in order to benefit from them. Finally, there has been a movement to propose management approaches for optimizing the exploitation sustainably, and for managing the recharge area of the water resource to prevent or mitigate its pollution. This last aspect of karst aquifer management will be examined, incorporating both quality and quantity approaches which are in fact often related to each other. However, a short synthesis of karst aquifer properties will be introduced as a useful reference for the better understanding of karst groundwater management.

12.2 Main Characteristics of Karst Aquifers and Problems

The functional model of karst systems, shown in Fig. 12.1, is now well accepted by hydrogeologists (Bakalowicz 2005). The recharge area is the first component of a karst system (KS) to be considered. It may include both karst and non-karstic portions (non-carbonate formations), such as where river system is drained by swallow holes close to an impermeable – karst contact. When a KS includes a non-karstified rock, it is considered binary, recharged by both allogenic and autogenic recharge. When it is only karstified formations, it is a unary KS, recharged only by autogenic inputs. Allogenic recharge generally has concentrated inputs and supplies the rapid, concentrated flow inside the karst aquifer through wide conduits. This flow is an important source of pollutions and sediment to springs.

The karst aquifer itself is recharged through two very different modes: (1) A dispersed, diffuse-type infiltration, through cracks and narrow joints, which mainly occurs as a two-phase slow flow at the bottom of the epikarst; (2) A concentrated infiltration, which produces rapid flow through wide openings in the epikarst.

The epikarst is a vital component of karst aquifer because it forms the interface between the aquifer, soil, plant cover, and human activities, and is a key to distributing infiltrating waters (Bakalowicz 2004). It plays a major role in the development of conduits by determining whether solution processes are either close to the surface or at depth. It retains and mitigates pollution, particularly diffuse events, and delays recharge to the phreatic zone and consequently the recession of spring discharge. For these reasons, epikarst is considered a major cornerstone by methods assessing the vulnerability of karst aquifers (Doerfliger et al. 1999; Zwahlen 2005).

The main practical consequences of the complexity of flow in karst aquifers are the:

- *Exploitation of the resource*. Drilling a well for water utilization using a pumping station can be risky due to the very high heterogeneity of bedrock permeability,

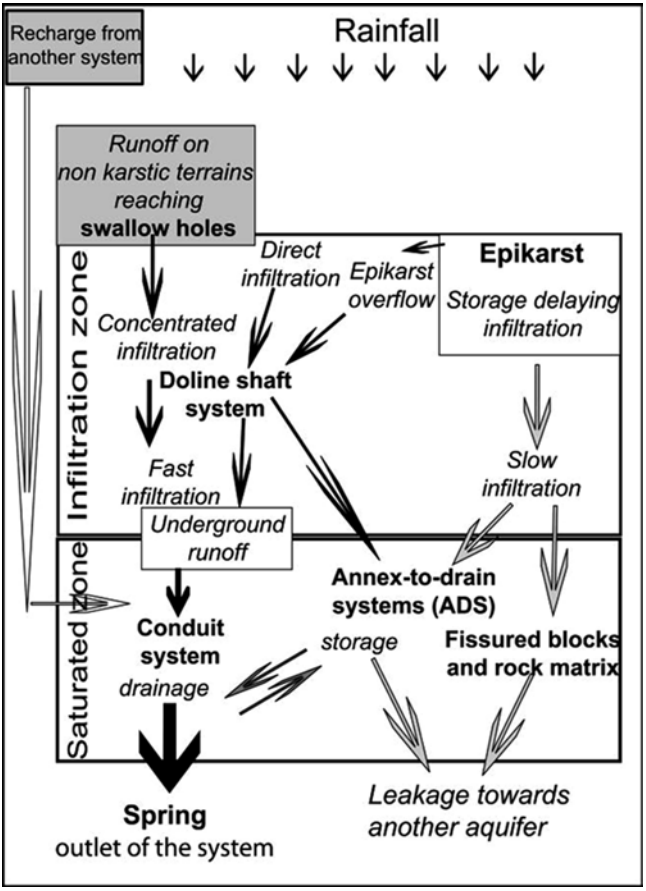

Fig. 12.1 The synthesis of the functioning of karst systems. Functions are written in italic, major components in bold

especially as the effects of pumping can impact wells located at several kilometres away without impacting closer ones.

- *Protection of the resource*. The determination of protection zones for wells often considers the whole recharge area as vulnerable, which imposes severe constraints on landuse for a large area surrounding the well. Moreover, the recharge area is often only estimated, and its limits are not well delineated, while the protection measures may appear inadequate.

The uniqueness of karst systems compared to other aquifers consists of the development of different, separated hydrologic components:

- Those draining the aquifer (conduits and open joints organized in a drainage system or "karst network"), where groundwater flows quickly, between 50 and several hundred meters per hour, as shown by tracing tests;

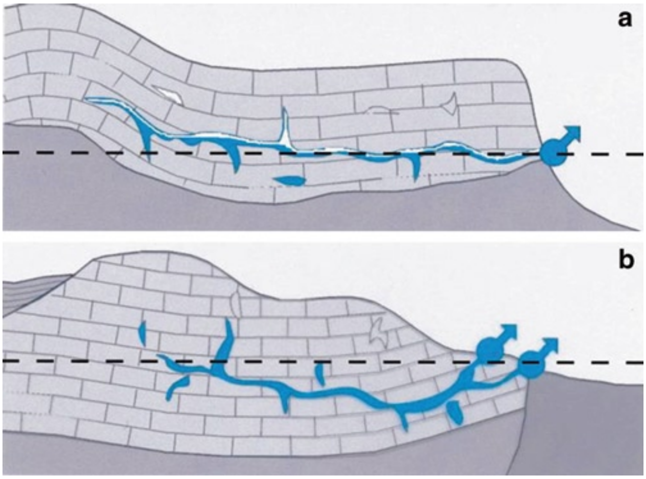

Fig. 12.2 Jura-type (**a**) and Vaucluse-type (**b**) karst aquifers. The cross sections show the conduit system with respect to the relative spring elevation represented by the dashed line and the development of potential storage below the spring level (from Marsaud (1997a))

- Those storing groundwater (porous matrix, or matrix blocks (Kiraly 1998), and karst cavities, the annex-to-drain systems (ADS) (Mangin 1994) which have poor hydraulic connections with the conduit system, allowing exchanges between them and the conduits, dependent on water head conditions and head losses.

Because storage and drainage are separate, it is especially important to know their respective part in the comprehensive functioning of karst systems and to be able to locate well sites while taking these two components into consideration. Moreover, knowledge of the position of the conduit system is absolutely essential. Marsaud (1997a) considers two organization types in karst aquifers (Fig. 12.2):

- *Jura-type systems*, where the conduits develop in the epiphreatic zone, i.e., in the zone of seasonal variation of the groundwater table. Flow in the main conduits, at least in some parts, may be surface-free flow. Water withdrawals from such karst systems by pumping at the spring or the well in the main conduit are controlled by the natural lowest discharge occurring during the low stage season; the exploitation flow rate cannot exceed the natural discharge of the conduit. The water reserves potentially developed around or below the conduits cannot be exploited by pumping.
- *Vaucluse-type systems*, where the conduits develop at depth in the phreatic zone. The flow in the conduits always occurs under confined conditions, where there is a permanent connection of the storage components through the conduit systems. Pumping in a conduit or in a storage area allows a significant drawdown controlled by the water head in the conduit. The extraction flow rate may be much higher than the natural flow at the spring by withdrawing water from storage due to the conduit connections pulling water from other storage sites.

12.3 Quantity Management of Karst Groundwater Resource

Due to the complexity and the variety of karst aquifers, the management plan of the groundwater resource has to be created on a case-by-case basis. No uniform “road map”, considering all the possible situations, exists for defining such a development and management plan. In the following sections, some guidelines will be outlined.

12.3.1 Active Management

Spring discharge is most often highly variable, due to seasonal changes in recharge. The ratio between minimum and maximum daily flow commonly varies from 1:4 to 1:100. In some cases, ratios occur up to 1:10,000 (Marsaud 1997a), which means that the base flow is too low to satisfy the water demand of a sizeable community. While the seasonally variable resource of a river may be regulated by resorting to artificial storage in dam reservoirs, the natural groundwater storage of a karst aquifer may be used for regulating the total withdrawals during base flow stage. Pumping aims at emptying more storage space, which will be recharged during the next rainy season. The best site for pumping is generally close to the main spring, directly in the main conduit, with the condition that its vertical development allows a significant drawdown, i.e., a Vaucluse-type conduit which drains up the whole phreatic zone, or at least a large part.

To do so requires knowledge of the aquifer resource, its seasonal variability, and storage capacity (dynamic storage in natural conditions), but also requires monitoring all withdrawals. Therefore, groundwater resources can be managed in the same way as a bank account; inputs and outputs are permanently monitored. Groundwater storage (savings) is used for regulating the total discharge, spring flow, and withdrawals. If storage is large enough, the theoretical total permanent withdrawal could be the mean annual discharge of the spring. In fact, European regulations require permanent flow in rivers fed by springs, the so-called “saved discharge”, so that part of the pumped groundwater must be discharged into the river bed downstream from the spring.

12.3.2 Evaluation of Resource and Reserves

Depending on the storage capacity value and on the length of duration of the season without recharge, it is possible to calculate the discharge which can be extracted from the reserves in addition to the natural discharge. Mangin (1974) proposed a method for evaluating the renewable storage of karst aquifers from the analysis of the spring hydrograph (Bakalowicz 2005; Ford and Williams 1989). Below is the example of the spring hydrograph of Fontaine de Vaucluse, France, for the 1997 hydrological year (Fig. 12.3).

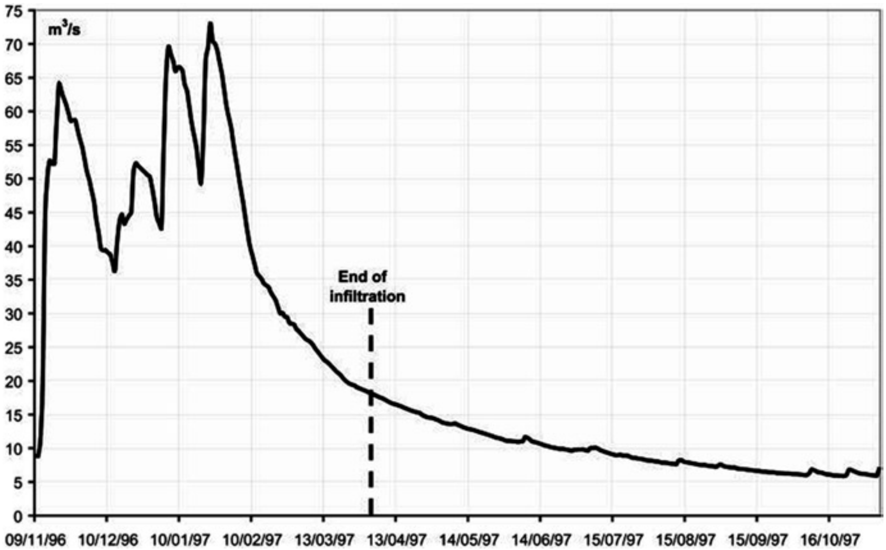

Fig. 12.3 Spring hydrograph of Fontaine de Vaucluse for the 1997 hydrological year

The characteristics of the recession of Vaucluse spring for the 1997 hydrological year (Fig. 12.3) are given in Table 12.1. Of importance are the characteristics of the phreatic zone, where most of the exploitable groundwater is stored. The dynamic storage, given by integrating the base flow hydrograph, according to Maillet's formula, is the volume of reserves in the phreatic zone which flows at the beginning of the base flow stage; it is an approach of calculating the lowest actual volume stored in the phreatic zone.

Drainage of the phreatic zone is quite fast ($\alpha = 0.0065$ day^{-1}) due to the highly karstified nature of the reservoir. The dynamic storage is important, with 359 million m^3, of which 226 million m^3 remains stored at the end of infiltration, which can be considered the beginning of the base flow stage. These 226 million m^3 of groundwater form the renewable storage which can be considered for extraction in the active management of the resource.

From the hydrodynamic characteristics of the infiltration and phreatic zones, Mangin proposed a classification method of karst aquifers, recently discussed and modified by El-Hakim and Bakalowicz (2007). The classification (Fig. 12.4) considers two indices, one related to the infiltration i, the infiltration delay between 0 and 1, and the second, k, related to the phreatic storage. The higher the i index, the slower the recharge flow to groundwater.

The k index, named regulating power (Mangin 1994), is the mean residence time, calculated by dividing the highest observed dynamic storage (m^3) by the mean annual transit volume in m^3/year (El-Hakim and Bakalowicz 2007). Most classical karst systems show that their regulating power is less than 1 year.

Table 12.1 Main characteristics of the recession of Vaucluse spring hydrograph during the 1997 hydrological year. They were calculated according to Mangin's method (Ford and Williams 1989)

Discharge at t_0 (23 Jan 1997)	73 m^3/s
Discharge at end of recession (6 Nov 1997)	6.9 m^3/s
α (low stage coefficient)	0.0065 day^{-1}
epsilon (coefficient of infiltration heterogeneity)	0.06 day^{-1}
Discharge of the phreatic zone at time t = 0	27 m^3/s
t_i (infiltration duration)	70 days
Q_0 (Q max at time t = 0, the beginning of the flood)	73 m^3/s
q_0 (infiltration discharge at t = 0)	46 m^3/s
eta (mean infiltration "velocity")	0.0143 day^{-1}
i (infiltration delay)	0.87
Nash criterion (quality of the simulation)	97.71
Dynamic storage	359 million m^3
Remaining dynamic storage at t_i	226 million m^3
Volume of infiltration	71 million m^3

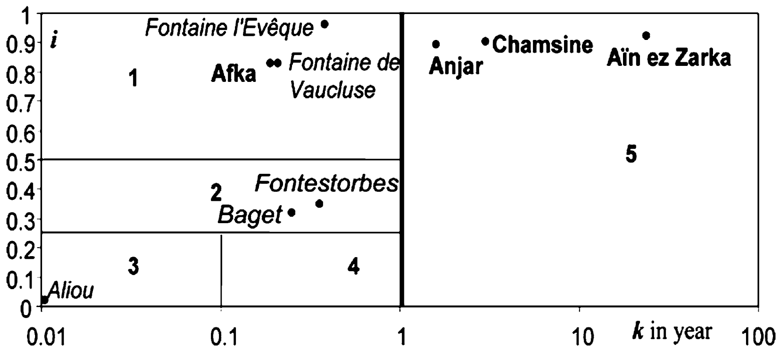

Fig. 12.4 Classification of karst systems from the recession analysis, accounting for karst systems with very large dynamic storage, corresponding to very long residence times (El-Hakim and Bakalowicz 2007)

The classification considers five domains, named 1–5 (Fig. 12.4), with the following characteristics:

1. $k<0.5$ and $i>0.5$: The domain of complex karst systems, very extensive and made up of several sub-systems;
2. $k<0.5$ and $0.25<i<0.5$: Systems where karst conduits are more developed in their upper regions than those closer to the spring, and characterized by a delayed recharge because of either non-karstic terrains, snow, or sediment cover;
3. $k<0.1$ and $0<i<0.25$: Intensely karstified systems in both the infiltration and phreatic zones, with a well developed conduit system directly connected to the spring;

4. $0.1 < k < 0.5$ and $0.1 < i < 0.25$: Systems with a well karstified infiltration zone and an extensive conduit network ending in a flooded phreatic zone;
5. $k > 1$ and $i > 0$ (in fact i should be > 0.5): Systems with a deep phreatic zone, partly or totally confined underneath impermeable sediments, and largely karstified during previous karstification phases. These karst systems named "non-functional karst systems" (13) which possess a large storage capacity due to a complex drainage structure partly or totally flooded are responsible for very long, multi-year, or secular residence times. However, the paleo-conduit networks existing in their phreatic zone remain partly functional.

From the exploitation and management viewpoint, the most useful aquifers are those of domains 1 and 5, with k values exceeding 0.1. Aquifers of karst systems classified in domain 2 may have limited utility, but only if the storage capacity is large enough to allow the regulation of the exploitation flow rate.

12.3.3 Modeling Aquifer Functioning for Managing the Resource

There have been many attempts to model the functioning of karst aquifers and conferences were specifically dedicated to this important issue (Palmer et al. 1999; Ford and Williams 1989). In managing karst groundwater resources, it is essential to predict the evolution of the spring flow and storage depending of rainfall and outflow. Modeling is then a necessary tool for predicting water levels and spring flow rate. However, when compared to porous and fractured aquifers, karst aquifers present a complexity which makes them difficult to model, such as the huge heterogeneity of the hydraulic characteristics, non-linearities and threshold effects, and the location of the conduit system. In a recent paper presenting a model for simulating the spring hydrograph of Fontaine de Vaucluse and predicting them by modeling (Fleury et al. 2007a), different types of models were presented in a short and very useful analysis.

Two types of models were used:

1. Physical or mathematical models, where heterogeneity may be taken into account by introducing several levels of porosity or permeability, such as in dual porosity models, and sometimes conduits. These models need huge amounts of data and are too complicated to be used for managing groundwater resources. Moreover, distributed models like MODFLOW are not adapted to simulate karst aquifer functioning because spatial heterogeneity is so large that it is impossible to obtain the necessary data.
2. Lumped or rainfall – runoff models, which consider that the aquifer functions as a set of reservoirs, whose characteristics are either obtained from spring hydrograph analysis.

All lumped models are particularly well suited to simulate spring hydrographs from rainfall, for instance at a daily time scale. Black-box or grey-box models, based on deconvolution or a simple or even complex transfer function, use either the time series analysis as proposed by Box and Jenkins (Mangin 1984) or neural networks. Among all the lumped models, the reservoir models are especially interesting because they give a rough representation of the aquifer whose behavior is broken up into several parts identified with its main components. However, they can be used only on the condition that the input function and the system functioning itself are stationary. This is true if the rainfall time series is not concerned with a drastic climate change, or if the system was not subject to physical changes, e.g., plugging or deplugging of conduits, high rate pumping. A reservoir model was developed using the Vensim© simulator in order to simulate spring hydrographs of some French karst springs, such as Fontaine de Vaucluse (Fleury et al. 2007a) and the Lez Spring (Fleury et al. 2009) on a daily time series for several years.

12.3.4 Different Types of Approaches for Capturing Groundwater

Karst groundwater may be exploited generally from sites not located in the conduit system. Possible sites are represented on a schematic diagram of karst system (Fig. 12.5). Pumping directly in the spring (site 1, Fig. 12.5) is possible if the spring is largely open and if the conduit is of the Vaucluse type, in order to lower as much as possible, the water table to draw down the reserve.

When the aquifer is of Vaucluse type, it may be more effective to pump from a well intersecting the drain at a depth lower than that of the spring (site 2, Fig. 12.5).

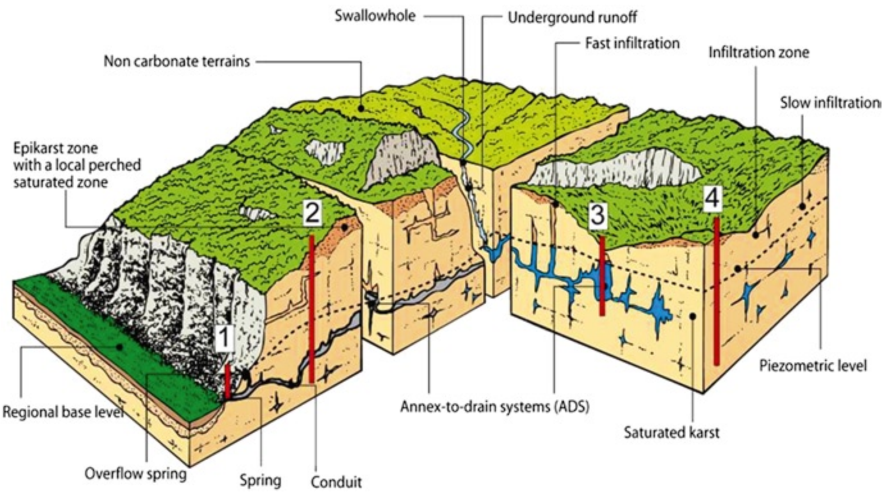

Fig. 12.5 Schematic representation of karst system (modified from 12) with the four different positions of pumping sites. *1* pumping directly in the spring. *2* pumping in (one of) the main conduit(s). *3* pumping in an annex-to-drain system (ADS). *4* pumping in a matrix block

The main difficulty is to locate the conduit from the surface. Geophysical methods are generally ineffective at revealing conduits or voids at depths more than 30 m (Al-Fares et al. 2002). When the conduit is accessible, it can be located by means of magnetic positioning, with a magnet and a proton magnetometer. This method was used for positioning boreholes intersecting a conduit at depths up to 300 m below the surface (see the case study). Pumping rates may be very high, limited by the highest possible drawdown.

When the well reaches an ADS (site 3, Fig. 12.5), usually by chance, the extraction efficiency is maximal in a Vaucluse-type aquifer, because the main conduit provides hydraulic continuity between all storage sites within the phreatic zone because it is located within confined conditions. However, in Jura-type aquifers, there is little hydraulic continuity between conduits; the ADS reached by the well acts as a local reservoir where storage is only supplemented when water levels are higher in the adjacent conduit. Then, the pumping rate may be temporarily higher than the natural flow in the conduit, because the natural flow is augmented by the volume withdrawn from the ADS. However, the volume of ADS, which is a small part of the dynamic storage of the whole aquifer, cannot be evaluated by means other than long-duration pumping tests (several weeks or even months (Marsaud 1997b)).

When the well does not reach a conduit or an ADS, statistically the most common situation (site 4, Fig. 12.5), the scenario does not favor a high pumping rate. Generally, the resource cannot be exploited from such sites. However, in some cases, especially in aquifers with a shallow water table, karst features are well developed in the phreatic zone so that the wells may intersect many enlarged joints which allow viable pumping rates. Under such situations, well fields may be developed, allowing the extraction of significant water quantities, comparable to those of alluvium aquifers. At Wadi Jilo, South Lebanon, a field of five wells in karstified upper cretaceous limestone are pumped at approximately 4 hm^3/year, i.e., 100 m^3/h for each well, suggesting relatively high hydraulic conductivity for the local aquifer (Mroueh 1997).

12.3.5 The Question of Interpreting Pumping Tests

Despite the fact that the assumptions behind the application of different models used to analyze pumping test data are not pertinent to karst aquifers (Al-Fares et al. 2002), most hydrogeologists still calculate hydraulic conductivity and storability. Those results can only be considered as general estimates, whose accuracy remains generally unknown. Moreover, these tests are often conducted over only a few days, which is too short a time to assess the effects of drawdown in a poorly transmissive medium. These results tend to be more indicative of conditions in the immediate vicinity of the well or around the conduit, if intersected by the well. From some recent tests undertaken in France by BRGM (Ladouche et al. 2006), it appears that several weeks or, better still, a few months of pumping at a rate in the same order of magnitude as the spring is the most informative method. For the moment, no numerical method of interpretation has been developed for interpreting pumping test in karst aquifers under high pumping rates over long periods.

12.3.6 Underground Dams

In highly developed karst aquifers, especially in binary KS, conduits drain most of water during a rainy season. Consequently, the storage may be trivial while the resource may be important, but great seasonal variation makes it unusable. Chinese engineers created underground reservoirs by damming conduits, either partially or totally (Bakalowicz et al. 1993). They observed that it is more efficient to build the dam inside the large conduit, not at the outlet itself because leakages occur in the shallow zone, where joints are mechanically open by the decompression occurring on the valley sides within the first 10 m below the ground surface. In South China, at Muzhu Dong, a dam completely sealing a conduit (Fig. 12.6) allowing storage of more than 3 million m^3 is used during the dry season for irrigation and water supply.

Milanovic (2000) provides several interesting examples of underground dams partially or completely sealing karst conduits in China. In order to avoid overpressure behind the dam, overflows are developed by enlarging fractures or pumping stations may pump directly into the flooded conduit from a natural pit. Some of these dams are also developed for producing electricity via an underground waterfall.

a

b

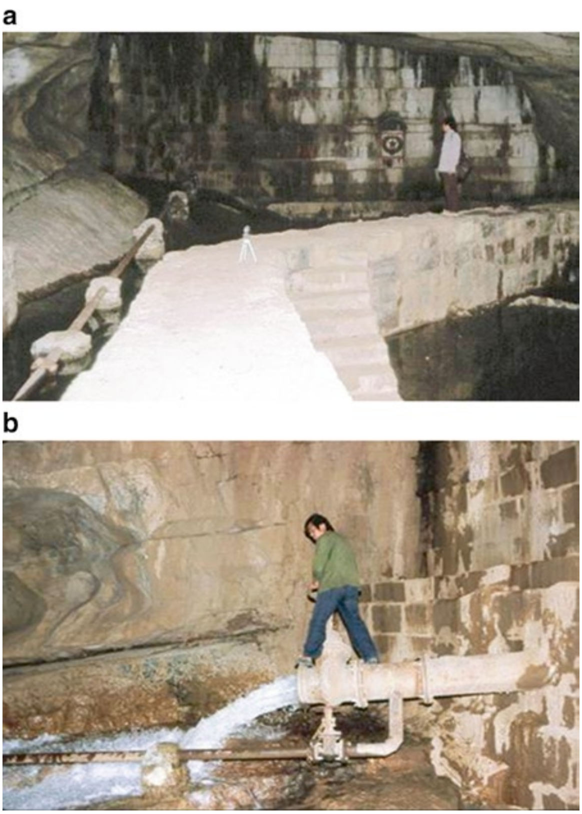

Fig. 12.6 Underground dam in Muzhu Dong Cave, Guizhou Province, China

12.3.7 Enhanced Recharge and Proactive Management

Managed Aquifer Recharge (MAR) is an emerging sustainable technique that to date has been successful in community, economic, and political spheres and is expected to solve many water resource supply and management problems, especially in the semi-arid and arid regions. Where karst aquifers are highly sensitive to overexploitation and seawater intrusion (Fleury et al. 2007b), the use of MAR could be helpful for augmenting storage in the aquifer by injecting excess water from local rivers during the rainy season, the result of which may even improve the quality of groundwater. MAR techniques (Dillon 2005) may present interesting possibilities for karst aquifers which offer exploitable groundwater resources, especially those in Mediterranean areas (Margat 2008). However, the technique has only been used in Australia (Vanderzalm et al. 2009), and there are a few similar pilot projects conducted in the USA and elsewhere.

The main difficulty in applying MAR, which is being presently explored (Daher 2010; Bakalowicz et al. 2008), is the selection of an appropriate site and method of injection. The direct injection through wells is probably not the best approach because, according to what was previously shown from pumping tests, if the injection is done directly into a conduit, water will be quickly flow away and will not be stored. It seems that the best method could be to inject water in the infiltration zone, in areas where it will not quickly reach the phreatic zone. When this method is refined, it will allow for more proactive management of karst aquifers.

12.3.8 Non-conventional Resources and Karst Aquifers

In order to satisfy the increasing demand for water, the search continues for new sources. When all known natural resources are already exploited, non-conventional resources are then considered by stakeholders. Desalinated water, treated water (Parizek 2007), and submarine groundwater discharge (SGD) are the three main non-conventional resources, in addition to reducing leakage and water conservation.

Some desalination plants in Spain (Pulido Bosch et al. 2007) prefer to pump brackish groundwater from coastal aquifers rather than sea water. Some pumping sites use groundwater from karst aquifers. However, with increasing costs of energy for desalination, an alternative may be to directly capture the fresh water of SGD from karst submarine springs (KSS). The frequent occurrence of KSS's along the Mediterranean coast has been well known since antiquity. However, only recently have they been considered as a potential, non-conventional resource that may satisfy increasing water needs. Several studies reported that KSS's along the Mediterranean coast may discharge several million to billion m^3 per year (Khawlie et al. 2000; Ayoub et al. 2002). However, the methods of those evaluations did not seem reliable and more detailed studies were undertaken in order to measure or at least evaluate the SGD from Mediterranean KSS's and to determine their origin and the reason for their particular abundance in the Mediterranean basin.

Recent investigations (Fleury 2005; Arfib et al. 2006; Cavalera et al. 2006; El-Hajj 2008; Al Charideh 2007) show that the flow rate of fresh water from KSS's had been greatly exaggerated due to the inappropriate methods and often these springs discharge brackish water during base flow. Moreover, Fleury (2005) in France, Fleury et al. (2008) in Spain, and El-Hajj (2008) in Lebanon, have shown that slight modifications in the natural as well as artificial conditions of discharge at the spring may contribute to uncontrolled intrusion of sea water. In addition, pumping at an on-shore well, even at a low rate, may stimulate sea water inflow into open conduits far inland from the coast. The reversal of flow at a permanent submarine spring was caused by an onshore pumping test at Chekka Spring in Lebanon (El-Hajj 2008).

As a consequence, coastal karst aquifers appear as particularly sensitive to every human action; therefore, their utilization must be undertaken with great caution. Detailed knowledge of their functioning, seasonal behavior, and relationships with sea water is the prerequisite to any management plan. It is necessary to reconstruct the recent evolution of the regional geology with the objective to determine the effects of the changes of the sea level. The dire need for this knowledge is shown in the Messinian crisis of salinity in the Mediterranean Basin (Rouchy et al. 2006).

The Fleury (2005), Fleury et al. (2007b), and El-Hajj (2008) studies focused on the possibility of capturing fresh water from KSS. Where SGD occurs offshore directly from a limestone formation, KSS's work generally in the same way as an onshore spring. Their discharge is highly seasonal, and overflow springs may work during floods, when the water head increases in the conduit system (Rouchy et al. 2006; Fleury et al. 2007b). However, the submarine overflow springs appear deeper than the main springs, while other overflow springs may also occur onshore. The evaluation of their discharge by different methods shows that earlier estimates were 10 or 20 times the actual values, which thereby reduced their economic significance. Moreover, the very important seasonal change in hydraulic head in the conduits and the occurrence of conduits open to the sea at different depths would create conditions favorable to natural sea water intrusion, potentially far inland. The situation may worsen if a pumping well is installed directly in a major drain. Because the sea water intrusion and the resulting mixing change considerably with hydrological conditions, the SGD water presents a wide range of salinity from 0% during floods to consisting of >60% sea water. Generally, such values suggest that KSS's cannot be considered as a future alternate non-conventional resource in coastal zones, despite the claim that their discharge might be considerable.

12.3.9 A Case Study: Lez Spring, France

Detailed studies using appropriate methodology and permanent monitoring can allow the sustainable use of karst groundwater. The best example is from Lez Spring, which was bought by the city of Montpellier, in Southern France. This spring was tapped during the nineteenth century to supply Montpellier and its suburbs by way of a 16 km long aqueduct. Until the 1960s, only natural base flow, around 300 L/s, was withdrawn. In 1969, a pumping station installed in the spring itself extracted

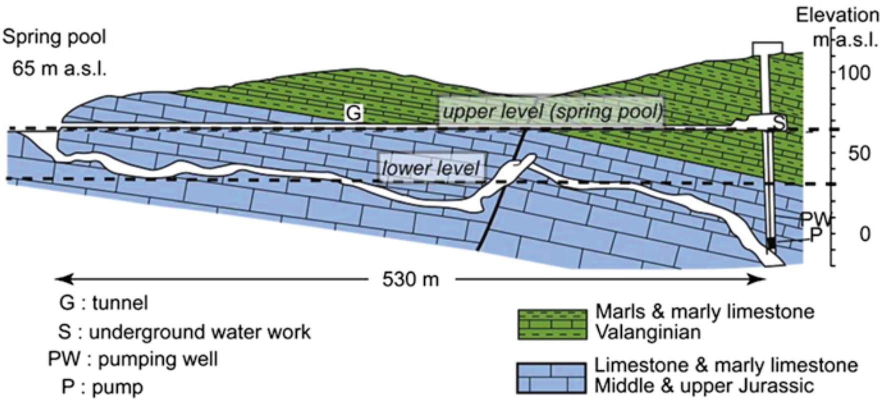

Fig. 12.7 Cross section of the Lez spring, with the main conduit, the pumping station and the upper and lower groundwater levels (source: Bakalowicz (2006))

~600 L/s, with a drawdown of 8 m. The pumps could not be placed deeper because of the shape of the conduit.

With increasing population and corresponding water demand, two conflicting projects arose during the 1970s. The first proposal was to supply Montpellier area with water from the Rhône River, which was already partly utilized for irrigation via a canal. However, the water was polluted by chemicals and hydrocarbons from the industrial zones of the city of Lyon, and needed special treatment to allow its use. The second project supported by several hydrogeological studies and proposed by Avias (1995), showed that the Lez Spring Aquifer was not recharged by concentrated infiltration from the main rivers and its storage capacity is large enough to allow a pumping rate ~1,500 L/s. These two projects involved different technical and economic approaches. After a long dispute, augmenting the city's water supply using the aquifer was the proposal finally chosen by the municipality. Thirty years of extraction without overuse shows that the chosen solution and the management method worked perfectly thanks to accurate knowledge of the aquifer characteristics.

Since 1980, four wells were installed 500 m upstream of the spring, crossing the main conduit 75 m below the spring level, i.e., at −10 m below sea level. The extraction flow rate is on an average 1,300 L/s (41 million m^3/year), with a maximum of 1,500 L/s, while the mean inter-annual flow rate is around 2,250 L/s, with a range of 40 and 90 million m^3/year (1981–2003). The new pumping station and the conditions of withdrawal were designed after detailed studies (Avias 1995; Bakalowicz 2006), have been controlled and modeled (Fleury et al. 2009) and are strictly defined by regulations. Thanks to the monitoring network, no overexploitation and pollution has occurred. Figure 12.7 shows a cross section of the spring area, with the pumping station and the upper and lower groundwater levels.

Lez Spring is neither the first nor the most important pumping site exploiting a karst aquifer with increases seasonally in withdrawals. Many Mediterranean cities use karst groundwater resources for their water needs. Damascus, probably the largest city to do so, uses two large karst aquifers (Kattan 1997). The main spring at

Figeh is pumped at a rate ~3.5 m^3/s. However, increasing demand and the erratic recharge in a semi-arid environment make its exploitation a difficult challenge.

However, there are two approaches for the use and management of regional water resources that are in direct opposition to one another. The exploitation of surface waters requires building reservoirs for regulating their natural flow and canals for transferring water. However, when groundwater is available, especially from a karst aquifer, it may also an important flow, often does not require canals due to its pre-existing conduit system (particularly when close to the spring), can have potentially huge reserves, and allows the natural control of withdrawals temporarily larger than the natural flow.

12.4 Quality Management of Karst Groundwater Resource

In porous and fissured aquifers, which when considered at an appropriate scale, can be delineated into homogeneous, protection zones using isochrones, i.e., lines corresponding to equal transit time to the spring or well captured for water supply. According to national or regional regulations, the 40-day or 50-day isochrone represents the upper limit of the protection zone. It is considered that a residence time of 40–50 days is sufficient for eliminating all pathogenic bacteria and to control the arrival of pollutants.

In karst, the presence of surface features, well connected to conduits and zones of preferential flow up to several tens of kilometres in length, would oblige the consideration of the whole recharge area, comprising even the non-karst regions. Until recently, such an approach led stakeholders to an impasse and scientists to look for a more appropriate method (Doerfliger et al. 1999; Zwahlen 2005). The issue is that many karst systems are large, from several tens or hundreds of km^2, hence it is impossible to impose strict conditions in terms of planning and control of human activities in such an area.

A final issue is how to determine the vulnerability of a karst system. This chapter will not give a detailed description of the different methods proposed by the European Action COST 620 (Petelet-Giraud et al. 2000) and subsequent individual karst research efforts. They are somewhat identical in their approach, so briefly presented here is the RISKE method (Petelet-Giraud et al. 2000) which was developed following the EPIK method (Doerfliger et al. 1999); because EPIK requires too many data, and is impossible or too expensive to collect for large karst systems.

Vulnerability mapping methods are inspired by the DRASTIC method (Aller et al. 1987). DRASTIC was developed by the US Environment Protection Agency for assessing the intrinsic vulnerability of groundwater to pollution. It is based on numerical counting of parameters considered for vulnerability mapping (depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, and hydraulic conductivity). Instead of these parameters, some of which are not important in karst, the RISKE method has five criteria:

- Reservoir rock (R),
- Infiltration potential (I), only function of the terrain slope,

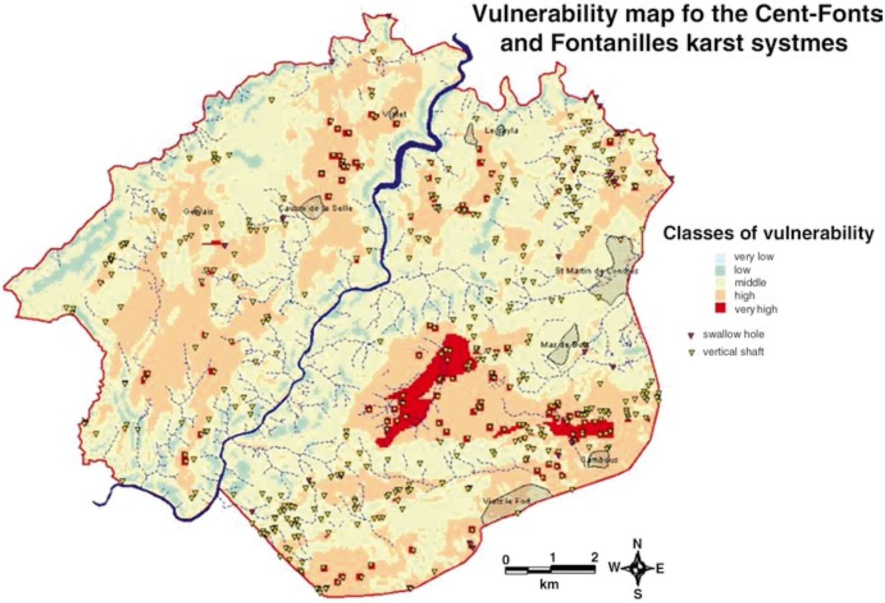

Fig. 12.8 Vulnerability map of Cent-Fonts and Fontanilles karst systems north of Montpellier. Areas in red are the most vulnerable to pollution while those in light blue are the least vulnerable (from Petelet-Giraud et al. 2000)

- Soil (S), often grouped together with the epikarst (E), and
- Development and behavior of karst (K).

Some of the criteria are obtained directly from existing documents: Geological map for R, topographical map for I, soil map for S. The epikarst E is mapped from field observations and a karst database. The karst behavior is determined for the whole system from literature and field observations. A synthetic map is finally built by allocating at each mesh or points of the grid a value of vulnerability calculated by:

$$V = a * R + b * I + c * S + d * K + e * E$$

V is the vulnerability in the considered mesh, and a, b, c, d, and e are coefficients of the considered criteria R, I, S, K, and E. These coefficients are rated according to the importance of each criterion, and must be tested for each study site. The experience shows that epikarst together with soil is certainly the most important criterion in mitigating pollution, either diffuse or concentrated. The final map describing the vulnerability of groundwater resource is one component to be considered during the process of creating resource protection zones. Figure 12.8 presents an example of vulnerability map using the RISKE method on two karst systems north of Montpellier, France (Petelet-Giraud et al. 2000). Areas in red and pink are the most vulnerable so that particular protection measures must be taken in order to protect the groundwater resource in those locales.

12.5 Conclusions

On a practical level, karst aquifers often provide an important groundwater resource. They can be highly productive, with rapid discharge through conduits and large cavities, though these are difficult, if not impossible, to locate from the surface. The complex evolution of karst due to changes in base level, particularly in Mediterranean regions, may give them a large storage capacity which is the key for long term withdrawals at high pumping rates, if combined with well informed regulation.

Methods now exist for karst systems that are very different to those used for porous aquifers, allowing the exploitation, management, and protection of karst water resources. Examples show that the exploitation must be based on the analysis of aquifer functioning and monitoring in the vicinity of the spring. However, the exchange of experiences comparable to what was done in Europe for the protection of karst resources is absolutely necessary for improving the methods and adapting the regulations to this complex medium, that is karst.

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Chapter 13
Management of Groundwater Species in Karst Environments

William F. Humphreys

Abstract Carbonate karst is characterized by subterranean drainage and contains the most biodiverse groundwater faunas globally. These faunas, which include a suite of higher taxa largely restricted to karst subterranean waters, comprise species that characteristically are narrow range endemics. They typically possess a suite of adaptations to subterranean life that render them especially vulnerable to anthropogenic disturbance. Most such faunas depend on imported energy, largely in the form of dissolved organic carbon, or on chemoautotrophic energy in particular circumstances. Karst is especially vulnerable to surface inputs at both local and broad scales owing to the absence of, or thin soil cover, and by the presence of open conduits that can transport materials such as sediments, pollutants, or nutrients to the deep subterranean waters without amelioration. Management actions – such as sustaining water supply, control of pollution and nutrification, regulating resource extraction, catchment surface management to sustain recharge and prevent siltation, and control of human access – may need to be applied at very different scales, ranging from a small cave, or extending to an entire catchment which may comprise extensive areas outside the karst itself.

13.1 Introduction

Karst is characterized by the predominance of subterranean drainage, the fauna of which this chapter is concerned. Karst is renowned for hosting obligate subterranean species (stygobionts) and the first such species described was the Olm, *Proteus anguinus* Laurenti, 1768, a blind, depigmented, salamander inhabiting cave streams

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in the classical Kras (karst) area of Slovenia, believed in mediaeval times to be the dragon larvae. Stygobionts often comprise ancient relictual lineages isolated underground millions of years ago, but this is not always the case. So, the evolution of subterranean life is a continuing process and the movement of fauna or the flow of genes between surface and subterranean populations needs to be maintained. Consequently, the thresholds to the subterranean world, including springs, caves, and sinkholes, are important elements in the management of groundwater fauna in karst. For the purpose of this chapter, I group all underground waters inhabited by fauna within the term groundwater although drips, pools, underground rivers, and streams within caves are not typically referred to as groundwater.

The last two decades have seen the recognition of groundwater as a significant source of biodiversity (Danielopol et al. 2000) that warrants protection both in its own right (Danielopol 1998) and also for the provision of environmental services of direct bearing on human well being (Boulton et al. 2008). The karst areas of the world support the most diverse assemblages of subterranean aquatic species (var. stygofauna, stygiofauna) and this chapter raises issues pertinent to their management and conservation.

Groundwater ecosystems have been recognized as dynamic systems comparable in complexity to surface ecosystems (Rouch 1977; Gibert et al. 1994), although they lack primary production. Although within cave species richness (α-diversity) is not especially great (Culver and Sket 2000), the great change in species composition between systems/karst areas (β-diversity) results in a high species richness in larger regions (γ-diversity). In some areas, the species richness of groundwater fauna exceeds that in surface waters, an increased knowledge that has arisen through both greater research effort and as a result of molecular analyses showing that there are many cryptic species in groundwater (Bradford et al. 2010). Consequently, previously widespread species are recognized to comprise an array of species each more circumscribed geographically, that is endemic to quite small areas (Proudlove and Wood 2003; Page et al. 2008; Trontelj et al. 2009; Zakšek et al. 2009). Elsewhere, it has arisen as a result of research in areas previously considered lacking in groundwater fauna, such as in Australia where more than 750 species of groundwater fauna were reported within about a decade (Humphreys 2008). The Balkan Peninsula is the longest most thoroughly researched karst region with more than 650 stygobiont species (plus 975 species of troglofauna; Sket et al. 2004) and Slovenia has the highest density of stygobionts with 114 species (Culver et al. 2004). Whereas six European countries (Belgium, France, Italy, Portugal, Slovenia, Spain) combined harbor 1059 stygobiont species (Michel et al. 2009), only 269 species of stygobiont are known from the 48 contiguous states of USA (Culver et al. 2003), with no more than 80 species in any karst region. Strategies for conservation of cave fauna on a regional basis, beyond the scope of this chapter, are addressed elsewhere (Culver et al. 2001; Ferreira et al. 2007; Gibert and Culver 2009**;** Malard et al. 2009; Michel et al. 2009).

The management of groundwater species in karst environments typically invokes images of cave streams and pools, and sometimes springs, but it requires consideration of a far wider range of subterranean habitats to encompass the entire karst ecosystem (Rouch 1977), and at a much larger scale, the extent of which may extend far beyond the karst system itself. The nature of karst, its past and present climatic, altitudinal, geomorphic, cultural, and developmental contexts vary widely both within and between biogeographic regions and nations. Consequently, it is not appropriate here to prescribe management practices but rather to raise some general principles and issues pertinent to the karst manager when contemplating the management of groundwater fauna in their particular circumstance and what needs to be considered and what questions need positing of researchers. Thus, it is not intended to provide a comprehensive coverage of the management issues, rather, to provide a guide to the issues of which managers needs to be aware and to provide pointers to where the information may be found or what direction research may need to take to address the management issues.

The management of each karst basin faces a unique set of circumstances for which it is not possible to be generally prescriptive. Humphreys (2002) identified three needs for groundwater fauna – a place to live, food, and oxygen – in order to focus attention on essential general elements of groundwater ecology without prescription. He further developed a string of issues that were known to impact groundwater fauna generally, or that may be expected so to do by extrapolation from surface waters or general ecological principles (Humphreys 2009).

The European PASCALIS project, comprising the karst rich nations of Belgium, France, Italy, Portugal, Slovenia, and Spain, is the first international attempt to assess groundwater fauna with a view to optimizing conservation planning (Michel et al. 2009). The general issue of conservation of subterranean fauna at a regional, national, and global scale is not covered here but is addressed in Culver and Pipan (2009) with leads to the pertinent literature.

To provide background to the conservation of karst aquatic fauna, there are many books and manuals dealing with the details of karst and water management at various levels of detail. Exemplar texts are, by topic: caves (biology – Culver and Pipan 2009; entity – Gillieson 1996); encyclopaedias (caves – Culver and White 2005; caves and karst – Gunn 2004; biospeleology, Juberthie and Decu 1994, 2000, 2001); fauna (Botosaneanu 1986); groundwater biology (Gibert et al. 1994; Griebler et al. 2001); hydrogeology (Ford and Williams 2007); mapping (Culver et al. 2001); protection and management (Watson 1997; Tercafs 2001; Jones et al. 2003); subterranean ecosystems (Wilkens et al. 2000; Culver and Pipan 2009); dedicated journal issues (Humphreys 1993b; Humphreys and Harvey 2001; Austin et al. 2008; Gibert and Culver 2009); dedicated journals (Subterranean Biology, formerly Mémoires de Biospéologie parts of International Journal of Speleology); and publications of the Karst Waters Institute, USA.

13.2 The Nature of Groundwater Fauna

Subterranean aquatic fauna comprise elements dependent to differing degrees on groundwater. They include stygobionts (var. stygobites) that are obligatorily dependent on groundwater throughout their life cycle, stygophiles that spend only part of their life cycle in groundwater, and stygoxens that opportunistically inhabit subterranean waters (Gibert et al. 1994). These degrees of dependence are reflected in the extent of their adaptation to subterranean life, being most marked in stygobites that characteristically lack visual and body pigments and so appear white and eyeless, are commonly translucent, and often vermiform permitting passage through small voids. They also exhibit behavioral adaptations that compensate, amongst others, for lack of vision (review: Langecker 2000; Parzefall 2000), and physiological adaptations such as low metabolic rate to compensate for the scarcity of food (review: Coineau 2000; Langecker 2000). Subterranean species typically have no resting life stage, exhibit a K-selected or A(adversity)-selected life history strategies and respond to environmental scarcity with delayed maturation, delayed reproduction, and lowered fertility (*sensu* Greenslade 1983; Southwood 1988). For example, tiny Bathynellacea (*Antrobathynella stammeri* and *Bathynella* sp.) may produce, but a single egg and take 9 months to mature (Coineau 2001; Giere 2009: 99).

Stygobionts typically occupy a very small geographic extent and are numerically rare, both factors that increase their vulnerability to extinction through stochastic environmental and population events, and genetic inbreeding. In the USA, 44% of stygobionts were limited to a single county (Culver et al. 2000), while in Western Australia, groundwater calcrete formations each harbor an endemic fauna, rich in diving beetles and crustaceans (Humphreys 2008). Aspects of rarity are discussed by Rabinowitz et al. (1986) and developed in the context of subterranean animals, together with population estimations, by Culver and Pipan (2009).

These attributes of groundwater animals have various management implications. The differing degree of dependence on groundwater means that some part of the fauna may require connection with the water surface even the air above, to complete the life cycle and that this connectivity is a prerequisite to maintain the faunal assemblage. For example, stygobiont diving beetles (Dytiscidae) breath at the water surface while stygobiont crustaceans in the same system respire within the water; so the crustaceans, but not beetles, could potentially disperse through subterranean water lacking contact with the air. Conversely, stygobiont species, typically long-lived and lacking resting stages, are dependent on the permanent presence of groundwater. Attributes such as low metabolic rate that adapt stygiobionts to the low food environment make them susceptible to competitive displacement by surface species if subterranean food energy is increased through pollution.

Stygobionts overwhelmingly comprise crustaceans belonging to many higher taxa, including those with broad ecological and geographical distributions (such as Copepoda, Ostracoda, Amphipoda, Isopoda, and Decapoda) (Fig. 13.1), and those with narrow ecological and geographical affinities, entirely or largely restricted in their distribution to subterranean waters (such as Bathynellacea, Remipedia, Thermosbaenacea, and Spelaeogriphacea) (Botosaneanu 1987). Many other higher taxa are represented amongst stygiofauna, including vertebrates (fishes, amphibians), meiofauna, hydroids, sponges, flatworms, nematodes, segmented worms, snails, mites, and beetles. Although this chapter focuses largely on visible fauna, there is a plethora of smaller meiofauna (Giere 2009) barely studied in groundwater sediments, and microbiota (Bacteria, Archaea) (Chapelle 2001; Griebler and Lueders 2009).

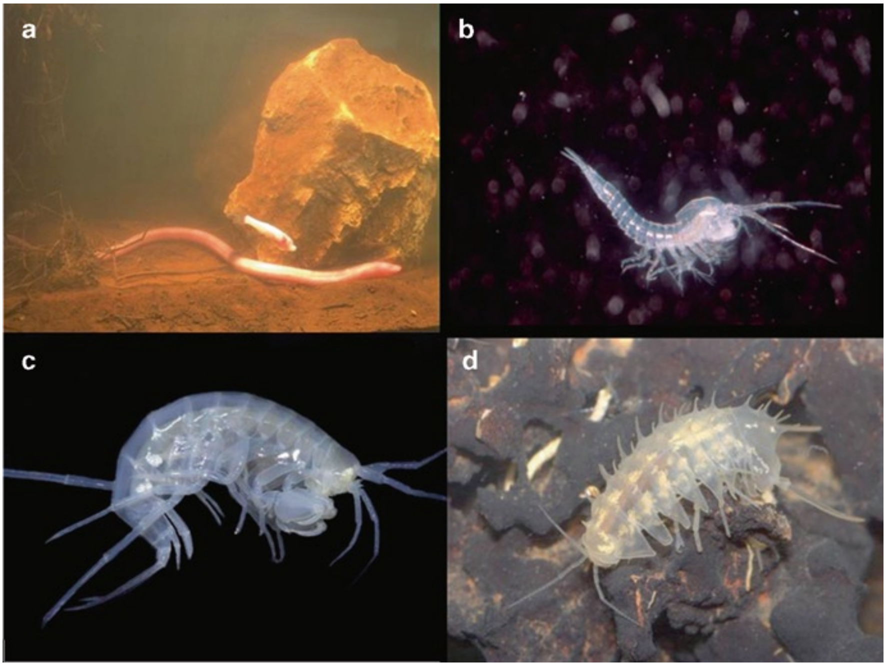

Fig. 13.1 Examples of stygobiontic animals. (**a**) Eleotrid cave fish *Milyeringa veritas* and synbranchid eel, *Ophisternon candidum,* from Cape Range, Western Australia; (**b**) thermosbaenacean *Halosbaena tulki* from anchialine system, Cape Range, Western Australia; (**c**) *Allocrangonyx pellucidus* from Oklahoma, USA; (**d**) isopod *Monolistra* (*Monolistra*) *monstruosa* Sket from western Bosnia and Herzegovina. (**a**) and (**b**) are associated with an anchialine ecosystem. Photo credits: (**a** and **b**) Douglas Elford, Western Australian Museum; (**c**) courtesy of John Holsinger; (**d**) Boris Sket

Subterranean habitats can be very old and groundwater fauna may survive under extreme conditions and in isolated subterranean habitats through geological eras (Longley 1986; Wilson 2008) and consequently through major changes in climate and geological context (Humphreys 2000b, 2008). It used to be thought that stygobites were largely a phenomenon in karst terrains in temperate regions; however, over the last two decades, it has been recognized that stygobites occur widely, both in terms of geology and climate. Speciose stygal communities occur in the tropics (Deharveng and Bedos 2000; Humphreys 2008) but are largely absent in areas closer to the poles. However, stygobites occur below the Pleistocene ice sheet in Iceland inhabiting water-kept liquid by geothermal heat (Bjarni et al. 2007). Groundwater fauna occurs in aquifers formed within a wide variety of substrates, such as fractured rock, alluvial gravels, sandstone, and lava (Humphreys 2008), but it is most widespread and prolific in karst systems. Groundwater fauna is known from fresh, marine, and inland hypersaline waters (Humphreys et al. 2009), from thermal springs (Monod 1924), and from beneath the ice sheets (see above). It is known from both unconfined and confined aquifers – artesian systems to depths of up to 1 km in Morocco (Essafi et al. 1998) and widely in systems dependent on non-tradition energy sources (Engel 2005), such as chemotrophic systems in Edwards Aquifer, USA (Longley 1992), Movile Cave, Romania (Sarbu 2000), Frasassi Cave, Italy (Sarbu et al. 2000), Ayyalon Cave, Israel (Por 2007), and the anchialine system in Mayan Blue Cenote, Mexico (Pohlman et al. 2000). Accordingly, most undisturbed saturated karst systems outside the polar regions are expected to support groundwater fauna.

Stygal species often represent ancient phylogenetic and geographical relictual lineages (review: Humphreys 2000) that have been isolated underground for many millions of years (e.g., Leys et al. 2003; Wilson 2008). However, under certain conditions, a lineage may independently invade the subterranean realm on numerous occasions, such as with the development of regional aridity (Leys et al. 2003; Cooper et al. 2008). Other stygal species are recent invaders with close surface relatives, or species that still have both surface and subterranean populations, both amongst vertebrates (Strecker et al. 2003, 2004) and invertebrates (Carlini et al. 2009). Thus, colonization of the subterranean realm is a continuing process and so it is not just those species markedly adapted to subterranean life, which often attract most attention, but also putative colonizers that deserve protection, together with the gateway to and from the subterranean realm, be it a resurgence or sink. There are hints, also, of subterranean lineages recolonizing the surface (Prendini et al. 2010; Kornicker et al. 2010).

'Connectivity is a primary process influencing ecosystem function and the distribution, abundance and persistence of all biota' (Lindenmayer et al. 2008). Surface and underground streams may both provide avenues of connectivity within a karst basin (Verovnik et al. 2004; Carlini et al. 2009) and so need to be considered as a whole in karst management, as in other systems. Conversely, cave populations inhabiting subsurface basins may be quite disconnected from spring resurgences because individuals of a species may be too large to traverse interstitial channels in phreatic sediments and porous rock where conduits confining the cave stream pass below the water table (Ford and Williams 2007), as was noted for *Gammarus minus* (Carlini et al. 2009) and *Niphargus virei* (Malard et al. 1997). Even meiofauna, such as Parabathynellidae, may be unable to traverse fine phreatic sediments between calcrete aquifer "islands" in a desert landscape (Guzik et al. 2008). In contrast, at karst outcrop areas, the spring ecotone may not modify the population structure of the drifting population and consequently sampling at springs proved to be an effective way to study the population dynamics of the amphipod *Niphargus virei* within the aquifer (Malard et al. 1997). It is widely recognized that vegetation provides the organic carbon that forms the basis of subterranean food webs but its role in connectivity is often overlooked. Roots may penetrate karst to a depth of at least 50 m (Gillieson 1996). Roots transport organic matter directly to the groundwater, both by growth and by the movement of sap and so provide a direct connection between the photosynthetic tissue and groundwater. Secondly, roots provide connection between groundwater and plant transpiration and this affects groundwater levels. One consequence is that tree plantations may lower groundwater levels and threaten cave invertebrate faunas (Jasinska and Knott 2000).

The degree of local endemism in karst subterranean fauna is unparalleled. Most stygal species are considered to occur over short distances, few more than 200 km and many very much less (e.g., Leys et al. 2003; Finston et al. 2007, 2009; Cooper et al. 2008; Page et al. 2008; Eberhard et al. 2009; Trontelj et al. 2009), commonly restricted to single caves (Iliffe and Bishop 2007). This constraint may be further strengthened as many cryptic taxa are being found further restricting the range of a given putative species (Page et al. 2008; Trontelj et al. 2009). Short range endemism makes the persistence of a species vulnerable to local scale impacts, such as quarrying, draining, or impoundments. Similarly, they may be vulnerable to loss through hybridization or by competitive exclusion by mixing of faunas through flooding by impoundments, or tunnelling to manage water supply or as a bypass for engineering and mining projects (Humphreys 2008).

The total species richness in subterranean water is difficult to determine because, as is generally the case (May 1976), most species are rare. The task of evaluating the diversity is compounded by limited access to an environment that, unlike the deep ocean, does not yield readily to technological solutions. Despite intense sampling, subterranean systems typically yield additional species for prolonged periods and species accumulation curves analyzed using various algorithms are used to estimate total species richness of a system, examples of which are found for the PASCALIS project (Dole-Olivier et al. 2009). Additional species are still being found in Vjetrenica (Bosnia & Hetzegovina) and Mammoth (USA) caves after 150 years of sampling (Lučić and Sket 2003). An exception to this is sampling at a very small spatial scale, by which means Pipan and Culver (2007a) were able readily to sample a full complement of species of copepods from epikarst drip water.

13.3 Scale

Scale affects most aspects of karst management, such as practicality of management, susceptibility to disturbance, temporal lags in hydrology, dispersal and vicariance of fauna, and intrinsic stability. Karst groundwater fauna are dependent on subterranean water-filled voids that may vary in scale through several orders of magnitude (Boulton 2001), from the spaces between particles in alluvia to massive caves and conduits in some karsts such as the longest known underground river, the 180 km long Ox Bel Ha cave system that links 130 cenotes (QRSS 2009) on the Yucatán Peninsula, Mexico. In addition, groundwater fauna occurs extensively in the smaller voids of carbonate deposits, even in the absence of overt karstification at the surface (Humphreys 2001a). Within these systems, the physicochemical attributes of karst groundwater also vary, from the redox gradients around sediment particles through finely structured vertical gradients in anchialine waters (Seymour et al. 2007), to the wide range of temporal and spatial scales enshrined in aquifer flowpaths (Morgan 1993). Groundwater residence time is a significant factor in the hydrogeochemical evolution of groundwater, the properties of which are important to aquifer ecology. For example, changed flow affects the flux of organic carbon in

Table 13.1 Karst recharge (After Smart and Worthington 2004a: 396)

Recharge	Autogenic	Allogenic
Origin of water	On karst	Outside karst
Chemical concentration	Enriched	Dilute
Flow	Steady	Variable
Sediment transport	No	Carried

groundwater that has a significant influence on the physicochemical variables such as pH and redox (Eh) (Pérez del Villar et al. 2004).

Although most karst fauna is collected in caves, most fauna probably occurs in the much more extensive void space in the leads and fissures far too small for people to enter. One approach to examine this has been to filter the entire drainage from a karst system (Rouch 1977, 1986) but it could be tested by having a cavernous area with many boreholes to enable sampling of both means of access within the same karst. However, multiple bores are rarely present in areas with accessible caves. Culver et al. (2009) surmounted this by sampling from individual cave drips (1–1,000 m) effectively obtaining point source diversity of the epikarst fauna. They demonstrated that frequency of occurrence of stygobiont copepods at these very small scales could predict occurrence of stygobiont species at one to two orders of magnitude of larger scales and argued that this supported dispersal at these scales. Conversely, Shabarova and Pernthaler (2010) sampled three cave pools, between 722 and 913 m below the entrance of Bärenschacht cave, Switzerland, and showed very high microbial diversity but minimal overlap, the pools sharing only one of 150 taxa (OTUs). They suggested that this may partly be the result of habitat filtering by different hydrochemical properties but largely due to hydrological properties with vadose pools serving as static collector of microbial diversity, while epiphreatic pools served as ephemeral habitat during the passage of bacteria between terrestrial habitats and rivers or estuaries.

The source of recharge water, whether from within (autogenic) or from outside (allogenic) the karst basin, has a great influence on the natural properties of the water (Table 13.1) and on the potential for influx of contaminants and nutrients. Allogenic karst may require that landscape-scale management has, of necessity, to extend upstream into non-karst landscape to provide adequately for the protection of the karst aquatic fauna.

The genetic variation in populations of stygobionts may vary widely in spatial scale. Guzik et al. (2009) demonstrated significant genetic structuring within populations of three sympatric species of subterranean diving beetles (Dytiscidae) within 3.5 km^2 of a superficial karst in Western Australia. This study indicated that the three sister species had different population histories with episodes of population expansion, various degrees of spatial heterogeneity in the distribution of genetic variation, isolation by distance and coalescence. Conversely, in anchialine karst and pseudokarst such as lava, genetic structuring may be strong between adjacent areas in the same region (Cape Range Australia, Page et al. 2008; Hawaii, Santos 2006), or negligible within and between islands throughout the Hawaiian archipelago (Russ et al. 2010). Spatial scale has temporal scale consequences in karst.

For example, groundwater "ages" with distance along its flowpath and so has different properties, typically being more nearly carbonate saturated with time (distance) and depleted of oxygen by microbial and eukaryote respiration, while excretion changes the chemical and redox conditions. The degree of change will depend in part on the duration of the biological and geochemical impacts (Humphreys 2008), and by the buffering effect reducing the temporal variation in flow rate.

13.4 Nature of Karst and Karst Hydrogeology

A succinct authoritative account of karst hydrogeology is provided by White (2005), and a fuller account by Ford and Williams (2007).

The development, structure, and hydraulic properties of karst affect the suitability of karst for groundwater fauna and the range of habitats available. Karst is characterized by the presence of a water-filled network of fractures in carbonate rocks (limestones, dolostones, and metacarbonates) but that part of the karst pertinent to groundwater ecology is not necessarily obvious. As water infiltrates to groundwater (saturated zone), it traverses many different pathways with varying velocities and so there are varying degrees of storage in the vadose (unsaturated) zone (Fig. 13.2). This epikarst is the site of significant biodiversity containing short range endemics,

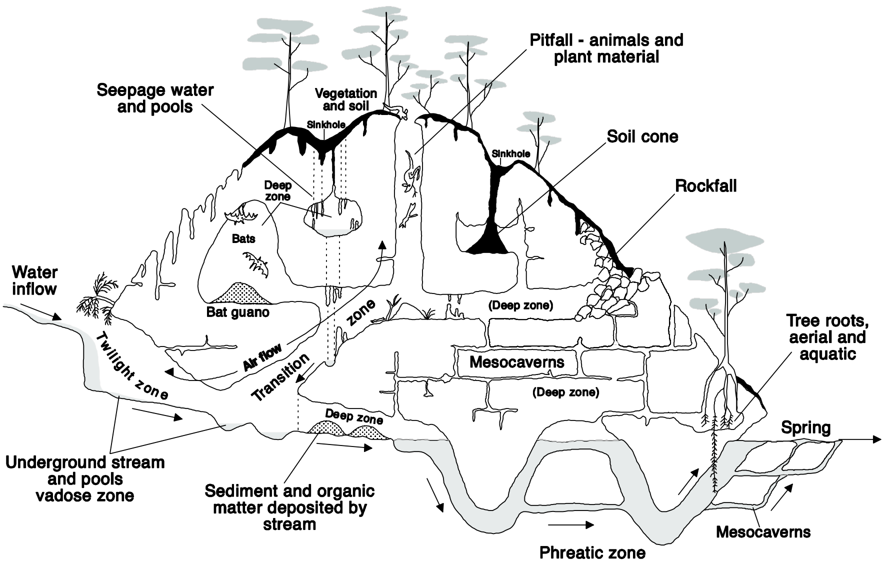

Fig. 13.2 Schematic section of karst showing how the subterranean voids are variously interconnected both internally and externally facilitating or impeding the movement of energy, materials, and organisms. Other subterranean habitats have similar attributes working at different temporal and spatial scales but largely lacking open conduit flow (From Eberhard and Humphreys 2003, reproduced with permission from University of New South Wales Press and S.M. Eberhard)

especially of micro-crustaceans (Culver et al. 2009; Pipan and Culver 2007a, b; Pipan et al. 2006). Conversely, conduits are known from a depth of more than 1,000 m and deep aquifers may contain rich (Edwards Aquifer, Texas; Longley 1992) or sparse stygobiont faunas (Plaine de Fès, Morocco; Essafi et al. 1998).

Although most karst hydrology has been developed from studies in caves and resurgences, there are many areas (e.g., buried karst) where only bores (wells) can provide access for both hydrogeological (Smart and Worthington 2004a) and biological sampling (Humphreys 2001a; Allford et al. 2008). In karst, boreholes typically intercept a few small conduits (<1 cm) that represent fractures that have been greatly enlarged by solution and which can be further enlarged if a bore is used for water extraction (Smart and Worthington 2004b). Poorly maintained or poorly constructed bores can become routes for contamination of the groundwater due to downward leakage of surface water, or upward leakage of groundwater from deeper aquifers, along the wall of the bore. While this can clearly have implications for subterranean fauna, both by mixing separate faunas and changing water quality, bore construction protocols are typically a regulatory issue that the karst manager needs to ensure that they are compliant throughout the catchment of the karst.

It is the dissolution of bedrock (karstification) that results in carbonate rocks becoming productive aquifers (Smart and Worthington 2004a), as well as suitable habitat for a range of stygiofauna with different lifestyles. However, matrix porosity is commonly two orders of magnitude greater than fracture and channel porosity (Smart and Worthington 2004a) and, although the small voids of the matrix make it unimportant as living space for groundwater fauna, the matrix porosity may support stable autochthonous microbial endokarst communities (Farnleitner et al. 2005) thereby affecting water quality. Conversely, seasonality/variation in water level due to temporal effects is important as it allows the deposition of sediments/clays, which are prime sites for biogeochemical activity, and organic carbon which is the basis of food on which stygiofauna ultimately rely (general account: Humphreys 2009). Hydraulic conductivity increases by 10^1–10^2 times from matrix to fracture, and from fracture to conduit domains (Worthington 1999). In consequence, the draining of karst following periodic recharge may occur in distinct phases as the different karst domains and pondings unload their water (Fig. 13.3) and this has consequences for the fauna. For example, sampling the fauna flushed from a spring draining an entire karst enabled understanding of the different domains within the karst. The rapid transit of water through open conduits (Mangin 1975) carried with it a groundwater fauna distinct from that found in the long residence time water of the karst matrix (Rouch 1977, 1986), an example whereby stygobionts can also be a tool to understand and monitor attributes of karstic groundwater (Malard et al. 1994; Humphreys 2009; Bonacci et al. 2009). However, recent work has suggested that these distinct phases of drainage may be due to the draining of ponded water behind constrictions in conduits (Eisenlohr et al. 1997; Covington et al. 2009).

The lack of light in subterranean waters means that primary production is lacking (the “truncated ecosystem” of Gibert and Deharveng 2002) and so energy input is

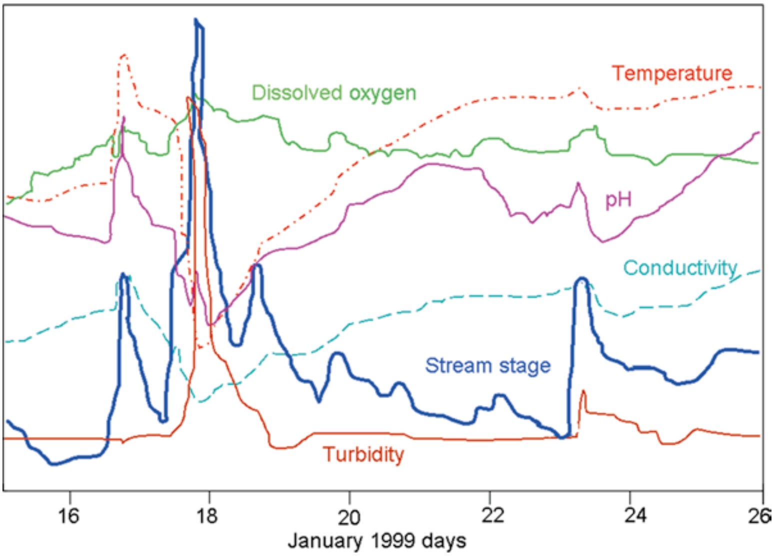

Fig. 13.3 Hydrographs showing asynchronous changes in physico-chemical parameters in Stemler Cave, St Clair County, Illinois, over a period of 10 days through a major flood event (17–19 January) (From Taylor and Webb 2000a)

generally imported (allochthonous) from the surface. Consequently, depth below the surface and lateral distance from inflow are issues of importance because they are related to the coupling of the groundwater physicochemical and biotic variables with the surface environment, both in terms of flux and temporal lags. For example, organic carbon flux decreases with depth below the soil surface and with distance along the groundwater flow path (review: Humphreys 2009). The duration of flow within an aquifer affects the chemical composition of the water (e.g., carbonate saturation), and is inversely related to the dissolved oxygen and organic carbon concentration that are utilized by the microbiota and fauna (cf Humphreys 2009). Thus, pertinent information on fauna management may be found in the hydrogeochemistry of karst aquifers, informing on the degree of connectivity of its different parts, the heterogeneity of the aquifer matrix, anisotropy – the time course of recharge and discharge events, and the chemical evolution of the groundwater.

13.5 Where Groundwater Fauna Occur in Karst

Understanding of the integration of biological and hydrological processes in karst, sometimes termed ecohydrology, is at an early stage, but Bonacci et al. (2009) provide background discussion and a framework for progress, a subject that overlaps with hydrogeoecology, an emerging discipline that encompasses all groundwater (Hancock and Boulton 2009). Karst aquatic biodiversity is partitioned between a number of different major habitats that may need to be managed separately. The cave streams and lakes, that are the dominant feature in many caves and the focus of most work on karst stygiofauna, may contain only a fraction of the fauna, both in terms of numbers of species and numbers of individuals. Most of the void space in karst is of dimensions far too small to access by people and in these areas, probably most of the fauna live – variously termed crevicular or mesocavernous voids (Fišer and Zagmajster 2009) –, but there are also rarer elements such as gour (rimstone) pools, permanent sheet flow down vertical walls (cave hygropetric, Sket 2004), meiofauna within sediments (Giere 2009) within the karst, and drips from epikarst, and others (Culver and Pipan 2009). They have been variously sampled by hand collecting, netting resurgences, boreholes or epikarst, or by baiting to attract such fauna to larger voids (sampling methods, Camacho 1992).

Although diverse stygal communities do occur in some deep confined aquifers, stygobites are most abundant and speciose in shallow unconfined aquifers. Gibert (1986) studied the entire 10.5 km^2 Dorvan-Cleyzieu karst drainage basin in the Jura Mountains, eastern France from where water drains primarily through the Grotte du Pissoir. She determined the evapotranspiration, runoff, and infiltration to derive the hydrological budget for the entire karst. Most carbon infiltrating the epikarst as dissolved organic carbon (DOC) rather than particulate carbon (POC), a result that is in accord with the later work of Simon et al. (2007). Although large numbers of animals enter karst from the surface (Rouch 1991), or via the epikarst (Pipan 2005), and carbon also enters the karst water as drift in cave streams, their combined total is small compared with DOC. Despite the great insights such a study provides on the functioning of the karst system, this study is still unique. This demonstrates the importance of connectivity (Lindenmayer et al. 2008) with the surface, and elsewhere, as a prime issue in karst management.

13.6 Threats to Karst Groundwater Fauna

Small scale endemism places stygobionts at risk through stochastic processes (Sket 1999) and from single land use changes. It is difficult to assess the degree of threat to groundwater fauna generally because in most places there is, or has been until recently, a lack of information on subterranean systems. Lack of information is highlighted in Australia where at least 750 species of groundwater fauna were found mostly in the 10 years to 2008, and largely in areas where no stygiofauna had previously been recorded (Humphreys 2008). There are, nonetheless, records of species loss and it is certain that local populations of invertebrates, fishes, and salamanders have been extirpated and some species probably lost (Veni 1987; Elliott 1993, 1994). Since some species are endemic to a single cave or a small cluster of caves, and many caves have been disturbed, filled, quarried, mined, submerged, drained, or polluted (Table 13.2), it is probable that some species have disappeared recently without our knowledge (Lewis 1996). Culver and Pipan (2009:10.4) provide many examples of threats to subterranean faunas in general (Fig. 13.4).

Table 13.2 Human activity threats to karst groundwater habitats (Partly after Jones et al. 2003: Table 5; Notenboom 2001; Humphreys 2003, Humphreys 2009)

Surface activities	Range of effects on groundwater
Construction and earth moving	Sedimentation, increased storm runoff, flooding, petroleum spills. Compaction of superficial karst changing drainage pathways
Logging	Increased storm runoff, soil loss and sedimentation, slash and debris inputs
Agriculture	Water extraction for irrigation lowers water table; increased nutrient and bacterial loads, increased storm runoff and sediment load, diffuse and point source pollution by agricultural chemicals (fertiliser, pesticides, persistent metabolic products), sinkhole dumping
Factory farming	Demand for water; disposal of waste products, especially NO_x; eutrophication of waterways
Urban and industrial activities (exacerbated by tourism)	General decline in quality of recharge water (nutrients, heavy metals, organic chemicals), change in amount of recharge, water level and periodicity of flow; septic system failure; over pumping gives water drawdown and decline in spring discharge; sewage; domestic, transport and industrial waste (heavy metals, hydrocarbons, salts); polluting leachates from landfill, and illegal or irregular dumping
Tourist development	Water level decline, salt water intrusion, sewage discharge to marine groundwater and its circulation, increased cave visits
Cave visitation	Sediment disturbance and compaction, trampling fauna, removal of fauna, change in microclimate
Quarrying and mineral extraction	Mobilisation of fine material leads to occlusion of voids and smothering of surfaces. Removal of matrix below the water table results in open pits converting groundwater to surface water; short circuiting hydrogeochemical evolution using bypass circuits. Alters groundwater levels and changes flow paths, changes physicochemical conditions, pollution with mining spoil (including clogging of voids), pollution by metals and petrochemical products
Water extraction	Lowers water table, changes flow vectors, alters physico-chemical conditions, saltwater intrusion, mixing of chemically stratified water, mixing of different aquifers
Water infiltration	Pollutants, nutrient enrichment, sediments
Artificial injection for storage of water, waste, thermal capacity, other products (both liquid and gas)	Change water level, physicochemical conditions and hydraulic gradients; contaminants and void occlusion
Oil and gas drilling	Contamination by lost drilling fluids and by hydrocarbons from spills or leaks from well casings, storage tanks or from pipelines, petroleum and salt contamination by disposal of produced water
Greenhouse climate drivers (gases, vapours, particulates)	Water recharge, discharge, erosion cycle, residence time, hydrogeochemical evolution, temperature

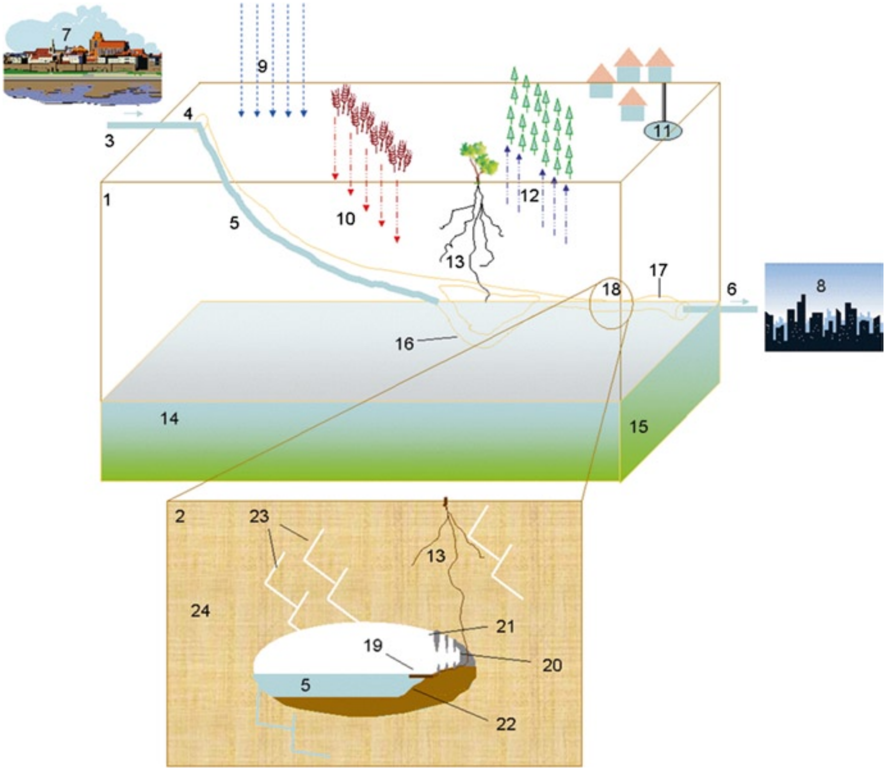

Fig. 13.4 Schematic diagram of a karst system (*1*), with an enlargement (*2*) of a section of a subterranean stream (*18*), depicting some routes of connectivity that may be managed to protect and or restore invertebrate communities. A stream flows onto the karst (*3*) from non-limestone region (allogenic) and descends underground at a sinkhole (*4*) forming a subterranean stream of river (*5*) which leaves the karst system via a vauclusian spring (*6*). The characteristics of the allogenic water is determined by the geology and land use in the catchment (*7*), and this is modified by passage through the karst and allogenic recharge (*9*) that together determine suitability for subsequent users, including human (*8*). Nutrients and pollutants in rain (*9*) and from arable and pastoral cropping (*10*) percolate to the groundwater through the thin soil cover typical of karst, or more directly from septic systems and sewage injection (*11*). Plantations increase evapotranspiration by intercepting rainfall and draw water from shallow groundwater (*12*). Deep roots may penetrate up to 50 m depth drawing on water, and providing carbon to the subterranean fauna by root growth and sap flow (*13*), sometime forming mats at the water surface providing habitat (*19*). The underground river conduit (*5*) passes below and above the regional water table (*14*) which is freshwater but overlies a saline layer (green). The saline layer is up-coning through the Ghyben-Herzberg effect in the downstream regions as a result of overdrawing of water from the aquifer (*15*), or as a result of seawater intrusion from the coast (not depicted). Upward and downward meanders in the river conduit serve as traps for high density (*16*) and low density non-aqueous phase liquids (*17*) that can consequently accumulate within the karst system from both allogenic and autogenic sources and smother sediments and conduit walls, and the organisms, including biofilm. Within a small part of the karst (*18*) enlarged (*2*) the underground river (*5*) flows through a conduit cut through the matrix of the limestone (*24*) which forms the majority of the water storage capacity of the karst and which connects with the conduit through fractures (*23*) which also provide access for roots (*13*). The sediments and gravel banks (*22*), both below the water and periodically flooded, provide habitat for fauna and substrate for biofilms, and may be destabilised through trampling by people. Some fauna is specialised to inhabit sheet water flows on walls, (*20*) or amongst the floor speleothems (cave formations). Dripping stalactites (*21*) provide effective sampling sites for epikarst fauna, and stalagmites growth using palaeoclimate methods provides information on the history of the cave and local climate, sometimes into deep history. For geochemical aspects refer to Fig. 3 in Humphreys (2009)

Poulson (1968) attributed the present rarity of the cave fish *Amblyopsis spelaea* in the Mammoth Cave System to silting and flooding associated with deforestation, forest fires, and water engineering projects. Groundwater fauna are largely threatened by changes in water level (Longley 1992; Rouch et al. 1993) and water quality, the removal of matrix (Humphreys 2009), and sedimentation smothering surfaces (Eberhard 1999; Hamilton-Smith and Eberhard 2000), and clogging voids although the activity of stygobionts may counteract this (Nogaro et al. 2006).

13.6.1 Pollution

There are many texts dealing with the issue of karst contamination (e.g., introductory – Schindel et al. 2004; major text – Fetter 2001; dispersed – Boyer 2004; point source – Schindel and Hoyt 2004; remediation – Schindel et al. 2004; protection – Drew and Dunne 2004; karst contamination in a USA – Elliott 2000; nitrates – Katz 2005; chlorinated solvents – Wolfe and Haugh 2001).

Pollution is the contamination of groundwater with substances not naturally present or changing the concentration of substances naturally present outside the natural range which may be harmful to life. Subterranean waters are typically poor in organic energy and subterranean fauna generally have low metabolic rates and other physiological adaptation to this low energy environment (Coineau 2000). An increase in energy input into the groundwater as a result of pollution (Fig. 13.5) may permit the successful invasion of surface forms into a previously oligotrophic environment (Notenboom et al. 1994; Malard et al. 1994).

While surface waters are more readily ameliorated by photodegradation and by the high oxic conditions, once pollutants enter groundwater, remediation is rarely practicable, typically very difficult and often impossible. Thus, the focus needs to be on prevention of contamination, and this is especially the case in karst environments that are highly vulnerable to pollution from both solid and liquid sources. This arises because karst typically lacks deep soil and from the rapid water flow through a conduit network, produced by karstification, that enables rapid transport of contaminants to the water table with little natural remediation (Ray 2005). In many cases, a diffuse network of conduits, such as those of the Dinaric Karst, makes tracking and prediction of pollution difficult (Sket 2005).

Acid mine drainage can become a pervasive issue for karst management. For example, the Rand goldfields on South Africa are overlain by compartmentalized dolomitic karst that was partly, but widely, drained to enable mining. For over a century, mine workings have penetrated the karst, including the continental drainage divide. When mines are depleted and pumping stops, sulfide rich water rises to the surface, is oxidized, and the resulting acid water, rich in uranium, decant to both sides of the continental drainage, divides and adversely affects both groundwater and surface water quality (Winde 2006).

As outlined by Webb et al. (1994), contaminants in solution, such as salts, acids, and endocrine mimics, will largely follow the dynamics of the water movement and the impact on the fauna will be determined by their physical and chemical properties.

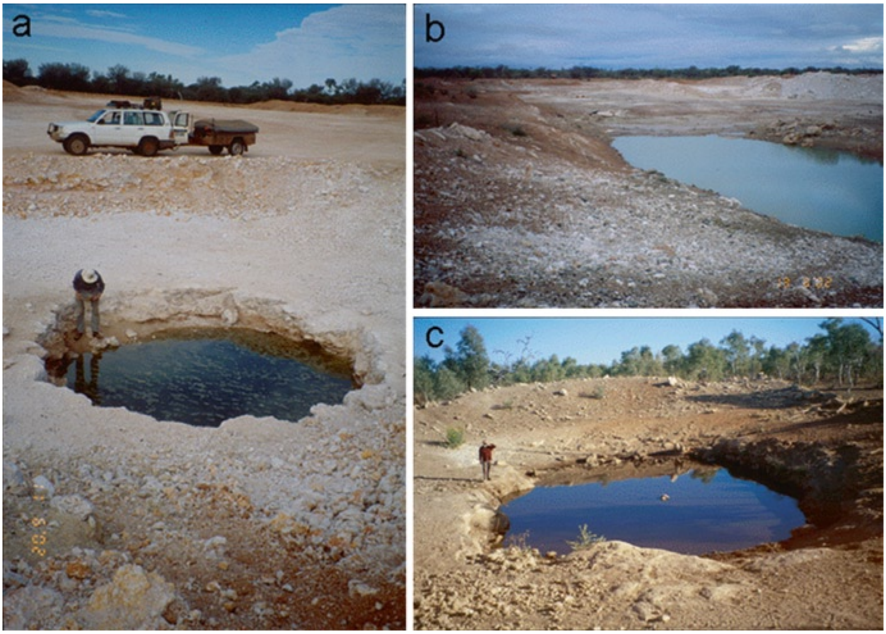

Fig. 13.5 Artificial exposure of groundwater ecosystems in groundwater calcrete bodies in Australia. (**a**), Road quarry with sinkhole development, an unusual feature in calcrete (Mt Padbury Station, WA); (**b**), Road quarry used for cattle watering, Lake Way Station, WA; c, specially constructed stock (cattle) watering point (Napperby Station, NT) (Photo: W.F. Humphreys). Such opening eliminate stygal habitat by making lakes of groundwater, increase nitrification of groundwater, and increases salinity by enhanced evaporation

Hydrophobic pollutants, especially non-aqueous phase liquids (NAPLs), are a particular concern as they are transported relatively rapidly within the aquifer, depending on groundwater velocity and conduit morphology, where they may smother matrix surfaces, including biofilm. Dense NAPLs sink to the bottom and smother surfaces, mix with the benthos and are incorporated in sediments, whereas low density NAPLs rise to the water surface preventing gaseous exchange and may accumulate in elevated parts of conduits. Consequently, both phases may lead to persistent pollution from a single point source pollution event (Schindel and Hoyt 2004).

Webb et al. (1994) provide a clear exposition of contaminant issues in Illinois in respect of groundwater fauna. Lewis et al. (1983) and Lewis (1996) reconstruct the processes that led to the elimination, as a result of sewage and heavy metal pollution, and the restoration of the subterranean fauna of Hidden River (Horse) Cave, Kentucky, which included *Typhlichthys* cavefish, *Orconectes* crayfish, and *Caecidotea* isopods. In this case, following rehabilitation, the fauna repopulated the cave from relatively unpolluted, upstream tributaries. Such dramatic examples should not mask awareness that even sublethal concentrations of insecticides in water may provide significant environmental stress, as indicated by fluctuating asymmetry on larval development (Chang et al. 2009) and behavioral abnormalities (Sandahl et al. 2004).

Toxicological studies of groundwater fauna are problematic as many stygobionts are naturally rare and are difficult to maintain in the laboratory. This has prompted the use of proxies in an attempt to address this problem (Hose 2005), but not without dissent (Humphreys 2007; Hose 2007). Meiofauna population densities are substantially greater than the mesofauna that is typically used in studies and offer potential to allow statistically robust toxicological experiments on groundwater species. However, as with other faunal categories, meiofaunal elements are differentially affected by pollutants, for example, atrazine was lethal to about 70% of several species of harpacticoid copepods but barely affected nematodes (Bejarano et al. 2005).

Special mention should be made of anchialine systems – near coastal groundwater affected by marine tides but lacking surface connection with the sea, typically markedly stratified with freshwater overlying seawater – not least because they are home to a remarkable diversity of higher taxa, especially crustaceans (Fig. 13.1), globally confined to this ecosystem and considered to be tethyan in distribution (Sket 1996). The most spectacular systems are in the karst platforms of the Bahamas Banks (Daenekas et al. 2009), and on the Yucatán peninsula, Mexico (Iliffe 1993; Iliffe and Bishop 2007) where a ring of cenotes surrounds the Chicxulub meteorite impact site – that arguably caused the end Cretaceous mass extinction – interconnected by caves including the Ox Bel Ha system (180 km). Although they may be extreme environments (Sket 1986; Humphreys 2001b), anchialine systems are considered especially vulnerable to pollution (Iliffe et al. 1984), those in Quintana Roo being polluted by sewage disposal by injection into the seawater underlying the freshwater layer (Beddows 2004).

13.7 Anthropogenic Changes to Water Regime

Although karst aquifers are a major source of water for human use, little is known about the impacts of water abstraction on ecosystems within aquifers (Rouch et al. 1993), especially deep aquifers (Longley 1992). Rouch et al. (1993) conducted a high discharge pumping test in a sinkhole to investigate its effect on the movement of stygiofauna out of the saturated zone of the Baget karst (Ariège, France). The water in the sinkhole was lowered by 21 m on three occasions over 4 days, and as a result, the micro-crustacean drift (mainly harpacticoid copepods) from the karst increased and the site had not recovered after 1 year. The diverse groundwater fauna of the Edwards Aquifer, Texas, which includes both vertebrate and invertebrate stygobites with both marine and freshwater affinities, is under threat from over-extraction of water which remove almost all of the natural recharge. The adverse effects are caused by loss of spring flow, dewatering of parts of the karst, and saltwater intrusion (Longley 1992). The Texas blind salamander, *Typhlomolge rathbuni*, inhabits the artesian part of the aquifer and is threatened by over-pumping (Elliott 2000). The use of Valdina Farms Sinkhole, Texas, as a recharge well for the Edwards Underground Water District appears to have extirpated the only known population of the salamander, *Eurycea troglodytes*, which is now probably extinct (Elliott 2000).

Owing to growing human demand on water resources, to enhance water storage, natural or treated waters are increasingly being used to artificially recharge aquifers but the effects on subterranean fauna are seldom studied. While this may seem a slight insult compared to industrial waste disposal, the impacts may be substantial. Injection in a sinkhole of 12,000 m^3 day^{-1} of treated wastewater water had marked effects on the occurrence of stygobiont species in fractured limestone in Nardò (southern Italy). In the Castro subregion alone, seven stygobionts, eight stygophile, and eight stygoxene species were not collected after the injection of reclaimed water started in 1991. However, the response differed between species and some omnivores, such as the stygobiont mysid *Spelaeomysis bottazzii*, were favored (Masciopinto et al. 2006).

Floods, and other large scale disturbances, can be important drivers of ecosystem and landscape processes (Lindenmayer et al. 2008). Increases in water level may also affect karst systems, the most overt being impoundments which may change the hydrodynamics and sediment transport within the karst as well as changing the water levels. Impoundments are commonly on the surface, but there is an increasing promotion and use of subterranean impoundments (Mengxiong 1987; Milanović 2004a) to utilize the storage capacity of karst areas while preserving surface utility and, important in hotter and arid climates, where the water is not lot by evaporation. Impoundments can have negative effect on both surface and subsurface water regimes. The plugging of river beds and ponors with cement to allow impoundments endangered the Olm, *Proteus anguinus*, by blocking connections between karst channels and surface, and it was also at rick by flushing during reservoir operations (Milanović 2004b).

Mammoth Cave, Kentucky, at 591 km, the world's longest cave system, has been well documented ecologically. The Green River, which naturally back-flooded the cave, was dammed in 1906 resulting in higher than natural flooding of the cave. Further impoundments in the 1970s reduced flood height but extended the period of flooding. These changes have had wide ranging ecological consequences with documented changes to *Palaemonias ganteri* (Kentucky blind shrimp), the cavefish *Amblysoma spelaea*, the crayfish *Orconectes pellucidus*, and two species of *Caecidotea* isopods, probably as a result of siltation, rather than the increase in toxins or organic enrichment (Poulson 1996). This detailed study may have more general implications because global climate change models on some aquifer systems predict changes in the amount of rainfall and in the seasonality of floods and low water (Scibek et al. 2008).

Changes, such as urbanization, that increase the magnitude or intensity of flood peaks in cave streams, may increase scouring of sediments. Wicks et al. (2010) found that the critically endangered pink planarian, *Macrocotyla glandulosa,* in Devils Icebox cave system, Missouri, occurred mainly in areas where numerical simulation of flow indicated stable sediment not prone to scouring.

13.8 Cave Visitors

Globally, caves and hot springs within caves, cenotes, and anchialine passages are visited by people for research, recreation, medical, spiritual needs, and mass tourism. Although they impact on a minor part of karst systems, they can have detrimental impacts on stygiofauna and each would require impact specific management. For example, the mass tourism in Waitomo Caves is renowned for the spectacular light display of the New Zealand Glowworm (Pugsley 1984; Broadley and Stringer 2002), and metal pollution from coins in the tourist section of the La Corona lava tube, Lanzarote, Canary Islands (Iliffe and Bishop 2007). The Yucatán is also a major centre for cave diving tourism and marine fish follow divers' lights into the caves and eat the anchialine fauna. This can be prevented by the simple expedient of divers turning off their lights while entering the cave from the sea.

Sediment banks are important locations of fauna in cave waters as they are areas of deposition and therefore of concentrations of organic matter which nourishes the biofilm (Dickson 1979) on which the fauna depend. Cavers following stream passages through caves may trample sediment banks, destabilize them, mix the contents, and disrupt the fauna. Caving protocols may reduce such impacts generally, and route marking and/or closures to entry of significant passages may protect them.

13.9 Inventory

A major impediment to protection and management of subterranean fauna is lack of knowledge of their current status, even of their presence – see the above example of Western Australia, a highly mineraliferous region, where a rich subterranean fauna occurred unknown until recently – exacerbated in some regions by a culture, now largely past, of secrecy amongst speleologists. However, in some places, this may be replaced by consultants who may retain information to protect some perceived advantage. A prime requirement for the management and conservation of cave fauna and the ecosystems in which they occur is an inventory to permit mapping of the distribution of the fauna in space and time to determine the species richness and assessment of their ecological status and vulnerability (Schneider and Culver 2004). This argument, generally applicable, is especially pertinent to karst subterranean aquatic systems which have exceptionally demanding requirements owing to difficulties of access, the hydrogeological complexities of the karst milieu, the perceived high level of vulnerability of the fauna (Box 13.1), and the exceptional degree of species endemism.

Inventory can occur at many levels of detail largely reflecting the financial and human resources available; a detailed study is shown in Fig. 13.6 and Box 13.2 in relation to the habitat of an endangered species. While major resources for long-term inventory of fauna may be available to inform the management of karst aquatic fauna in affluent and karst aware jurisdictions, this is a minority position. Even in

Box 13.1 Case Study: Coastal Stygiofauna of Cape Range, Australia

Cape Range comprises a low limestone range (to 330 m) in Western Australia forming a peninsula that projects northward about 100 km into the Indian Ocean. When there was still little knowledge of the stygiofauna – it contained the only two species of cave fish in Australia and two sympatric species of atyid shrimps – and before the anchialine nature of the groundwater was recognized, in order to inform large scale development planning, it was necessary, rapidly, to develop elementary understanding of the groundwater ecosystem on the surrounding coastal plain – did the fauna extend throughout the peninsula in a freshwater lens, or was it restricted to a linear peripheral system around the coastal plain? The approach adopted was to sample the few known sites for fauna and conduct an allozyme study, the results of which pointed to a strong disjunction across the peninsula but a linear system extending along the coastal plain, including species level variation (Humphreys and Adams 1991; Adams and Humphreys 1993), a finding that has since been extended and confirmed in a DNA study (Page et al. 2008).

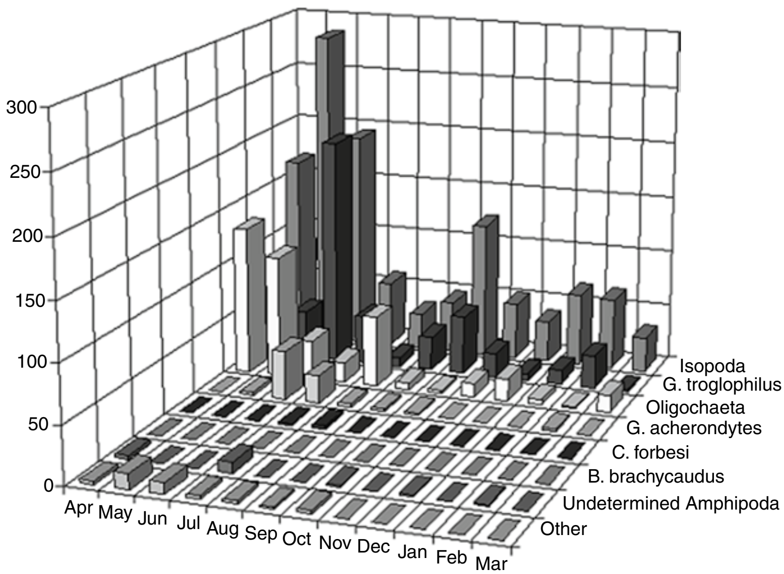

Fig. 13.6 Average number of animals per m^2 (N = 7 samples/month/cave) for all taxa in cave stream substrate of Fogelpole Cave, Monroe County, Illinois. The four identified Amphipoda are *Gammarus troglophilus, G. acherondytes, Crangonyx forbesi* and *Bactrurus brachycaudus* (From Taylor and Webb 2000b, with permission)

Box 13.2 Endangered Species – Illinois Cave Amphipod

Venarsky et al. (2007) undertook a study, using non-lethal methods, of the U.S. Federally listed Illinois Cave Amphipod, *Gammarus acherondytes* and were able to demonstrate that basic life history information obtained via non-lethal sampling in Reverse Stream Cave, Illinois, U.S.A, could provide managers with the information required to develop conservation strategies for endangered species. They recommended to reduce cave visitation during the major phases of recruitment to aid recovery of the population and suggested the establishment of a laboratory population for reintroduction.

industrial countries, the sampling for inventory work is often largely the province of capable amateur speleologists, with professionals involved only for specialist identification, and taxonomic and systematic development. In many, perhaps most, parts of the world, inventory, if at all, is elementary and the province of intermittent amateur and perhaps professional speleological expeditions is often associated with institutes devoted to taxonomy and systematics.

Nonetheless, there are useful guidelines to follow whatever level of inventory is possible for a given karst. This may range from a one-off collection establishing a minimum species occurrence baseline, through to the routine monitoring of the distribution and abundance of the cave fauna that will permit the detection of subtle changes in conditions and allow for the possibility of remedial action in the face of adversity. Hence, a basic requirement of management is to have an inventory of spatial information on the fauna and, as a minimum, to *record what is where, when, in what, how and by whom* were the data gathered**.** Each category can be expanded as human and financial resources and knowledge improvement (Table 13.3). A specimen progressively becomes a formally described species located in a phylogeny and placed in an historical biogeographic context. The aquatic habitat can later be expanded to include the hydrological and physicochemical properties of the water and its variation. An individual's field notes may progressively develop to become a compilation of multivariate data through time in a GIS system. But it is the minimum level of data that provides an essential baseline against which to start to make management assessment. This is often lacking for specific areas and even across major regions before profound changes to the landscape were made, for example in Australia (Hamilton-Smith and Eberhard 2000) and North America (Elliott 2000: 685). There are few areas of the world where subterranean fauna are a specific requirement for environmental impact assessments; Western Australia is one among them (EPA 2003). Although US research infers for management that groundwater quality is best protected by protecting the ecosystem (Job and Simons 1994), only in Switzerland has the maintenance of functioning aquifer ecosystems enshrined in ordinance (GSchV 1998).

Generally, most species cannot be identified from field photographs and so specimen collection, and arrangement for their long term preservation, storage, and data

Table 13.3 What, where, when, in what and by whom – guide to inventory information acquisition to guide management from basic essential background information progressively to more sophisticated understanding of distribution and variability of fauna

Level of information	Basic	Adequate	Good	Extended
What (unknown fauna)	Specimens labelled with data in this column and deposited in collection (collection method)	Named species identified by competent authority	Morphological and molecular material deposited in permanently managed collection	Phylogeny and historical biogeographic context developed
What (known fauna)	Individual identified to species by competent observer	Number of individuals	Life history data: developmental and reproductive stage and dynamics, sex	Behavioural observations
Where	Geographical location and situation	Location in cave, etc., habitat (flowing water, in sediment, gour pool, ……)	Coordinates with grid and method details (e.g., UTM zone ## using GPS on grid ##)	3-D GIS
When	Date	Time	Cross reference to previous samples	
In what	Medium	Physical parameters velocity, depth, specific conductance, pH, Eh, DO, temperature	Basic chemical water quality	Natural and induced variability, contaminants
By whom	Name of collector of specimen or data	Supplementary data deposition		

base, is an essential corollary of inventory work. The long term storage, particularly of the type material from which new species have been described, is best handled by institutions maintained to manage and research fauna collections, typically state museums – voucher material to aid local identification can be maintained at the laboratories involved with research in a particular karst region. Although sparsely utilized, taxonomic expertise is essential in all ecological studies (Bortolus 2008), but is especially important where high β-diversity results from the very short range endemism characteristic of subterranean fauna. Once the fauna of a particular cave or karst is well characterized, then conservation strategies can be supported by non-lethal life history sampling (Venarsky et al. 2007).

Data derived from karst fauna management are essentially field data ultimately derived from all scales of biological organization, spanning orders of magnitude of temporal and spatial scale, and which is very heterogeneous in format and content. The protocols established for the Resource Discovery Initiative for Field Station (RDIFS) in the USA (Brunt and Michener 2009) provide a valuable framework on which to establish both a karst specific data collection and management, and the means of intergenerational and between karst region sharing of research and training and management information to better monitor their own responsibility and to establish a broad research base on which to undertake the management of karst aquatic fauna. RDIFS is focused on enabling cross jurisdictional exchange of data by promoting consistent terminology, standard field methods, and quality assurance and control of data.

13.10 Management in Faunistic Ignorance

Although the subterranean biodiversity warrants protection in its own right and this is best achieved by the application of ecology to cave and karst management (Whitten 2009), the protection of the quality and quantity of human water supply provides the strongest avenue indirectly to aid the protection of stygiofauna. Real protection of karst waters depends on protection of the entire catchment and so, as mentioned above, landscape management may need to extend beyond the jurisdiction of the karst manager (Jones et al. 2003: 36). At its most basic, but rarely possible, the area and the catchment can be maintained in its original, unaltered state. However, global fallout of anthropogenic products negates pristine areas especially as even sub-lethal concentrations involved may induce developmental (Chang et al. 2009) and behavioral abnormalities (Sandahl et al. 2004). Boulton (2009) considered that the "biggest challenge as aquatic conservationists is to increase (and sustain) public and political awareness of the importance of groundwaters and GDEs, how they are threatened, and the need for applied research on groundwater processes and response functions to help managers assess groundwater resource use." At the local level, effective engagement by the karst manager with those responsible for water quality for human consumption is advocated, as they often have authority over the water and are better resourced for effective action if they are persuaded of the synergy between water quality and aquatic ecosystems. Such linkage could be explored between the studies of Masciopinto et al. (2006) and Masciopinto et al. (2007) of the Salento peninsula, southern Italy.

13.11 Education and Protection

Danielopol and Pospisil (2004) emphasized reasons for protection of groundwater fauna that are useful in educational programs for the protection of karst, including scientific, moral, and practical economic arguments to protect groundwater organisms and prevent deterioration of the environment. Management of karst groundwater can be implemented only if the occupiers of the land, both within the karst and the upstream catchment, and visitors, are made aware of the properties of karst systems that make their groundwater fauna particularly vulnerable to anthropogenic disturbance. In consequence, any management of stygiofauna will, of necessity, be part of an integrated and sustained educational effort of comprehensive karst management, a topic that is extensively developed elsewhere (Watson et al. 1997; Tercafs 2001). "A major emphasis on education is crucial if we are to effectively implement changes in land-use practices associated with urbanization and agricultural activities in ..... [southwestern Illinois], and changes that help sustain the aquatic cave community will also improve the quality of life for ..... residents in this karst area" (Taylor and Webb 2000a). The value of cave species to the public, often, is considered low, but cave species have potential scientific, practical, and educational value. For example, they may serve as "indicator species" in karst areas as a natural alarm for regulators and public health agencies to groundwater contamination, and they may provide ecosystem services by contributing to maintaining groundwater quality or aquifer porosity. Interestingly, a survey showed that visitors were willing to pay an increased entry fee (ca. 30%) to Yanchep National Park, Western Australia, to support a recovery plan for a root mat ecosystem containing a cryptic fauna threatened by groundwater drawdown (Perriam et al. 2008).

There is a substantial literature on the legislative approach to species and community protection, that includes subterranean fauna, in many countries (e.g., Elliott 2000; Hamilton-Smith and Eberhard 2000; Juberthie 2000) and this is reflective of the increased consideration for groundwater protection to maintain biodiversity (Danielopol et al. 2004). Although groundwater fauna are included in various international treaties and conventions, aquifer ecosystems, generally, are specifically protected at a national scale only in Switzerland by the Water Protection Ordinance that defines both water quality standards and ecological goals, "groundwater biocenosis [ecosystem] should be in a natural state adapted to the habitat and characteristics of water that is not or only slightly polluted" (GSchV 1998).

Awareness of the vulnerability of species and communities may be raised by inclusion of sites in listing of threatened fauna at local, national, and international levels, such as a Ramsar site (Beltram 2004) or Redbook listing (IUCN 2008). The listing of species under national endangered species legislation typically requires a level of scientific knowledge that is unavailable for rare subterranean species (but see Box 13.2). Where possible, despite the rather haphazard and arbitrary listing processes, listed species may protect associated unlisted species by proxy (Elliott 1990), particularly pertinent to karst groundwaters that often contain short range endemic species.

13.12 Some Management Actions

Alteration of land use practice is probably one of the principle factors affecting subterranean waters in karst because changes to or removal of vegetation changes water quality and flow regimes. The increased water yield exacerbates flooding in caves, while the more rapid run-off from cleared land increases peak discharge to cave streams and so previously permanent streams may become periodic. Four short examples of management actions on stygiofauna are given here, all from Australia.

(1) In south-western Australia, root mats develop in water table caves and they and the associated fungi are grazed by a rich stygiofauna (Jasinska and Knott 2000), and these root mat communities are listed under both Western Australian and Australian Commonwealth fauna protection legislation. Groundwater levels are declining, at Yanchep, north of Perth, as a result of excessive water extraction from the Gnangara Mound aquifer (Perriam et al. 2008), and, at Jewel Cave, Augusta, from unknown causes, hypothesized to be due to reduced rainfall infiltration as a result of increased understorey growth in the karri forest resulting from a change in fire frequency (Eberhard 2004). Stranded root mats and associated invertebrate communities are dying and, considerable efforts have been made to maintain artificially from bores the water supply at Yanchep, but with poor success, owing to iron rich water (Venn 2008).

(2) The operations of a limestone quarry at Ida Bay, Tasmania, caused adverse impacts on aquatic cave fauna as a result of sedimentation, eutrophication, and toxins that resulted in the extinction of fauna in Chesterman Cave (Eberhard 1995). In Exit Cave, the sedimentation restricted the distribution of hydrobiid snails, and while the quarry was operational, snail abundance was significantly lower in sediment affected streams than in control streams. A rehabilitation program was initiated after closure of the quarry to prevent further environmental degradation by restoring natural in-flow regimes and limiting further influx of sediment. Subsequently, snail populations were similar in control and sediment affected sites (Eberhard 1999).

(3) Barrow Island comprises a low limestone anticline on the shallow North West Shelf, Australia, and was declared an A-class reserve in 1910, the highest level of conservation protection in Western Australia. Since 1961, it has been a production oilfield requiring disposal of ever increasing volumes of oil contaminated “produced water”. From 1968–1979 and 1987–1994, produced water was discharged nto superficial karst to “B Block caves” and “F Block caves” respectively. In 1996 alone, this amounted to 2.3×10^6 m^3 of hypersaline water (40–45 g L^{-1} TDS) disposed with an residual oil content of 100–2,000 ppm (Wapet 1996),

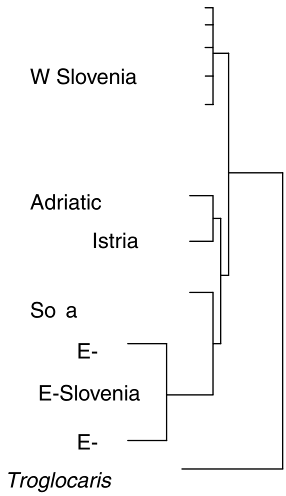

Fig. 13.7 Stylized molecular phylogenetic relationship within *Troglocaris anophthalmus* (Decapoda: Atyidae) based on nuclear gene ITS2 rooted on *T. bosnica* showing the major clades indicating the presence of cryptic species within *T. anophthalmus* (After Zakšek et al. 2009: Fig. 2)

that is between 230 and 4,600 m^3 of oil. Neither the anchialine nature of the ecosystem (Humphreys 2001b), nor the existence of a high conservation value groundwater fauna were recognized until the 1990s (Humphreys 1993b) and now known to include endemic species of crustaceans and fish. Although disposal of produced water in the superficial karst was subsequently stopped, in favor of disposal to deeper geological formations, the lack of pre-impact surveys of subterranean fauna precludes complete assessment of any impact of oil field operations on the original stygiofauna of this A-class reserve.

(4) Cryptic species generally are increasingly being exposed with the aid of molecular methods (Bickford et al. 2007; Bradford et al. 2009). It is commonly found that isolated populations of stygiofauna (Fig. 13.7), especially amongst the various amphipod families, show deep phylogenetic divergences based on DNA although they cannot easily be separated using morphological criteria (Finston et al. 2004, 2007; Cooper et al. 2007). The discovery of stygobiont fauna in a groundwater calcrete deposit near a new iron ore mine, Ore Body 23, at Newman, Western Australia, resulted in delay in commissioning of the mine. The initial diversity assessment was made on stygiobiont paramelitid amphipods – a group that has proven to be intractable to morphological study (Cooper et al. 2007) – which indicated 14 species of amphipod were present (Bradbury 2000), making it a global hotspot for amphipods. Molecular analysis was eventually commissioned which suggested a much lower diversity of amphipods (Finston and Johnson 2004; Finston et al. 2004), although the local endemism of other stygobiontic taxa was ultimately found (Karanovic 2006; Finston et al. 2007; Reeves et al. 2007). Subterranean fauna was previously unknown from this region, but it was later recognized to contain a globally significant subterranean biodiversity (Humphreys 2008); procedures introduced to ensure subterranean fauna were included in the environmental assessment process (EPA 2003), and a broad scale regional assessment of the stygiofauna was undertaken by the fauna authority (Eberhard et al. 2009; Karanovic 2006, 2007).

13.13 Conclusions

There are about 126,000 described freshwater animal species representing 9.5% of the total number of animal species recognized globally. As surface freshwaters cover only about 0.01% of the total surface of the globe, freshwater ecosystems support a disproportionately large fraction of the world's total biodiversity (Balian et al. 2008b) that is disproportionately threatened (37% of freshwater fish species are threatened; IUCN 2009). Despite increased awareness of inland waters in many regions and innumerable restoration projects, the biodiversity and biological resources of inland waters face a major crisis related to water resource integrity that is linked with the essential ecosystem services provided by aquatic ecosystems (Balian et al. 2008a). Freshwater systems are being destroyed at an increasing rate as a result of extraction of water for domestic use, for industry and irrigation, by draining and infilling, and by gross contamination by industrial and agrochemical pollutants and salination. Constrained in distribution by its milieu, freshwater fauna globally is consequently under immense pressure. While these influences are apparent in surface waters, they are well hidden in groundwater which comprises 97% of all liquid freshwater resources on earth (L'Volich 1974) and about 25% of the world's population is supplied largely or entirely by karst waters (Ford and Williams 2007).

Knowledge of the biodiversity within all types of groundwater is rapidly increasing and untangling the ecosystem services it provides has commenced (Boulton et al. 2008; Hancock and Boulton 2009); but the task is challenging and new challenges emerge, such as climate change. Karst systems provide the more dynamic and accessible groundwater systems but also those most readily contaminated and through which contaminants can most rapidly spread. Maintenance of the biodiversity within karst waters is the default option in the absence of empirical evidence of what constitutes key components of these simplified ecosystems.

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Part IV
Management of Karst Regions as Integrated Units

Chapter 14
National Karst Research Institutes: Their Roles in Cave and Karst Management

George Veni

Abstract This chapter defines "national cave and karst research institute" as "an organization created to conduct, facilitate, and promote state-of-the-art cave and karst research, education, and management, and recognized nationally as a leading authority on such matters." Twelve institutes from nine countries were identified; one institute is inactive. Most were created as governmental programs, often affiliated with a university, while the rest are non-profit, for-profit, or hybrid (combining at least two of the other three organizational structures). Each structure inherently lends itself to different levels of authority and engagement in cave and karst management issues.

The role of national institutes in cave and karst management is a subset within each of the institutes' basic purposes: Research, education and publication, independent advice and arbitration, data archiving, funding generation and granting, and collaboration facilitation. To date, most institutes have focused their efforts on theoretical research, archiving of data, and production of publications, and not on applied management issues. While activity in karst management is generally increasing, it is conducted mostly by the younger institutes and includes greater education efforts, funding, and advisory service. Because of widely different circumstances in each institute's origin, administration, age, and national laws and culture, generalizations are difficult but some trends are proposed for the next few decades:

- Karst institutes will increasingly develop hybrid organizational structures.
- Karst institutes will predominantly focus on karst management issues.
- Technical and public education will become prominent karst institute programs.
- Karst institutes will increase their support of digital open access karst libraries and the creation of virtual karst research tools.

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- Karst institute funding will increase through diversification of services and perceived increase in value.
- Karst institutes will formally link for greater effectiveness and better use of limited resources.

14.1 Introduction

Until the middle to late twentieth century, relatively little research occurred in caves and karst areas, even though about 20–25% of the world's land area is underlain by soluble rock (Ford and Williams 2007). In many areas, caves were considered curiosities rather than sites of serious scientific inquiry that could yield valuable information beyond archeological or paleontological data. This attitude changed as cities expanded into surrounding karst areas, and people discovered their understanding of these complex natural resources was inadequate for effective management.

Cave and karst research institutes grew from the desire to better understand these areas and their contents. Some early institutes grew from the research interests of a motivated individual (e.g., Emil Racovita's fascination with cave biology leading to the Romanian institute) or from the discovery of an important research site (e.g., development of the Karst Research Institute in Slovenia within the karst type area). Although most did not emerge in response to the needs of natural resource management, all were developed with the common purpose of consolidating knowledge, information, talents, and funds to facilitate research.

The purpose of this chapter is to describe the types of national cave and karst research institutes, the advantages and limitations of their structures, the roles they play in cave and karst management, and what changes they are likely to see in the future. While regional institutes and related organizations exist, they will not be addressed in this chapter except to distinguish them from national institutes. Much of the information on national institutes applies to them when scaled to their local level or specific function.

This chapter is the first report to comprehensively discuss national karst research institutes. Little information is directly available on this subject. Much of this information was gathered through personal experience with most of the institutes. Many aspects of the institutes' histories, programs, and administrative details have not been published, except through ephemeral brochures, leaflets, and Web site postings.

14.2 Types of Institutes

Cave exploration and research is a passion for certain people. Caves' high vulnerability to environmental impacts often directs their passion into education and management. Caves and karst also serve as the focus for many businesses, most notably tourism, but also, especially in the past 30 years, for environmental management consulting. Cavers (cave explorers) serve as the foundation for research, education, management, and commercial efforts. Their discoveries and maps lead the way for others to follow, and most cave and karst professionals build their careers on the inspirational foundation of their own caving experiences.

This wide range of interests, purposes, and specialization makes cave-focused organizations among the most diverse types in the world. The Union Internationale de Spéléologie (UIS) is typical of many such organizations down to the local level. It has the dual purpose of representing those who are interested in exploration and the recreational aspects of caves, as well as those fixed on the sciences and non-recreational issues. Its commissions include groups focused on "Archeology and Paleontology," "Atlas of Karst Regions," "Cave Mineralogy," "Cave Rescue," "Education," "Glacial, Firn, and Ice Caves," "Karst Hydrogeology and Speleogenesis," "Microbiology and Geomicrobiology," and "Speleothem Protection and Conservation," among numerous other topics (UIS 2010). Many cave-interest organizations function separately from the UIS and focus exclusively on these or other specific subjects. Are they cave and karst research institutes?

Merriam-Webster (2010) defines "institute" as "an elementary principle recognized as authoritative; an organization for the promotion of a cause; an educational institution and especially one devoted to technical fields." Probably, all of the UIS commissions and similar-interest organizations qualify as promoting a cause. All are devoted to the technical field of cave and karst science, often specializing in a sub-discipline, but few offer educational programs. The definition of "institute" also requires recognition of authority, which is difficult to quantify; all organizations are seen as authoritative at some level and by certain groups. This is complicated by the fact that, while the situation is improving, outside of the cave and karst community, relatively few cave and karst organizations are known to the general public, mainstream science, education, and management groups, or governmental agencies. Fewer still are accepted as authoritative.

This chapter defines "national cave and karst research institute" as "an organization created to conduct, facilitate, and promote state-of-the art cave and karst research, education, and management, and recognized nationally as a leading authority on such matters." Institutes which have not fully met those requirements are included in this chapter if they are working to fulfill them. Organizations that use "institute" as part of their name but do not fit the definition are not.

Table 14.1 summarizes basic information about all known national cave and karst research institutes as defined above. Table 14.2 summarizes their goals and programs. The information, including discussion in the following sections, was collected through a questionnaire, and supplemented by the institutes' Web sites and publications, and interviews with their staffs. Web site addresses are included in the list of references at the end of this chapter (except for the Cuban Speleological Society which does not currently have a Web site). The sections that immediately follow examine the different types of institutes and their functions in greater detail, with an emphasis on karst management.

Table 14.1 Leading international karst institutes. [Center for Cave and Karst Studies (2010); Emil Racovita Institute of Speleology (2010); Hoffman Environmental Research Institute (2010); Institute of Karst Geology (2010); Instituto do Carste (2010); Karst Research Institute (2010); Karst Waters Institute (2010); National Cave and Karst Research Institute (2010a); Swiss Institute of Speleology and Karstology (2010); Ukrainian Institute of Speleology and Karstology (2010); Veni G (1985)]

Institute	Year created	Country	Type	Staff	Funding source(s)
Cuban Speleological Society (CSS)	1940	Cuba	Governmental	n/a	Government
Emil Racovita Institute of Speleology (ERIS)	1920	Romania	Governmental	40 fulltime, variable part-time, and students	Government, grants, contracts
Hoffman Environmental Research Institute/Center for Cave and Karst Studies	1999/1979	USA	Hybrid	7 fulltime, 3–8 part-time, 6 students	University, grants, contracts
Institute of Karst Geology (IKG)	1976	China	Governmental	153	Government
Instituto do Carste (IC)	2007	Brazil	For-Profit	1 fulltime, 18 variable	Private donations, event fees
International Research Center on Karst (IRCK)	2008	China	Governmental	n/a	Government
Italian Institute of Speleology (IIS)	1926	Italy	Governmental	3	Government
Karst Research Institute (KRI)	1947	Slovenia	Governmental	25	Government
Karst Waters Institute (KWI)	1991	USA	Non-Profit	15 (all volunteers)	Grants, contracts, event fees, private donations
National Cave and Karst Research Institute (NCKRI)	1998	USA	Hybrid	6 fulltime, 2 part-time, variable students and volunteers	Government, grants, contracts, event fees, private donations
Swiss Institute of Speleology and Karstology (SISK)	2000	Switzerland	For-Profit	11 fulltime, variable students and volunteers	Contracts, grants, membership fees
Ukrainian Institute of Speleology and Karstology (UISK)	2006	Ukraine	Governmental	4 fulltime, 7 part-time	Government grants, university

Table 14.2 The purposes and programs of the international karst research institutes. [Center for Cave and Karst Studies (2010); Emil Racovita Institute of Speleology (2010); Hoffman Environmental Research Institute (2010); Institute of Karst Geology (2010); Instituto do Carste (2010); Karst Research Institute (2010); Karst Waters Institute (2010); National Cave and Karst Research Institute (2010a); Swiss Institute of Speleology and Karstology (2010); Ukrainian Institute of Speleology and Karstology (2010); Veni G (1985)]

Institute	Purpose	Programs
Cuban Speleological Society	Initially, to conduct cave and karst research in Cuba	Research programs were absorbed into other governmental departments. Now it serves primarily to train and organize cavers and host related conferences
Emil Racovita Institute of Speleology	Conduct interdisciplinary research on physical and biological components of the karst environment and related fields to provide a better understanding of karst processes to assess best practices for their preservation and conservation; provide scientific consulting for cave and karst management; coordinate the national cave inventory; publish karst books and journals; promote educational activities	Romanian karst science: geology, mineralogy, hydrogeology, and karst hydrochemistry; taxonomy, morphology, ecology and zoogeography of edaphic and subterranean fauna; use relative and absolute dating to reconstruct paleoclimate and paleoenvironmental conditions based on a variety of cave and karst deposits; karst water properties, establishing mechanisms for transfer of chemical contaminants using geochemical and radio-nuclear methods; conferences; scientific advisors to caving organizations and for cave management; and publications; formal education through coursework at undergraduate and graduate levels
Hoffman Environmental Research Institute/Center for Cave and Karst Studies	To be a leader in basic and applied research that aims to better understand landscape/atmosphere/water/human interactions, primarily through post-doctoral, graduate, and undergraduate study programs and associated research in the environmental discipline	Research in hydrogeology, geomorphology, geochemistry, climate change, and water resource issues; formal education through coursework and field studies programs; karst resource inventory, management, and training; water resource development through training; training in air quality monitoring and research in carbon sequestration technologies; support of international communication and efforts in karst science and conservation through leadership and active participation
Institute of Karst Geology	Undertake basic and applied karst geological research to establish foundational, strategic, and forward-looking karst theory and work	Major research subjects include basic karst studies, rehabilitation of desertification, development of karst water resources, geological hazards prevention, construction of a national Chinese karst geology database, development of a karst geology information service, and international exchange and cooperation

(continued)

Table 14.2 (continued)

Institute	Purpose	Programs
Instituto do Carste	To conduct and support karst research and sustainable usage of karst resources	Groundwater and biological research; management and restoration of karst environments; support for young cave scientists; annual invited distinguished scholar-led workshops; public education presentations; organize speleological events; publications
International Research Center on Karst	Understand karst systems at a world scale, and develop science and technology for sustainable development in karst regions	Research on environmental problems of karst, such as water, soil, mineral, and tourism resources, especially those related to world heritage qualities, as well as rock desertification, water quality, surface collapse, and flood disasters. Cooperative karst research; international karst technical consultation; karst scientific exchange; training in karst
Italian Institute of Speleology	Organize national register of Italian caves and speleological library, and support cave and karst research	Publications; research in speleogenesis, karst mineralogy and hydrogeology; data collection and archiving; formal education
Karst Research Institute	Develop interdisciplinary basic research covering the majority of the most important topics (karst geomorphology, groundwater, speleogenesis, biology, ecology, and history of karst science); planning for landscape protection; post-graduate study program; organize annual international karst seminar; administrative location for UIS; publish karst books and journal; develop a leading karst library	Postgraduate program in karst; publish a cave and karst journal and numerous books; library development; water resources and protection (road and rail construction, cave and karst data collection, consultation and management for tourism); multidisciplinary research on karst hydrology and ecology; laboratory analysis; computer modeling; international collaborations
Karst Waters Institute	Improve the fundamental understanding of karst water systems through sound scientific research and the education of professionals and the public	Specialty conferences, usually focused on a specific topic and multidisciplinary in nature; publication of karst research; support graduate level research in hydrogeology, geology, geochemistry, biology, and microbiology; workshops to provide training for professionals working in karst areas; inventories of cave and karst resources; introducing the general public to the importance of karst research; award to recognize major researchers

National Cave and Karst Research Institute	Further the science of speleology; centralize and standardize speleological information; foster interdisciplinary cooperation in cave and karst research programs; promote public education; promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and promote and develop environmentally sound and sustainable resource management practices	Research in cave and karst hydrogeology, geophysics, geomicrobiology, geochemistry, management and land use, and extraterrestrial speleology. Undergraduate to doctoral student programs in the above research topics. Formal, informal, and non-formal public education program through conferences, presentations, workshops, and field instruction. Two scientific book series and one children's book series
Swiss Institute of Speleology and Karstology	Develop and maintain the Swiss speleological archives; encourage and participate in karst research; educate the public to promote respect for karst environments; establish links with university departments to promote academic karst education and research; become the source for assistance, information, and guidance in Swiss cave and karst management; improve the Swiss public's view of and respect for caves and cave science	Research in the sustainable management of karst waters, including the development of an underground laboratory, and the effect of climate change; cave climatology, including ice caves; paleoclimatic reconstruction; speleogenesis. Applied research in the development of an underground positioning system, improving the prediction of karst occurrences for civil engineering work, and 3D underground modeling. Consulting in cleaning polluted karst sites, procedures for karst conservation, evaluating cultural value of caves and karst, and urban and natural area development of karst. Teaching programs, conferences, and excursions for schools and the public. Production of instructional materials for teachers. Publication of scientific books and literature, as well as informational books and materials for the general public
Ukrainian Institute of Speleology and Karstology	Develop, promote and coordinate scientific interdisciplinary research in caves and karst; conduct and promote fundamental, pilot and applied research on priority topics of caves and karst; develop scientific collaborations in cave and karst science; serve as a repository for cave inventory, documentation, and information relevant to caves and karst; provide scientific guidance in issues of protection and use of cave and karst resources; promote and conduct cave and karst educational programs, particularly on post-graduate and Ph.D. levels; raise public awareness of knowledge about caves and karst and their vulnerability	Research in karst hydrogeology, geomorphology, geospeleology, speleogenesis, high mountain karst, gypsum karst, environmental problems in karst, cave survey, cartography and visualization, and cave management, including studies at two karst field stations; Ph.D. program in karst/cave studies; database development (including on-line): cave and karst bibliography, regional karst GIS, cave registers, hydrochemistry, and cave archeology; publication series

14.2.1 Governmental Karst Research Institutes

Governmental national karst research institutes are those created by national governmental decree. As such, they officially represent those nations on matters involving caves and karst. Some governmentally created institutes have varying levels of authority to manage caves and karst, or to review and approve activities in caves and karst areas. Even when the institutes have no formal management authority or review capacity, as true governmental organizations, they can access sites and information that are not available to other institutes. Additionally, their opinion and approval, if not required, carries greater influence.

More than half of the national karst research institutes described in Tables 14.1 and 14.2 are governmental: Cuban Speleological Society (CSS), Emil Racovita Institute of Speleology (ERIS), Institute of Karst Geology (IKG), International Research Center on Karst (IRCK), Italian Institute of Speleology (IIS), Karst Research Institute (KRI), and Ukrainian Institute of Speleology and Karstology (UISK). They include the oldest institutes and in general have the largest number of employees and highest levels of funding. While this sounds like a highly favorable situation, it may be limited by cultural and economic factors. For example, institutes in countries with weak economies generally have funds to hire numerous people, but little money to invest in equipment, travel, and research projects.

Governmental support can change, strengthening or weakening an institute. CSS was created as the center for cave research in Cuba. However, by the mid-1960s, its research scope was transferred to governmental agencies within the Cuban Academy of Sciences. It no longer functions as an institute as defined in this chapter but is included for its historical role; CSS now mainly serves to train cavers, conduct speleological conferences, and through them, support karst research programs (Fig. 14.1). In contrast, IKG grew and consolidated much of the national cave and karst research in China, which led to expansion and the creation of its Karst Dynamics Laboratory in 1997 (Karst Dynamics 2010), and establishing the IRCK in 2008 (IRCK 2010).

Karst protection and management was not a mandate in the creation of the older institutes, although it is a component of all of the institutes' programs. Some have updated their original mandates. Prior to the 1970s, karst management was not widely recognized as a necessity or even a topic for study or action. It is still a secondary field of research for most of these institutes, attracting the most attention in China (IKG and IRCK) and Slovenia (KRI).

14.2.2 Non-Profit Karst Research Institutes

Non-profit national karst research institutes are privately created. They may or may not have a paid staff and all funds they receive are directed into the institute to conduct programs, buy necessary supplies, and pay fair staff wages. Surplus funds do not accrue to the institute's staff or board, the body that governs most non-profit organizations, but are distributed to support the institute's goals.

Fig. 14.1 The Cuban Speleological Society's Escuela Nacional de Espeleologia offers dormitory, classroom, and research space to train cavers in safe caving, rescue, mapping, and other techniques on site and in nearby Caverna de Santo Tomas

Only one of the listed national karst research institutes is a non-profit organization: Karst Waters Institute (KWI). It has no paid staff but a dedicated group of volunteers who serve on its board and assist with its functions. KWI is best known for producing an excellent series of conferences and associated proceedings. While it has a broader scope, other activities are limited by available funding and personnel. KWI is focused on basic research, and so its experience is not directly pertinent to the karst management theme here. Still, the experience of KWI and other non-profit cave and karst organizations has much to teach about the roles of non-profits in karst management.

Non-profits lack immediate recognition as actual authorities and must earn respect through action, such as providing information, conducting research, hosting conferences, and offering grants and scholarships. The presence of one or more regionally or nationally recognized karst experts on their board or staff also builds prestige. Once these organizations become recognized authorities, their representatives might serve on committees and advisory groups created by regulatory authorities to offer consul on management issues.

Non-profit institutes, by definition as privately created, have no authority to manage caves and karst beyond those they may own. As of 2009, 25 non-profit organizations in the U.S. acquire and protect caves and karst areas; some were created for that specific purpose (Wilson and Cousineau 2009). In most of the other countries containing karst research institutes, the ownership of caves and all underground resources is limited to the governments.

In the U.S., major non-profit cave-interest organizations date to the founding of the National Speleological Society in 1941, but it was not until the 1980s when several began to form with the primary purpose of cave and karst conservation. Most rely on volunteer staff. Some organizations are not focused on karst, and with a wider base of support, they have the means to hire employees and protect caves through both specific and broad action. For example, The Nature Conservancy is the largest private cave owner in the U.S. with 113 preserves protecting cave ecosystems in 1999 (Foster 1999; Wilson and Cousineau 2009). Fewer non-profit cave protection organizations exist outside the U.S., but those in Europe began to work together in 2008 as the European Cave Protection Commission (ECPC) in an attempt to more effectively meet their goals (Grebe et al. 2009).

The success of non-profit institutes is tied directly tied to the availability of funds and staff. The most successful raise funds aggressively and often hire experts to serve in key staff positions. Consequently, they experience smaller decreases in funding and their staffs provide their programs continuity and historical memory, which suffers when volunteers are less available. However, even under ideal circumstances, the lack of actual authority may defeat their efforts. Lacking notable funding and paid staff, the ECPC failed in its admirable initial efforts to establish a written declaration for cave protection by the Parliament of the European Union (Christiane Grebe 2010, personal communication).

14.2.3 For-Profit Karst Research Institutes

For-profit national karst research institutes are privately created. They have a paid full- or part-time staff and may hire part-time contractors. All funds are directed to conduct programs, buy necessary supplies, and pay wages, but they function as businesses where surplus funds may wholly or partially accrue to the institute's staff, board, or owners in addition to supporting the institute's goals. Theoretically, ownership can take any form, from sole proprietorship, to partnerships, to incorporated boards, or stockholders.

Two of the listed national karst research institutes are for-profit organizations: Instituto do Carste (IC) and the Swiss Institute of Speleology and Karstology (SISK). IC chose the for-profit status by design, while SISK chose it from necessity. IC is the second youngest karst research institute. It was formed in response to bureaucratic conditions that stymied efforts to create an institute within a university, along with a concurrent increase in the availability of grants and public funds for the creation of an independent research organization. SISK began with broad goals and attempted to gain public funding through government programs, but as those funds proved inadequate, it diversified its sources of income through consulting work, sales, and other for-profit activities.

IC has one staff member and several people who work and assist as needed. SISK is an older organization and employs 11 people full-time and several part-time.

Although IC and SISK operate for profit, their broader vision and purpose, which qualifies them as true karst research institutes, attracts students, professionals, and cavers to volunteer their services to support the institutes' overall goals.

From around 1980, the need for cave and karst expertise for environmental management has steadily increased, as demonstrated by the proliferation of cave and karst management, conferences and consultants. The field is lucrative, especially in areas with few cave and karst experts and where regulators and land developers recognize and appreciate such expertise. This creates opportunities for karst research institutes to conduct necessary investigations while generating funds to support their broader and more-difficult-to fund programs.

As with non-profit organizations, for-profits may lack immediate recognition as actual authorities and must earn respect through their research, unless at least one of the principle investigators is a regionally or nationally recognized cave and karst expert. However, for-profit institutes must also overcome the perception that their actions and views are biased toward making a profit. For-profit institutes may interact more frequently with regulators than other institute types. Assuming no conflicts of interest, their representatives could be more quickly recognized as authorities to serve sooner and on more karst management committees and advisory groups created by regulatory authorities.

Measuring the success of for-profit institutes is partly a matter of which standard is used. If success is determined by profit alone, an institute could potentially make enough money to pay employees and grow the institute. However, they may not have enough money to support their broader programs, which may not be financially self-sustainable through their own activities but are important to understanding and managing karst. The rich scientific publication record of the SISK and the developing programs of IC demonstrate that both organizations are channeling profits into their broader mandates.

14.2.4 Hybrid Karst Research Institutes

Hybrid national karst research institutes are created and/or sustained through means that define at least two of the above three institute types. They usually begin as one type of institute, but then change to encompass major traits of a different type of organization. Two of the listed national karst research institutes are hybrid organizations: Hoffman Environment Research Institute (HERI) and the National Cave and Karst Research Institute (NCKRI) of the U.S.A.

HERI was created in 1999 and includes the Center for Cave and Karst Studies (CCKS), which originated 20 years earlier. Both are research institutes at Western Kentucky University, U.S.A. CCKS began as a government institute, funded through a state university. Many university institutes apply for grants and external funds, and could in themselves qualify as yet another institute category, but the CCKS soon expanded beyond such grants and functioned effectively as a non-profit business. It established numerous consulting contracts for environmental management research and established a commercial dye tracing laboratory. Funds from these projects paid non-student staff and numerous students who worked part-time and occasionally used project results in undergraduate and graduate theses. Since HERI's acquisition of CCKS and some shifts in the institute's goals, the number of consulting projects has deliberately declined while the laboratory and student assistants are still active.

NCKRI was created in 1998 by the U.S. Congress as an institute within the U.S. National Park Service (NPS). Its mandates were defined by Congress, and it was funded by a partnership between the federal government, represented by NPS, the State of New Mexico, represented by the New Mexico Institute of Mining and Technology (New Mexico Tech or NMT), and the City of Carlsbad, which constructed NCKRI's headquarters. In 2006, the partners decided to reorganize NCKRI into a non-profit for greater flexibility in achieving its mandates than was possible through the NPS. NCKRI currently maintains its governmental obligations and funding, with the funds administered by NMT, yet is a federally registered non-profit corporation.

Hybrids are the most recent type of karst research institute and may prove the most effective, based on the short periods that HERI and NCKRI have existed. Their hybrid format gives them greater administrative and financial agility in gaining funds and building effective partnerships. HERI is based on government/university funding and support, while supplementing its programs through consultations, lab fees, and grants. NCKRI is similarly situated, and soon plans to diversity its income sources through bookstore sales, workshops, rental of meeting space, and research equipment, as well as through consultations and grants. This diversification allows each institute to more easily overcome situations where a source of income may be temporarily decreased or permanently lost. Both hybrid karst institutes possess small but growing numbers of employees. HERI's staff is supplemented by students while NCKRI's is supplemented by volunteers.

The strength of a hybrid institute's organizational diversity also includes its ability to work with other organizations and be readily recognized as an authority. NCKRI's creation by the U.S. government provides nearly automatic recognition and access to government leaders, agencies, regulators, and membership on relevant committees. However, its non-profit status gives NCKRI greater administrative freedom and the ability to work with organizations and qualify for projects and funds that are restricted to non-profits and/or non-governmental organizations.

HERI's history and goals are more focused on karst management than NCKRI's, and have resulted in HERI working throughout the U.S. and several countries on multiple projects and issues. NCKRI plans to hire a director for its Applied Science Program; until then, its efforts on karst management are opportunistic. Neither organization plans to develop a cave acquisition program as part of its management efforts.

14.3 Roles in Karst Management

Table 14.2 shows that karst research institutes have similar purposes, generally to support, facilitate, and conduct cave and karst research, education, and management efforts through their own strengths and collaborations with other organizations, and the collection, analysis, and publication of information. While specific interests differ, cave and karst management has become an increasingly important priority for the institutes, in part due to societal needs, but also because of increasing funding available for such work. The following sections review the primary functions of karst institutes relative to their efforts in the protection and management of caves and karst areas.

14.3.1 Research

The most active institutes in cave and karst management research to date are HERI, IKG, KRI, and SISK. All focus their work primarily within their own countries, except for HERI which works internationally, especially in China, in addition to the U.S.; IRCK and NCKRI's fledgling research programs are intended to be large and international. Most of an institute's research is focused locally, so the range of management issues it studies is usually based on local topics. But common trends in their research are described below as three phases in conducting environmental management investigations.

The first phase begins with issues of great urgency. An institute will typically first evaluate and/or solve a groundwater contamination, flooding, or land stability problem (Fig. 14.2). This work fell especially to the institutes before consulting hydrogeologists and engineers with karst expertise were broadly available, and it is still the case in regions which lack such consultants. Examples of such research abound: Crawford and Groves (1995) for HERI/CCKS, Yang et al. (1999) for IKG, Kogovšek and Petrič (2007) for KRI, and Wenger (2008) for SISK. Such studies may establish the authority and value of an institute, and thus be critical to assuring its long-term financial security.

The second phase of investigations involves long-term rather than immediate management problems. Water supply availability and regional land use research is common. Desertification due to soil erosion, even under humid conditions, is a major concern for karst in China (e.g., Shan 2006). Some of these studies overlap with student thesis and dissertation research, often requiring similar levels of data collection and analysis, and are conducted occasionally by students supported by the institutes (e.g., Petrič 2000). The third phase of karst management investigations involves long-range planning, with SISK and its partners making the most notable contributions in developing karst aquifer vulnerability assessment methods (e.g., Perrin et al. 2004).

Most karst research institutes do not list archeological, biological, paleontological, or tourism studies within their mandates or programs. Whether by design, recognized urgency, or availability of funding, all of the institutes have focused on geological and hydrogeological research. ERIS and KRI have the broadest research programs and include studies in other disciplines, but little has been produced specifically on the conservation and management of the rich non-geological resources often found in karst and caves. Archeological and paleontological studies have mostly been descriptive (e.g., Horáček et al. 2007) and not protective or prescriptive.

Fig. 14.2 CCKS/HERI was called to consult on the sinkhole collapse that swallowed part of a street in Bowling Green, Kentucky, USA

The same holds true for many biological studies. Most ecosystem studies by IKG address surface communities (e.g., Zeng et al. 2007) and not true karst endogenous species. The majority of karst research institute reports on the management of true cave fauna examine biodiversity as a foundation for conservation (e.g. Moldovan et al. 2005). They have done little to date on the recovery of listed threatened and endangered karst species or White Nose Syndrome, the condition that began rapidly spreading through North America in 2006, devastating bat populations.

Karst research institutes frequently use show caves for research. Studies occur within and beyond the tourist areas. Most examine some fundamental issue of cave science, but few investigate how to best minimize the potential impacts of tourism (e.g., Racovita 1999). While IKG has probably conducted the most studies of all institutes on the impact of tourism on caves (e.g., Zhang and Zhu 2008), much remains to be learned.

14.3.2 Education and Publication

Most karst research institutes list "education" as one of their goals or at least as among their programs. But what is "education"? Within the context of how it is organized and conducted by the institutes, it can be defined within three broad categories:

(1) *Technical Education*. Seminars, lectures, workshops, and classes for undergraduate to professional level audiences interested in advanced, specialized information necessary for professional jobs that involve caves and karst. These programs provide formal credit for participation that may be applied to a degree and/or to continuing education requirements for a job or a professional or research license.
(2) *Public Education*. Lectures, workshops, classes, and entertaining events that provide general, simplified or non-technical, cave and karst information for the public. This includes presentations to pre-college students because of the technical level of the content. The purpose of public education is to elevate society's general awareness of caves and karst, including their importance and vulnerability to human activities.
(3) *Publications*. Publications are not usually considered an education category but an education tool. They are listed here as a category because they constitute an important program of nearly all of the institutes. "Publications" are not limited to printed books, journals, and newsletters, but include digitally produced media that relay similar information, such as Web sites, videos, interactive learning programs, and webinars. Publications reach out to people of all ages and knowledge levels, and are not restricted to only the technical or public education categories.

Half of the karst institutes include teaching as one of their mandates; ERIS does not, a result of its early origin when institutes were typically located at universities and their education component was assumed. Nearly all of these institutes are within a university and/or directly supported by a university, and consequently, they provide cave and karst educational support to the students in return. Romania's Babes-Bolay University, which is affiliated with ERIS, and Slovenia's University of Nova Gorica, which is affiliated with KRI, are the only universities known to provide degrees in karst science. HERI and NCKRI are the only other institutes that offer specific university courses on cave and karst topics (several universities around the world offer cave and karst courses, but are not affiliated with a national karst research institute).

Nearly all institutes offer some form of technical education, as defined above. Most are occasional seminars offered outside of the typical university curriculum. Some are offered through affiliated universities. The longest-running and possibly the earliest university program is the series of week-long annual summer field courses offered through CCKS (HERI) since 1979 at Western Kentucky University. The course titles, such as "Cave Geology," "Cave Ecology," etc., span the range of major karst research topics, but karst resources management courses were not offered until "Management of Karst Aquifers" in 2002. Similarly, KRI's week-long International Karstological School focused on basic research topics since its start in 1993, until offering "Sustainable Management of Natural and Environmental Resources on Karst" in 2006 (Fig. 14.3).

Fig. 14.3 Students of KRI's annual international karstological school examine a stream flowing into a Slovenian cave

Most of the institutes provide public education through lectures, brochures, and books with stunning photos that highlight the beauty of caves and karst landscapes. Little specific information is available on these informal activities. From around 1990, karst management has increasingly become the focus of these efforts, especially in response to well publicized local karst problems. Public education's primary challenge is teaching people why they should care about the complicated, unfamiliar, and poorly understood topic of how caves and karst function. It must teach why caves and karst are important, while overcoming deeply held myths and superstitions, all within a typically 5–30 min presentation. This is where karst research institutes can excel, through programs honed to concisely yet effectively provide that information. Such programs can extend through communities in many ways as periodic reinforcement.

Only three institutes have defined education programs that make public education a major priority: ERIS, SISK, and NCKRI. ERIS' public education efforts are focused through the Emil Racovita Speleological Museum in Cluj, Romania. While a significant portion of the museum is dedicated Emil Racovita, it also includes rooms with information on cave exploration equipment and techniques, cave and speleothem restoration methods, the creation of ERIS, cave biology, and reasons and means for protecting cave and karst environments. The museum also hosts a weekly public lecture series on cave and karst topics.

SISK has a public lecture series and teaching program, but also sells a unique set of cave and karst education tools for teachers within two compact, sturdy suitcases. Materials in the first suitcase focus on the theory of cave and karst development, and includes course notes, teacher's guide, bibliography, list of relevant Web sites, games, puzzles, photos, and rock samples for discussion, and a CD with two PowerPoint presentations. The second suitcase contains equipment and instructions for six experiments:

(1) Limestone dissolution;
(2) Speleothem formation;
(3) Infiltration of water into karst aquifers;
(4) Karst groundwater networks and spring discharge;
(5) Transmission of pollutants in karst aquifers;
(6) Karst recharge areas.

NCKRI's Education Program is scheduled to begin in 2011. Cave and karst management is fully integrated, as reflected by the draft mission statement: *NCKRI's Educational Program works to increase the perception, awareness, and knowledge of caves and karst to result in careful and responsible stewardship* (NCKRI 2010b). NCKRI has hired an Education Director who works to better include cave and karst instruction at universities, as well as through the gamut of public education methods. Key efforts of its Education Program are to add cave and karst knowledge into the national education standards, and to work cooperatively or expand on existing teach-the-teacher programs to more quickly and widely disseminate karst information. Project Underground (1993) and the American Cave Conservation Association are among the few organizations that offer cave and karst curricula to teachers, and NCKRI is working with both to cooperate with and/or integrate those efforts (NCKRI 2010c).

14.3.3 Independent Advisor and Arbiter

A poorly publicized and often private function of karst research institutes is to provide expert advice and insight on questions involving caves and karst. This service is based solely on the institutes' existing experience and information and is separate from the institutes' research role, where they might conduct studies to resolve an issue. The topics in these circumstances are almost always related to cave and karst management and fall into one or more of three categories: Planning, problem-solving, and dispute resolution.

Members of karst research institutes often serve on technical committees to assist in creating research programs and management plans for caves and karst areas. NCKRI (2010c) discusses its activities, including examples involving karst management and related planning:

- The Executive Director sits on the Aquifer Science Advisory Panel of the Edwards Aquifer Authority (a regional governmental agency in Texas, U.S.A., charged with the protection, study, and management of that major karst aquifer) to review research and proposals by the agency and advise on improvements for the agency to better meet its goals.

- The Education Director works on a U.S. Forest Service (USFS) cave and karst management plan writing committee; the plan is expected to become the USFS national cave and karst management plan.
- The Education Director serves on a committee of Carlsbad Municipal Schools; the committee gained the City of Carlsbad recognition as one of the "Top 100 Communities for Young People" by the America's Promise Alliance.
- The Academic Program Director is a member of the NASA Advisory Council Committee on Planetary Protection and the National Academy of Sciences COMPLEX committee.

Most of the time, this type of assistance is informal, undocumented, and provided through personal communications in response to specific questions.

Institutes also participate in problem-solving missions. The situations frequently require urgent action, are often potentially or truly legally and/or politically sensitive, and information on an institute's involvement is generally unpublished or not published within the readily accessible literature. NCKRI (2010c) offers one example as its Executive Director serves on a committee to evaluate the risk of a potential catastrophic sinkhole collapse and to explore what can be done to prevent it. Depending on the issue and urgency, and the time, funds, and information needed to solve the problem, an institute may be the only or primary group contacted, or it may be part of a committee.

Based on a literature review and personal communications, which cannot be cited due to legal issues, it appears that karst institutes seldom function as arbiters of disputes. The disputes commonly revolve around whether an action was sufficient to protect a cave or karst resource, or if an individual's use of the resource impinges on the rights of others. Governmental institutes are more likely to be involved in such matters, as well as in planning and problem-solving. The specifically designated roles of each governmental institute and the legal codes of their countries affect the institutes' positions as advisors, arbiters, and regulatory authorities.

14.3.4 Data Archive

Every national karst research institute maintains a data archive of speleological information, whether or not this is listed as a goal or program. Institutes function on information; a data archive is not optional. However, some institutes expand and/or focus on this task.

The IIS archive is a traditional library, possibly the world's largest karst collection, with over 70,000 items catalogued. Creation and maintenance of the library was one of original goals of the IIS. Like most traditional libraries, its materials are primarily used by those who can physically access the location. Until the creation of the Italian Speleological Society, the IIS library also contained the database of Italian caves. Other institutes which currently host cave databases, or work collaboratively with the organizations that do, include KRI, SISK, and UISK.

The problem with traditional libraries and paper-based archives is that karst science is an intrinsically multidisciplinary field of study that is poorly indexed and difficult to access. While there is a significant body of internationally useful literature, important works remain largely unknown or inaccessible. Some of the more difficult-to-access documents include maps, databases, technical reports, graduate theses and dissertations, images, video, and government publications. Also, karst-related documents published in less-accessible languages are hard to retrieve or find. Consequently, two of the newer institutes, while building their traditional libraries, are also creating virtual cave and karst libraries for easy international use and access.

Speleogenesis (www.speleogenesis.info) is the official Web site of the UIS Commission on Karst Hydrogeology and Speleogenesis. While officially a UIS activity and supported by many commission members, it is unofficially powered by UISK and its Executive Director, Dr. Alexander Klimchouk, who chairs the commission. The Speleogenesis site functions as an on-line journal but also provides free on-line access to a cave and karst bibliographic search engine, theses and dissertations, several journals, a glossary of terms, and an atlas of morphologies found in caves. While some of the linked journals include papers on karst management, Speleogenesis is focused on the theoretical aspects of cave origin and karst hydrogeology.

NCKRI is also developing a virtual library, the Karst Information Portal (KIP) (www.karstportal.org), with partners from the University of South Florida, University of New Mexico, and UIS. Also supported by UISK and Speleogenesis, KIP was created in 2007 and specifically designed to address the information access and management problems presented by traditional libraries. It provides an open-access global portal as an on-line gateway to karst information and services. About 5,600 documents on all cave/karst-related topics were available via KIP in mid-2010, including theses, dissertations, databases, bibliographies, images, gray literature, maps, and 39 journals from 11 countries. Considerable information is available on cave and karst management. KIP's usage is increasing dramatically, with a projected doubling in 2010 from 2009 (NCKRI 2010c).

14.3.5 Funding Generator and Provider

In principle, national karst research institutes, as recognized authorities and productive entities, should readily generate funds to build their research programs and to support others. Unfortunately, that has not generally been the case. Institute directors interviewed for this chapter were asked, "What would you like your institute to do that it is currently unable to do, and what is preventing your institute from meeting those goals?" Their uniform hope was for additional funding to better sustain and grow their programs.

Measuring the financial success of the institutes is difficult. They need to be evaluated relative to their individual goals and circumstances. Fundamentally, they are all successful since they sustain their current activities. HERI, KRI, KWI, and NCKRI are discussed below as examples; they provide significant contrasts in measuring the current success and likely growth as future funding generators and providers.

HERI is arguably the most financially successful institute. It may not have the largest budget, but it employees several people, and continues to find funds to expand its general and student research programs, locally and internationally. While it hosts conferences and a summer field school that build cooperation and scientific knowledge, the funds HERI generates are primarily directed inward to support additional students and programs.

KRI is also clearly successful as evidenced by its large staff, diverse research program, prolific publications program, periodic conferences, and annual International Karstological School. Like HERI, its funding is primarily directed inward, as is necessary for an organization to survive and flourish, but grants are also given internationally for students to attend their annual school.

KWI does not have a staff or a regular income source, and possibly has one of the smallest budgets, but it still stands as a successful funding generator and provider. This institute hosts one of the world's most successful and respected karst conference series. High quality, scientifically valuable publications are produced through each event. Additionally, while its income may be irregular, KWI has the financial stability to provide an annual scholarship to support student thesis or dissertation research.

NCKRI receives more annual funding than most karst research institutes, but currently lacks a grant program. During its early history, NCKRI sponsored three visiting scholars, but its funds are presently directed inward to build its headquarters, buy equipment, and hire additional staff. Its newest employee is an Advancement Director, hired to help increase and diversify its funding sources. Once its critical start-up construction, purchases, and hiring are completed, NCKRI plans to establish a grants program and find other ways of directing funds outward to support cave and karst research.

14.3.6 Collaboration

While the stature of the national karst research institutes has not yet generally produced money for significant external funding of programs and projects, it is a proven catalyst for collaboration to facilitate those activities. Institute collaborations can be defined as four general categories: Volunteers, conferences, projects, and agreements.

Volunteers. Most of the volunteers and vital partners for karst research institutes are cavers and cave scientists, people whose life-long passion and dedication is to caves. When karst institutes organize research or other projects, they are the first to assist. Cavers and cave scientists are often the only ones with the abilities to reach remote and difficult areas of caves to collect data, make observations, and install research equipment. For example, caves and sinkholes are used worldwide as trash dumps, threatening cave ecosystems and human drinking water supplies. Cavers especially have the skills required to enter and clean those dangerous and disgusting sites. From 2004 to 2009, SISK cleaned more than 100 of the most polluted cave and karst sites in Switzerland. They provided the leadership and coordination, and cavers supplied most of the muscle and skill.

Conferences. In recent years, fewer conferences have been planned by single organizations, especially if the organization is a karst research institute. The institutes understand the value of collaboration and pooling resources. Other organizations often become involved to connect with an event that is larger than their individual ability to host. They gain prestige by association with the institute. Conversely, when other organizations host a conference, they seek institute sponsorships, not just for financial support, but for the validation that increases attendance and assistance. For example, the UIS' 15th International Congress of Speleology in 2009 is widely considered North America's most significant speleological conference. Part of its high attendance and success resulted from its sponsorship by HERI, KWI, and NCKRI, and the direct participation of the directors and staff from several other institutes who coordinated sessions, symposia, and other functions.

Projects. Historically, collaborative projects among karst research institutes, as well as with other organizations, were limited by politics and technology. As political barriers fall and the Internet makes international communication easy and inexpensive, institutes work increasingly with other organizations. Uncommon, but gaining in frequency, joint projects between institutes and other organizations focus on karst management. The most significant collaborative environmental karst project initiated to date by a karst research institute is the China Environmental Health Project (CEHP), organized by HERI and supported by the U.S. Agency for International Development, two Chinese universities, and other prominent organizations. The purpose of CEHP is to develop and enhance the quality of public health in China by finding solutions to karst water access and quality issues and coal-related air quality degradation. A key element of the project is engaging and training Chinese scientists, students, local governments, citizens, and Chinese environmental NGOs to meet and sustain the project's goals.

Agreements. While karst research institutes are increasingly seeking to collaborate on conferences, projects, and other activities, formal cooperative agreements for long-term collaboration are new. In 2010, NCKRI signed memoranda of understanding with ERIS, KRI, and UISK (NCKRI 2010c) to establish and formalize a foundation for closer inter-institute cooperation, exchange of information, publications, students, and scholars, open access to conferences, workshops, etc., and to cooperate in developing research, management, and educational projects, programs, and conferences whenever practical. NCKRI has also begun developing a collaborative memorandum with the U.S. Department of the Interior, which in turn would facilitate developing partnerships and projects with the Department's bureaus (e.g., Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, U.S. Geological Survey). On the other side of the world, IRCK was recently developed through an agreement between IKG and UNESCO (IRCK 2010).

14.4 The Future of National Karst Research Institutes

Since the mid-1970s, the number of national cave and karst research institutes has increased on a near-exponential trend (Fig. 14.4). Except for CSS' decline in the mid-1960s, the institutes have demonstrated steady growth and important accomplishments. As a group, their series of successful projects, publications, conferences, and increasing influence in mainstream science and regulatory arenas, have served as impetus for the creation of new institutes. The prolific ease of international communication through the Internet has concurrently served to widely publicize the institutes' successes and raise awareness of their value in other countries.

Because caves and karst are important resources in dozens of countries, the emergence of new national karst research institutes should continue for decades. But what other trends and changes are likely to occur? The synthesis provided by this chapter, and observations of related academic, scientific, social, and political trends, suggest the following set of predictions for the next 20–30 years.

14.4.1 Karst Institutes Will Increasingly Develop Hybrid Organizational Structures

The success of two relatively new institutes (HERI and NCKRI), one of which is still adjusting to its recent organizational change, may not constitute a reliable statistical trend for concluding that hybrid karst research institutes will become more common in the future. However, the short but highly productive record of these institutes is hard to ignore. The flexibility to work easily with more groups, pursue more diverse

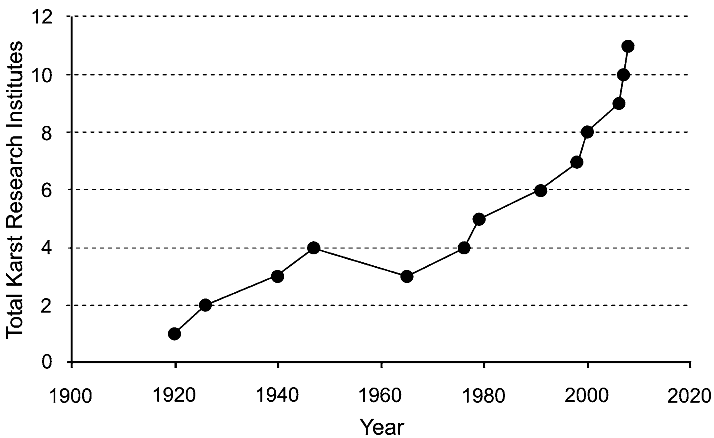

Fig. 14.4 Changes in the number of national karst research institutes over time

sources of income, and create a broader array of programs to support cave and karst research, education, and management is readily apparent. But the creation of such an institute and its initial administration to assure its activities are legal, fiscally sound, and effective is difficult. Once this hurdle is passed, a young institute will likely to find itself partnered with a well-established governmental agency, university, corporation, or the other organization that will help propel the institute to attain its goals.

14.4.2 Karst Institutes Will Predominantly Focus on Karst Management Issues

When ERIS was established as the world's first national karst research institute in 1920, the following terms were largely unknown: Carrying capacity, endangered species, groundwater contamination, human-induced land subsidence, overdrawing of aquifers, sustainable usage. Times have changed, and these and many other terms are now commonly applied to describe the modern world's environmental management problems.

Karst aquifers are the most vulnerable to pollution, and karst regions pose a complex set of ecosystem and engineering challenges unlike any seen in other terrains. The appearance of multiple karst management conferences in the U.S.A. in the 1980s resulted from management, not academic interests, as populations grew into karst regions, degrading and depleting their karst resources, while accelerating karst processes like sinkhole collapse.

But research into the theoretic aspects of cave and karst development will continue. The topics have not been exhausted but have expanded from newer and far more in-depth insights offered by modern technology. They are also important in solving management problems, but "problems" require mandates and funding to fix. National karst research institutes, as recognized authoritative bodies, should be increasingly selected as the natural choices to receive money to address environmental management problems in karst and conduct research to create or improve policies for the prevention and remediation of karst-related problems.

14.4.3 Technical and Public Education Will Become Prominent Karst Institute Programs

As karst management problems increase, there should be an increased demand for technical and general karst information. Most consultants and regulators who work in karst areas receive little information on the subject during their formal education and are either self-taught on the job or supplement their education by attending karst conferences, workshops, and seminars. Karst research institutes will likely expand their education programs to meet this growing need for information. First, they will likely expand their ranges and frequency of technical education activities (e.g., conferences, workshops, etc.). Next, they will probably introduce accurate cave and karst information into formal school and university curricula at all levels. Similarly, the institutes will probably expand their public education activities, in response to the public's interest in recent karst-related problems and to develop a better public awareness of karst to prevent some environmental problems in the future.

14.4.4 Karst Institutes Will Increase Their Support of Digital Open Access Karst Libraries and the Creation of Virtual Karst Research Tools

Paper books and documents will long be collected and archived by karst research institutes, but the institutes' physical libraries of those materials will be used less over time. Reports from the American Library Association (2010) and other sources offer mixed statistics on library usage. Most sources report that book circulation has increased in U.S. public libraries, apparently because nearly 100% of academic, public, and school libraries in the U.S. are connected to the Internet for staff and public use. Sixty-seven percent of U.S. libraries report they are the only provider of free public access to computers and the Internet in their communities, and their public computer and Wi-Fi use increased in 2009 by more than 70%. In contrast, some academic libraries report dramatic declines in book circulation as more research by students and teachers is conducted on-line.

As computers and on-line access become more available to general society, and as more books and information become freely accessible on the Internet, book usage at public libraries will probably decline as seen at academic libraries. For karst research institutes to be effective in their education programs, they will need to provide abundant, easy-to-access, accurate, and state-of-the-art information on the Internet for public and technical use. KIP is designed to serve as a one-stop source for all cave and karst information needs. While its use is rapidly growing, it is too early to say if it will achieve its goal of becoming the primary international karst information source. Additional documents are steadily added, but the development of research tools has been slow and to date depends mostly on volunteer efforts. A planned multi-language interface and search capability will increase its international use, although target dates for their implementation have not yet been announced.

14.4.5 Karst Institute Funding Will Increase Through Diversification of Services and Perceived Increase in Value

Historically, karst institutes have been funded mostly through grants and government appropriations to conduct basic research. In the future, as institutes expand their scope into karst management and become more publicly visible and valued,

Fig. 14.5 NCKRI conducts geophysical surveys to map subsurface karst hydrogeology and to evaluate the potential for collapse or subsidence

funding opportunities should also expand. Karst institutes will increasingly be hired to consult and advise on karst management issues. They may be called to develop and sell specialized equipment or software, or rent existing equipment and the services to operate it (Fig. 14.5). Expanded educational programs will lead to increased sales of books, videos, and other educational materials published by the institutes. All of the institutes, especially non-profits, will be positioned to receive more funding from grants, bequests, fund-raising events, and general donations. As long as the institutes continue to produce and share valuable results with existing and potential sponsors and partners, funding should continue or increase.

14.4.6 Karst Institutes Will Formally Link for Greater Effectiveness and Better Use of Limited Resources

"Strength in numbers" is a long-held truism but it has only recently been implemented among karst research institutes. Since 2000, a few collaborations and cooperative agreements have developed, and a comprehensive means of connecting all karst institutes, national or not, has started to emerge. In 2006, Dr. Alexander Klimchouk of UISK, led an international effort to create the International Cave and

Karst Research Institutions Network (ICKRIN). It was proposed as a collaboration of cave and karst research institutes, working together to build a network that would facilitate cooperation and partnership through the sharing of resources, results, experiences, and opportunities. Essentially, ICKRIN would be an organization of karst research organizations that would supplement, not compete, with any cave exploration, management, education, or research groups (www.speleogenesis.info). The proposal was discussed among some institute directors and at a few conferences (e.g., Groves 2007), but limited time and resources among its principle organizers has limited its development.

In 2010, Dr. Tadej Slabe, Executive Director of KRI, began developing the Karstological Academy (KA), and worked with Dr. Klimchouk and Dr. George Veni, NCKRI Executive Director, on its mandate and structure. Tentatively, KA will encompass the proposed function of ICKRIN, using resources already in place for KA. It may be expanded in the future to include individual karst scientists, if this course of action would not inadvertently weaken other organizations. No matter the ultimate fate and form of ICKRIN and KA, national karst research institutes will grow in number and prominence in the next few decades, along with a deeper collaboration among them.

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Chapter 15
Using Public Policy to Affect Human Behavior on Karst Landscapes in the United States

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Abstract Karst systems are often extremely sensitive to the nature of human activities taking place on the surface. Pollutants and contaminants can wash into karst landforms and downward through sinkholes and fissures in the hard carbonate bedrock, rapidly entering the aquifer below. Because so much of the world's population (some sources estimate as much as 25%) draws drinking water from karstic aquifers, there is a significant incentive to understand and develop land use regulations that work to prevent the inadvertent contamination of groundwater supplies in karst landscapes. This chapter provides an overview of karst-related land use regulation in the United States including commonly used techniques, geographic distribution of different regulatory approaches, and factors that tend to influence the regulation-writing process.

15.1 Introduction

Hundreds of years ago, in western Ireland, the local population sought fuel for its growing metal working industry. They found it in their abundant forests, but their aggressive approach to deforestation had the unforeseen consequence of clogging – and eventually drying up – the local aquifer. As a result, this once-productive landscape quickly turned into a scarred and barren wasteland (Back 1983). During the twentieth century, southwestern China underwent an intensive process of industrialization. For decades, hundreds of factories there have produced noxious air pollution which has been enough to strip most vegetation from the landscape; here, too, rainwater was unable to seep into the aquifer and recharge it on a regular basis. It soon suffered the same fate as the western Irish aquifer (Back 1983).

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In the Yucatan Peninsula, Spanish explorers brought with them the technology to extract groundwater from very deep wells. This made it easier to settle and tame the lands further from the coast, which in turn attracted more and more new settlers. Eventually, water-intensive agricultural practices developed into a key part of the local economy. All this environmental stress over all these years was simply too much for the landscape and as a result, by the early 1900s, the aquifer had become a "virtual sewer" (Back 1983). In Allentown, Pennsylvania, in 1979, the bottom of an industrial retention pond crumbled and gave way, dumping the pond's contents directly into the local aquifer (Memon and Azmeh 2001). The same thing happened at a golf course in Pinellas County, Florida, in 1988 (Tihansky 1999). Both of these retention ponds were located directly above sinkholes; fortunately, in both cases the actual damage to the aquifer was manageable.

While each of these events occurred in different eras and different parts of the world, they share some common traits. Each resulted from inappropriate land use practices in karst terrains, and each could probably have been mitigated or avoided completely if the people living there had used a bit more foresight and care when deciding how to use those lands. Of course, in medieval Ireland and eighteenth century Mexico, nobody knew anything about karst landscapes or what could happen when those landscapes are subjected to the stresses of human-driven change. Nor is it likely that initially local people clearly understood the relationship between land use practices and local environmental health. Still, these incidents provide a stark lesson in the dangers of inappropriate land use practices in karst terrains and an example of the seriousness of the environmental consequences. Unfortunately, these are reoccurring problems. The goal of this chapter is to provide an overview of the issues of human-karst interaction, some of the most commonly used regulatory techniques involved in managing those issues, and the process that goes into developing those regulations. This is done with an eye toward developing a more standardized understanding of where karst land use regulations fit in the interaction process between human systems and karst systems.

This chapter focuses primarily on karst regulations in the United States. Many of the examples come from Florida and Pennsylvania. This is because both states have significant karst formations and employ myriad techniques to address the issues of human-karst interaction. It is hoped that this diversity provides the reader with a broad understanding of both the common issues in karst regulation and the regulatory toolbox planners and regulators have at their disposal.

15.2 Issues of Human-Karst Interaction

Rarely are human societies able to avoid having an impact on the landscape they occupy; this is even truer for societies in fragile environments like karst terrains. Cities, towns, and agricultural enterprises located above or near karst systems often alter the conditions necessary for equilibrium in those systems, generally through inducing cave degradation, groundwater contamination, and land subsidence. In turn, these impacts often define how and to what extent humans can interact with the karst landscapes they occupy.

The physical characteristics of karst landscapes render them extremely susceptible to damage and degradation. The demands of sustaining human settlements on karst are all but guaranteed to have some effect on these fragile landscapes. However, whether out of carelessness or ignorance, humans have been abusing karst landscapes for centuries. In many cases, human societies have suffered serious consequences as a result of the impacts of their own actions on the karst below them. It is possible that these impacts may sometimes be unavoidable, but if it is possible to avoid damaging the local karst system, what is the best way to go about it? Many municipalities have taken an approach based in land use policy to protecting karst and regulating development in its vicinity.

15.3 Karst Land Use Regulation in the United States

The issues raised by human-karst interaction cut both ways: Human societies can simultaneously threaten and be threatened by karst landscapes. One way to manage this interaction and minimize the risks of subsidence, groundwater contamination, and cave destruction is to regulate how construction, development, and settlement can take place on karst terrains. In the United States, certain karst issues are often addressed via a state's administrative code (in many cases, the karst protections that are provided in this way are more of an afterthought or byproduct, usually in the course of setting rules for runoff management or dumping). But in many karstic areas with human populations, there are no municipal codes or ordinances that manage how humans and karst systems interact. While policy-based solutions have been successful in some locations – for example, the wide-ranging policy controls in place in Austin, Texas, are often cited as having had a major role in protecting the Edwards Aquifer – in others land use policies have been less effective in protecting karst environments. In many cases, this failure is a result of lack of appropriate policy tools, weak or nonexistent enforcement, vaguely defined goals, poor conception or execution, or one of the other standard traps that often bedevil policy-based approaches. By their very nature, problems of human-karst interaction often require solutions derived from more than one field; however, local regulatory bodies often have more narrowly focused areas of responsibility that make taking an interdisciplinary approach difficult. Under those circumstances, organizations without any actual regulatory power – geological surveys, for example, or karst-related research institutes – can act as catalysts for policy-based solutions and as clearinghouses for the data required to shape such solutions (Vineyard 1976). There is no reason to assume that karst protection is inherently too complex an issue to benefit from a policy-based approach. However, many existing karst protection regulations have important flaws that hamper effectiveness.

15.3.1 Commonly Used Regulatory Tools

When policy protection for karst is implemented in the United States, it is often done through the zoning and land development approval processes. Because of the potential of flooding, surface and groundwater contamination, and sinkhole formation and collapse, municipalities certainly have an interest in enacting karst-related regulation. Differences in physical and social landscapes between individual cities and towns often influence the choice of regulatory techniques employed in each municipality. However, there are several regulatory techniques that are used with more frequency than others; these include zoning codes, subdivision ordinances, stormwater management rules, and setbacks. Comprehensive plans also frequently address karst-related issues, and while they are a significant influence on land use decisions, they cannot by themselves be considered an effective tool for managing development in karst landscapes.

15.3.1.1 Zoning Ordinances

Generally speaking, zoning ordinances are implemented by both city and county governments; however, the exact division of responsibility for zoning varies from state to state. Zones that include areas where threats to local karst formations are higher – or where threats *from* the local karst formations are higher – may be subject to certain additional construction requirements that are intended to mitigate that threat. These are often related to stormwater or surface water drainage and runoff, or to implementing mandatory setbacks between human-built structures and karst landforms, usually sinkholes. In some cases, zoning overlays are used; this approach makes sense in cases where existing zoning laws would be difficult to change, or where the karst system spans multiple zones.

15.3.1.2 Subdivision Ordinances

Subdivision and land development ordinances (SALDOs) are commonly used to regulate development in karst terrains. However, because it is often easier for developers to get a variance from a SALDO, they are usually weaker forms of protection than zoning ordinances. In some places, the differences between subdivision ordinances and zoning ordinances are not clear; for example, both may be incorporated into a larger Land Development Code, particularly in smaller municipalities.

15.3.1.3 Stormwater Management Ordinances

In a karst context, stormwater management ordinances often forbid directing or piping surface runoff straight into sinkholes, and in some cases require a passive filtering system (gravel, wild grasses, etc.) be placed around the perimeter of a sinkhole near new construction or development. The popularity of stormwater management as a tool for managing development on karst landscapes seems to be an approach borne of practicality. Surface water is a source of contaminants and is simultaneously a contributing factor in sinkhole development; furthermore, the consequences of poor or ineffective stormwater management practices are often highly visible, making it easier to build a political consensus to do something about it than it is with other karst-related regulatory tools.

15.3.1.4 Setbacks

Setbacks are another widely used approach to karst protection and land use management, though not as common as stormwater management. One advantage to the use of setbacks is that they are easy to understand conceptually, and theoretically require only a tape measure to enforce. However, they also make it more difficult for landowners to develop parcels with karst features (which is often the intent of the regulations in the first place). Because of this, setbacks often come under heavy political pressure from developers or property owners who are seeking waivers or exemptions from setback requirements. One major shortcoming of the setback tool is that they generally only address sinkholes or, in some cases, springs. Contaminants can often find their way into the aquifer along other pathways (Rubin 1992). In other words, while setbacks may be effective in protecting human-built structures from subsidence dangers, they are not sufficient for protecting entire karst systems from human impacts.

15.3.1.5 Comprehensive Plans

Comprehensive plans are visible, high profile examples of local land use planning. Often, the development of a comprehensive plan is a process that incorporates significant community input and can take several years to complete. Comprehensive plan recommendations and goals are usually not binding, which means they rarely have the power of law. Because there is no power vested in comprehensive plans to compel developers and landowners to act in any particular way, this chapter does not address their role or impact.

15.4 Policy-Based Approaches to Karst Protection

Karst-related land use regulations and ordinances have been used in the United States since the mid-1980s (Richardson 2003). These ordinances often focus on a single aspect of human-karst interaction, such as imposing strict controls on new construction or management of groundwater inflow. At the same time, “multi-concerned” karst ordinances that focus on the impacts of new development on groundwater and the structural integrity of new buildings are becoming more common. Examples can be found in Johnson City, Tennessee, where an interim multi-concerned policy statement was adopted in 1994 (immediately following an extended period of excessive rainfall and flooding) (Reese et al. 1997) and in Austin, Texas, where a combination of land use management techniques and engineering controls are employed to protect the Edwards Aquifer from the consequences of urbanization (Butler 1987). Karst regulations are not universal because governments are often not given a sufficiently wide range of tools with which to manage karst. The available tools are typically limited to the comprehensive plan, the zoning ordinance, the subdivision ordinance, and the stormwater management ordinance. However, since the general public is largely unaware of karst and the planning issues that go with it, local governments are typically forced to handle karst issues in a reactive, rather than proactive, manner (Richardson 2003).

As human populations grow, so too do the challenges of waste disposal. The presence of karst can make disposal operations more difficult because of the inherent threat to groundwater quality. Requirements and regulations for handling the potential contamination of aquifers by landfills differ across the United States. For example, states take different approaches to defining both karst areas – only a handful specifically mention karst, while the rest use vague definitions of "unstable areas" – and landfills. However, there are minimum standards imposed by the US Environmental Protection Agency (EPA); for example, all landfills must have a groundwater monitoring system in place in the immediate vicinity of landfills. At the state level, Florida regulations suggest a double liner for landfills but do not require one; Kentucky, on the other hand, does require the use of such a design (Davis 1997). The benefit of this approach is that regulations can be tailored to meet local needs; the drawback is that local political culture is more likely to influence the process, and can potentially do so in a way that is not consistent with karst protection.

Policy-based approaches face even greater challenges when they are designed for implementation across multiple jurisdictions. The European Water Framework Directive, published in 2000, served as the catalyst for efforts to develop an effective and consistent European approach to groundwater protection in karst areas. The scientists working on this had the goal of integrating karst groundwater protection into the land use planning process throughout Europe. However, such integration had to be applicable to all karstic areas in Europe, which can vary greatly in terms of geologic and political conditions. Because of the difficulties in achieving this, they were forced to abandon the conceptual framework goal and instead attempt to develop a more general, common European approach to karst waters that was less comprehensive and less binding than they had originally intended (Zwahlen 2003).

15.5 Influences on the Design and Implementation of Karst-Related Land Use Regulations and Ordinances

Differences in karst regulations from one place to another are often the result of differences in the regulatory process and regulation-writing experience between those places. Each locality will face a different set of influences and inputs – or example, the level of stakeholder interest and input, or the physical characteristics of the karst system itself – into the regulation process. With so many variables at work, uniformity is perhaps beyond hope.

The following discussion is limited to inputs that are either a significant factor in the process of writing and developing these regulations, or seem to have an unexpectedly weak impact on the process. Precisely quantifying the significance of each input to the system is almost certainly an impossible task; indeed, it is challenging enough to simply identify each input. However, existing research does indicate that some inputs generally seem to have greater impact on the regulatory process and results than others. Some of the more interesting inputs from both groups are described below.

Technical expertise: Input from non-elected professionals like geologists and hydrologists has been cited as being a critical factor in the development of karst-related land use regulations (Fleury 2009). This is not surprising, as Sabatier and Jenkins-Smith (1988) emphasized the importance of specialist knowledge ("policy-oriented learning") in their Advocacy Coalition Framework of the policy process. The research suggests that consulting technical experts has significant benefits (i.e., acquisition of the theoretical and practical knowledge required to target and design effective karst-related regulations) that are not accompanied by significant drawbacks (these professionals do not seem to be inclined to promote excessively restrictive regulations, even as their influence over the process increases). But because of the generally intangible nature of the benefits of technical expertise, its impact on the regulation writing and implementation process is almost impossible to quantify. There do seem to be some tangible results of higher levels of influence from non-elected professionals: Survey results also show that the use of extra steps in the permitting process, of dumping and waste disposal regulations, and of fertilizer and chemical application regulations is more frequent in municipalities where non-elected professionals were more influential on the karst land use regulation process (Fleury 2009).

Enforcement authority: Without the ability to enforce karst protections, stakeholders with an incentive (particularly, a financial incentive) to ignore regulations are very likely to do exactly that. Outside of a protected area context, both the existing literature and interviews suggest that enforcement authority is a factor in karst land use regulation in non-protected areas in the US (Fleury 2009). For example, a comprehensive plan that attempts to control growth in carbonate areas is not likely to be effective if a zoning ordinance to implement and enforce the priorities of the comprehensive plan is absent (Day 1996; Jepson et al. 2002; Kueny and Day 2002). Additionally, subdivision and land development ordinances with karst-related components are easier to waive than zoning ordinances, and thus do not provide the same level of protection or enforcement authority.

Nature and "framing" of the problem: The nature of the specific karst problem quite naturally has a strong influence on the character of the land use regulations. Addressing a groundwater contamination issue, for example, would require a different (if partially overlapping) set of tools than addressing a land subsidence problem. Results from the survey (Fleury 2009) suggest that developing and implementing karst regulations is more likely to succeed if the underlying problem is highly visible, and if the proposed regulations can be readily connected to that specific problem. But even when the problem is visible and urgent, regulation can die on the vine if it is not properly framed. Contamination of groundwater resources and structural damage from land subsidence seem to be effective ways to frame the problem.

Stakeholder input: In this case, the term "stakeholder" is given a broad definition, and includes both local residents and those with an economic interest in the location (i.e., the construction industry, or resource users). The influence of each group of stakeholders varies widely. Fleury (2009) suggests that, for the most part, local residents do not seem to have a major influence on the development and implementation of karst regulations; the ones who do are generally the ones who are both well-informed and most likely to be affected by such regulations. This group may not be representative of the general population. In the study conducted by Fleury (2009), data collected from follow-up interviews indicate that this can change with time, through public education programs; one respondent argues that such education programs can help preserve the regulation itself by mitigating any shifts in political priorities that occur with changing administrations. For example, a new mayor may be more sympathetic to the perspective of the construction industry than his/her predecessor. In that case, a voting public with a well-developed understanding of karst and the need for its protection can act as an obstacle to weakening existing regulation.

Extent of the karst system: The size of the underlying karst system seems to play a role in determining the form of the karst-centric land use regulations that are ultimately implemented, but not on the restrictiveness of those regulations. According to Fleury (2009), municipalities with more extensive karst systems were more likely to employ mandatory setbacks/non-buildable areas and dumping/waste disposal regulations than those with less extensive karst. Simultaneously, there is no strong connection between the extent of a particular karst system and the strength of the karst regulations that are ultimately implemented.

"Keeping up with the neighbors," or the need for strategic behavior: It is appropriate to take into consideration what neighboring municipalities have done with regard to regulating development on karst terrains, but only to a point. Fleury (2009) found, in follow-up interviews with planners and land use professionals, that the experiences of other towns can be illuminating in identifying effective regulatory techniques for preventing karst degradation and aquifer damage. One reason for this is that towns in close proximity to each other are more likely to be subject to the same external influences (geologic, economic, political, etc.). However, research suggests that there is little reason to consider the mere existence of such regulations in neighboring towns as a factor in deciding whether to implement regulations focused on karst or not, as they seem to have no statistically detectable impact on indicators of economic growth and health. Additionally, results from the survey confirm that this lack of impact is generally understood by land use professionals to be the case. This contradicts expectations rooted in economics and game theory, and may indicate that karst regulations are generally not sweeping enough to have a widespread impact on growth and development patterns.

Attitudes of planners and land use professionals: The attitudes of land use professionals are critical in the process of crafting and implementing karst land use regulations (Fleury 2009). Most generally feel that regulating development on karst or near karst features is appropriate. Opinions diverge on the question of what will happen as a result of any such implementation. Counties, cities, and towns in which land use regulations do not address karst-related issues are more likely to employ land use professionals who expect karst land use regulations to result in mostly negative outcomes than are municipalities where such regulations can be found. Planners and land use professionals must be convinced that benefits will accrue, or the regulations are highly unlikely to get off the ground; this is almost certainly due to their role as "gatekeepers" in the process.

15.6 Regulatory Impacts on Urban Systems and Human Settlements

There are two ways to assess the impacts of karst-related land use regulations. The first is through direct assessment of physical changes to the karst system itself, via water quality tests, or quantifiable measures of cave protection. The second is through observation of more indirect measures – these include settlement patterns, density, and economic considerations, among others. These metrics can be indicative of the ways in which local populations inhabit and use the landscape, which can change in response to the influence of karst-related land use regulations. This section focuses on these less direct methods of observing the impact of regulations in karst terrains.

Expectations and perceived outcomes: Survey results and follow-up interviews indicate that the most commonly observed outcomes of implementing karst regulations are a decline in damage from subsidence, and an improvement in groundwater quality. However, Fleury (2009) demonstrated that these outcomes are expected to occur more frequently than they are actually reported to occur. Whether this is due to inadequate methods of regulation or something else is not yet known. Indeed, it is not even known if these perceptions are in fact accurate. It is entirely possible, for example, that groundwater quality improves far more frequently than survey respondents reported. This suggests that expectations for the benefits of implementing karst-related land use regulations may be too high, perhaps leading to an eventual consensus that the regulatory route is not adequate for managing development on karst, and that the benefits of these regulations are not worth the time and effort of implementation.

Lawsuit prevention: According to survey results and follow-up interviews conducted by Fleury (2009), karst-sensitive land use regulations seem to be an effective way to discourage lawsuits filed against the city or county. Typically, these lawsuits arise from unanticipated land subsidence activity that significantly damages property. In Lexington-Fayette County, Kentucky, for example, reducing lawsuits filed against the county was an explicit goal of the development and implementation of the county's sinkhole ordinance (the ordinance takes the form of a minimum setback/non-buildable area restriction); the ordinance has been successful in this goal (Rebmann 2006, personal communication). The presence of such ordinances or similar regulations may make it more difficult for potential plaintiffs to successfully argue that any subsidence damage to structures built near a sinkhole is actually the city's fault for negligently issuing a building permit for an unsafe area.

Economic growth and development: Higher housing costs and lost development opportunities were both cited by several respondents in Fleury (2009) as expected outcomes of implementing karst regulation. However, the same research indicates that these outcomes are not often observed. Data from karstic areas in Pennsylvania suggest that the implementation of karst regulations does not, in fact, have a statistically significant impact on median housing value within the community. As for lost opportunities for development, these can be directly tied to karst regulations only via anecdotal evidence at best (Fleury 2009).

Regulatory strength and restrictiveness: Most respondents to Fleury's 2009 survey describe their local regulations as either "not very restrictive" or "somewhat restrictive." There is some relationship between perceived restrictiveness and the increased rates of implementation of many commonly applied regulatory tools (this relationship does not apply to stormwater runoff regulations, which are almost universally applied). However, whether or not regulatory restrictiveness has any tangible impact on the urban system itself is an open question. Restrictiveness was shown to have no impact on either median home values or on the number of residential construction permits issued (Fleury 2009).

Form of regulations: Survey results suggest that stormwater runoff regulations are the easiest type of karst-related land use regulation to push through local political infrastructures. Follow-up interviews indicate that the reason for this is the straightforward nature of the problems they generally address, as well as the straightforward nature of the regulations themselves. Respondents seem to generally feel that, if done properly, stormwater runoff and management ordinances can be effective tools in karst land use regulation. They are extremely common, or the most common, in Pennsylvania local land use regulation (Fleury 2009).

While mandatory setbacks/non-buildable areas are based on a similarly straightforward idea, interviews suggest that it can be difficult to make these effective, unless it is difficult for developers and landowners to get variances. In order for that to occur, the body responsible for issuing variances must be sympathetic to the goals of regulating land development and use in karst areas; it also must have the ability to resist political pressure to grant variances in cases where a variance would be inappropriate (Rebmann, 2006 personal communication).

Interviews with those in the professional planning community suggest that zoning ordinances may often be too blunt a tool for karst-related land use regulation. This is due to the oft-localized nature of karst landform development; regulations intended to manage development near such landforms may not be appropriate for all development in a given area. Instead, it may be best to simply require developers working in a vulnerable area to hire a geologist for a site-specific analysis.

15.7 Conclusions

Ultimately, the role of regulation in karst terrains is twofold: First, to protect human-built structures from damage caused by some of the more hazardous aspects of karst terrains, like sinkholes or flooding; and Second, to mitigate and prevent damage to local karst systems and the resources (e.g., groundwater supplies or tourist attractions) that they provide. There is no single, unified approach to the implementation of this type of regulation. The variety we see in the nature and structure of karst-related regulations between towns cannot be completely explained by factors such as region, population, the extent of the local karst system, or the nature of the specific karst-related issues. The patchwork, individualized nature of karst regulations, and ordinances at the local level makes it difficult to generalize; what works in one place might not in another. However, we can draw some useful conclusions from the preceding pages. First is that less obtrusive karst regulation has the best chance of implementation, particularly if a connection can be made to a separate, more visible issue like stormwater runoff. This is because the low level of karst knowledge in the general population makes it much harder to pass more specific, restrictive karst-related regulations.

Second, karst regulations that are presented as protections for residents and their homes and roads *against* karst landforms like sinkholes may fare better than regulations that are framed as environmental protections. This is because, in the policy-making arena, fear can be an effective motivator; certainly, the idea of losing one's home to an unstoppable, expanding sinkhole would be a higher concern for most people than the idea that an unseen ecosystem might suffer irreparable damage. Regulations intended to address water quality issues can also be presented in this way, as a means to protect residents from nature's threats.

This is not intended to suggest that deception should be employed when seeking to pass karst-related land use regulations. Instead, scientists, planners, and land use professionals are urged to keep in mind that the general public often does not share their understanding or concern regarding the threats posed by human activities to local karst systems. We should, whenever possible, bear this in mind when seeking to protect karst systems from human activities via the regulatory process.

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Chapter 16
Karst and Sustainability

Robert Brinkmann and Sandra Jo Garren

Abstract The modern sustainability movement focuses on the maintenance of a sound human society while sustaining healthy environments, sound economic systems, and social justice. Several major themes in this movement emerged in recent years including the development of sustainability indices and benchmarking tools that evaluate an individual or organizational environmental footprint. Such measurements take into account a variety of factors including energy use, water consumption, building practices, transportation, economic health, social variables, and innovative practices to preserve and protect the environment and natural resources. There are a number of ways that the study of karst landscapes intersects with sustainability assessments. Karst should be considered when measuring the sustainability of energy resources, water supply, building materials, agricultural and food practices, land preservation and management, tourism, and greenhouse gas management. Specifically, this chapter discusses how karst contributes to sustainability and sustainable development and highlights instances where the current use of karst landscapes may be unsustainable.

16.1 Introduction

Sustainability is not a catchword for all things environmental. Instead, the modern sustainability movement focuses on developing clear plans that quantitatively demonstrate how humans can sustain a healthy society in a way that is environmentally, economically, and socially sound. Karst landscapes integrally fit into sustainability in a number of ways. They provide valuable ecosystem services, most notably by

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storing pristine water, providing local building materials, and mitigating climate change. However, maintaining sustainable karst systems may be at risk due to increased human development in these vulnerable regions.

The purpose of this chapter is to delve into sustainability issues that surround both the sustainability of karst and the services provided by these landscapes. The chapter is divided into two parts. The first part summarizes the roots of the modern sustainability movement and reviews some important emerging themes within the field of sustainability. The second part focuses on sustainability issues in karst terranes and is discussed in terms of energy; building; water supply; agriculture and food; land preservation, management and tourism; and greenhouse gas management.

16.2 The Modern Sustainability Movement

The last several years has seen a resurgence of interest in the environmental movement, particularly in the field of sustainability. The roots of this movement extend back to the development of twentieth century environmentalism that started with the publications of *A Sand County Almanac* (Leopold 1949), *Silent Spring* (Carson 1962), and other important contributions of the period. Such works led to widespread questioning about the environmental impact of industrialization and modern life. It is not surprising that much of the focus of the second half of the twentieth century environmental movement involved the development of rules and regulations as to how to manage pollution brought about by industrialization and how to protect ecosystems. In the United States, important legislation, such as the Clean Air Act, the Endangered Species Act, and the Clean Water Act, was passed (U.S. Congress 2002a, b, 2004). Many state and local governments also developed sound environmental policies around the world (Portney and Stavins 2000). However, while industrial nations developed practical policies, environmental issues that eluded rule making and management remained.

One of the more important issues that emerged in recent years is environmental equity and social justice (Shallcross and Robinson 2006). This issue can be examined at different scales within the context of small areas, such as environmental justice within a city (Cole and Foster 2000) or within a global context that examines, for example, the impact of industrial western societies on resource-rich, but undeveloped, nations (Roberts and Parks 2009). Such works have demonstrated that while environmental regulations in some areas have made improvements in the environment, issues of consumerism and development remain problems for society. One of the most important documents to emerge from this discussion was the report, *Our Common Future,* produced by the World Commission on Environmental Development, known widely as the Brundtland Commission (United Nations World Commission on Environment and Development 1987). The report detailed a variety of emerging issues that hinder the long-term environmental health of the planet. Specifically, the commission elucidated that sustainable development is a key to economic and environmental health of regions and defined sustainable development as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations World Commission on Environment and Development 1987)." The significance of the Brundtland Commission report is that it clearly questioned the impact of individual actions on the entire world, particularly on the world's poor. It also suggested that there are limits to technology, social organizations, and the environment in meeting the needs of the future. While many developed countries made strides in cleaning up pollution, the broader impact of their economic systems and consumer societies were making a large impact on the world. In addition, the concept of globalization within the context of environmental sustainability became more significant.

Around the same time as the publication of *Our Common Future*, there was a growing concern about the impact of greenhouse gases on our planet (Intergovernmental Panel on Climate Change 1990). Unlike many pollutants that have local impacts, greenhouse gases can impact the atmosphere of the entire earth (Intergovernmental Panel on Climate Change 2007b). Therefore, due to growing international concerns, the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations in 1988 to evaluate the risks associated with greenhouse gas emissions and associated climate change. Since its founding, the IPCC published several reports that summarize the state of climate change science and the expected impacts of global warming on the planet (IPCC 1990, 1995, 2001, 2007a). There have been distinct international policy impacts as a result of these reports, most notably the Kyoto Protocol that requires signature countries to meet specified greenhouse gas reduction targets that would achieve an overall global reduction of 5% greenhouse gas emissions from 1990 levels by 2012 (United Nations Framework Convention on Climate Change 1992). The United States is the only major developed nation that has not ratified the treaty.

While the Kyoto Protocol did impact greenhouse gas emissions, there is growing concern that it did not go far enough in reducing greenhouse gas emissions, particularly since one of the largest emitters, the United States, is not participating (United Nations Framework Convention on Climate Change 2009). In addition, the mixed results of the 2009 Copenhagen United Nations Climate Change Conference, dubbed Hopenhagen by many hoping for an international agreement beyond 2012, further clouded the ability of the world's nations to adapt a comprehensive policy to address global climate change (Heilprin 2009). Nevertheless, there is growing interest in other ways of forging successful greenhouse gas policy, particularly among local governments, nongovernmental agencies, and certain industries. However, the nature of these approaches is much broader within the context of more holistic sustainability goals.

It would be naive to trust that recent interest in comprehensive approaches to sustainability emerging from the Brundtland Commission's report and the ratification of the Kyoto Protocol would sufficiently address global climate change. There is no doubt that the current economic crisis facilitated the public interest in adopting sustainable practices (Betsill 2001). From 2008 to 2009, the global economy shrunk by 0.8% and the United States' economy shrunk by 2.5% (International Monetary Fund 2010). Particularly hurt in the United States has been the real estate market with many homes losing more than half their value, leaving borrowers upside down on mortgages. Associated with this is the overall loss in jobs over the same period. In the United States, over 4 million jobs have been lost in 2009 alone and the nation faces ~10% unemployment-- one of the largest unemployment rates in history (U.S. Department of Labor 2010). At the same time, there is instability in many of the world's oil-energy-producing nations and concerns over the future of other basic natural resources. Such a mix of economic volatility has influenced individuals in ways not seen for generations. Much of the developed world has had to readjust their consumerist approach for leaner times. Within this context, it made sense for budget-minded individuals and organizations to embrace broad-based sustainability measures in order to save money.

The belt-tightening comes at a time when many in the west are questioning their relationship with the prevailing consumer economy (Esty and Winston 2006). There are many examples of how individuals and organizations are exploring how to reduce their impact on the environment by changing buying habits. Movements such as community gardening, buy local campaigns, "buy nothing" day, and personal downsizing highlight how many are changing behaviors (Hess 2009).

Yet, such approaches mean nothing if there is no measureable improvement in the environment. Indeed, some green policies, practices, and programs have come under critical analysis as either environmentally neutral or harmful to the environment (Naish 2008). Some organizations have been charged with greenwashing by touting small environmental successes while continuing or expanding harmful practices (Vos 2009). Such examples demonstrate the need for clear accounting of environmental benefits. In response to these concerns, a number of benchmarking tools have been developed in recent years to assess environmental sustainability.

There are dozens of ways to measure environmental sustainability and no single measurement tool is widely accepted at this point. Each is designed for a specific purpose. For example, there are community-level tools that measure sustainability at the local level, and there are other indicators that can compare different countries. In addition, some tools take into account only quantifiable measures such as water consumption. Others take a broader approach and may measure the types of policies that are in place. It is worth reviewing several, different sustainability measurement tools since they inform the ways in which karst systems can be analyzed through a sustainability lens. The tools discussed below are not meant to be a comprehensive list, but instead are meant to provide examples of very different approaches to measuring sustainability.

One of the most widely recognized national-level scales is the Environmental Performance Index (EPI) (Yale University and Columbia University 2010). The EPI builds on sustainability targets proposed by the United Nations Millennium Development Goals by providing clear quantitative metrics to compare the environmental and ecosystem performance of national policies. The index is calculated using a variety of measurements of environmental health and ecosystem vitality including environmental burden of disease, water quality, air pollution, biodiversity and habitat, productive natural resources, and climate change. In contrast to this index are the Happy Planet Index developed by the New Economics Foundation

(New Economics Foundation 2010) and the Gross National Happiness Indices developed by Bhutan (The Center for Bhutan Studies 2010). While the EPI is concerned with national policies and outcomes, the happiness indices focus more on life satisfaction, life expectancy, wellness, and ecological footprint. These indices are in stark contrast to more traditional indices that rank countries by economic output or gross domestic product.

At a more local scale, a number of approaches have been used to benchmark sustainability measurements. One of the most widely known is the Leadership in Energy and Environmental Design (LEED) certification program used to certify communities and buildings as green. Started by the U.S. Green Building Council, LEED certification has become internationally recognized as one of the most important third-party benchmarking tools available to measure sustainability. While many are familiar with LEED-certified buildings that use innovative approaches to reduce the ecological footprint of a building, most are unfamiliar with the use of LEED in benchmarking neighborhood development using a point system similar to that used for assessing green buildings (U.S. Green Building Council 2010). In the neighborhood development assessment tool, LEED uses a variety of categories to assess development, including location and linkage, pattern and design, green infrastructure and building, and innovation in the design process (U.S. Green Building Council 2010). Some variations of the LEED system have been developed to fit unique settings. For example, the Florida Green Building Coalition (FGBC) certifies residential and commercial developments similar to the LEED process, but modifies it for the local subtropical characteristics of the region (Florida Green Building Coalition 2010). In addition, the FGBC certifies green local governments and evaluates local government environmental practices, incentives and ordinances that promote green practices and educational activities. The FGBC index focuses on energy, water, air, land, and waste (Florida Green Building Coalition 2009). Several communities in Florida have attained this designation and many more are seeking it (Upadhyay and Brinkmann 2010).

Interestingly, the U.S. Council of Mayors in 2005 adopted benchmarking goals to address global climate change and reduce greenhouse gas emissions according to Kyoto targets (U.S. Conference of Mayors 2010). To date, over 1,000 mayors representing close to a third of the U.S. population from cities in all 50 states have signed this agreement and are currently reporting sustainability efforts, specifically in the areas of greenhouse gas emissions. While there is still no clear U.S. federal policy on greenhouse gas emissions, local governments are leading the way to try to assess local emissions and finding ways to reduce them. In support of these local efforts, several states have led the drive toward environmental sustainability and greenhouse gas reduction, particularly California, Florida, and New York (Rabe 2010).

Several entities are also developing sustainability benchmarking tools. For example, in the United States, the American College and University Presidents Climate Commitment encourages universities to develop climate action plans that address how best to reduce greenhouse gas emissions from their practices (American Colleges and University 2010). Private organizations have also become involved with sustainability benchmarking through a number of third- party benchmarking tools such as that developed by the Sustainability Business Practices organization (International

Institute for Sustainable Development 2010) and Technology Business Research (Technology Business Research 2010). Most of these tools focus on greenhouse gas reductions but include analysis of waste streams, water consumption, transportation, corporate policy, and other practices. Nevertheless, like all other sustainability benchmarking procedures, these require a quantitative analysis of practices in order to understand the overall impact of an organization on the environment. The analysis includes collecting and assessing particular data on a number of variables.

16.3 Sustainability and Karst

The above section details how the modern sustainability movement has become significantly quantitative in recent years with benchmarking of activities that have become the dominant exercise undertaken by organizations seeking to reduce their impact on the environment. The benchmarking is used to compare and share data and to provide a starting place for understanding how to improve sustainability performance. Such efforts are primarily spreadsheet driven and allow comparison of many variables among different organizations. These variables can be measured within the broad categories of energy, water use and supply, building, and waste and recycling. As discussed below, karst systems significantly impact the effectiveness of sustainability efforts which makes sense since karst systems are intimately involved with carbon and water cycles. From a review of the sustainability performance indicators discussed in the previous section, the following sustainability categories pertain to karst landscapes: energy; building; water supply; agriculture and food; land preservation, land management and tourism; and greenhouse gas management. However, before turning to these topics, it must be noted that karst has distinct physical, social, economic, and cultural aspects that make the landscape significant.

Karst systems contain a number of important physical features, such as caves, springs, and sinkholes that make them important geologically and that set them apart from other landscapes. They exist in a variety of interesting settings such as islands or near-shore coastal plains, as well as in older continental interiors where ancient seas once aided the development of carbonate rock. In some locations, their beauty or uniqueness has brought tourists, such as in Gulong, China or Mammoth Cave, Kentucky, USA, and in others, their droughty and hazardous nature makes settlement challenging. Karst, like no other landscape, is uniquely vulnerable to human impacts due to its underground and surface connectivity. It is for these reasons that it is a suitable landscape to examine from a sustainability perspective.

16.3.1 Energy and Karst

Much of the world's significant carbon-based energy reserves are stored in karst systems. Whether it is the coalfields of the Appalachians or the plains of the Persian Gulf, carbonate rocks are a significant component of the world's energy resources. However, extraction of coal, oil, and natural gas can be problematic due to the interconnected nature of karst systems (Trice and C & C Reservoirs Ltd 2005). Specifically, in the case of oil production, karst systems are notoriously leaky and make optimal oil extraction difficult (Drew and Hotzl 1999). In addition, the extraction of such materials can lead to pollution of associated aquifer systems. Some regions have developed particular rules for how petroleum should be extracted in karst systems to preserve natural resources (see for example: http://www.in.gov/nrc/2394.htm).

One of the tenets of the sustainability movement is to use local resources whenever possible. This is difficult in the case of energy, since in many areas of the world, energy resources are not present or developed. Thus, the world has developed an integrated network of energy distribution to service the needs of most people on the planet who can afford energy resources. Oil extracted in sparsely populated places, such as Saudi Arabia, can be transported to more densely populated regions like Japan and Germany (planning group for the workshop on trends in oil supply and demand and the potential for peaking of conventional oil potential 2006). However, the economic, environmental, and social costs of transporting these resources are not fully understood. It is clear that the world has a nonsustainable approach to energy use and that there are social equity issues associated with the production, transportation, and use of petroleum products.

One of the more interesting places to examine karst and energy is in the state of Florida, USA. Known as the Sunshine State, Florida produces a limited amount of energy and must rely on the import of energy reserves such as oil, coal, and natural gas to fuel its economy. However, Florida has a significant amount of oil and natural gas reserves offshore within sedimentary rock systems in the Gulf of Mexico. Instead of using these local reserves, it imports thousands of trillions of BTU-equivalents of fuel. The main reason for this is that the majority of the state does not wish to develop a petroleum and natural gas industry due to the fears of hurting the tourism industry. Venezuelan and Western Gulf of Mexico oil is cheap, plentiful, and easy to access through one of several petroleum ports. Concerns over the impact of offshore drilling off Florida's beautiful beaches caused Florida's political leaders to ban offshore drilling for the last two decades. Indeed, the recent oil spill in the Gulf of Mexico raises even more concerns over the future of energy production within the region. Thus, while Florida could tap local energy resources, it chooses instead to import oil in order to protect its shoreline and tourist economy. It must be noted that Florida also imports significant amounts of coal from the Appalachian region of the United States, where mountaintop removal is practiced to reach coal reserves. This practice is highly criticized by environmental groups, which note the devastating impact of removing a mountain from a landscape in order to access the coal. Again, the complexity of the Florida energy situation demonstrates how protection of one resource, such as coastal systems, can deleteriously impact another environment and lead to environmental and social injustices.

It also must be noted that concerns over emissions from power plants that burn fossil fuels, particularly coal, led to the development of "scrubbers" that remove harmful materials from the emissions prior to release in smokestacks (Ma et al. 2000). These scrubbers utilize, in part, limestone in the cleaning system (Kaminski 2003). Thus, limestone is an important agent in improving air quality near power plants.

16.3.2 Building and Karst

The construction of green buildings and green communities is one of the most important aspects of the modern sustainability movement. As previously discussed, there are several certifying agencies that certify buildings as “green.” However, they all use more or less the same criteria. For example, in the LEED building certification process, buildings earn points for meeting some basic guidelines. These guidelines are divided into the following criteria: sustainable sites, water efficiency, energy and atmosphere, indoor environmental quality, innovation and design, and regional priority (U.S. Green Building Council 2008). Some of the more interesting aspects of these rating systems from a karst perspective are the use of local building materials, on-site renewable energy, storm water control, and site selection. Certainly, karst areas have an abundance of local building materials. Whether it is native limestone, marble, dolostone, or whether it is cement manufactured from this rock, natural building materials in karst areas can be used in green building. It would be inappropriate from a sustainability perspective to import granitic materials, for instance, when limestone is available. However, it must be noted that using local limestone can lead to new issues in sustainability (Bandyopadhyay and Shiva 1985). For instance, natural groundwater systems can be disrupted and cave ecosystems can be destroyed. Thus, using locally derived materials brings about local environmental challenges that must be addressed (Gunn and Bailey 1992).

Locating a building so that subsurface voids can be used for geothermal cooling or heating as an innovative renewable energy source can also earn points in the LEED system. However, overuse of geothermal energy can disrupt natural underground temperatures that could lead to changes in underground ecosystems. Little research has been done on this topic in contrast to the abundant research that has been conducted on geothermal heating (Kagal et al. 2007). Storm water management is a unique problem in karst areas. While often storm water is not a serious issue in most places due to rapid infiltration into the subsurface, special problems exist in some locations. For instance, flooding can occur in poljes during high rainfall events (Mijatovic 1988) and groundwater pollution is a serious issue in many parts of the world due to nonpoint pollution infiltration (Goldscheider 2003). Nevertheless, storm water can be routed to ponds or other areas to protect aquifers in karst areas.

16.3.3 Water Supply and Karst

Karst regions store vast amounts of groundwater. Indeed, karst aquifers are among the most productive in the world, with up to 25% of the world’s population obtaining their water from karst sources (Brown and Open University 1989). Yet, surface water supplies are often scant due to the quick percolation of rainwater through conduits within karst landscapes. Therefore, there is both great supply and significant lack of water within many karst regions. Soils and surfaces generally lack perennial water supplies and groundwater is abundant but not always easy to access. In the karst regions of Southern China, for instance, there is an abundance of rainfall, but most of the water is transported to subterranean rivers (Guo et al. 2007) where it is susceptible to pollution from agricultural and industrial runoff. Groundwater reserves can also be threatened by poor waste management and illegal dumping. In Apulia, Italy, and other locations, caves and sinkholes are frequently used as places to dump trash, which can lead to serious groundwater problems (Parise and Pascali 2003). Dumps and landfills can also cause serious groundwater contamination (Zhu et al. 2005).

Saltwater intrusion is also a significant issue in many islands and coastal karst areas. Along the Adriatic Sea, for example, saltwater intrusion is a serious issue that impacts local water supplies (Bonacci and Roje-Bonacci 2000). Also, small islands, such as the Bahamian archipelago, can lose local potable water supplies due to overuse (Cant 1996). These small islands are particularly vulnerable during droughts when small freshwater lenses are consumed and replaced by saltwater intruding from the sea. In addition, subtle changes in natural rainfall can significantly impact the long-term viability of these vulnerable aquifers (Jocson et al. 2002).

In continental settings, karst aquifers provide significant drinking water supplies to large numbers of people. The ownership of karst waters can become contested, especially due to the growing privatization of public water supplies (Trawick 2003; Balch et al. 2005). In addition, the bottled water phenomenon is a relatively new global trend whereby one can purchase a bottle of water at a price, not that dissimilar to a similar quantity of gasoline. Bottled local spring water has regional chemical variations (Misund et al. 1999) and can be considered as a consumer product since there is little evidence that the subtle chemical variations are particularly better than tap water. Nevertheless, the bottled water industry is a multi-million dollar industry that takes a local commodity and markets it for external purchase. But, who owns the water? The springs collect water from very large watersheds and discharge at a point where it can be bottled, setting up the potential for conflict among stakeholders within a basin (Hall 2009). Conflict can be compounded during dry seasons when springs are still active but surface waters evaporate and regional water tables decline. The karst springs ownership problem is part of a growing trend over the conflict of privatized water systems globally. In recent years, many public water agencies have privatized operations leading to concerns over water access and social justice (Shiva 2002). There are dozens of important springs that are used for water supplies around the world. Some of them have become impacted due to the use of water as a commercial product (Boldt-Van Rooy 2003).

16.3.4 Agriculture and Food and Karst

There is a new movement afoot for organic food, slow food, and locally grown food (Cole 2008). This is in response to the issues associated with corporate agriculture, genetically modified food (so-called frankenfood), and poor conditions for animals in large holdings (Cole 2008). In some karst areas, large agricultural land holdings are partly responsible for regional groundwater pollution, lowering of the regional water table and even sinkhole collapses.

The issues associated with karst and agriculture evolved due to the generally poor nature of karstic soils and the droughty nature of karst lands. Many of them require extensive fertilization and an irrigation infrastructure to make them productive. One of the more interesting places to examine the long-term implications of karst and agriculture is within the Yucatan peninsula of Mexico, where the Maya developed an advanced system of agriculture in support of large communities. However, the civilization was vulnerable to drought and overuse of the land due to the poor nature of the soil (Santley et al. 1986). It is believed that the collapse of the Mayan agricultural system, perhaps brought on by drought, was in part responsible for the general decline of the Mayan culture (Hodell et al. 1995).

The impact of agriculture on land stability has received extensive attention recently in Florida where huge volumes of water are sprayed on crops like strawberries to protect them from freezing during particularly cold nights. The groundwater withdrawals are massive and occur suddenly over short periods of time (Bengtsoon 1989). In some locations in Central Florida, this results in the formation of sinkholes. In the late twentieth century, several notable sinkholes formed, leading to a significant amount of property damage as a result of this pumping. In 2010, during a prolonged cold snap, even more sinkholes formed, accounting for millions of dollars worth of damage (Newman 2010). While agriculture is a significant portion of Florida's economy, many are questioning whether protecting crops during the coldest days is worth the associated damage brought on by massive water withdrawals.

One of the more interesting developments in agriculture in recent years is the growth in the biofuels industry. The expansion is largely driven by the desire to move away from nonlocal fossil fuels. Brazil, which derives a significant amount of its energy from sugarcane-based biofuels, is often seen as the model for biofuel production. While many biofuel crops require some degree of fertilization and/or irrigation, there is growing interest in using native plants that require little to no fertilization or irrigation. This may prove to be a boon to karst lands where traditional agricultural crops require greater tending than in areas with better soils and hydrologic regimes. There is a strong focus in some karst regions, particularly in Jamaica and the Dominican Republic, to learn from Brazil's example and develop local energy from agricultural products (Espinasa 2008). However, there is a growing concern over the development of biofuels, particularly in Southeast Asia where there has been a loss of biodiversity due to land conversion of tropical rainforest to biofuel crops (Danielsen et al. 2008).

Finally, it is worth remarking that karst systems are at great risk from overuse of pesticides and herbicides due to the connectivity of the surface and subsurface environments. Sustainable solutions in karst environments must include solid agricultural management to reduce the risk of pollution. In addition, there should be a focus on crops that do not require extensive fertilization or pesticides. In recent years, sustainable agriculture, including organic agriculture, community gardens, and community-sponsored agriculture, has grown in significance in karst regions around the world. This trend has the potential to improve agricultural practices in order to limit agricultural pollution.

16.3.5 Land Preservation, Land Management and Tourism and Karst

Land preservation of karst lands is another important aspect of the modern sustainability movement. There are a variety of public and private organizations involved in karst conservation that include a plethora of management options. Perhaps the best known preservation efforts originate from federal, state, and local governments. In Romania, for example, the Apuseni Nature Park consists of over 180,000 acres of land that contains a variety of caves and other karst landscape features. Interestingly, the park was designed to not only preserve the karst landscape, but also to preserve Romania's rural villages and culture (Fleury 2009). Thus, one can visit a well-preserved cave, such as Scarisoara Ice Cave or Bear Cave, while also staying in a rural farm incorporated within the agrotourism plan of the park. Jamaica too has large areas of karst lands under preserve called Cockpit Country (John and Newman 2006). This land, which is managed by Jamaica's forest service in partnership with local stakeholders, is home to some of the more unique karst features in the Caribbean as well as unique ecosystems (Day 2009). This is in contrast with the approach taken in many other countries, particularly the United States, where parks such as the 46,000-acre Carlsbad Caverns National Park, are natural preserves without significant human settlement. The management plans for these parks typically focus on the preservation of the natural resources of the park and the visitor's experiences. Similarly, the Philippines have set aside large areas of parkland for preservation (Restificar et al. 2006).

Private organizations and individuals are also involved in cave preservation (Baus 2009; Bodenhamer 2009). For example, many cave clubs or grottos raise funds to purchase lands to protect caves or preserve them for recreational or scientific purposes. In addition, several nonprofit organizations, such as the Speleological Federation of the European Union, actively raise funds for cave and karst lands preservation. Many individuals and private companies are also involved in cave and karst protection.

The management of caves and karst lands can be a contested issue. There are many commercial caves with limited conservation efforts, and there are many others with strict conservation rules and limitations on the number of visits to the cave each day. Two well-known caves illustrate the dilemma facing cave managers. In 1940, a remarkable cave near Lascaux, France, was discovered by two young boys. The caves contained amazing prehistoric cave art depicting a variety of animals and actions. Once known, the cave was a public sensation and thousands visited each year. However, the management of the cave became problematic, and the cave was damaged due to the change of temperature, lighting, and input of microbes brought by the circulating air and the many visitors (Bastian et al. 2010). Eventually, the cave was closed to the public in order to protect the cave art. A replica, Lascaux II, was constructed so that visitors could tour a facsimile of the cave near the original.

In contrast, Lechugilla Cave, in Carlsbad Caverns National Park, consists of over 100 miles of cave passages containing some of the most unique speleothems ever discovered. The cave is publically owned and thus is part of the overall management plan of the Carlsbad Caverns National Park. Early in its exploration in the 1980s, the park determined that the uniqueness of the features required special management separate from other caves in the park (National Park Service 2006). Unlike Lascaux, the managers set distinct access restrictions, and it was never opened to the public. Permission to enter is given only to experienced cavers with special permits to conduct scientific and exploratory research (National Park Service 2006). Well-regarded and beautifully filmed documentaries are available to the public that show the important cave features and the extent of the cave.

These two caves illustrate well-known efforts to preserve important cave and karst resources while still providing opportunities to view the caves, albeit virtually. In contrast, many privately owned caves with thousands of annual visitors have measurable impacts ranging from algae or other microbial damage to speleothems. Nevertheless, these caves often are important ways that the public learns about caves and karst. Indeed, education on caves and karst within these public caves provides support for the conservation of caves that are not open to the public.

It must be noted that many karst landscapes, including those around Lascaux and Lechugilla, are important for local tourist economies and for archeological significance (Crothers et al. 2007). Carlsbad National Park is in a desert landscape relatively inhospitable for most economic activity, and the Dordogne region of France is not within the major tourist trails of Europe. The presence of the karst brings tourists and associated jobs to the region. Indeed, ecotourism of karst lands and diving of springs and caves provides thousands of jobs worldwide and helps to preserve karst systems and educate the general population about the environmental significance of karst (Yan and Zhan 2002).

16.3.6 Greenhouse Gas Management and Karst

As concerns have expanded about the impacts of climate change on our planet, the scientific community has searched for ways to reduce greenhouse gases, remove them from our atmosphere, and store them on our planet. In recent years, there has been a great focus on developing inventories of greenhouse gas releases and storage to estimate changes in the greenhouse gas cycle. These inventories can be aggregated by region, organization or individual. For instance, many states, cities, and universities have conducted greenhouse gas inventories (Selin and VanDeveer 2009), and there are many online sites where one can enter data to obtain one's carbon footprint. These are the first step in developing plans to reduce greenhouse gas emissions or sequester and store carbon in order to mitigate these emissions.

Clearly, karst landscapes, formed from carbonate rocks and their dissolution and intimately involved with the carbon cycle, are critical to understanding greenhouse gas management. There have been some innovative projects proposed to reduce the impact of carbon emissions on our planet that involve karst systems. One of the more promising areas that emerged from this effort is carbon storage within deep aquifers in karst landscapes. To facilitate this, carbon dioxide is pumped deep within the earth in a similar fashion to deep aquifer waste storage (Lee et al. 2010). While research is continuing on this topic, and there are concerns about the impact of pumping carbon dioxide into deep aquifers, there is no doubt that there is potential for changing the dynamics about how we think about greenhouse gases and climate change via deep carbon storage.

Another way of storing carbon is to encourage reef growth to create new limestone. This has received significant attention because the development of artificial reefs can store tons of carbon within shallow marine environments by creating new limestone. However, there are problems with this approach. Many coastal areas are polluted, limiting reef development (McKeown 2010). In addition, the emerging problem of ocean acidification, whereby the ocean becomes more acidic with increases in atmospheric carbon dioxide, is demonstrably limiting the production of shell material in some areas of the world (Feely 2004). Thus, while artificial reef development has potential, the natural oceanic carbon cycle is damaged because of pollution and high levels of carbon dioxide in the environment.

It must be noted that many karst lands are among the most uninhabited in the world. Thus, they store millions of tons of carbon in forests and grassland and can be considered as carbon sinks. In other areas, karst lands have been damaged by overdevelopment or inappropriate agricultural practices, which could lead to revegetation projects to restore carbon in forest and grassland preserves within cap and trade carbon credit programs. In many areas of the world, there are economic benefits to landowners who enter their lands into carbon storage programs. These opportunities bring funds to rural areas, enhance job opportunities, and promote ecotourism.

Much of what we know about prehistoric climate change comes to us from the study of speleothems in caves (Polk et al. 2007). While most are familiar with the results of the analysis of ice cores and ocean sediment used to decipher past climates, many are unfamiliar with the use of cave deposits. In fact, speleothem records have been used around the world to accurately date climates within distinct geographic settings. Speleothems are analyzed to ascertain particular temperature and moisture conditions. Because the speleothem layers can be dated, the temperature and moisture variables can be charted with time to produce detailed charts. Climate records using speleothems demonstrate that there is remarkable climatic variability that studies using other techniques have not been able to demonstrate.

16.4 Discussion and Conclusions

Karst lands have tremendous potential to be part of the solutions to many of the global environmental problems we face. The new sustainability movement, with its focus on benchmarking and assessment, leads organizations into a new way of thinking about resource use to preserve environmental, economic, and social systems into the future. Within this context, there is great interest in karst lands since they are so crucial to water and carbon cycles, and because they contain an abundance of traditional energy sources and are emerging as major biofuel production regions. In addition, many karst lands are considered poor for agricultural uses and are under consideration for reforestation or have already been converted into forest lands after the failure of agriculture in the nineteenth and twentieth centuries (Hart 2010).

Efforts have already been underway to understand the implications of karst regions from an environmental perspective. For example, van Beynen and Townsend have examined how to classify the disturbance of karst lands by looking at a variety of factors associated with environmental degradation of karst including pollution, cave destruction, and development (van Beynen and Townsend 2005). The index can be modified for sustainability measurements in a way that could allow regional assessment of karst sustainability. Such a karst sustainability metric would be useful for planning purposes.

One of the more troubling aspects about karst landscapes is the fact that many of them are located in areas where poor environmental management in the past caused modern sustainability problems and associated environmental justice issues. For example, many Caribbean Islands have significant saltwater intrusion problems and must import water by container ship for tourists while locals must harvest rainwater. In these locations, there are many social justice issues that are compounded by the nature of the modern globalized world.

Perhaps one of the more interesting ideas associated with karst and sustainability is in the area of greenhouse gas management. Karst systems are intimately involved with the global carbon cycle and therefore can be managed to enhance carbon storage within sediments or rocks. In addition, the use of deep aquifers for storage of carbon dioxide holds significant promise for reducing the impacts of greenhouse gases within the atmosphere.

Regardless of the specific uses of karst lands as we proceed with sustainability enterprises on our planet, there is no doubt that the role of carbonate rocks in the global carbon cycle will be of interest to sustainability planners for many decades.

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Chapter 17
Human Disturbance of Karst Environments

Philip E. van Beynen and Kaya M. van Beynen

Abstract Karst environments have been impacted by human activity for thousands of years, ever since people started living in caves for shelter, needing building supplies and water. As human population has increased, so has its disturbance of the karst landscape. Quarrying, pollution, groundwater extraction, construction, and agriculture are the major culprits for disturbing both surface and subsurface karst. Ecosystems in this type of environment have been shown to be quite vulnerable to human activities. Methods to quantify this disturbance, such as the karst disturbance index, have been created to help resource managers formulate approaches to reduce this anthropogenic impact. In addition, models to measure karst vulnerability, in particular karst aquifers, have grown in number over the last two decades. When measuring human disturbance, it is important to consider matters of time and scale, as both will influence how and what data is collected.

17.1 Introduction

Humans have the capacity to disturb their environment in multiple ways in order to provide food and shelter. Karst environments are particularly vulnerable to disturbance due to the nature of their very creation, the dissolution of the bedrock. This removal of carbonate rocks allows the rapid flow and substantial decrease of groundwater filtering, sinkhole formation, and potential decimation of fragile ecosystems

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in karst waters and caves. In this section, we provide some examples of human disturbance from different karst regions of the world and describe the various means of measuring, monitoring, and responding to these changes. To ensure rigorous measurement and comparability across geographies, scientists need a common set of tools to classify karst disturbance, collect data, and interpret results.

17.2 Types of Disturbance

The many types of human disturbance of karst environments are shown in Fig. 17.1 (Williams 1993). The most destructive practice for surface karst is large opencast mining. Quarrying alters the hydrology of an area by reducing spring discharge and drawing down the water table, which can produce sinkholes. Tailing ponds that result from silver and lead mining, common in karst areas, can introduce toxic chemicals to the local water supply if they leak or collapse. Even landscapers inflect small-scale damage by removing limestone pavement (Goldie 1993). The massive extent of environmental disturbance to karst landscapes is evident in the example of Great Britain; with its abundant limestone quarries, a total of 124 metric tons of rock were removed during 1987 alone (Gunn and Bailey 1993). Mining operations are common in karst, particularly for the zinc, lead, and silver found in carbonate rocks. Red Dog Mine, Alaska, is the world's largest zinc mine with an

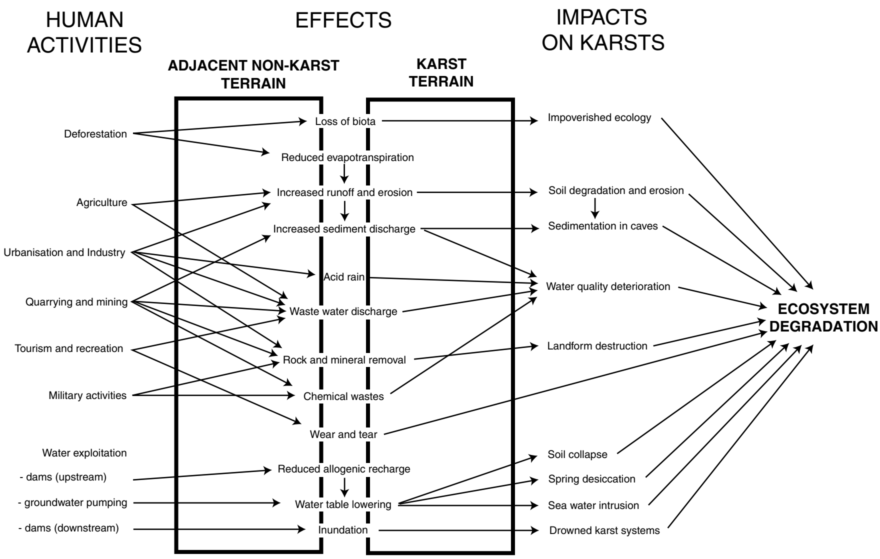

Fig. 17.1 Impacts of anthropogenic activities on karst environments (Reproduced with permission, Williams 1993)

ore body of 19.5 million metric tons (Williams 2000). The world's largest opencast limestone quarry is Calcite Quarry in Michigan, measuring 7 km by 4 km. Between 7 and 10 million tons of rock have been removed annually for the last 85 years (Micketti 2004).

Large-scale disturbance can also result from valley flooding caused by reservoir construction. The Three Gorges Dam construction in China flooded vast areas of karst landscape, thereby inundating caves which contained religious shrines that were thousands of years old, as well as flooding out any troglobite species that may have existed in these caves. This massive inundation alters the hydraulic regime of karst systems by saturating the vadose zone, and in extreme cases, as in the Vajont Dam in Italy (Ford and Williams 1989), it can destabilize slopes by increasing hydraulic pressure within the bedrock. Small-scale flooding and pollution occurs when sinkholes are used for storm water drainage, a common practice (Crawford 1984; White et al. 1984; Keith et al. 1997). Flooding caused by rice production can also be detrimental for karst, as in the Philippines (Urich 1993).

Sinkholes are often unwanted natural features and are often filled during urbanization either by purposely concreting over the sinkhole during urban development or through illegal dumping of refuse, a common practice in both urban and rural areas (Quinlan and Ewers 1985). Unfortunately, this infilling can lead to later subsidence and damage to overlying structures (Sinclair et al. 1985). Parise et al. (2004) stated that high levels of chromium were found in rivers in Albania, the source being pollution dumped into sinkholes.

Caves are among the most highly identifiable features of karst environments; they are also among the most disturbed (Donahue 1990; Silverwood 2000; Veni et al. 2001). Human impacts can range from the wholesale destruction of caves due to limestone quarries, unintentional impacts from paths and lighting in tourist caves that can dry out speleothems, and vandalism of speleothems or their collection for sale as unique commodities of the underworld. Huppert et al. (1993) provide a detailed overview of this problem.

The decline of cave biodiversity is discussed by Roth (1993). Cave lights, lint from clothes, artificial entrances, skin flakes, dust and spores, and even alteration of water chemistry due to seeping sewage contribute to loss of diversity. Gunn et al. (2000) documented the impacts of quarrying, agriculture, waste disposal, groundwater removal, and tourism on the macro-invertebrate species of the Peak-Speedwell Cave System, England. The caves of Tasmania, Australia, have been severally impacted by forestry activities, leading to the decline of cave species numbers, diversity, and individual species presence (Clarke 1999).

Deforestation caused by agriculture or urban expansion causes increased sedimentation rates in caves, higher turbidity in waters, changes in nutrient levels of seepage waters, and greater flooding of conduits (Harding and Ford 1993; James 1993; Sauro 1993; Wood et al. 2002). While deforestation is often seen as a cause for desertification in karst, Xiong et al. (2009) are among the first to imply that anthropogenic climate change has increased rocky desertification on surface karst in

Hunan Province, China. They state that higher temperatures and heavier rainfall are the main contributors to creating desert-like conditions by increasing soil erosion.

Changes in the water quality and quantity above the caves can upset the delicate ecosystems that exist within the caves (Gillieson 1996; Gunn et al. 2000). Human agricultural and industrial practices can contaminate percolating karst water with pesticides, herbicides, volatile organic compounds, and dense nonaqueous phase liquids, such as trichloroethylenes (Loop and White 2001). These and other pollutants not only affect the cave ecosystem (Drew 1996) but also contaminate the underlying aquifers used for human consumption (Xie et al. 2002). The overuse of karst aquifers through pumping of groundwater leads to sinkhole generation (Tihansky 1999), desiccation of caves (Pugsley 1984; Baker and Genty 1998; Craven 1999), loss of species (Boulton et al. 2003), and salt water intrusion (Arfib et al. 2000). Examples of these human disturbances can be seen in Fig. 17.2.

Fig. 17.2 Examples of human disturbance of karst landscapes in Apulia, Italy. (**a**) Garbage illegally dumped into a cave, potentially contaminating groundwater and killing cave biota; (**b**) tires which were illegally dumped into a sinkhole; and (**c**) widespread landscape alteration during quarrying operations (Permission from Mario Parise)

Fig. 17.2 (continued)

Fig. 17.2 (continued)

17.3 Attempts to Reduce Disturbance

Disturbance of karst environments can be prevented through the passage of legislation, preserving fragile areas, and creating severe penalties for disturbance. Examples of legislation protecting karst areas are Sites of Special Scientific Interest (SSSI), which falls under the British Wildlife and Countryside Act of 1981 (Gunn and Hardwick 1996), and the Federal Cave Resources Protection Act of 1988 in the United States (Huppert 1995). National Parks have been created in North America to protect significant karst systems. Some of the most famous are Mammoth Cave, Wind Cave, and Carlsbad Caverns National Parks (USA), and Nahanni National Park (Canada). International recognition through UNESCO and the IUCN World Commission on Protected Areas (Watson et al. 1997) helps preservation at such sites as Ha Long Bay (Vietnam), the stone forests of Shilin (China) and the Aggtelek Cave and Slovak Karst region (Hungry and Slovakia). In the Caribbean, Central America, and Southeast Asia, protection of karst regions occurs through national parks, national forests, nature reserves, and on private property (Day and Urich 2000; Kueny and Day 1998, 2002; Day 1996; Urich et al. 2001). However, this protection is only as effective as its enforcement, which is often weak, especially in developing countries. An example of this issue is given in De Waele and Follesa (2004), who discussed the case of Lusaka, Zambia. There, unrestricted population growth with its accompanied waste production and uncontrolled dumping had led to severe pollution of the local karst aquifer, the main drinking water supply for the city. No efforts were made to control this problem.

Best Management Practices (BMPs) for agricultural areas, outlined by Urich (2002), can reduce the negative impacts of soil erosion in karst areas. These include (1) planned grazing, which involves pasture rotation and allows vegetation to recover and (2) livestock exclusion, which keeps animals away from sinkholes and cave entrances so that their effluent is less likely to directly flow into the subterranean realm. Veni (1999) suggested the development of environmental impact assessments (EIAs) for karst areas, with special attention paid to surface and epikarst areas of infiltration and the use of buffer zones around them. Veni also suggested limiting the amount (15%) of impervious surfaces in a karst area to help reduce impacts on water quality.

Parise and Suarez (2005) provide a case study of a show cave in Cuba that can be seen as a model for low-impact tourism. Efforts have been made to limit both the number of visitors through small group sizes and restricting access to certain passages in the cave. No fixed light system has been installed in the cave, and only wooden ladders (natural products) are used throughout the cave.

17.4 Methods of Determining Actual and Potential Impact or Vulnerability

17.4.1 Karst Disturbance Index

In 2005, van Beynen and Townsend outlined a new composite method for evaluating human impacts exclusively for karst landscapes (van Beynen and Townsend 2005). The Karst Disturbance Index (KDI) used an environmental index approach with five categories: geomorphology, hydrology, atmosphere, biota, and cultural. Indicators were selected to measure disturbance levels for specific subsets of the environment, while efforts to protect karst were rated through several indicators under the cultural category. In all, 30 general indicators, consisting of comparable data that sensitively reflect the state of a karst environment, were selected to evaluate the level of disturbance (Table 17.1). As karst environments are characterized by unique properties, more indicators can be added for specific locations if needed. However, as a general guideline, indicator data has to be inexpensive to gather, easily reproduced across time and space, and responsive to changes in condition. Data sources for indicator assessment consisted of field surveys, information collected in local municipalities, Geographic Information System (GIS) databases, topographic maps, aerial photographs, websites, and personal interviews with local cavers and state officials. In certain locales, an extensive speleological literature already exists and should be the initial resource for collecting karst disturbance information. The KDI was created to allow the measurement of disturbance in a format that was comparable over time and place.

As with other environmental indices, indicators have to be scored, which is done either quantitatively or qualitatively depending on the indicator. Scores from 0 to 3

Table 17.1 The karst disturbance index as applied to west central Florida

Category	Attribute	Scale	Indicator	3
Geomorphology	Surface landforms	Macro	Quarrying/mining	Large open cast mines
		Macro/meso	Human-induced hydrologic change	>34% of surface karst hydrology altered by flooding or flood suppression
		Meso	Stormwater drainage (% of total stormwater funneled into sinkholes)	>66%
		Meso	Infilling (% of infilled caves and sinkholes)	>66%
		Meso	Dumping (% of sinkholes affected)	>66%
	Soils	Macro	Erosion	Severe
		Micro	Compaction due to livestock or humans	Widespread and high levels
	Subsurface karst	Micro	Flooding (human-induced flooding due to surface alteration)	Permanent cave inundation
		Micro	Decoration removal/vandalism	Widespread destruction
		Micro	Mineral/sediment removal	Most of material removed
		Micro	Floor sediment compaction/ destruction	Most of floor sediment/ decorations affected
Atmosphere	Air quality	Macro	Desiccation	Widespread and high levels
		Micro	Human-induced condensation corrosion	Widespread and high levels
Hydrology	Water quality (surface practices)	Meso	Pesticides and herbicides	>34% region covered by urban development and/or horticulture and/or golf courses
		Micro	Industrial and petroleum spills or dumping	>5 brownfields and/or >10 toxic spills
	Water quality (springs)	At all scales	Concentration of harmful chemical constituents in springs	Concentrations harmful year round
	Water quantity	Macro	Changes in water table (decline in meters)	>35
		Meso	Leakage from underground petroleum storage tanks	7+ gas stations within 10 km^2
		Micro	Changes in Cave Drip Waters	Total cessation
Biota	Vegetation disturbance	At all Scales	Vegetation removal (% of total)	>66%
	Subsurface biota – ground water	Micro	Species richness (% decline)	50–75
		Micro	Population density (% decline)	50–75
	Subsurface biota – caves	Micro	Species richness (% decline)	50–75
		Micro	Population density (% decline)	50–75
Cultural	Human artifacts	At all scales	Destruction/removal of historical artifacts (% taken)	>50
	Stewardship of karst region	At all scales	Regulatory protection	No regulation
		At all scales	Enforcement of regulations	Widespread destruction, no enforcement
		At all scales	Public education	None, public hostility
	Building infrastructure	Macro	Building of roads	Major highways
		Meso	Building over karst features	Large cities
		Micro	Construction within caves	Major modification

2	1	0
Small working mines	Small scale pavement removal	None
34–10% of surface karst hydrology altered	<10% of surface karst hydrology altered	No alteration
34–66%	1–34%	None
34–66%	1–34%	None
34–66%	1–34%	None
High	Moderate	Natural rate
Widespread but low levels	Few isolated concentrated areas	None
Increased intermittent flooding & >50% infilling	Increased intermittent flooding & <50% infilling	Only natural flooding due to high rainfall
~50% of speleothems removed	Isolated spots of removal	Pristine
~50% of cave floor affected	Some isolated spots	Pristine
~50% of floor sediment/decorations affected	Small trail through cave	Almost pristine, mostly rock surface
Widespread but low levels	Isolated and very low levels	Pristine
Widespread but low levels	Isolated and very low levels	Pristine
34–10% region covered by urban development and/or horticulture and/or courses	<10% region covered by urban development and/or horticulture and/or golf courses	No alteration
5 brownfields and/or 5–10 toxic spills	≤4 brownfields and/or ≤5 nontoxic spills	No spills and no brownfields
Concentrations harmful for short periods	Concentration just above background levels	Pristine water
15	<5	Only natural variability
3–6 gas stations within 10 km^2	<3 gas stations within 10 km^2	No gasoline stations
Long dry spells (not seasonal)	Slight reduction	No change
34–66%	1–34%	0
20–49	1–19	0 or increasing
20–49	1–19	0 or increasing
20–49	1–19	0 or increasing
20–49	1–19	0 or increasing
20–49	1–19	0
A few weak regulations	Statutes in place but w/loopholes	Region fully protected
No policing, but little damage done	Some infrequent enforcement	Strong enforcement
None, public indifference	Attempts through NGOs	Well funded gov't programs
Some two lane roads	Some country lanes	Minor trails
Towns	Small settlements	No development
Tourist cave	Cave trail marked	Pristine

are based on the degree of disturbance: the lower the score, the lesser the disturbance. If an indicator is not applicable to a certain study area, it can be discarded. Total disturbance can be measured by tallying individual indicator scores and dividing this total by the highest possible score. A value between 0 and 1 will be obtained, corresponding to a karst disturbance level: 0.0–0.19 (pristine), 0.20–0.39 (little disturbance), 0.40–0.59 (disturbed), 0.60–0.79 (highly disturbed), and 0.80–1.0 (severely disturbed). The strength of the index approach is that karst scientists and other stakeholders can transparently identify how and why each indicator is rated, while the overall state of the karst environment is refined to an easily comparable and comprehensible category for environmental managers and policy makers.

Thus far, KDI has been applied to Florida and Italy (Calò and Parise 2006; van Beynen et al. 2007; De Waele 2009; North et al. 2009) and to Jamaica (see following Chapter by Michael Day). Human impact for the Italian study area has occurred for thousands of years compared to shorter time spans in Florida. Nevertheless, the higher population density of Florida's western countries produced disturbance levels of those reached in Italy. The most destructive practices in Southeast Italy karst were quarrying, stone clearing, and garbage dumping into caves. In contrast, Florida karst experienced infilling of sinkholes, soil compaction, water table changes, and deforestation. For resource managers and policy makers, the main reasons for applying the index were to: (1) establish a benchmark of human disturbance for a region that, with future applications of the KDI, would enable land managers to determine whether the quality of the environment is improving or declining and (2) to target limited remediation funds to the indicators that received the highest disturbance scores.

17.4.2 Other Methods to Measure Karst Disturbance

A more focused technique for determining human impacts on caves was developed by Lavoie and Northup (2005), who identified bacteria introduced by humans traveling through caves as a means of quantifying the level of human-cave interaction. *Staphylococcus aureus, Escherichia coli,* and high temperature *Baillus,* introduced by humans, are not naturally present in karst regions and can have substantial impact on the subterranean environment. These bacteria are introduced to the environment through human excrement found in camps, urine dumps, drinking water sites, and along travel routes. These bacteria are brought into the cave from the surface and will die if no more are introduced over time. However, it was not clear whether the presence of these bacteria is harmful to the endemic cave biota in any way, and as such, the quantities of bacteria simply gauge whether a cave is exposed to human activities.

Previous efforts had tried to highlight disturbed karst areas, but these were based more on which areas had the strongest advocates who could draw attention to their region rather than an approach based on a systematic scientific method using data looking at the whole karst environment. In particular, the Karst Waters Institute previously published the top ten disturbed karst regions of the world, but these sites were selected mostly on cave biota or surface disturbances, with little regard to investigating the entire spectrum of human disturbance.

17.5 Karst Groundwater Vulnerability

Karst aquifers are resources of growing importance throughout the world. Approximately 25% of the world's population gets its water from these aquifers, particularly vast regions in Asia, the Mediterranean, and the United States (Ford and Williams 2007). With an increased demand for water from growing populations, these aquifers will experience more stress from withdrawals. The accompanying urban and industrial expansion that eventuates from more people increases risk of groundwater contamination from chemical spills, dumping, and landscaping. Karst aquifers are particularly vulnerable to such risk because of the infiltration of water through the epikarst or sinkholes, which often provide direct connections between the surface and aquifer.

When defining karst aquifer vulnerability, it can be viewed as either intrinsic or specific. Intrinsic vulnerability is governed by the physical characteristics of the karst setting that influence the degree of vulnerability to the aquifer. These include soil characteristics (infiltration rates and thickness), epikarst intensity, sinkhole density, and hydraulic conductivity (characteristics of the karst "plumbing"). Consequently, these physical parameters determine the potential for vulnerability, whereas specific vulnerability adds the human element, taking the above parameters and adding landuse, thereby incorporating actual anthropogenic threats (Leibundgut 1998). One of the most concerted efforts to define karst groundwater vulnerability was undertaken by the European Coordination Program, in which 16 countries took part in a 5-year study (COST-Action 65 1995).

This vulnerability of all aquifers to groundwater contamination has been reconstructed and led to the creation of groundwater vulnerability models (GVMs) whose aim is to quantify an aquifer's level of vulnerability to human-induced contamination. Probably the most widely used is DRASTIC, a generic model that incorporates various physical components of both aquifer and overlying substrate (Aller et al. 1985). More recently, researchers in Europe have attempted to create their own GVMs that include GOD (Foster 1987), AVI (van Stempvoort et al. 1993), EPIK (Doerfliger et al. 1999) and PI (Goldscheider et al. 2000). The Florida Department of Environmental Protection (DEP) commissioned a new model (FAVA) that measures vulnerability specific to the three aquifers in Florida (Arthur et al. 2007). Most recently, Guo et al. (2007) adapted DRASTIC to create another model (DRARCH) to assess for arsenic contamination for a Chinese aquifer. All of these models have two common threads: they concentrate on the physical parameters of the hydrologeological setting of their region and are based on GIS.

EPIK (Doerfliger et al. 1999) is one of the more well-accepted GVMs specifically designed for karst aquifers and deserves elaboration. Four GIS-based layers of

Table 17.2 Scoring of the layers for EPIK

Layer	Characteristic	Score
Epikarst (E)	Highly developed	1
	Moderately developed	2
	Small or absent	3
Protective cover (P)	0–20 cm soil	1
	20–100 cm	2
	100–200 cm	3
	>200 cm	4
Infiltration conditions (I)	Perennial or temporarily losing streams	1
	I1 with slope >10% cultivated and 25% meadows	2
	I1 with slope >10% cultivated and 25% meadows	3
	Rest of catchment	4
Karst network development (K)	Well-developed karst network	1
	Poorly developed karst	2
	Springs emerging from porous terrain	3

epikarst (E), protective cover (P), infiltration conditions (I), and karst network development (K) are used to measure vulnerability, with each layer being scored accord to characteristic seen in Table 17.2. EPIK is a point count system model and its four attributes (layers) are weighted: $Fp = \alpha \text{ x } Ei + \beta \text{ x } Pj + \gamma \text{ x } Ik + \delta \text{ x } Kl$ with $\alpha = 3$, $\beta = 1$, $\gamma = 3$, and $\delta = 2$. The total score is termed aquifer protection (Fp), with higher values equating to lower vulnerability as shown below:

Vulnerability areas	Protection factor F
Very high	F less than or equal to 19
High	F between 20–25
Moderate	F higher than 25
Low	Presence of P4

Ravbar and Goldscheider (2009) investigated four different intrinsic vulnerability models for a karst catchment in Slovenia. These models included EPIK, PI, the Simplified Method, and the Slovene Approach. The purpose of their study was to delineate protection zones for the karst aquifer in this study region. Above, we have already outlined EPIK, therefore, what follows is a brief overview of each of the other methods. Goldscheider et al. (2000) developed PI, which incorporates protective layers above the saturated zone (P) and "I" stands for infiltration conditions. The Simplified Method (Nguyet and Goldscheider 2006), as the name suggests, simplifies the PI model by only measuring overlying layers and concentration of flow. Finally, the Slovene Approach is the most sophisticated method of all the models, incorporating nine parameters for measuring the karst unsaturated zone, six for recharge conditions and three for the karst saturated zone, as well as including measures of resource vulnerability and source vulnerability.

The application of these four models is shown in Fig. 17.3, and while there are certain similarities between the methods, some clear differences exist as well. Both

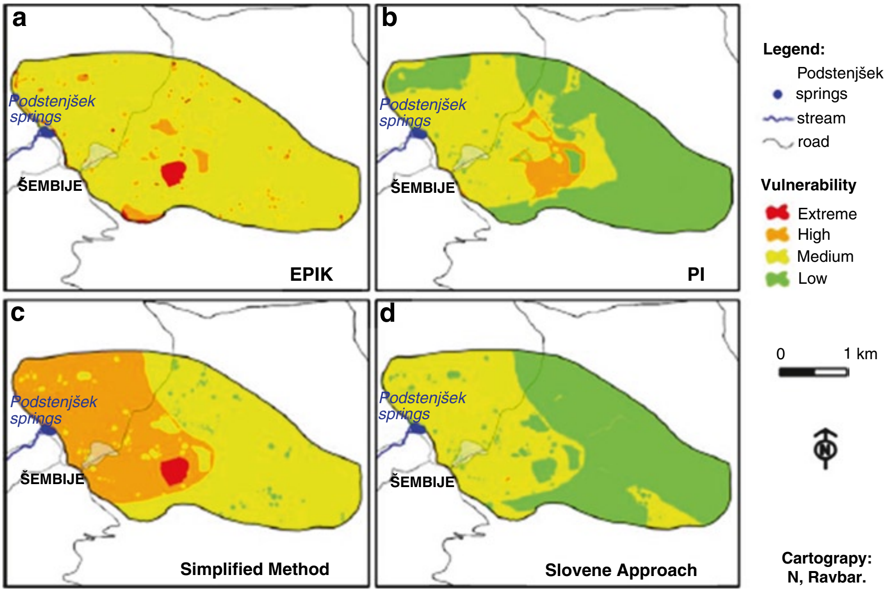

Fig. 17.3 Comparison of various vulnerability models as applied to a Slovene karst catchment (Reproduced with permission, source: Ravbar and Goldscheider 2009)

EPIK and the Simplified Model show greater vulnerability compared to the other two methods. Nguyet and Goldscheider (2006) suggest this is because of differences in how all the various models treat temporal hydrologic variations. These authors validated each of the models using a multi-tracer dye test. The Slovene Approach provided the most reliable results as derived from the validation test. However, its greater number of parameters may also limit its adoption due to lack of necessary input data and the limited resources of water resource agencies.

17.6 Data, Time, and Scale

17.6.1 Data Availability

One main challenge facing any researcher investigating karst disturbance is the lack of data pertaining to human impact. Quantitative studies of biota of the surface and subsurface karst are extremely limited though researchers around the world are attempting to fill this void. It has been recognized that karst ecosystems are highly vulnerable to human disturbance, yet these effects have received little study (Wood et al. 2008). For example, Whitten (2009) found that, in China, very few environmental assessments undertaken before construction projects in karst areas investigate cave fauna. Consequently, it is unknown what effects such projects may have or have had on cave fauna.

Four main obstacles have lead to this issue: public ignorance, too few biospeleologists, difficulty of collecting data, and the massive number of caves around the world. Firstly, the general public, even those who live on limestone and get their drinking water from karst aquifers, have little idea of the fragile ecosystems below their feet and what effects dumping of trash, petrochemicals, and fertilizers have on them. As Wood et al. (2002) state, "out of sight, out of mind." Secondly, the total number of scientists who study karst are not large compared to other disciplines, and biospeleology is a subset of that small group. Consequently, relatively few biologists are trained or have interests in cave fauna, even though caves are considered a biodiversity hotspot (Whitten 2009). This then limits the number of studies done on karst biota, leading to a lack of knowledge of species assemblages. Another obstacle is the subterranean environment itself, with many caves being small, difficult to enter and navigate. Surveys of the biota within these systems can be inaccurate as often the cave organisms can venture places people cannot. Finally, the sheer number of caves around the world, many with endemic species, makes comprehensive datasets difficult.

Inaccurate or incomplete monitoring of human activities in karst environments can also make measuring human disturbance problematic. For example, developers may face the dilemma of reporting a cave and potentially holding up their construction projects or simply filling it without notifying the proper authorities. In many places, builders are not even required to notify the infilling of sinkholes or caves, thereby inhibiting land managers from gaining a comprehensive understanding of how the landscape has changed. Development on karst areas can continue with proper oversight to limit the disturbance. Solutions to encountering caves could be creating setbacks to protect the cave "catchment" or by moving roads and buildings. The lack of reporting of chemical spills or even purposeful dumping is probably the most common problem in determining the true extent of human disturbance of karst groundwater. Companies or individuals can face fines for spills or costs of correct disposal and often illegal dumping is a cheaper solution. A major corporation in Tampa, Florida, dumped methylene chloride, trichloroethene and lead into the karst groundwater for a decade before its activities were discovered in the 1980s (Business Wire 2005). In the developed world, environmental protection agencies have been created to prevent this from occurring, but in the developing world, with their lack of resources, these agencies either do not exist or are ineffective.

A fundamental shortcoming when determining possible disturbance is the lack of knowledge about the physical parameters of the karst landscape itself. Examples of this problem include definitive boundaries for karst, directions and velocity of water flows, the areal extent and depth of karst aquifers and even the location of caves. Accurate knowledge of these parameters helps determine if certain human activities even have the potential for disturbance based on location or whether a particular chemical spill has a major or minor effect on groundwater. For example, the extent of the PCB spill site in Smithville, Ontario, was not determined until well after the event due to the lack of knowledge of where and how quickly the contaminants flowed through the landscape (Worthington 1999).

Data voids can also apply to records kept by municipalities with regard to activities that create disturbance. These data voids could include the number and locations of mining and logging operations or the infilling of sinkholes. Other governmental information that may be lacking is the effectiveness of legislation for controlling potential harmful pursuits or the results of public education efforts to curb disturbance. For example, in Belize, illegal logging is common in karst terrane, yet there are no official records of where or how widespread this practice may be (Reeder, 2006 personal communication).

17.6.2 Matters of Time and Scale

When investigating disturbance, one must consider both temporal and spatial matters. Temporal matters involve how the quality of the environment has changed over time. Questions to be considered are:

1. What was the pristine state of the karst environment?
2. When did the disturbance start?
3. Can you clearly delineate between natural vs. anthropogenic change?
4. Has there been a steady degradation over time or has the situation improved?
5. Does the natural system recover over time or is it permanently altered?

The first question can be problematic as some regions of the world have been disturbed for thousands of years, as in the case of Europe and Asia. In these situations, the environment can be so altered that it is impossible to determine what is pristine. To complicate matters, people may want to preserve the altered environment, such as in the case of Mayan burial sites or cave structures (walls, pots, shrines) in Central America. The third question can be difficult to answer, especially pertaining to water levels in aquifers, erosion rates, percolation rates of seepage waters into caves or changing cavern microclimates. One must recognize that all natural systems undergo natural shifts in their state.

The matter of degradation raised in question four is significant because as Wood et al. (2008) discovered, certain species recovered within 12 months in a British cave after an organic spill above the cavern, whereas other species did not. In fact, some species were not affected at all, while other species appeared that were absent prior to the event. Only investigations across a decade could reveal such changes (Wood et al. 2002; Wood et al. 2008), which touches on the issue raised in question five.

Matters of scale come into consideration when trying to measure impacts ranging from groundwater pollution to damage in individual caves. Scale was discussed in detail in van Beynen and Townsend (2005) and North et al. (2009), with the former incorporating it into the KDI and the latter suggesting scale may be used as a weighting mechanism for scoring of disturbance indicators when applying the KDI. However, they ultimately decided against this option as the interconnectedness of karst systems defeated the idea of one parameter being more important than another. For example, as with the above example, groundwater pollution can be deemed a macro-scale disturbance, while a loss of biodiversity in one small cave may be deemed micro-scale. However, the pollution may have lead to the loss of the cave biota, thereby highlighting the unity of scales in karst for certain parameters of disturbance.

17.7 Conclusions

The above discussion has highlighted how humans can affect karst systems and methods designed to measure their disturbance and vulnerability. Determining environmental disturbance and vulnerability provides necessary data for policy decision makers and planners to allow them to make comparisons of the state of their environment across time and space, and generate environmental quality estimates (Esty et al. 2005; Ebert and Welsch 2004). We stress the need for such an approach for karst settings. Systematic monitoring of karst environmental quality is required to allow this approach to occur. An overarching question is: How can people respond to this disturbance? There are models that have been created to help resource managers deal with such matters at broad scales. For example, environmental researchers and managers have created response models such as the Pressure-State-Response (PSR) framework used by the OECD and the Driving Force State Response (DFSR) used by the UN Commission in Sustainable Development; however, these are for nations as a whole and do not consider specificity of landscape type. There are no response models that specifically target karst environments: one approach that could be used.

One final point of consideration is how to best communicate this scientific information about disturbance and vulnerability to land managers, the general public, and decision makers to create informed land management decisions and adequately protect, remediate, and conserve fragile karst environments. Such a matter is not trivial and would require a concerned effort between interested parties to create clear communication linkages to dessimate relevant information via press releases, workshops, public hearings, and information sessions.

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Chapter 18
The Cockpit Country, Jamaica: Boundary Issues in Assessing Disturbance and Using a Karst Disturbance Index in Protected Areas Planning

Michael Day, Alan Halfen, and Sean Chenoweth

Abstract The Cockpit Country is Jamaica's only remaining pristine karst area and is perhaps the most significant karst landscape in the Caribbean. It may be a candidate for UN World Heritage status but its boundaries are contentious. The Karst Disturbance Index (KDI) is an important tool for karst conservation, providing an objective numerical measure of the extent to which karst landscapes have been disrupted by human activities. Its application is, however, constrained by issues of boundary determination and location, and the Cockpit Country exemplifies this phenomenon when different boundaries are determined on geomorphic, historical, existing, and proposed management criteria. Analysis of land use data from 1998, together with extensive field surveys, reveals that the measure of the extent of human disturbance is closely related to the positioning of the boundary, with the incremental inclusion of peripheral areas beyond the core forest reserve resulting in a dramatic increase in the disturbance index. Not only is this a methodological concern in using the KDI, but it also illustrates how the KDI may be useful in planning and establishing potential protected area boundaries.

18.1 Introduction

The Cockpit Country of Jamaica is the iconic "type example" of polygonal cockpit karst, and it has been the subject of considerable academic and applied research. It plays a significant role in the regional hydrology of Jamaica's north-central region,

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and it has great biological significance, together with a deep cultural meaning to Jamaica. Since 1950, it has been partially protected as a forest reserve, but it is under increasing pressure from peripheral populations and from various unsustainable land use designs. Additionally, its integrity is challenged by the impacts of anthropogenic climate change, which threaten significant changes in the geomorphological environment.

Mitigation of these various threats is central to future conservation of the Cockpit Country, which is Jamaica's only remaining pristine karst area and perhaps the most significant karst area in the Caribbean. It may also be a viable candidate for UN World Heritage status if its future status can be guaranteed. This will not be without difficulty, however, because the development of an appropriate management strategy mandates careful consideration of both physical and human dimensions of the Cockpit Country landscape, including social, political, and economic considerations of the area that should be protected.

The precise extent of the Cockpit Country has never been definitively established, which further renders efforts to conserve it difficult. Four alternative boundary demarcations are currently available, encompassing an area between 228 and 1,142 km^2. The most compact area is the existing forest reserve, whereas the most extensive is that proposed by those favoring greater protection as a national park and World Heritage site.

The KDI developed by Van Beynen and Townsend (2005) is an important weapon in the arsenal of karst conservationists, since it provides an objective numerical measure of the extent to which karst landscapes have been disrupted by human activities. Its application is, however, constrained by issues of boundary determination and location, and the Cockpit Country exemplifies this phenomenon. Analysis of land use data from 1998, together with extensive field surveys, reveals that the measure of the extent of human disturbance is closely related to the positioning of the boundary, with the incremental inclusion of peripheral areas resulting in a dramatic increase in the disturbance index. Not only is this a methodological concern in using the KDI, but it also illustrates how the KDI may be useful in planning and establishing potential protected area boundaries.

18.2 The Cockpit Country Karst

18.2.1 Physical Dimensions

The Cockpit Country is the "type example" of what Ford and Williams (2007) describe as the "egg-box" style of humid tropical polygonal karst (Day and Chenoweth 2004). Centered on Trelawny Parish (Fig. 18.1), the Cockpit Country covers about 600 km^2, although its precise limits remain under discussion (Lyew-Ayee 2005). The cockpits are steep-sided, more or less enclosed karst depressions, some over 100 m deep and 1 km in diameter, surrounded by residual hills or ridges, and are so named because they resemble the arenas formerly used for cock fighting (Sweeting 1958).

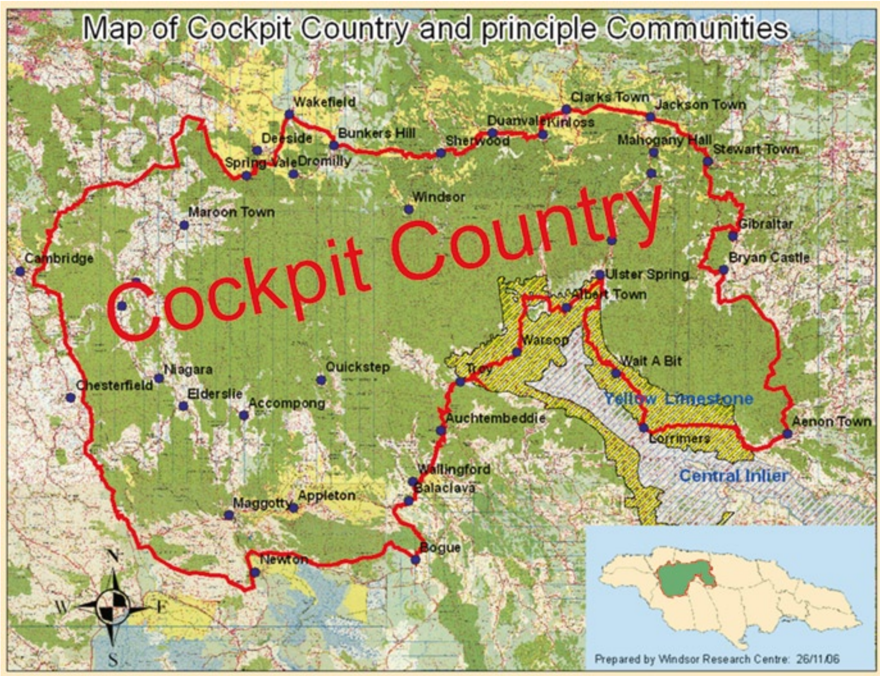

Fig. 18.1 Location of the Cockpit Country (courtesy Windsor Research Centre)

The residual hills and ridges are serrated by elevated saddles, and many cockpits are connected to one or more of their neighbors by a lower corridor (Chenoweth 2003; Chenoweth and Day 2001). Some cockpits are elongated, reflecting structural influences or inheritance from abandoned surface drainage systems (Day 2002). The residual hills are rarely conical or isolated; rather they are linked at their bases as irregular ridge remnants, and it is the enclosed depressions, rather than the hills, which are the focus of geomorphic activity (Day 1979).

Cockpit slopes and the surrounding hilltops and ridges are highly irregular, with patchy clay soil cover. Slopes consist of combinations of vertical cliffs, inclined bedrock surfaces, "staircases," or talus accumulations (Aub 1969a, b). By contrast, the depression bases often have a deep regolith cover, and some contain relict, debris-choked vertical shafts (Smith et al. 1972). Internal drainage is centripetal, although dominantly vertical (Day 1979). Regional drainage is largely autogenic and northward, although there are allogenic inputs on the southern boundary (Versey 1972). On the northern periphery, underground drainage emerges at a series of springs, which supply rivers draining to the north coast (Day 1985).

The Cockpit Country is developed primarily in Eocene carbonates of the White Limestone Formation, although some of the south is formed by older rocks of the Yellow Limestone group. The White Limestones are generally extremely pure, mechanically competent, and well bedded, with blocks of strata dipping towards the

NNW and separated by NW-SE and NE-SW trending faults (Barker and Miller 1995; Miller 1998). The oldest formation, the Troy-Claremont, is ~300 m in thickness and is generally unfossiliferous, recrystallized, and dolomitized, except where the Claremont itself is a fossilferous biomicritic limestone. The Swanswick Formation, in the northern part of the Cockpit Country is a rubbly, fossiliferous biosparite up to 100 m in thickness. There continues to be uncertainty about the origin of the bauxite deposits that occur in the vicinity of the Cockpit Country, although the most plausible explanation is that they are derived from Miocene bentonitic clays of volcanic origin (Comer 1974).

The Cockpit Country is important ecologically both nationally and in a Caribbean context (World Wildlife Fund 2003). The vegetation includes a range from wet to dry limestone forest in which there is considerably floristic diversity and an extraordinary number of endemic species (Proctor 1986; Kelly et al. 1988; World Wildlife Fund 2003). The fauna includes threatened bats, snakes, frogs, and all but one of Jamaica's 28 endemic bird species (TNC 2003).

18.2.2 Historical and Cultural Dimensions

The Cockpit Country has considerable national historical and cultural value in Jamaica, particularly as a stronghold of Maroon resistance to British occupation during the eighteenth century (Eyre 1980; Day 2004a). Maroon resistance represents an important aspect of Jamaican national consciousness, and in this sense, the Cockpit Country, with its attendant military history, folklore, and vestigial place names (Look Behind, Me No Sen, You No Come, Don't Come Back, Flagstaff, Gun Hill), has a cultural significance which has not been adequately appreciated in the context of potential conservation.

The Maroon Wars ended with the duplicitous Pond River Treaty of 1796, of which the British took subsequent advantage to seize Maroon lands and transport Maroon leaders and their followers (Black 1965; Robinson 1969). Treaties gave the Maroons a degree of autonomy that they have maintained ever since, although Maroon land claims have never been resolved satisfactorily, and they remain a source of contention between the present-day Maroons and the Jamaican government (Ward 1990). Uncertainty of land tenure remains an issue throughout the Cockpit Country (Barker and Miller 1995).

18.3 Anthropogenic Challenges

18.3.1 Human Impacts

Both rational use and despoliation of the Cockpit Country have, to date, been limited by the restricted access, by the rugged terrane itself and by the lack of surface water. During colonial times, slaves were permitted to grow crops in marginal areas adjacent to plantations, and this legacy has persisted on the margins of the Cockpit Country. In particular, the flatter areas on hilltops or within cockpits are used for the cultivation of yams, with more extensive flat areas being used for bananas, selected tree crops, and the grazing of livestock. Less accessible areas are used for marijuana cultivation. Increasing conservation and management concerns include agricultural encroachment, particularly around peripheral population centers such as Troy (Miller 1998), tourism, species extinction or introduction, increasing utilization and contamination of water resources, and urbanization and industrial activities, including limestone quarrying and bauxite mining (Day 2007). The severity of these impacts can best be reduced by appropriate land management and land use planning, including the effective maintenance of the Cockpit Country as a protected area (Day 2004b, 2006, 2009).

The Cockpit Country is also threatened by predicted anthropogenic climatic change, which will lead to increasing temperatures, decreasing precipitation totals, and the increasing frequency of extreme events, such as droughts and hurricanes. These will disrupt the karst hydrological cycle, resulting generally in increased aridity and possible desertification, but interspersed with storm damage and flooding, with concomitant impacts on geomorphic processes and ecology (Day and Chenoweth 2009).

18.3.2 Conservation Issues

Since 1950, much of the Cockpit Country has been designated as a 223 km^2 forest reserve, although there has been little enforcement of conservation directives. The immediate vicinity has a population of some 10,000 people and is exploited for bauxite mining and agriculture (Barker and Miller 1995). Less than 6% of Jamaican forests remain intact, and deforestation rates nationally are among the world's highest (World Wildlife Fund 2003).

In the forest reserve, illegal logging, farming, hunting, and trapping for the pet trade are particular problems (Miller 1998) and local deforestation has been estimated at about 3% annually (Eyre 1989). Despite these threats, the area is recognized as a critical area for plant diversity and endemism (Davis et al. 1997). As such, the Cockpit Country has been proposed as a U.N. Natural World Heritage site (Eyre 1995), and there are currently plans to inscribe it as a national park (Chenoweth et al. 2001; Day 2004b).

Less than 550 km^2 of Jamaica's 7,500 km^2 karst lands, or about 7%, is conserved within six protected areas (Kueny and Day 1998). The Cockpit Country is the largest and most significant of these. In the Caribbean context, the Cockpit Country remains perhaps the most significant karst landscape to be spared from exploitation and degradation. Jamaica's Country Environmental Profile (Field and Troy 1987) identified considerable threats to national long-term ecological sustainability and promoted the establishment of the Natural Resources Conservation Authority in 1991 and the initiation of the USAID Protected Area Resource Conservation (PARC) project in 1990 to create a sustainable national protected areas system (McDonald 1996).

The proposed Cockpit Country National Park is one component of the PARK Project and was recommended as a protected area by the Jamaica Conservation and Development Trust in 1992 (JCDT 1992).

Preliminary funding for a Cockpit Country conservation project, potentially involving establishment of a national park, was obtained by the Jamaican government from the World Bank in 1999, and this rekindled controversy over the area's future status and use. Awareness of the need for conservation was also elevated by a controversial government plan, now modified, to route a new highway (Highway 2000, from Kingston to Montego Bay) through the area. Opposition to this project from environmental groups and the Maroon community resulted in a proposed rerouting of the road around the Cockpit Country, but the issue of potentially improved access remains contentious. Stakeholder reaction to the national park proposals has been very mixed (Day 2004b, 2006). International reaction has been generally positive and international NGOs such as the Nature Conservancy have taken leading roles in advocacy and in developing conservation strategies (TNC 2003). National conservation organizations have been supportive of the national park proposal, but the attitude of local residents has been ambivalent, with support but also reluctance, suspicion, and opposition, the latter from those involved in illicit activities (Day 2004b, 2006). There is uncertainty about potential benefits and detriments and how these will impact local individuals and organizations.

Opposition derives primarily from business concerns, especially the logging, quarrying, and bauxite mining industries, which object to the likely proscription of their economic activities. Bauxite mining, associated largely with North American conglomerates, is Jamaica's second largest industry, accounting for about 20% of GNP. Major bauxite reserves are located within the Cockpit Country, but their extraction is patently incompatible with the national park's conservation imperatives (National Environment and Planning Agency 2003). Competing claims for economic development come from other commercial sectors that hope to benefit from the park establishment. Finally, but crucially, the attitude of the national government appears equivocal, with various agencies voicing differing degrees of caution and support for the national park proposal. These agency alignments generally reflect their areas of responsibility, e.g., the National Resources Conservation Authority lists declaration of a Cockpit Country protected area in its Environmental Strategy, while the Forestry Department endorses protection of existing forest reserves in its 2001 Forest Policy (Forestry Department 2001).

18.4 Boundary Definitions

The precise extent of the Cockpit Country has never been established definitively, which makes its demarcation and its conservation that much more difficult. Establishing and recognizing boundaries are critical elements in effective protected area management (Chape et al. 2008; Hanna et al. 2008).

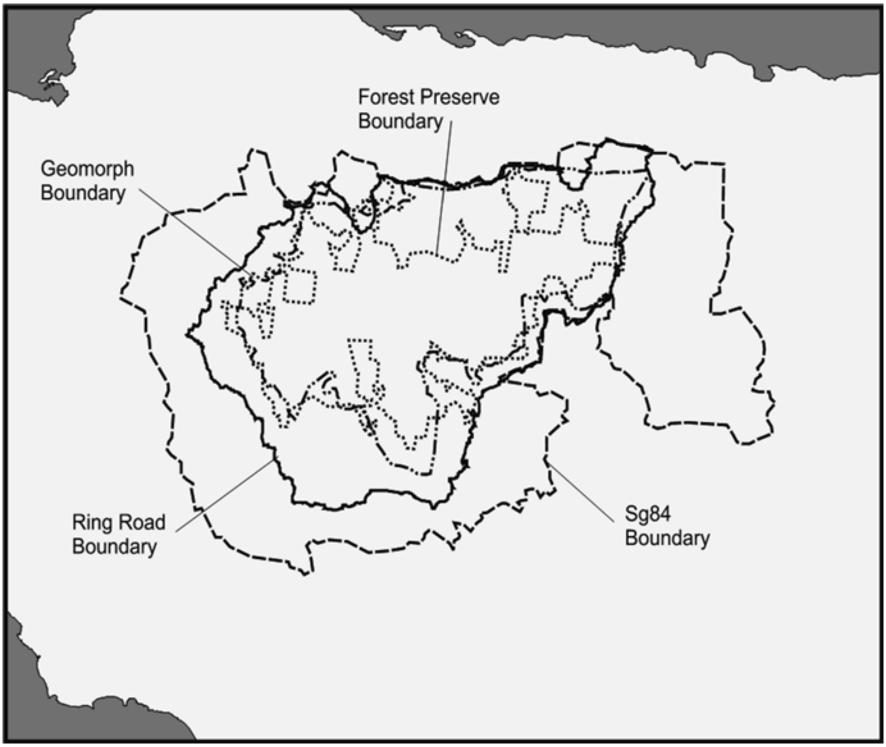

Fig. 18.2 Cockpit Country boundaries (scale 1:600,000)

Four alternative Cockpit Country boundary demarcations are currently available (Fig. 18.2), each based on differing criteria, hatched in different times, and couched in different frames of reference. Each has its rationale, but each also has its limitations.

The existing forest reserve boundary dates to 1950 and is a colonial legacy reflecting a long-term commitment to forest management for watershed protection and sustained economic timber viability (JFD 2010). The forest reserve boundary is the most conservative of the four, encompassing an area of 288 km^2, but it is currently the only boundary associated with any level of land use regulations (Chenoweth et al. 2001; Day 2004b, 2006). Its management is under the auspices of the Jamaica Forestry Department, which legislates for conservation and sustainable management of forests (JFD 2010), although enforcement of the regulations is sporadic (Day 2004b, 2006).

The second boundary definition is a geomorphological one, which demarcates the contiguous area of cockpit karst and distinguishes it from adjacent areas of doline and tower karst. This boundary dates to the 1950s and is based on the regional geomorphological work of Marjorie Sweeting (1958), who undertook some of the first detailed studies of the cockpit karst. This boundary encompasses 415 km^2 and is the most rational from a strictly geomorphic perspective, since it essentially excludes noncockpit karst. Although the precise location of the geomorphological boundary has recently been challenged by Lyew-Ayee (2005), the general location of his geomorphic boundary is broadly similar, extending somewhat to the northwest and more to the southeast. The modified geomorphological boundary (Lyew-Ayee, dated 2005 but not actually published until 2009) was not available to us when this research was undertaken.

The third feasible boundary definition is essentially an historical one, dating originally to the time of the Marroon Wars in the 1700s, when British colonial military forces established a *cordon sanitaire* around the cockpit topography that was occupied by rebellious combatants. This historical boundary was subsequently reinforced by the construction and maintenance of a so-called “Ring Road,” which still persists essentially intact today. This “Ring Road” boundary encompasses 618 km^2.

The fourth and most recently proposed boundary was suggested in the early 2000s by conservation groups hoping to bring about a negotiated decision about the future conservation status of the Cockpit Country, in particular its possible inscription as a national park, with a view to future designation as a World Heritage site (Day 2004b, 2006). This boundary, referred to here as the JET/CCSG boundary, after the Jamaican Environmental Trust and the Cockpit Country Study Group, is the most liberal, encompassing 1,142 km^2.

18.5 The Disturbance Index

A KDI was first proposed by Van Beynen and Townsend (2005) as an objective numerical procedure for assessing human disruption of karst landscapes. The index has subsequently been modified from its original format and has been tested and employed in several regional studies (Calo and Parise 2006; Van Beynen et al. 2006; North et al. 2008; De Waele 2009; Parise et al. 2009), although none of these studies has explicitly examined the influence of boundary determinations and none of them has focused on the potential use of the KDI in planning and establishing protected area boundaries.

The index involves five primary disturbance indicators: geomorphic, atmospheric, hydrologic, biotic, and cultural, under which were initially subsumed 31 subindicators (Van Beynen and Townsend 2005). Each subindicator has a possible numerical range from 0 (no disturbance) to 3 (highly disturbed).

The KDI is computed by dividing the subindicator sum by the total sum possible, and overall KDI scores are interpreted as follows:

0.0–0.19	Pristine
0.20–0.39	Little disturbed
0.40–0.59	Disturbed
0.60–0.79	Highly disturbed
0.80–1.0	Severely disturbed

A confidence level is determined by: nSI/LD/100, where nSI is the number of subindicators and LD is the number of subindicators for which data is unavailable. A confidence level of <0.1 is high, whereas one >0.4 is low.

18.6 Testing the Disturbance Index in Relation to Cockpit Country Boundaries

The KDI was tested in the Cockpit Country utilizing the four alternative boundaries represented as shape files in ARCGIS. The primary data source was the 1:100,000 1998 land use database and map compiled by the Jamaica Forestry Department (JFD 2009) (A 2007 land use database is forthcoming but is not yet available). The land use map indicates land use types based on forest vegetation cover (JFD 2010), and these provide an initial assessment of disturbance. For example, Closed Forest (Code PF) represents pristine undisturbed forest, with other codes representing greater degrees of human influence (JFD 2009).

The 1998 database and map were supplemented by literature review and by extensive field surveys conducted by UW-Milwaukee personnel in 2003, 2005, and 2007. Literature review was conducted to identify prefieldwork cases and locations of specific disturbances such as forest clearance, water contamination, air pollution and construction, and to make general assessment of broad factors such as general air quality and biological integrity. Field survey on foot and by vehicle was utilized to "ground-truth" the overall land use/disturbance derived from the JFD database and to gather supplemental data about features and activities that are not readily apparent from the land use map. Land use categories identified in the initial database were broadly confirmed qualitatively and were not modified, but specific disturbances such as pits and quarries, evident soil erosion, livestock grazing, new construction, and crop cultivation were quantified and incorporated relatively into the subindicator enumeration. Field survey covered ~1% of the forest reserve, much of which is essentially inaccessible, and perhaps 5% of the area within the geomorphological boundary, which is accessible by track and road. Approximately 50% of obvious and passable roads within the Ring Road boundary were used, and about 20% of roads within the JET/CCSG boundary. As such, the determinations of the subindicators and the resultant KDIs are based essentially on the JFD database, with the field data being supplementary, incomplete, and relative.

Thirty-one subindicators were employed in the KDI assessment, with data lacking only for five subindicators (decline in water table, subsurface cave and groundwater declines in species richness and population density). The calculated disturbance indices were as follows:

Forest Reserve Boundary:	0.13 (pristine)
Geomorphological Boundary:	0.24 (little disturbed)
Historical "Ring Road" Boundary:	0.44 (disturbed)
JET/CCSG Boundary:	0.61 (highly disturbed)

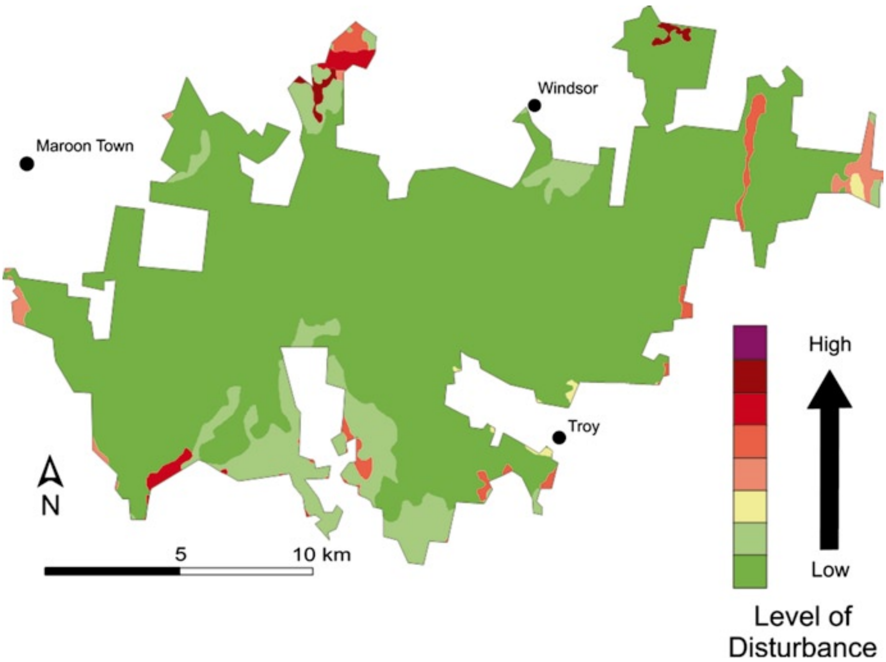

Fig. 18.3 Disturbance within forest reserve boundary

The differing levels of disturbance are shown in Figs. 18.3–18.6, which show clearly the increasing incorporation of disturbed areas as the boundary is extended outwards from the forest reserve. In the relative context of the KDI, pristine areas are shown in dark green, little disturbed areas in light green and yellow, disturbed areas in pink and red, highly disturbed areas in maroon and brown, and severely disturbed areas in purple.

The computed confidence level was high, at 0.052, reflecting the combination of a high-resolution satellite-based land use database together with supplementary field surveys. The main factors accounting for KDI differences within the four boundaries were quarrying/mining (0–2), mineral removal (1–3), forest fragmentation (1–3), introduction of exotic species (0–2), existence of regulatory protection (1–3) and enforcement of regulations (1–3).

The resulting disturbance indices for the areas encompassed within the four different boundaries clearly were not only significantly different from a conservation perspective, but also a regression between the areas within the different boundaries and the level of at least moderate disturbance within those boundaries yields an R^2 value of 0.9867 (Fig. 18.7), emphasizing the critical role of the boundary selections. Likewise, a chi-square analysis of the subindicator value frequency distribution (Table 18.1) results in a chi-squared value of 52.774 with 15° of freedom and an extremely statistically significant two-tailed p value of less than 0.0001.

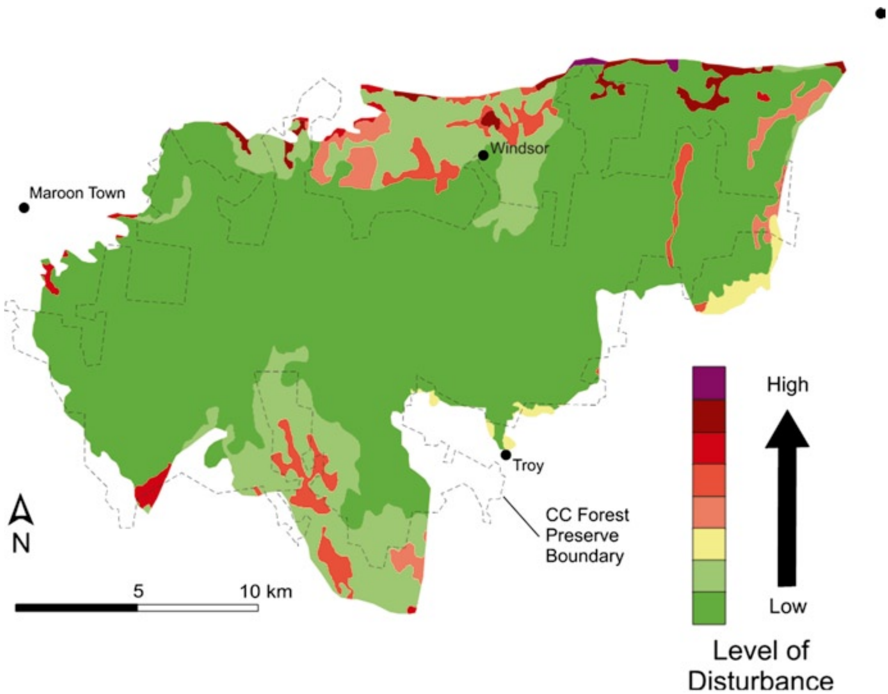

Fig. 18.4 Disturbance within geomorphological boundary

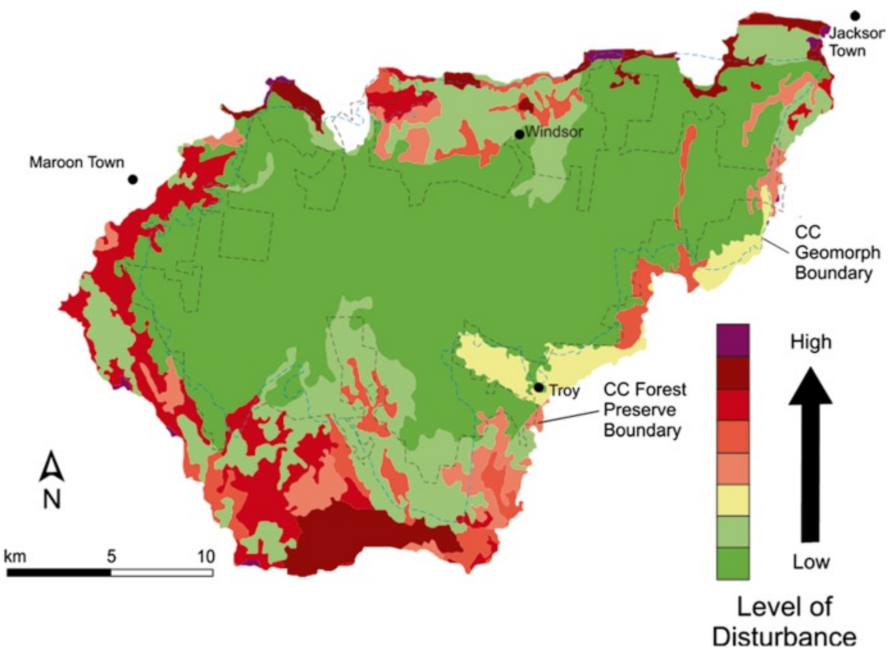

Fig. 18.5 Disturbance within "ring road" boundary

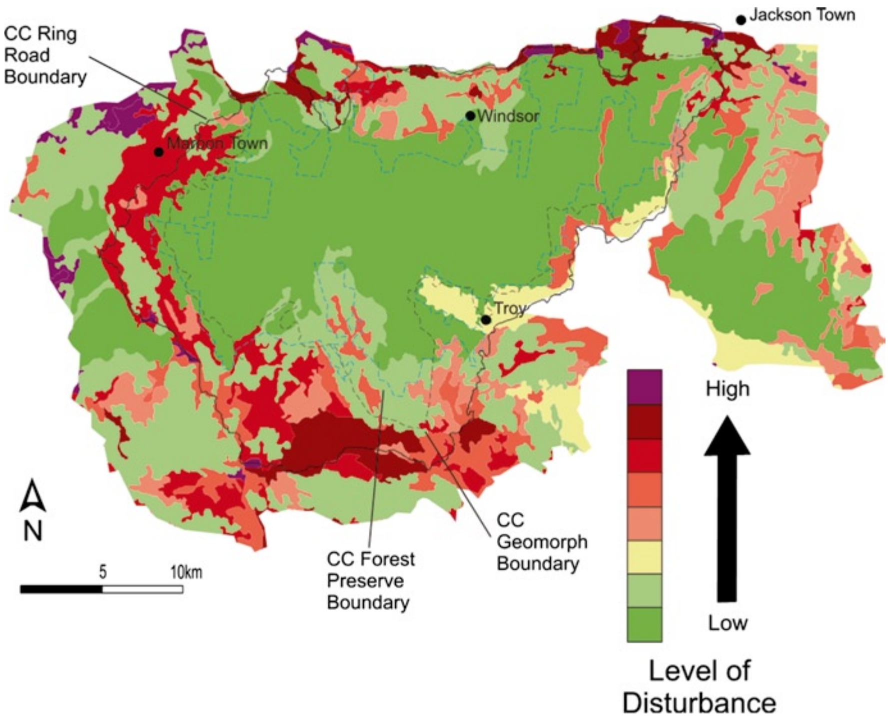

Fig. 18.6 Disturbance within JET/CCSG proposed boundary

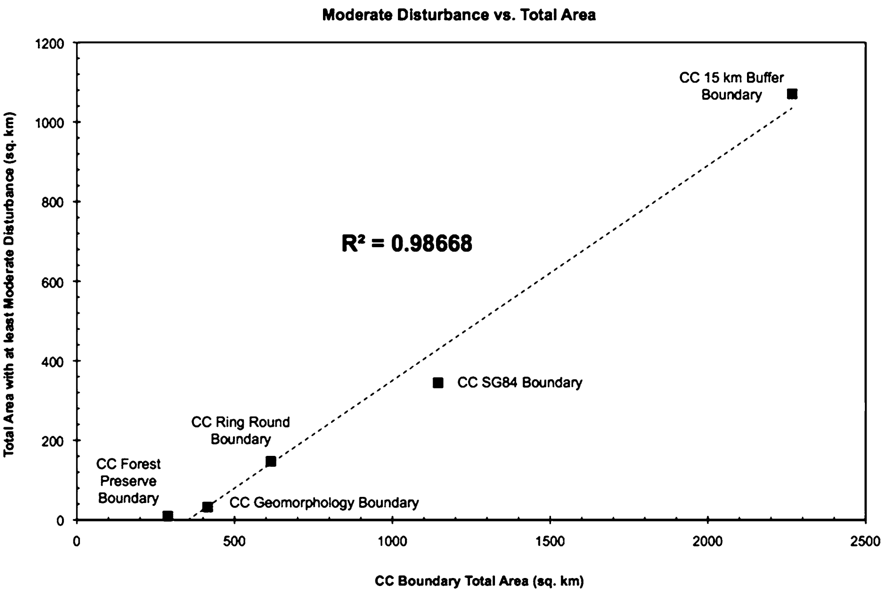

Fig. 18.7 Regression between selected Cockpit Country area and amount of at least moderate disturbance

Table 18.1 Frequency distribution of sub-indicator values

Selected boundary					
Sub-indicator value frequency		FR	GB	RR	SG
	0	16	10	5	4
	1	15	13	15	10
	2	0	6	7	10
	3	0	2	4	7

18.7 Conclusions

An agreed demarcation of the Cockpit Country is an essential precursor to its effective management as a protected area and to its potential future status as a national park and World Heritage site. Each of the four potential boundaries is based on legitimate criteria, but each demarcates a differing area of landscape which has been disturbed to differing degrees by human activity.

The existing forest reserve is essentially pristine and would be a strong candidate for recognition as the "core" of the Cockpit Country. Similarly, the area within the geomorphological boundary is little disturbed and certainly merits incorporation within any proposed national park or other expanded category of protected area. Incorporating the additional area within the "Ring Road" changes the KDI to disturbed, reflecting increased human activities and potentially more resistance from the local population to stricter land management policies. This additional area might well function as a partial primary buffer zone around the core protected area, although it is discontinuous. Finally, the JET/CCSG boundary incorporates highly disturbed karst areas which might also act as an expanded buffer zone.

Planning for the future of the Cockpit Country has proceeded haphazardly, with differing motivations and not a little controversy. Conservation and management are clear imperatives, but there is also potential for local economic benefit from sustainable ecotourism. Application of this research on the levels of disturbance within various potential boundaries would be a valuable tool in the planning process, and the results are currently being disseminated to government agencies, local and international NGOs.

The influence of the boundary location upon the KDI calculation is not surprising, and it echoes the role of boundary selection in influencing other statistical computations, such as that of nearest-neighbor statistics (Charlton 1976). Ideally, application of the KDI should be constrained by testing of similarly sized areas with similarly shaped boundaries, although this may be difficult in practice. Karst area boundaries are naturally irregular, but imposition of boundaries arising from human constructs, such as political boundaries, is equally problematic. In this study, the use of variable boundaries has served to illuminate consideration of protected area conservation strategies, but boundary issues merit further consideration in continued statistical studies of karst landscapes.

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Chapter 19
Expanding South Nahanni National Park, Northwest Territories, Canada, to Include and Manage Some Remarkable Sub-Arctic/Arctic Karst Terranes

Derek Ford

Abstract South Nahanni National Park Reserve (Lat. 61°N, Long. 124–8°W; ~4,700 km^2) was created in 1972 to protect three great canyons and a major waterfall from hydroelectric development. In 1978, it was one of the first natural sites to be granted UNESCO "World Heritage" status, based substantially on the author's geomorphic analyses. In the course of that work, extensive tracts of limestone karst landforms, some of them unique, were explored up to 40 km north of the Reserve boundaries. Following agreements with the First Nations peoples of the region, in 2009, these were incorporated into an expanded park of ~32,000 km^2 that now includes most of the hydrologic basin of the South Nahanni plus the smaller Ram River north of it.

The case to expand the national park outside of the topographic boundaries of the South Nahanni basin was made in three steps: (1) a demonstration by fluorescent dye tracing that the underground drainage to major karst springs in South Nahanni. First Canyon extended far to the north of the topographic boundary, the catchment being the southern half of a belt of unique karst terrain, and the northern half is drained into the Ram River basin via a second group of major karst springs at the northern extremity; (2) recognition that the headwaters of the Ram River contained an ancient, intensely dissected, remnant karst terrane on an anticline that contrasts sharply with (3) a downstream anticline in the same limestone that has little karst development due to its more recent uplift, with stripping and exposure taking place under permafrost conditions. In 2010, a number of "hub-and-spoke" and "trekking" routes for walkers and backpackers were being proposed to display the karst. Potential management problems for these developments included a possible zinc-silver mine to the west that is accessed by a winter road across the karst belt and accelerating melting of the permafrost in susceptible silts and shales that is creating many new landslides in the karst basins.

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19.1 Introduction

The Mackenzie Mountains are a chain of ranges extending between Lats. 60° and 67°N, dividing the Pacific drainage (Yukon Territory) from that of the Mackenzie River and Arctic Ocean (northwest territories). They are scarcely populated. Along the spine, batholithic rocks of Cretaceous age are carved into typical alpine topography – the "Ragged Ranges" that rise to 2,800 m above sea level (asl) or more. During the ice ages, they supported extensive valley glaciers which coalesced to form part of the "Cordilleran Ice Sheet" that covered most of the western mountains of Canada and extended into the Northwestern United States. A few valley glaciers and small icecaps remain today. To the east, the plutonic injections deformed thick sequences of Paleozoic sedimentary rocks, creating fold and overthrust topographies with rivers flowing eastwards across them – the "Canyon Ranges". Their western parts were invaded by the Cordilleran valley glaciers, while the Laurentide Continental Ice Sheet was able to override the most easterly ranges. In between, there is a never-glaciated corridor with magnificent river canyon landscapes. Limestone, dolomite, and gypsum are prominent amongst the sedimentary rocks and there is salt at depth. As a result, karst phenomena are frequent, exhibiting many different morphologic styles as consequences of their differing composition, lithology, geologic structure and glacial or periglacial history. This account focuses on the most spectacular of the limestone landscapes, which are found in the Southern Mackenzie Mountains between Lats. 61° and 62°N, in the eastern sector of the South Nahanni River basin and in the smaller Ram River basin to the north of it (Fig. 19.1).

The existence of magnificent river canyons and a great waterfall along the course of the South Nahanni River was well known to the Dene aboriginal people of the region. The Deh'Cho ("Big River") clans, who today have their center 100 km to the east in Fort Simpson on the banks of the Mackenzie River, hunted in the eastern mountain ranges where a subgroup, the Naha, dwelled semipermanently. Further north, the Sahtu ("Great Bear") clans established trade routes across the headwaters into the Yukon Valley (Fig. 19.1). Exploration by Europeans began when the Hudson's Bay Company established trading posts at Fort Simpson and on the Liard River close to the mouth of the South Nahanni in the 1820s but was very limited until the Klondike Gold Rush began further west in 1898. Some may have tried to use the South Nahanni as a backdoor route to the Yukon gold fields while others set off hoping to make new strikes within the river basin itself. The river canyons were named as they were encountered when paddling or lining canoes upstream, so "First Canyon" is the furthest downstream, "Second" and "Third" place in sequence above the First, and an unofficial Fourth canyon terminates in the mighty Virginia Falls, which are up to 100 m in height and can only be passed by a long, steep portage. Some minor showings of gold were made above the falls and followed up by two prospectors who failed to return from wintering over in 1907–1908. The Royal Canadian Mounted Police went up-river looking for them and found their two bodies, less the heads, in a burned-down cabin just upstream of First Canyon. Another

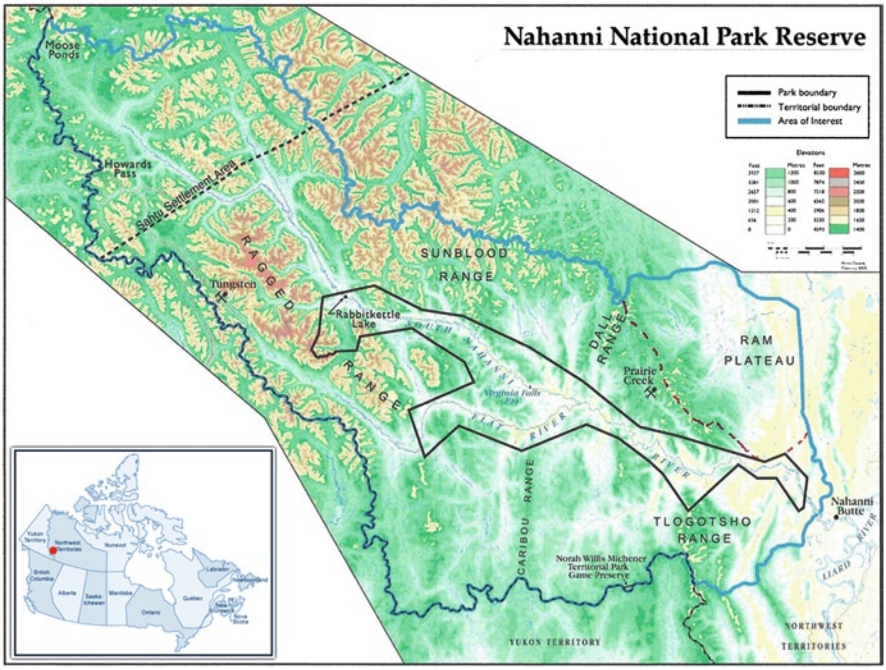

Fig. 19.1 The hydrologic boundaries of the South Nahanni and Ram river basins, which are the desired boundaries of the expanded South Nahanni National Park. In *black line*, the boundaries of the South Nahanni River National Park Reserve established in 1972. *Dashed line* – the boundary between the Deh'Cho First Nation territory to the east and the Sahtu First Nation claim to the west. In *red* – the topographic boundary between the S Nahanni and Ram river basins. The expansion of the park to include the Ram River basin is the subject of this chapter. Map courtesy of the Canadian Parks and Wilderness Society

prospector also died mysteriously there in 1915. This history gave rise to cheerful place names (Deadmen Valley, Funeral Range, Headless Range, Somber Range) which, with some tricky rapids in the canyons, created the legend of "The Dangerous River" (Patterson 1966). It was beginning to attract sport canoeists and other adventure tourists when, in 1967, there were engineering proposals to harness the hydro-electric potential of the Falls and the canyons with a series of dams. Opposition quickly mounted. The Prime Minister of Canada at the time, Pierre Elliot Trudeau (a passionate canoeist), was shown the canyons and the Falls. In 1972, a "South Nahanni National Park Reserve" was created to protect them from development. It was extended to the Rabbitkettle Hotsprings further upstream (two spectacular travertine mounds formed at the junction between the sedimentary rocks and the plutonic rocks injected into them), to part of the Flat River where there was richer boreal forest and to some attractive sand blow out features downstream towards Nahanni Butte, the nearest permanent settlement. It is seen in Fig. 19.1 that the "Reserve" that was created for these reasons is a strip of varying width along the rivers, enclosed by an arbitrary set of landlines. It totals about 4,700 km^2 in area.

In 1970, a party of Quebec adventurers parachuted into the Moose Ponds at the head of the South Nahanni and came down it in inflatable rubber rafts. Towards the mouth of the First Canyon, they noticed some cave entrances high in limestone cliffs and explored a few of them. Parks Canada funded the party to return for more detailed investigations the following summer and asked me, as a professional cave scientist, to evaluate their discoveries. My group from McMaster University arrived on the day that two of the Quebec party made the most significant find, Grotte Valerie (see below), and together we explored and mapped it in the following days. I had studied geological maps and air photographs before going in and noted that the limestone extended far to the north of the topographic watershed of the Nahanni tributaries here, into the Ram River basin. When leaving the area, I was able to direct the small aircraft to fly over this at low altitude and thus got a first view of some of the most spectacular karst topography that is known in any arctic or sub-arctic location. Intensive investigations followed in the next few years; I studied the general geology and geomorphology of the Reserve (Ford 1973, 1974a, b, 1991; Harmon et al. 1977), a body of work that provided the core documents for the successful nomination of the Reserve as one of the first three UNESCO World Heritage natural sites to be recognized: Ph.D. candidate, George Brook, investigated the karst to the north (Brook 1976; Brook and Ford 1978, 1980), and Jacques Schroeder of the Quebec group undertook detailed research in the First Canyon caves (Schroeder 1977, 1979). During those years, I, several times, wrote to Parks Canada and senior political persons urging that all of the karst lands should be protected. Later, many other interested parties asked that the entire South Nahanni drainage basin be included in an expanded South Nahanni National Park/World Heritage property (CPAWS 2001). I worked to add the Ram River basin to such expansion in order to protect the karst. In June 2009, the Government of Canada promulgated the expansion east of the Sahtu settlement line, less some set-asides for potential mineral extraction west of the karst; a decision on the Sahtu lands is pending. The purpose of this chapter is to outline the sequence of steps in the Ram River karst campaign, the tourist developments being proposed now that it has been successful and the hazards that remain.

19.2 The Geologic and Physiographic Settings

In South Nahanni National Park, the Cretaceous batholithic rocks of the Ragged Range (Fig. 19.1) are composed of massive and very resistant quartz monzonite, a variety of granite. It supports the highest and most rugged mountains in the region, which display the full suite of alpine glacial landforms such as cirques with precipitous headwalls, U-shaped valleys with sharp trimlines and fresh recessional moraines of the Little Ice Age. The intrusion deformed a thickness of more than 6 km of marine clastic and carbonate sedimentary rocks of Paleozoic age. The effect can be likened to dropping a stone into a pond, creating ripples spreading outwards – in the present context, spreading eastwards down the courses of the regional rivers. Strata close to the intrusion were highly deformed by a combination of folding,

Fig. 19.2 *Left.* The Rabbitkettle Hotsprings Mounds in the upper S. Nahanni valley. These are hot springs precipitates of calcite (travertine), deposited at the junction between Paleozoic carbonate sedimentary rocks and an igneous intrusion of Cretaceous age. These are the largest *constructional* karst landforms in Canada. Tourist access to the mounds is restricted to one trail and footwear must be removed on the travertine mounds themselves. *Right.* "The Gate" in the Third Canyon, South Nahanni River, viewed from the upstream side. This is a river capture through the neck of a hairpin meander incised 250 m into limestones. It was probably initiated as an underground (karst) capture

overthrusting and local and regional block faulting. Subsequent erosion has removed all Upper Paleozoic rocks there. The Lower Paleozoic strata are mostly mechanically weak formations of shales or relatively thin-bedded sandstones and carbonates; as a consequence, the mountain ranges are lower, rounded and more intensely dissected. One pair of landforms stand out, the Rabbitkettle Hotsprings Mounds, at the juncture with the pluton (Fig. 19.2). These beautiful features are the largest constructional karst landforms known in Canada, precipitates of calcite travertine in rising sequences of rimstone dams (Ford 1974a). The more prominent "wedding cake" North Mound is 75 m in diameter. The waters have constant temperatures between 21.5°C and 22.0°C in a region where the mean annual air temperature is around −8°C. Total hardness is 475–550 mg/l; Brown and Wright (1979) estimated that ~200 mg/l of this load was precipitated as the emerging waters degassed and flowed across North Mound.

An exception to the generally weak character of the Lower Paleozoic sedimentary rocks is the Sunblood Formation (Middle Ordovician). Its lower 200+ m consists of resistant limestones and dolomites. Virginia Falls, a receding waterfall like Niagara Falls, is developed in them. This formation is emplaced by block faulting further

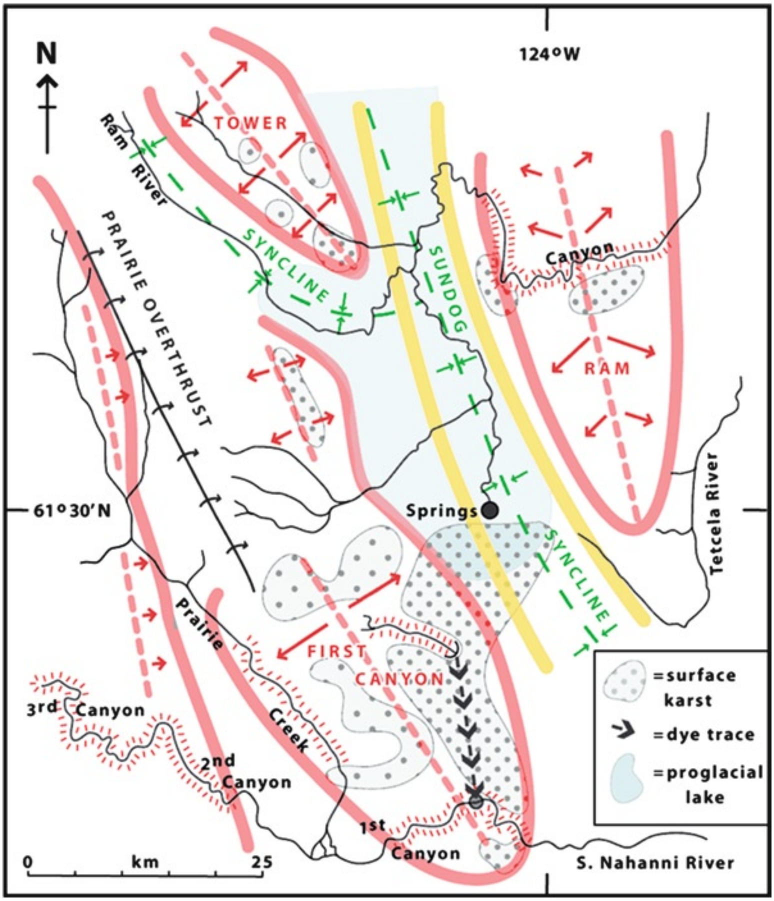

Fig. 19.3 Sketch diagram to show the location and principal topographic and geologic structural features of the South Nahanni karst lands. The denser pattern represents greater densities of karst landforms; see the text for details

downstream also, in the Third Canyon, where a deeply incised hairpin meander has been cut off across the neck, creating "The Gate", a famous feature on the canoe trip (Fig. 19.2). The cut-off is ~300 m in length and probably originated as an underground karst capture of South Nahanni River (Ford 1974a).

To the east of the Third Canyon, the Upper Paleozoic rocks are predominant and karst development becomes regional in its scale. The principal karst stratum is the Nahanni Formation (Middle Devonian), 180–220 m of thick-to-massive, regularly bedded, platformal limestones. They are chemically pure and mechanically resistant, very like the well-known karstic limestones of the Yorkshire Dales in England and the Burren in Ireland in their characteristics. They are overlain by mechanically weak shales and limestone shales that are readily stripped off. The underlying facies are more complex. Broadly, underneath the First Canyon and Ram Plateau anticlines (Fig. 19.3), there are medium-thick bedded, mechanically strong, and cliff-forming dolomites >1,000 m in total thickness. They display a few scattered dolines and other karst forms at the surface and may channel groundwater flow in solution conduits. In contrast, underneath the Tower anticline, there is a facies transition, the upper dolomites being replaced by much weaker shales and calcareous shales that together function as an aquitard.

As Fig. 19.3 suggests, the structural features are bold and simple. The three anticlines have broad, symmetrical, domal forms with gentle stratal dips except for occasional oversteepening on their eastern flanks. They rise to 1,800–2,000 m asl. Ram Plateau retains a cover of the Nahanni limestone, which passes beneath overlying shales north of the Ram River canyon. The Tower anticline is gutted, with limestone remnants only on the eastern flanks and scattered along the crest. The limestone is removed from the crest of the First Canyon anticline, exposing the dolomites there, but it is widely retained on both flanks. On the east flank, it dips below the shale cover, creating a *karst barré* (impounded karst) situation. The lowest point in the impoundment occurs where the South Nahanni River crosses it at the mouth of First Canyon; here, Kraus Hotsprings, some H_2S-rich discharges at ~35°C, mark the discharge of a deep but small groundwater flow component beneath the domes.

It is most important to appreciate that these structures have been active during Neotectonic times. The epicenter of the strongest earthquake experienced anywhere in continental Canada during the past 50 years (Richter 6.9) was at shallow depth just to the east of the Ram anticlinal trend and 40 km further north (Hyndman et al. 2005); it triggered a major landslide in the limestone there. As consequences of this continuing activity, the trunk rivers have carved antecedent, meandering canyons 300–1,000 m in depth across the updomings in their paths and the tributary Prairie Creek cut a comparably deep canyon along the strike in the flank of the First Canyon anticline (Fig. 19.3; Ford 1991).

At its greatest extent, the Laurentide Icesheet buried Ram Plateau and the Sundog Syncline and extended up to elevations of ~1,400 m asl on the eastern flanks of the First Canyon and Tower anticlines (Ford 1974a; Brook 1976). Land to the west was not glaciated. In the last glaciation, ice advanced up the Syncline to a terminus south of the northern springs marked in Fig. 19.3, impounding proglacial "Lake Sundog" at ~900 m asl to the north of it. Deposition of ~80 m of lacustrine silts buried much of the preexisting karst. The Lake drained abruptly at some time after 40 ka BP (based on a ^{14}C date of tree wood in the silts – A. Duk-Rodkin, personal communication, 2006): it cut a broad spillway through the silts and into the top of the karst beneath it.

Today, karst features extend from 240 m asl (the springs in First Canyon, Fig. 19.3) to ~1,900 m asl on the crest of the First Canyon dome. The climate is sub-arctic to arctic. Mean annual temperatures range from −3°C, on the low ground, to −10°C or below, on the crests. Treeline (Northern Boreal Forest) is at ~1,200 m asl. Permafrost is widespread but discontinuous below that elevation and technically continuous above it. Annual precipitation ranges 400–800 mm or more across the elevations, about half of it falling as snow. Summer rains can be intensive when systems from the Northeast Pacific and the Beaufort Sea (Arctic Ocean) clash (Brook and Ford 1980). There is some evidence to suggest that the frequency and intensity of these storms are increasing as a consequence of the greater summer melt of sea ice over the Beaufort Sea; this is suggested by a great increase of landslides over permafrost on lacustrine silts and steep shale slopes in the region.

19.3 The Relict Caves of First Canyon

More than 200 relict karst solution caves (i.e., caves drained of their formative waters) have been found in the region but unfortunately most are sealed off by ground ice or frozen silts within a few meters of their entrances. The lengthiest open systems are preserved along the North (updip) wall of First Canyon, near its mouth and within the 1972 National Park Reserve boundaries. Their form is of underground dendritic drainage from the former sink points of streams flowing from a shale cover that is now largely or entirely removed. Flow was downdip into the River at and just below the contemporary water tables. A first example, Grotte Valerie, has 1 km of passages now stranded in cliffs 450 m above the River (Fig. 19.4). It has partial fillings of silts and winnowings of an older till cemented by calcite. South facing, in summer, cold air drains from a low exit, drawing warm air in to replace it via an entry that is 40 m higher. This creates (1) a "warm entrance cave" (+6 to +1°C), where summer warmth has thawed permafrost and there is active deposition of small speleothems today; this supplies moist air to (2) a "cool exit cave" that is covered with hoar frost because the wall rock temperatures remain below 0°C; and both behind and below there is (3) a "permafrost cave" or *glacière* which is a cold trap receiving only winter air – dry and dusty, without speleothems or ice and preserving the remains of 80 or more mountain sheep. It is the type example for cave climatic zonation in cold regions (see Ford and Williams (2007, 294–8) for details).

Nearby, Grotte Mickey has more than 3 km of galleries at several different levels between 250 and 330 m above the river. This multi-level, multi-phase pattern points to extended development that kept pace with the entrenchment of First Canyon for some time (Schroeder 1977, 1979).

An important feature of these caves and some in the Labyrinth (discussed below) is the occurrence of large, highly ornamented, stalagmites, columns, and flowstones of calcite. They are no longer growing (modern growth is limited to very small deposits), and most are weathered or partly eroded by invading streams or shattered by freezing. They are indicative of much warmer conditions in the past, which (allowing for cave truncation by cliff recession since) extended much further into cave interiors than today. There is an abundance of uranium in the cover shales which, re-precipitated in the calcite, has made the speleothems particularly suitable for U series dating. This region saw much of the pioneer dating work as a consequence (Harmon et al. 1977). The large majority of samples proved to be >350 ka in age (the limit of the dating method using 1970s alpha spectrometric technology), although they were <1.25 Ma. The first application of U series speleothem dating to a geomorphic problem was by the author, who showed that the mean rate of South

Fig. 19.4 Scenes from Grotte Mickey and Grotte Valérie in the First Canyon, South Nahanni River, Northwest Territories. These are relict stream caves now raised high above the River in the canyon walls. *Upper centre* – glaciolacustrine silts on the floor of a large stream cave passage. *Upper right* – modern speleothem deposition in the warm sector of Grotte Valérie. The stalactites and stalagmites are typically small. Their bright red coloration is due to contained organics. *Lower left* – above the figure is a typical relict stalagmite and flowstone of the warm period >400 ka BP; only stalagmites of ice grow in this gallery today. *Lower centre and right* – ice stalagmites and hoarfrost in the cool sector, Grotte Valerie. The base of the hoarfrost in the centre frame marks the surface of a lake of very cold air that is trapped behind the ice dam; it is renewed only by winter inflow (Photos by Derek Ford and Jacques Schroeder)

Nahanni River entrenchment below Grotte Valerie could not be more 0.8 m/ka and that there had been possibly as much as 350 m of uplift on the First Canyon anticlinal axis since 1.5 Ma BP (Ford 1973).

19.4 Making the Case to Include All of the Nahanni Limestone Karst in an Expanded National Park

By political happenstance, the northern boundary of the 1972 Reserve was an arbitrary landline drawn only 2–3 km north of Grotte Valerie and Grotte Mickey and cutting across Lafferty Canyon, an important north bank tributary of South Nahanni River. The topographic division between the South Nahanni basin and the apparent drainage basin immediately north of it (a tributary to the minor Tetcela River) lies along the ridge crest north of Lafferty Canyon, as shown in Fig. 19.5. There is a

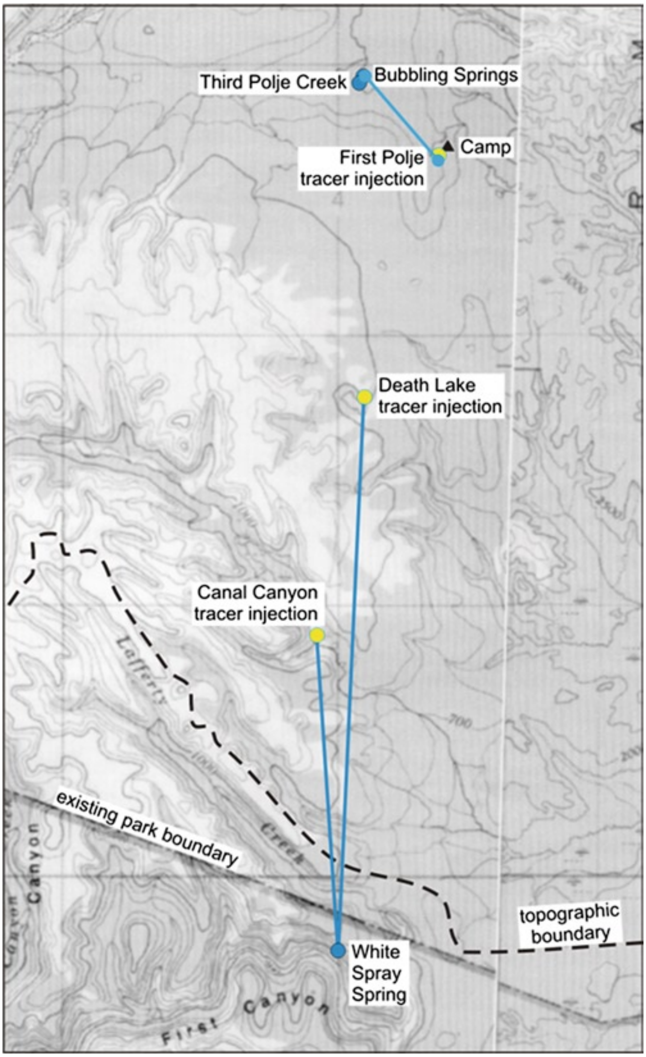

Fig. 19.5 Map showing the straightline courses of successful dye traces in the main belt of karst lands between First Canyon, South Nahanni River, and the “Bubbling Springs” which drain to Ram River

major belt of karst terrane, (limestone pavements, labyrinths of solution corridors and bogaz, large sinkholes, small poljes, sinking lakes) extending for 40 km between the First Canyon and the southern end of Ram Plateau, however, and it has been recognized since 1972 that this captures all water flow except for some very minor surface overflows that can occur during the melt season or extreme summer rains (Brook and Ford 1980).

19.4.1 Step 1 – Establishing the Principal Karst Groundwater Basins

The major karst belt drains to just two sets of springs. In the south, the "White Spray" spring discharges at 240 m asl in First Canyon, from the foot of dolomite cliffs that are stratigraphically ~580 m below the base of the Nahanni limestone. Most of the discharge is into the riverbed where its contribution to the flow cannot be gauged separately; it must be considerable, however, because it keeps this stretch of the River free of ice throughout the winter, a unique feature. "White Spray" itself is a summer overflow spring that jets from the cliffs a few meters above the River and has an estimated discharge of ~2.5 m^3/s. These springs must drain much of the First Canyon (Nahanni Plateau) dome and its karst, including Canal Canyon (30 km in length, up to 1,000 m in depth) which drains underground where it is blocked by a terminal moraine at its mouth. Dye traces from there (Fig. 19.5) and from Death Lake further north proved underground flow of 21+ km at mean rates >3,500 m/day on a hydraulic gradient of 0.03. Although no enterable caves have been found in them yet, the dolomites can thus rapidly develop integrated systems of underground solutional conduits.

At the north end, "Bubbling Springs" (700 m asl) rise where the stratigraphic top of the limestone dips under impermeable cover shales in Sundog Syncline. They drain perhaps the northern one-third of the belt, with discharges >10 m^3/s during wet summer spells. Bubbling Springs are a major southern tributary to Ram River.

19.4.1.1 The Nahanni Labyrinth

Between Canal Canyon and Bubbling Springs, the Nahanni Labyrinth is developed in the limestone. It is the largest example of karstic labyrinth morphology reported in the Northern Hemisphere (Fig. 19.6). The outstanding landforms are dissolutional corridors ("streets") that follow major vertical fractures created by the doming (Brook 1976; Brook and Ford 1978). Individual corridors are 30–100 m deep, 15–100 m wide and up to 6 km in length. For a distance of 13 km, they intersect one another to form a natural labyrinth. The walls recede from frost shattering, causing some parallel corridors to amalgamate into broader closed depressions, like squares in a pattern of city streets; the greatest measures 800 × 400 m. Isolated towers are preserved within them. Floor profiles of corridors and squares are highly irregular, with local streams sinking into depressions between talus accumulations or into bedrock shafts. In the labyrinth and elsewhere on the limestone are large, vertical-walled sinkholes and smaller, elliptical solutional shafts such as the Cenote Col group shown in Fig. 19.6. Many trap the water of successive melt seasons, its depth increasing slowly until pressure bursts an ice plug below and the feature drains with catastrophic rapidity. Raven Lake, an unusually large doline within a corridor, is 300 m in length and 150 m deep; under flood conditions, waters rise >75 m in it, at rates of 3 m/day or more. Enterable caves are few and filled by ice or silt short

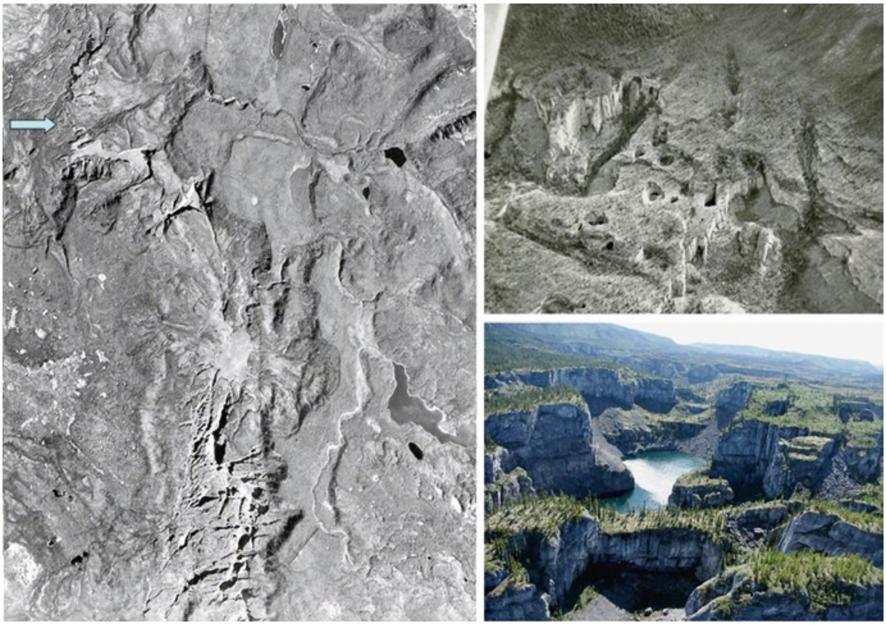

Fig. 19.6 *Left.* Air photo showing the northern half of the Labyrinth at the bottom. *Arrow* indicates the principal spring of Bubbling Springs. There are three small polje landforms between the springs and the Labyrinth. On the *left* – Mosquito Lake, with large collapse and suffosion sinkholes to the south of it. On the *right*, a terrace of glaciolacustrine silts conceals the limestone. It has many further suffosion sinkholes. The true width of this frame is ~9 km. *Upper right* – "Cenote Col", a tight cluster of limestone shafts and sinkholes in the Labyrinth. Individual shafts are up to 40 m in depth, some water-filled, some not. On either side of the col are deeper sinkholes up to 500 m in length. This photograph was taken on the flight out from the author's first visit to Nahanni in 1971. *Lower right* – "Raven Lake", a seasonally inundated sinkhole at the northern end of the Labyrinth. It is ~150 m in depth, with ~50 m of standing water in this scene (Photos by Derek Ford)

distances inside. Relict stalagmites >350 ka in age have been recovered from two of them (Brook 1976).

At the north end of the labyrinth, the shale cover and glacio-lacustrine silts encroach to reduce the limestone outcrop to a narrow spillway with three small (<2.5 km^2) but fully formed poljes developed in it. Their sinking streams have been dye-traced to Bubbling Springs. There are many collapse and suffosion dolines in the shale and silts terraces, extending as far as 5 km away on the flanks: this points to the existence of a mixture of maturely developed open and covered karst that is now partially clogged by the proglacial injecta. Although all is drained by a mature karst groundwater system that existed before the last glacial invasion and formation of Glacial Lake Sundog, the extent to which the karst landforms exposed today were modified by scablands *jøkulhaup* processes during their re-excavation remains undetermined.

The location of the divide between groundwater flow southwards to White Spray and northwards to Bubbling Springs lies somewhere in the Labyrinth Karst. Possibly, it has a seasonal component, with base flow draining south down the higher hydraulic gradient, but some of the summer surcharge spilling over to the north. Given this uncertainty and the morphological continuity of this remarkable karst, Parks Canada readily accepted the proposition that this karst belt should be included in an expansion of South Nahanni National Park Reserve.

19.4.2 Step 2 – Incorporating the Headwaters of Ram River in the Expansion

The Ram River headwaters drain Tower Anticline and Syncline and the northern end of the Nahanni (First Canyon) Anticline (Fig. 19.3). The two anticlines were upraised and stripped of their shale cover at broadly the same time, probably later Miocene and the Pliocene. The Nahanni limestone has also been largely removed from Tower Anticline because, as noted, the strong, karstifiable dolomites beneath it at First Canyon are replaced here by a weak, largely impermeable, limestone-shale formation. In both the sector that was glaciated and further west in the never-glaciated zone, Tower Anticline first developed an extensive plateau epikarst with limestone pavement and small dolines, but this was then almost entirely destroyed by undercutting as flashflood canyons enlarged and cut back in the underlying shales. Figure 19.7 shows three scenes in this relict karst; it is best preserved at the eastern end (upper scene), where stripping of the protective shale cover above the limestones was more recent.

In the Tower Syncline, the shale cover is also removed, but little karst has developed on the limestones. It is believed that this is because their exposure took place largely or entirely after permafrost became established in the region (possibly late Pliocene), prohibiting the development of efficient epikarst drainage. The same constraint applied to the more dramatic Ram Plateau, discussed below.

In contrast to the simple form on the Tower Anticline, the limestone on the northeastern flank of the Nahanni Anticline has been deformed by local folding and overthrusting. Along two coalescent ridges, dissolution and periglacial shatter and solifuction processes have produced a visually striking series of ridgeline tors, “The Castellated Karst”, with morphologies reflecting the differing amounts of deformation (Fig. 19.8). There is nothing similar elsewhere on the Nahanni limestones, reinforcing the case for including this area in the park expansion.

19.4.3 Step 3 – Incorporating Ram Canyon and the Ram Plateau in the Expansion

Ram Plateau offers magnificent landscapes, including some that are distinctly different from those seen on the Nahanni and Tower domes. Ram River has cut a deep, antecedent canyon across its dome but, unlike the South Nahanni canyons, it

Fig. 19.7 Three scenes on the Tower Anticline. *Upper* – looking down into the Sundog Syncline across glaciated pavement with dolines on the well preserved southeastern end of the anticline. *Lower left* – relict pavement at the gutted crest of the anticline. *Lower right* – a final remnant of the karst at the western end (Photos by Derek Ford)

exhibits a meandering form only in the middle (earliest exposed) sector. Upstream and downstream the canyon is straight (Fig. 19.9), suggesting that it was not being entrenched before the onset of periglacial conditions had added considerable bed-load that halted the meandering (Ford 1991). During the last glaciation, the canyon was blocked by ice from the east, while its western entry became infilled by Glacial Lake Sundog silts. After glacier recession, the River was diverted northwards and re-entered the old canyon partway, where it carved the young and spectacular "Scimitar Canyon" (Fig. 19.9). South of Ram Canyon itself, the Plateau is deeply dissected by consequent canyons that cut through the Nahanni limestone into resistant dolomite strata below. Karst landforms (sinkholes, bogaz) are seen only on the earliest exposed surfaces or where some shale cover is retained to provide local stream flow onto the limestone contacts.

On both Ram Plateau and in the Tower Syncline, the cover shales have been largely stripped off of the Nahanni limestone, and high hydraulic gradients for

Fig. 19.8 "The Iron Age Fortress", a mesa-like tor in the Castellated Karst, buttressed by solifluction ramparts. For contrast, the pyramidal tor in background right is in near-vertically dipping beds in the same limestone (Photo by Derek Ford)

groundwater flow have been created in it by entrenchment of consequent canyons. Yet, there is little development of karst landforms when compared to First Canyon, Nahanni Plateau and the Labyrinth because, as also suggested by the straight form of most of the course of antecedent Ram Canyon, permafrost set in before the essential groundwater solutional channels could be established. The result has been the creation of dissected limestone landscapes of pleasing regularity and symmetry on both the antiform and the synform, as illustrated in Fig. 19.10. Ram Plateau, thus, was readily accepted to complete the expansion of the Park on the Nahanni limestone.

19.5 Display and Management of the Karst Lands

The South Nahanni and Ram karst lands are true wilderness country, uninhabited and almost entirely undeveloped. There are no permanent buildings of any kind except three or four small registration booths for canoeists. A winter road was constructed across the northern end of the main karst belt in 1979 to service an incipient zinc and silver mine on Prairie Creek but the operation was abandoned and the road is currently untrafficable, although permission has been given for it to be reopened.

Fig. 19.9 *Upper left* – the central sector of Ram River Canyon, Ram Anticline, exhibiting the same incised meander form as the South Nahanni River canyons. *Upper right* – the downstream end of Ram River Canyon is straight, suggesting incision after the onset of periglacial conditions in the emerging anticline. *Lower* – "Scimitar Canyon", the glacial diversion channel that is the very spectacular head of the modern Ram River course through the anticline. Note the many fresh landslides in the limestone-shale slopes overlooking the sharp incision of the canyon itself (Photos by Derek Ford)

The foremost management question in the Nahanni karst thus is deciding on how it can be displayed while maintaining the wilderness state.

The karst is rich in plants and animals. Around the hot springs and sheltered places in the valleys, the boreal forest is exceptionally lush for these latitudes. There is a great variety of woodland flowers, including orchid species that are rare elsewhere. There is a diverse alpine flora on the tundra. Moose, wolves, and woodland caribou live in the forests, the latter also enjoying the open park-like country found on the lower karst and occasionally moving up to the tundra to escape mosquitoes. Black bears and grizzly bears live chiefly in the forest but forage widely above it in search of berries. The steeper areas of the canyons and the open tundra plateaus above them are home to mountain sheep and goats, which winter up there where high winds will keep the browse free of snow. There are many species of birds, chiefly migrants.

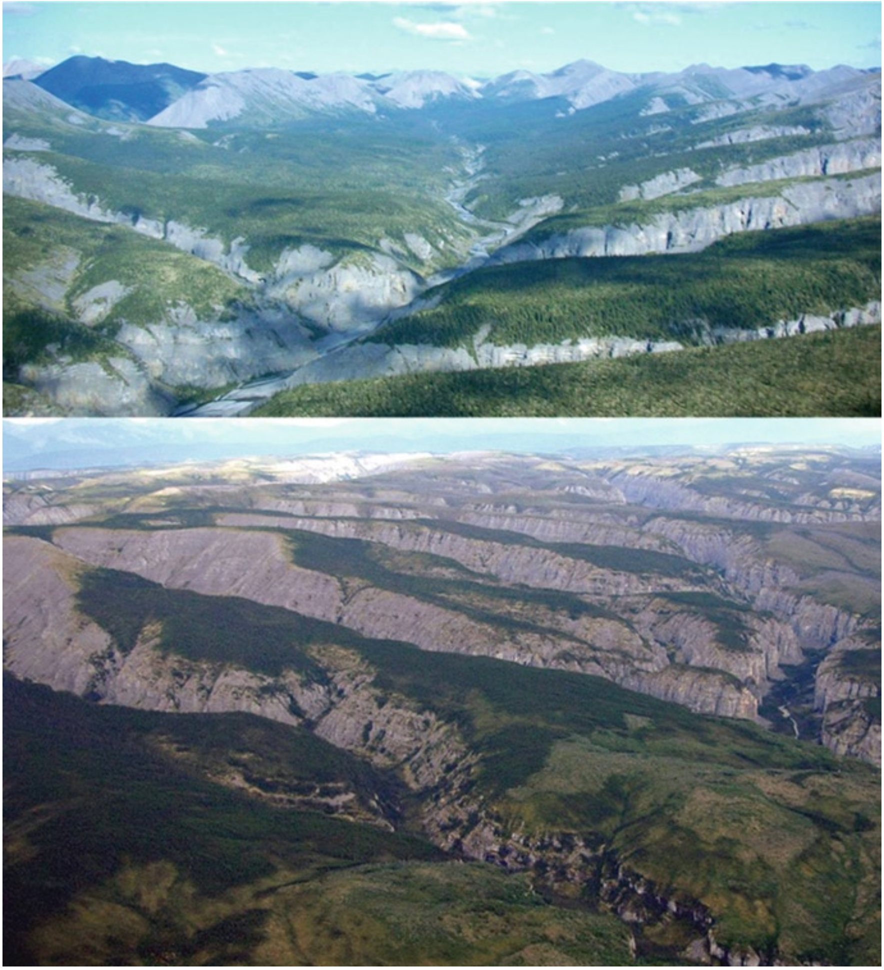

Fig. 19.10 *Upper* – the Nahanni Limestone formation, stripped of its limestone-shale cover and dissected by consequent canyons at the head of the Tower Syncline. *Lower* – the same situation is seen on the southern half of the Ram Plateau anticline (Photos by Steve Worthington and Paul Sanborn)

Before the coming of Europeans, the Dene people traveled extensively on foot throughout this country in addition to using South Nahanni River as a principal travel corridor. Prairie Creek itself is named for a large natural prairie/open forest in the headwaters that served as a winter base because it is rich in game. Downstream, the Prairie Creek canyon becomes very difficult to tread on, and so parties crossed the eastern divide into the southern headwaters of Ram River instead and from thence through the karst *en route* to the Liard and the Mackenzie Rivers for trading and social business. They have left little trace from, probably, some centuries of such use. We have noted only a couple of remnants of animal traps, with metal parts, cached in cave entrances.

For visitors from elsewhere in the world seeking wilderness experience today, the karst country offers hill walking and trekking possibilities of outstanding quality. At and above treeline, the footing is nearly always firm and reliable, on rock or loessic soils with thin grass, moss, or lichen cover. Below the treeline, because of the edaphic stresses created by karst drainage, there are large areas of open, park-like grasslands so that the patches of denser forest on the limestones can usually be avoided. Lengthy, though discontinuous, game trails are common in the forests, canyons, and on the plateaus. There are beautiful vistas everywhere. In June, July, and early August, it does not become truly dark at night. Autumn begins in late August on the high plateaus. All of the terrane is covered by 1:50,000 topographic maps of good quality and there is adequate satellite coverage for route finding with a handheld GPS device.

19.6 The Potential for "Hub-and-Spoke" Walking and Backpack Trekking

The author has proposed the set of potential walking and trekking developments shown in Fig. 19.11 (Ford 2010). Two types of expeditions are suggested, either a "hub-and-spoke" central camp offering a variety of daily walks out and back or a backpack trek between a given starting point and a finish, with overnight (or longer) camping stops *en route*.

Access poses a major constraint for both types of visit. Helicopters can place a camp almost anywhere but are relatively expensive and have limited payloads. The karst is about 1 h flying time from the nearest base, Fort Simpson. Floatplanes are significantly cheaper but they can be landed at only three places: (1) Mosquito Lake, from which point excellent camping in the First Polje can be easily reached. This is a good hub for the exploration of the northern half of the main karst belt, including the exciting Labyrinth; (2) Death Lake, a hub for the central karst, plus the finest of the limestone pavements and Canal Canyon and (3) The South Nahanni River at Kraus Hot Springs, hub for the cave-rich area of First Canyon and southern karst on the plateau above it. The Hot Springs can also be serviced by power boats chartered from Nahanni Butte. In the Summer of 2010, the outfitter, Canadian River Expeditions (www.nahanni.com) operated a successful helicopter-serviced hub-and-spoke camp on the top of Ram Plateau, south of Ram Canyon. The walking and vistas are outstanding, while sheltered camping can be found in a small patch of karst a few hundred meters south of the highest ground. The author had a hydrological survey camp in the center of Ram Canyon in the later 1970s that served as a hub-and-spoke base for a range of field studies. It too could be serviced only by helicopter. Other attractive hub-and-spoke camps with helicopter-only access include the Eastern Tower Dome (valley of 22 caves) and the Castellated Karst, for cavers and for those who enjoy very high hill walking respectively, and Canal Canyon, where the alluvial floor supports rich wetland and forest habitats of particular interest to botanists and ecologists.

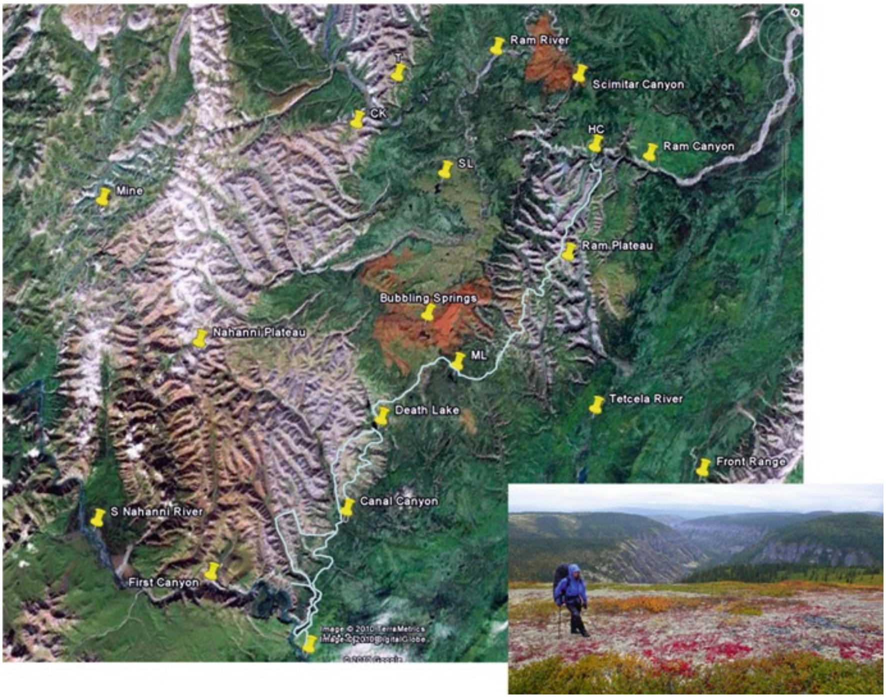

Fig. 19.11 Important sites in the Nahanni karst lands, showing the author's suggestions for the location of hub camps and the general outline of a trekking route from Ram Canyon to Kraus Hot Springs in First Canyon. *T* – the southeast end of Tower Anticline and a possible Valley of 22 Caves hub; *CK* – the Castellated Karst; *SL* – Sundog Lake, Sundog Syncline; *HC* – author's hydrology camp in Ram Canyon. See the text for further details. *Inset* – a backpacker prepares to leave the tundra and descend into the boreal forest at the southern end of Ram Plateau, 20 August 2008. The Fall colours are already in full splendour in the tundra (Photo by Stefan Doerr)

Between Ram Plateau and First Canyon, longer or shorter backpacking treks in the karst will offer magnificent challenges and wilderness experience, ones in which the difficulties of "bush-bashing" through dense forest can be largely, though not entirely, avoided. The location of hubs and potential trekking routes are set out in Fig. 19.11. A full trek from the bottom of Ram Canyon to Kraus Hotsprings will involve 180–200 km or more of walking. The author has traversed most of this in separate segments on and off over the years, but it has never been undertaken as a single thorough trip (in either direction) to his knowledge. Several parties have used the Mosquito Lake floatplane landing to start a trek to First Canyon, allowing 10–14 days: this is enough time in good weather for several side excursions with day pack only. One party has trekked from a helicopter landing on Ram Plateau to a pick-up point just short of First Canyon, spending 10 days of rather poor weather on the trip. There are good spots for lightweight overnight camping everywhere.

At present, it is Parks Canada's opinion that such walking and backpacking will not have significant negative environmental impacts in the karst. The historic land use by the Dene supports this view. Regulation is therefore simple and not restrictive. All intending walkers must submit their plans for approval at the park headquarters in Fort Simpson, a sensible precaution. Wood fires are permitted (with care) except at times when there is strong fire hazard. Metal fire boxes must be used in hub camps. It is Parks policy that all camping solid waste must be carried out. At hub camps, there may be a requirement that all human solid waste be taken out also. Walkers should be properly equipped with maps, a GPS device and a satellite telephone. Most will choose to carry bear spray and "bear bangers" as well. Firearms are prohibited in all national parks in Canada.

A large majority of the known caves are quite short, simple, and robust in morphology and will not be severely impacted by occasional human visitors. Grotte Valerie, Grotte Mickey, and a few others in First Canyon are more complex and fragile, in need of protection and thus currently gated; over time, it is proposed to develop a modest visitor program with Parks guides for them. All caves should be left undisturbed during the lambing season because the entrances are widely used as safe birthing spots and nurseries by the mountain sheep.

19.7 Hazards in the Karst Lands

Prairie Creek Mine (Canadian Zinc Corporation) is a mixed vein and stratiform zinc/lead/pyrite sulfide deposit in dolomite strata in the upper Prairie Creek canyon, west of Ram River (Fig. 19.11). There is subsidiary silver, antimony, and other trace metals of economic interest. The deposit also contains unusually high concentrations of mercury which must be removed, and the ore concentrated, on site before shipping out. Transport of concentrate out and of fuel and other supplies in must be by haulage on the winter road for any chance of economic success. As noted, a first attempt to develop the prospect at the end of the 1970s quickly failed, and the site was abandoned for many years.

The winter road extends from Nahanni Butte to the mine site. It crosses the main karst belt between the first and second of the three poljes in the northern quarter, descending silt and shale terraces from Mosquito Lake onto the limestone and then climbing out west again to traverse further glacial silt terraces. There are more than 50 suffosion sinkholes in silt or shale along or close to its route. It is certain that any spillage of hazardous substances along this sector of the road must enter the karst aquifer draining to Bubbling Springs unless it can be cleaned up entirely at the surface. There have been no studies of the aquatic fauna in the aquifer; if such fauna exist, past precedent suggests that they will include new species.

Prairie Creek Mine is not yet developed. A more obvious and immediate hazard in the karst, as it is in many other places in arctic and sub-arctic Canada, is the accelerating melting of permafrost to produce sinkholes, rotational slumps, landslides, and debris flows, some of them with catastrophic rapidity. In areas of karstic

Fig. 19.12 A very recent landslide into the head of the Second Polje (inundated) in the Nahanni main karst belt. The slide is caused by the melting of permafrozen silt in a glaciolacustrine terrace overlying the karst. It has already filled a smaller limestone sink in the lower centre of the frame. There are further, smaller slides from silt and shale slopes to the right. The photograph was taken from a passing helicopter on 15 September 2009 (Courtesy of Parks Canada)

drainage in the Nahanni and Ram basins, the author noted the occurrence of at least 40 new slides between finishing spells of work there in 1978 and returning in 2006–2010. Most of them probably occurred since around 1990 because they are still active. Melting is taking place chiefly in the glacial lake silts because these are particularly frost susceptible. But it is also apparent on steep slopes of the shale bedrocks above the Nahanni limestone, as is seen in Fig. 19.10. The greatest slide, by volume, occurred during or shortly after heavy rains in the Summer of 2009, when the edge of a silt terrace overlooking the second polje collapsed and many thousands of tonnes of melting silt blocks and slurry engulfed the approaches to the polje and then entered it (Fig. 19.12). There was subsidiary sliding on the underlying shale slopes. The author inspected the site at the beginning of July 2010, when it was seen that all the headward parts of the slide remained unstable and will likely fail again in future heavy rains. The winter road passes close to this slide and is threatened. There have also been other slides near it in the vicinity of Mosquito Lake. Continuous turbidity in one of the largest springs of the Bubbling Springs group is attributed to melting slurry entering the aquifer from some further, unknown site on the southwest flank of Ram Plateau. The melting is caused primarily by regional warming that appears to be taking place at a rapid pace across Northern Canada (Ford et al. 2010). As noted above, it is probably abetted by increases in the magnitude and frequency of severe summer rain storms due to the increase in the seasonally ice-free surface on the Beaufort Sea.

19.8 Conclusions

The case for the inclusion of the Ram River basin within an expanded South Nahanni National Park was argued primarily on the basis of the variety and continuity of the karst terranes that extend across both basins, and their global significance as the most complex limestone karst topography yet reported from any part of the arctic or sub-arctic regions. The magnificence of the Ram Plateau and Tower Anticlines and their canyons was a strong supporting factor. The inclusion was signed into law in June 2009. The first steps to publicize, display, and manage the karst lands while maintaining their integrity as a true natural wilderness are being made currently. Global warming is impacting the karst by melting permafrost, which induces landslides and slumps. Possible development of a zinc/silver mine on Prairie Creek, a north bank tributary immediately west of the Ram basin, threatens to pollute the South Nahanni River itself and its access road poses hazards to the northern half of the main karst aquifer.

Acknowledgements The author's debt here is primarily to his students and other companions in the field in the beautiful but remote South Nahanni country. Over the years many officers of Parks Canada have given valuable advice, technical and financial support for the work in the karst lands, and have always backed the case for their inclusion in the expanded national park, as have the people of the Deh'Cho First Nation. The Canadian Parks and Wilderness Society helped the cause of all of the expansion with its vigorous campaigning.

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Chapter 20
Protection of Karst Landscapes in the Developing World: Lessons from Central America, the Caribbean, and Southeast Asia

Michael Day

Abstract Protection of karst landscapes in the developing world faces significant physical and human obstacles. Recognition of karst is not always straightforward, in part because there is much topographic and environmental heterogeneity. Protection of karst is often indirect in that the karst is protected because of its biological diversity, resources, anthropological significance, or aesthetic appeal. Although the designation of protected karst areas has been recognized as imperative, much of the karst is under increasing anthropogenic pressure. National efforts are highly variable, and there is little regional integration. Different karst styles are represented unevenly in protected areas, with emphases on spectacular forms, upland areas, and coasts. Protected area legislation is often inadequate and enforcement is constrained by conflicting priorities. Local populations can play important roles, particularly in boundary determinations. Protected karst areas need to be integrated into regional land use management, but the status of many protected karst areas is volatile.

20.1 Introduction

Approximately half of global karst landscapes are located in the developing world, where they play a critical part in water conservation and the maintenance of biodiversity and important but diverse roles in human activities such as forestry, water supply, agriculture, and tourism (Day 1993, 2007a, 2009). Similarly, the developing world contains some of the most significant protected karst areas, including many national parks, nature reserves, and UN World Heritage sites. At the same time, many of these karst landscapes have been the subject of only cursory scientific

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research, and few of them have received the holistic scientific investigation that they warrant. In this respect, their conservation is all the more important, and their management needs to take into account both their unique ecology and their disparate cultural settings. Here, the protected karst areas of Central America, the Caribbean, and Southeast Asia are examined to provide broader lessons about karst conservation and management in the developing world, where ecological and human sustainability are increasingly challenged by human population growth and anthropogenic environmental impacts (Day 2009, and 2010).

20.2 Central America, the Caribbean, and Southeast Asia

Central America, the Caribbean, and Southeast Asia are among the premier karst regions of the world with a combined carbonate rock area, excluding China, of over 750,000 km^2 (Day and Urich 2000; Kueny and Day 1998, 2002). In 1997, the IUCN World Commission on Protected Areas (WCPA) recognized karst landscapes as significant target areas for protection (Watson et al. 1997), and at about the same time, regional concerns about protecting the environment and establishing protected areas began to gain support in the developing world through both government and nongovernment efforts. The World Conservation Monitoring Centre (WCMC) has compiled a worldwide database of protected areas (WCMC 2010), but it does not specifically identify protected karst areas in its database. This report is an assessment of karst protection in the developing world, building on prior regional studies.

Information about the regional karst in Central America, the Caribbean, and Southeast Asia is available from numerous and diverse sources, including geological maps, atlases, and previous research (Day and Urich 2000; Kueny and Day 1998, 2002). Although much of the regional karst is striking and well documented, some exhibit more subtle karst characteristics and are relatively poorly known. To ensure consistency, it is assumed here that all expanses of carbonate rocks indicated in geological sources do in fact represent karst landscapes, an assumption that appears justified by several decades of personal experience (Day 2000).

Reliable information about protected areas is more difficult to acquire, particularly given the wide array of protected area legislation, variations in terminology and size, and the difficulties of verification. The primary source of information is the United Nations (UN) List of Protected Areas maintained and updated by the WCMC (WCMC 2010). This is supplemented by information for separate regions and individual countries, such as that contained in Thorsell (1985a), WCMC (1992), and Hopkins (1995). Information about additional protected areas, which do not conform to UN recognition criteria, can be obtained from individual government sources and other studies. “A protected area is a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values.” (WCMC 2010). However, in light of varying protected areas criteria and terminology regionally and nationally throughout the developing world, a protected area is defined here as any unit of land, regardless of size or legal status, which is managed with primary concern for conservation. As such, protected areas incorporate national, state and private parks, and forests, wildlife, forest, and archeological reserves.

20.3 Karst in Central America, the Caribbean, and Southeast Asia

Carbonate rocks in Central America and the Caribbean are relatively young, ranging from Quaternary to Jurassic in age (0–200 ma BP). Some Southeast Asian carbonates are within the same age range, but others are as old as the Cambrian (500 ma BP). In these tropical settings, dissolution has produced karst landscapes including dry valleys, dolines, cockpits, poljes, towers, pinnacles, and extensive cave systems. The karst lands are extremely heterogeneous with respect to geologic and geomorphic factors, and climate, soils, biota, and human histories are also variable, leading to a wide range of specific karst environments. The most impressive karst is developed in the older, uplifted, fractured, and crystalline limestones of Southeast Asia, the Central American mainland, and the Greater Antilles. Reflecting the broader geologic histories of the regions, some carbonates are covered by volcanic ash, some are brecciated and others have been extensively folded and faulted. Karst elevations range from sea level up to 4,000 m; some are mountainous, others planar; some are hydrologically isolated, while others receive allogenic drainage from adjacent nonkarst terranes. The karst landscapes have been and still are influenced by regional tectonic, eustatic, and climatic changes (Day 1993; Day and Urich 2000).

In general, the tropical humid climate results in very efficient and rapid karstification, and virtually all regional carbonate rocks have been affected by karst processes and/or have developed karst landforms (Day 2000). Soils are extremely variable, but generally tend to be clay rich, heavily leached, patchy, and thin, except in depression and valley bases, where they are thicker. Steep slopes may have no soil cover except in joints and solutional pockets. Differences in climate, vegetation, age, and relief account for major differences in regional karst soil types, and many soils have been altered by human agricultural practices. The natural karst land vegetation varies from xerophytic scrub to dry and wet tropical broadleaf forest, including both deciduous and evergreen trees, although much of the original forest has been cleared, with only fragments remaining in remote karst areas. Wet/dry seasonality is an important aspect of many of the karst ecosystems. Central America, the Caribbean, and Southeast Asia also support diverse wildlife assemblages and specifics of the regional karst land ecologies warrant additional studies. Biological significance is a major factor in designation of protected areas within the karst (Vermuelen and Whitten 1999; Wong et al. 2001; Schilthuizen et al. 2005; Clements et al. 2008; Struebig et al. 2009).

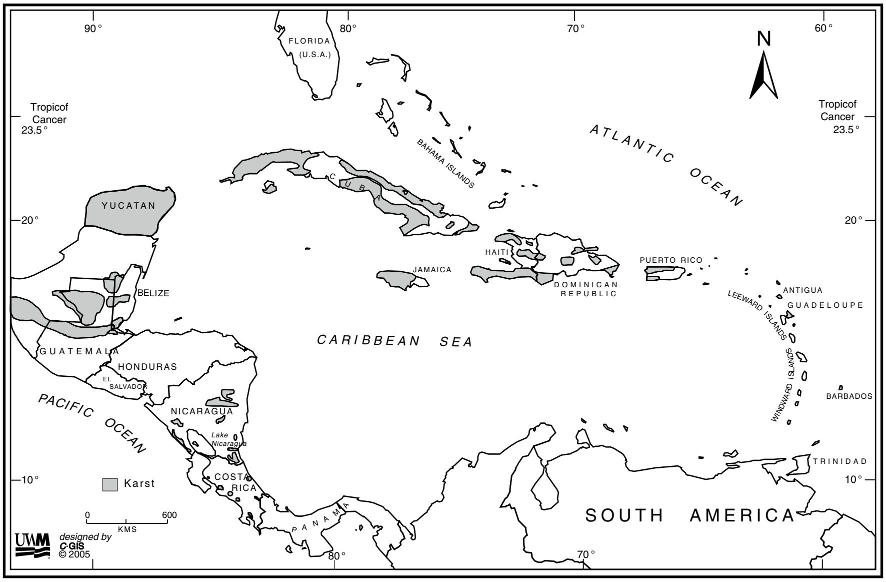

Fig. 20.1 Karst areas in Central America and the Caribbean

Human impact on the karst has been long term and severe, in particular through forest clearance, settlement, species introduction, hunting and gathering, agriculture, the pet trade, degradation of water resources, and industrial activities, including mining and quarrying (Day 1993; Vermuelen and Whitten 1999; Wong et al. 2001; Hobbs 2004). Important archeological sites, both surface and subterranean, are significant facets of many of the karst lands, and indigenous populations are locally significant. Contemporary threats to the karst include quarrying, urbanization, agricultural expansion, logging, and unsustainable tourism (Day 2007b and 2010, Molerio Leon and Parise 2009; Parise 2010).

The most extensive Central American karst, excluding the Yucatan, is in Guatemala and Belize, where cockpit, tower and other karst, developed in Cretaceous and Tertiary carbonates, extends over nearly 20,000 km^2 (Fig. 20.1). Honduras has three major karst areas covering ~10,000 km^2, and there are also significant karst areas in Nicaragua and throughout Costa Rica (Troester et al. 1987). There are several small karst areas in Panama, and one small area in El Salvador (Day 2007a). The greatest extent of karst in the Caribbean is on the islands of the Greater Antilles (Cuba, Hispaniola, Jamaica, and Puerto Rico) with a total karst area of ~115,000 km^2 (Fig. 20.1). The Islands of the Bahamas, the Lesser Antilles, Trinidad, Tobago, and the Netherlands Antilles contain an additional 13,000 km^2 of karst (Day 1993; Tarhule-Lips 2004).

Karst is widespread throughout Southeast Asia, with significant contiguous karst areas of over 5,000 km^2 occurring on the Asian mainland and New Guinea, and smaller patches, typically no more than 2,000–3,000 km^2 occurring on the carbonate islands of the Sunda and Sahul platforms and adjacent to the region's

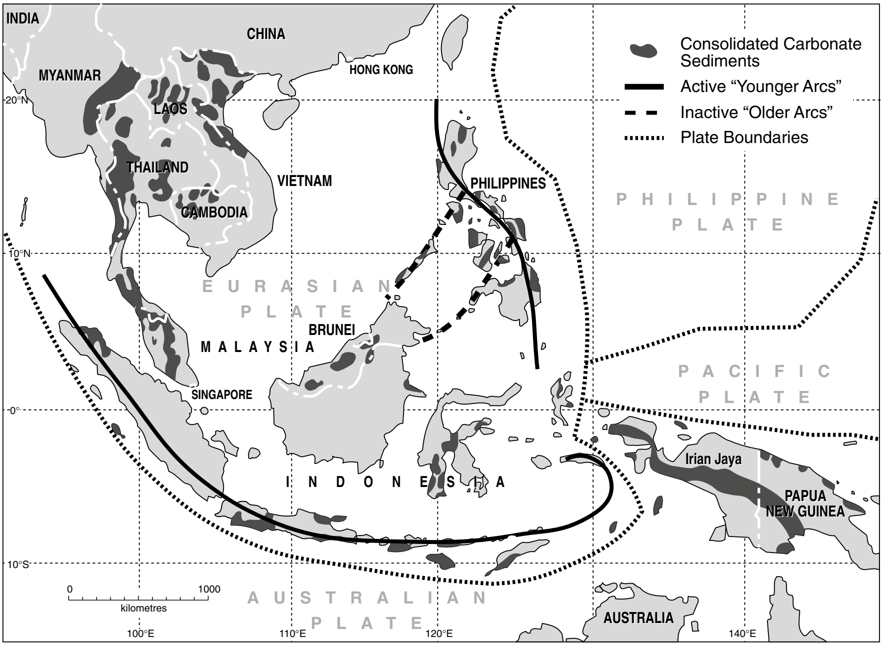

Fig. 20.2 Karst areas in Southeast Asia

volcanic island arcs (Day and Urich 2000; Gillieson 2005) (Fig. 20.2). There is considerable karst in Burma (Tin and Si Si 2004) and Thailand (Gillieson 2005), with other significant areas in Laos (Kiernan 2009), Vietnam (Tuyet et al. 2004), Cambodia, and peninsular Malaysia (Gillieson 2005).

20.4 Protection of Developing Karst Landscapes

With a total land area of nearly 6 million km^2 and a population approaching 800 million people, human pressures on the karst in Central America, the Caribbean, and Southeast Asia are severe, although most nations now recognize the importance of resource protection for environmental, economic, and social reasons. Protected areas are critical tools for long-term conservation of nature with associated ecosystem services and cultural values (WCMC 2010).

The importance of karst landscape protection was highlighted in 1997 by the International Union for the Conservation of Nature and Natural Resources (IUCN) Working Group on Cave and Karst Protection (Watson et al. 1997). Significant rationales for the protection of karst landscapes include the following:

- As habitats for endangered species of flora and fauna
- As areas possessing rare minerals and/or unique landscape features
- As important historic and prehistoric areas with cultural importance

- As important areas for scientific study across a variety of disciplines
- As religious and spiritual areas
- As areas of specialized agriculture and industry
- As important areas to the understanding of regional hydrology
- As recreation and tourism areas with important economic and aesthetic value

Many different protected area designations and definitions have been implemented because protected area systems vary from one country to another depending upon the countries' needs and priorities, laws regarding natural areas and resources, and financial and institutional support. The WCMC database includes many regional sites which do not qualify for inclusion in the UN List because of size constraints. The 1,000 ha minimum area requirement is particularly relevant to small countries, including many in the developing world, where landscapes are of restricted expanse.

Protected areas legislation throughout the developing world is highly variable as a result of the multiplicity of sovereign nations, government agencies, and nongovernment organizations (NGOs). IUCN/WCPA has organized regional commissions and regional bodies such as the Association of Southeast Asian Nations (ASEAN) Environment Program and the Caribbean Conservation Association Act as regional arbiters of conservation strategies, but individual countries' levels of participation in regional programs are highly variable. International treaties, such as the UN Convention for the Protection of World Natural and Cultural Heritage, have been adopted throughout Central America, the Caribbean, and Southeast Asia, and the UNESCO Man and the Biosphere (MAB) Program has been adopted by all except Laos. Regional summaries for Central America, the Caribbean, and Southeast Asia are available in Guerrero and Sguerra (2009), WCPA (2007), and McNeely (1994); individual country information is provided by IUCN (1982) and WCPA (2010).

In some Asian countries, protection of wildlife has a long tradition, associated particularly with Buddhist religious sites (Collins et al. 1991). Elsewhere, throughout the developing world, many countries inherited colonial legislation that restricted certain activities in designated areas, especially forest reserves, although this was largely intended to protect economic rather than environmental interests, particularly those in timber production and mining. Most protected areas legislation is of more recent, postindependence vintage, with the majority of countries adopting late twentieth century constitutional provision for the designation of protected areas. Throughout Central America, the Caribbean, and Southeast Asia significant karst landscapes are variously encompassed within national parks (e.g., Tikal in Guatemala, Viñales in Cuba, Gunung Mulu in Malaysia, and Phangnga in Thailand), forest reserves (e.g., the Chiquibul Reserve in Belize, Rio Abajo in Puerto Rico, and the Ulu Muda and Gunung Jerai Forest Reserves in Malaysia), wildlife reserves, refuges and sanctuaries (e.g., Santo Tomas Wildlife Refuge in Cuba and the Phu Luang Wildlife Sanctuary in Thailand) and other designated protected areas (e.g., Gran Parque Sierra Maestra in Cuba and the Danum Valley Conservation Area in Malaysia). Karst lands are present in at least 14 UNESCO World Heritage Sites, including Viñales, Alejandro de Humboldt, Tikal, Darien, La Amistad, Sian Ka'an, Lorentz, Gunung Mulu, and Halong Bay (Williams 2008), several of which are also MAB Reserves. Much of the Guatemalan Peten karst is incorporated in the Maya Biosphere Reserve.

The pattern of protected areas legislation throughout the developing world is highly uneven, with levels of protection reflecting population, economic, and political pressures. In Central America and the Caribbean, there is significant legislation protecting karst areas in the Yucatan, Belize, Costa Rica, the Dominican Republic, and Cuba, but protective legislation is minimal elsewhere. Intermediate situations pertain, for example, in Honduras, Guatemala, Jamaica, Trinidad, and Puerto Rico (Kueny and Day 1998, 2002). In Southeast Asia, there is significant legislation protecting karst areas in Thailand, Vietnam, Malaysia, Indonesia, and the Philippines, but, by contrast, effective protective legislation is minimal in Burma, Cambodia and Laos (Day, and Urich 2000). Regionally, there is considerable scope for the continued development and implementation of effective protected areas legislation, management policy and enforcement (Margules and Pressey 2000).

Although the regional summaries for Central America (Kueny and Day 2002), the Caribbean (Kueny and Day 1998) and Southeast Asia (Day and Urich 2000) have not yet been updated, they themselves made clear the volatility of the situation, and significant changes have occurred both in individual countries and in broader regions. In Central America, for example, there have been important developments in Belize, where the status of several important protected karst areas has changed, where NGO involvement has increased and where there have been illicit incursions into several national parks and reserves. In Jamaica, there continues to be debate and uncertainty about both the present and future status and extent of the Cockpit Country reserve (Day 2004, 2006; Lyew-Ayee 2005). In Southeast Asia, NGOs have been lobbying for new karst protected areas: Fauna & Flora International in Vietnam, The Nature Conservancy in East Kalimantan, Indonesia, and the Malaysian Karst Society in Malaysia. Malaysia has also established its first Geopark on Langkawi Island, which includes large areas of karst, and new nature reserves in karst in Sarawak at Bau and Gunung Kapor. Gunung Buda is under consideration for designation as a national park and the Sarawak state government has established a Karst Management Unit within the Parks and Wildlife Division of the Forest Department (Sarawak Forest Department 2010).

In Central America and the Caribbean, about 33% of the regional land area, a total of 285,000 km^2, is karst landscape. Karst-protected areas totals for individual countries and the region as a whole are shown in Table 20.1. In the Caribbean, there are 166 protected karst areas, collectively encompassing 46,357 km^2, ~16% of the entire regional karst total. The greatest number of protected karst areas in the Caribbean (62) and the largest total area of protected karst (11,500 km^2) are in Cuba, where ~16% of the total karst is protected. Comparatively, the Dominican Republic affords protection to a lesser area of karst (4,600 km^2) but the four protected karst areas represent 18.4% of the total karst area. Of the other Caribbean countries, only the Bahamas and Puerto Rico afford protection to ten or more karst areas and only the Bahamas protects 10% or more of its total karst landscape (Table 20.1). Karst-protected areas in the remaining Caribbean countries are small, both in terms of absolute area and proportion of the total.

Table 20.1 Protected karst areas in Central America and the Caribbean

Country	Karst area (km^2)	Protected karst area	% Karst protected	No. of areas
Anguilla	90	<10	<1	5
Antigua/Barbuda	120	<10	4	3
Bahamas	11,500	1,432	12	10
Barbados	370	<10	3	6
Cayman Is.	200	<10	5	7
Cuba	70,000	11,500	16	62
Dominican Rep.	25,000	4,600	18	4
Guadeloupe	580	<10	0	0
Haiti	10,000	60	1	2
Jamaica	7,500	539	7	6
Neth. Antilles	800	60	5	3
Puerto Rico	2,500	150	4	10
Trinidad/Tobago	750	60	1	7
Belize	5,000	3,400	68	18
Costa Rica	2,000	68	3	5
El Salvador	300	0	0	0
Guatemala	15,000	1,517	10	7
Honduras	10,000	3,500	35	7
Nicaragua	5,000	0	0	0
Panama	2,000	80	4	1
Total	285,000	46,357	–	166

Source: Kueny and Day 1998, 2002

In Central America, the greatest number of karst-protected areas (18) is in Belize, where 68% of the karst is protected, with the largest total area of protected karst (19,351 km^2) in the Mexican Yucatan states, where ~18% of the total karst is protected. Honduras affords protection to seven karst areas, representing 35% of its total karst. By contrast, in Guatemala, the seven protected karst areas represent only 10% of the national karst total. Karst protected areas in Costa Rica and Panama are comparatively small, both in area and proportion, and El Salvador and Nicaragua have yet to designate any karst areas as protected. Costa Rica and Panama both have extensive national-protected areas systems, but they include only relatively small areas of karst.

Almost 10% of the Southeast Asian land area, a total of about 458,000 km^2, is karst. Karst-protected area totals for individual Southeast Asian countries and the region as a whole are shown in Table 20.2. Regionally, there are 154 karst-protected areas, collectively encompassing 51,150 km^2, ~12% of the entire regional karst total. The greatest number of karst-protected areas (44) and the largest total area of protected karst (22,000 km^2) are in Indonesia, where ~15% of the total karst is protected. Comparatively, Malaysia affords protection to a lesser area of karst (8,000 km^2) but the 28 karst-protected areas represent 45% of the total karst area. Of other countries, Thailand affords protection to 41 karst areas, representing 25% of the total karst, and the Philippines protect 29% of their total karst landscape (Table 20.2). Karst-protected areas in Burma, Laos, and Vietnam are comparatively

Table 20.2 Protected karst areas in Southeast Asia

Country	Karst area (km^2)	Protected karst area	% Karst protected	No. of areas
Burma	80,000	650	1	2
Cambodia	20,000	0	0	0
Indonesia	145,000	22,000	15	44
Laos	30,000	3,000	10	10
Malaysia	18,000	8,000	45	28
PNG	50,000	0	0	0
Philippines	35,000	10,000	29	14
Thailand	20,000	5,000	25	41
Vietnam	60,000	4,000	7	15
Total	458,000	53,150	–	154

Source: Day and Urich 2000

small, both in terms of absolute area and proportion of the total; Cambodia and Papua New Guinea have yet to designate any karst areas as protected, although differences in land tenure systems, especially in the latter, mean that effective protection may be provided through private land ownership rather than through government agencies.

These situations, although specific to the karst, also reflect overall designations of terrestrial-protected areas according to the UN and the WCMC (Table 20.3). Note that the UN/WCMC data are constrained by criteria of size and legal status, meaning that protected areas totals in Tables 20.1, 20.2, and 20.3 reflect different data sets and are not directly comparable. In Southeast Asia, for example, there is also a relationship, although not always straightforward, between conservation of forest resources and designation of protected areas within the karst. MacKinnon and MacKinnon (1986) identify "Forest on Limestone" as a distinct vegetation category, assessing the areas and percentages protected by country as follows: Thailand, 200 km^2, 100%; the Philippines, 20 km^2, 11.1%; Malaysia, 240 km^2, 9.7%; Indonesia, 3,700 km^2, 3.3%; Vietnam, 210 km^2, 2.1%; and Laos, 0 km^2, 0%. More broadly, overall regional-protected area percentages and those for protected karst show similar magnitudes and trends, as follows: Caribbean overall 11.7% (14% karst), Central America 24.8% (18%), and Southeast Asia 14.8% (12%) (IUCN 2003; Day and Urich 2000; Kueny and Day 1998, 2002).

20.5 Significant Protected Karst Areas

In the Caribbean and Central America, the 16% of the karst that is afforded protected area status includes some individual karst areas that are extensive and significant in terms of scientific, cultural, and recreational criteria. Most of the 166 karst-protected areas are so designated because of their specific biological, archeological, or recreational significance, and few are recognized on the basis of geomorphic criteria. Indeed, it is unclear whether it is even recognized that some protected areas contain karst.

Table 20.3 National terrestrial protected areas summary statistics

Country	Protected area (km²)	No. of areas protected	% protected
Anguilla	10	6	11
Antigua/Barbuda	45	12	10
Bahamas	1,549	43	11
Barbados	1	7	2
Cayman Is.	153	33	58
Cuba	20,829	71	19
Dominican Rep.	13,850	59	29
Guadeloupe	299	21	18
Haiti	73	8	<1
Jamaica	2,297	71	21
Neth. Antilles	63	11	8
Puerto Rico	603	50	7
Trinidad/Tobago	1,796	64	35
Belize	10,227	99	45
Costa Rica	15,846	165	31
El Salvador	281	77	1
Guatemala	35,641	163	33
Honduras	23,531	77	21
Nicaragua	22,007	74	17
Panama	21,205	53	28
Burma	45,024	49	7
Cambodia	43,399	30	24
Indonesia	299,925	469	16
Laos	37,545	25	16
Malaysia	66,972	684	20
PNG	44,882	67	10
Philippines	51,461	204	17
Thailand	104,452	206	20
Vietnam	18,621	116	6

Source: WCMC 2008

In Central America, the Yucatan Peninsula is the largest karst area and has the most protected karst (Table 20.1 and Fig. 20.1). The largest single protected area is the 7,232 km^2 Calakmul Biological Reserve in Campeche, which adjoins the Maya Biosphere Reserve in Guatemala. The states of Quintana Roo and Yucatan each contain at least three karst-protected areas (Kueny and Day 2002).

Belize has the highest level of karst protection in Central America (Day 1996), including the Chiquibul National Park, which encompasses 1,865 km^2 in the Western Cayo District. The park contains the Caracol Archeological Reserve, as well as portions of the Chiquibul Cave System, the longest known cave system in Central America (Miller 2000). The Rio Bravo Conservation and Management Area (1,010 km^2) in the Orange Walk District is managed by the Program for Belize, an NGO. Other significant karst-protected areas include forest reserves, nature reserves, and smaller national parks (Day 1996). Guatemala has 1,517 km^2 of protected karst contained in seven protected areas. The Rio Chiquibul-Montanas

Mayas Biosphere Reserve (619 km^2) is the largest contiguous karst-protected area in Guatemala and adjoins the Vaca Forest Reserve in Belize. Rio Chiquibul-Montanas Mayas is part of the Maya Biosphere Reserve (18,449 km^2), the largest protected area in Guatemala, established in 1990 and located in the Department of Peten. The Reserve contains many important archeological sites, including Tikal National Park, but it remains under great pressure from unauthorized agricultural clearance. Proposed agreements between Belize, Guatemala, and Mexico are designed to protect the border areas between the three countries. An international-protected area in the Gran Petén would include Calakmul, Rio Bravo, Chiquibul, and Chiquibul-Montanas Mayas (WCMC 1992; Kueny and Day 2002).

The largest karst-protected area in Honduras covers 2,400 km^2 within the Patuca National Park and Tawahka Anthropological Reserve, in the Cordillera Entre Rios and the Montanas de Colon in Southeastern Honduras. Patuca National Park contains ~1,600 km^2 of karst and Tawahka Anthropological Reserve ~800 km^2 of karst. Other karst-protected areas are Sierra de Agalta National Park, Pico Pijol, Cerro Azul Copan, and Santa Barbara National Parks, and the Cuevas de Taulabe National Monument. Costa Rica has ~2,000 km^2 of karst landscape distributed in small areas throughout the country (Mora 1992). The largest karst-protected area is the Isla del Coco National Park in the Pacific Ocean off the Peninsula de Nicoya. On the Peninsula de Nicoya, karst is protected within the Barra Honda National Park and the three relatively small karst-protected areas of Cabo Blanco Nature Reserve, Ostional National Park, and Curu National Park.

In the Caribbean, the inherent characteristics of karst landscapes are recognized most explicitly in Cuba, where several protected areas, totaling over 500 km^2, are designated as specific karst reserves. Karst in Cuba is deemed important historically, culturally, economically, hydrologically, and aesthetically, and its conservation is emphasized (Nuñez Jimenez 1984; Tyc 2004). It is not coincidental that Cuba has the highest rates of karst-protected area designation in the Caribbean (Table 20.1). Some 225 km^2 of protected karst is in the classic tower karst area in the province of Pinar del Rio, and the tower karst near Viñales is recognized for its scenic beauty. The karst of the Gran Parque Sierra Maestra is designated an Integrated Management Area incorporating both inviolable reserves and development areas.

Hispaniola contains the second largest area of karst in the Caribbean, with 13% incorporated into six designated protected areas. The Massif del, a Hotte karst aquifer in Haiti, is protected because of its importance to the water supply of Port au Prince (WCMC 1992); otherwise, less than 1% of Haiti's karst is afforded protection. Los Haitises National Park is the largest karst-protected area in the Dominican Republic, covering over 1,500 km^2. It is in part protected for its karstic formations but is under extreme pressure from rural populations clearing forests for farming and grazing land (Brothers 1997). Karst is also protected in Jaragua National Park, Sierra Bahoruco, and Del Este National Park.

The ten karst-protected areas in Puerto Rico encompass just 150 km^2 of land including the Mona Island Nature Reserve (56 km^2). The UN List of Protected Areas does not include some 100 km^2 of karst in seven state forests that are included in the total in Table 20.1. The largest of these is the Rio Abajo State Forest with ~40 km^2

of karst south of Arecibo. Other karst-protected areas are relatively small and also not included in the UN List. Less than 5% of the Puerto Rican karst is afforded protected area status, but there are plans to expand this significantly (Lugo et al. 2001). Urbanization is a particular threat, but local conservation efforts are increasingly effective (Mujica-Ortiz and Day 2001).

The six karst-protected areas in Jamaica also encompass surprisingly limited areas, containing 539 km^2, just 7% of the total karst. The World-renowned Cockpit Country (223 km^2), designated as a Forest Reserve in 1950, has long been under consideration as a national park, and has been mooted as a World Heritage site (Eyre 1995; Chenoweth et al. 2001; Day 2004, 2006). Conservation efforts at the local, national, and international level are increasing, but the area is under pressure from encroaching agricultural activities (Miller 1998) and is threatened by bauxite mining. Karst is also incorporated within the Blue Mountains-John Crow Mountains National Park (419 km^2) and within several small forest reserves.

Most of the ten karst-protected areas in the Bahamas are at or below sea level and incorporate underwater cave systems, notably that within Lucayan National Park on Grand Bahama. The largest karst-protected areas are Inagua National Park (743 km^2), Exuma Land and Sea National Park (455 km^2) and Abaco National Park (205 km^2). In total, some 12% of the karst is designated as protected areas, many of which have been established for the protection of marine bird colonies.

Elsewhere in the Caribbean, karst-protected areas are few in number (22), restricted in area (totaling ~160 km^2) and account for less than 7% of the remaining karst landscape. In Northern Trinidad, seven karst areas are incorporated into forest reserves, totaling about 60 km^2 (Day and Chenoweth 2004). Notable karst is present in the St. David, Matura and Valencia Forest Reserves. On the smaller islands, restricted karst areas are included in small parks, gardens, and cave reserves.

Although only 12% of Southeast Asia's karst landscape is afforded protected area status, this total includes some individual karst areas that are extensive and significant in terms of scientific, cultural, and recreational criteria. While the majority of the 154 karst-protected areas are so designated because of their specific biological, archeological, or recreational significance, a few are recognized on the basis of stricter geomorphic criteria, acknowledging the intrinsic value of karst landscapes themselves.

Indonesia, by far the largest country in the region, with a land area of nearly 2 m km^2, protects the largest number of karst areas (44) and the largest area of karst (22,000 km^2), although only 15% of the total karst area. Much of the protected karst is in Irian Jaya, for example, in the Lorentz National Park and in the Misool Selatan and Pulau Waigeo Nature Reserves. Relatively little karst is protected in Java, Kalimantan, and Sumatra, but there are numerous small karst-protected areas in the Moluccas and the Lesser Sunda Islands. Many more protected areas are proposed (Collins et al. 1991; MacKinnon 1997).

Karst is protected within 21 of Thailand's national parks, with notably large areas in Erawan, Kaeng Krachan, Khao Lunag, Khao Sok, Khao Yai, and Sai Yok. Three National Marine Parks - Tarutao, Phi Phi-Hat Nopparat Thara, and Koh Surin – also encompass extensive karst. The Ao Phangnga National Park includes impressive marine tower karst (Uhlig 1994). Karst is also protected within the Thungyai-Huai Kha Khaeng Wildlife Sanctuaries, which constitute a UN World Natural Heritage Site and represent the largest conservation area in mainland Southeast Asia, covering some 6,000 km^2. Numerous caves are also conserved as archeological, religious, and tourist sites (Dunkley 1995; Vermeulen and Whitten 1999).

The intrinsic and diverse value of karst landscapes is recognized particularly in Malaysia, where ~8,000 km^2 is protected in national parks, forest reserves, wildlife reserves and sanctuaries, and other conservation areas. It is not coincidental that Malaysia has the greatest proportion of protected karst in Southeast Asia (Table 20.2). Caves and karst are important culturally, economically, and aesthetically, and more than a dozen important caves are conserved for archeological, religious, and tourism purposes, including the caves in the Niah and Mulu National Parks. Langkawi Geopark, Malaysia's first UNESCO Geopark, established in 2007, includes over 400 km^2 of karst.

Vietnam's first national park, Cuc Phuong, was established in 1962 and a national system of protected areas has been established since 1980. Seven of Vietnam's nine national parks, including Cuc Phuong, encompass karst landscape, and karst constitutes about 65% of the total national park area. Additionally, karst covers about 30% of Vietnam's nature reserves (Chuyen 1995). Some 100 km^2 of karst is protected in Cat Ba National Park, which is within the Halong Bay UNESCO World Heritage Site, encompassing some 1,500 km^2 of drowned tower karst. Many caves are protected as natural heritage sites, for example, caves in Ben En National Park and in Con Dao National Park, for the conservation of the Cave Swift, Colocalia francina, whose nests are highly priced as the primary ingredient of birds' nest soup (Day and Mueller 2004). Karst is also protected in Phong Nha Nature Reserve, in the Son Tra Protected Area and in Bach Ma, Ba Vi, and Ba Be National Parks. Even so, accepting Do's (1998) estimate of the total karst landscape (60,000 km^2), Vietnam affords protected area status to less than 10% of its karst.

Burma (Myanmar) contains the second largest area (80,000 km^2) of karst in Southeast Asia, but less than 1% is incorporated into two designated protected areas, the Shwe u Daung, and Shwesettaw Game Reserves and in the vicinity of Pindaya Cave. Some 3,000 km^2 of karst are conserved in the protected areas of Laos, notably in the Khammoune National Park, the Hin Namno Karst Reserve and the Xe Bang Fai and Vang Vieng Nature Reserves. Numerous caves are protected, at least nominally, but only about 10% of the total karst in Laos is afforded protection. Although Papua New Guinea has no integrated protected areas system, three sites have been nominated for World Heritage status (Williams 2008).

The situation in the Philippines is in some respects the most confusing, both because the legal basis for protected areas is complex and because administrative responsibility is vested in a multitude of management units (Restificar et al. 2006). Fifty five percent of the Philippines is "Public Land" (Kummer 1992), but its conservation status is often questionable. It is even unclear exactly how many national parks exist or what their precise boundaries are (WCMC 1992). Significant karst is protected within the Puerto Princessa (formerly St. Paul Subterranean River) National Park on Palawan, within the Central Cebu National Park and in Rajah

Sikatuna National Park in Bohol. On the last named island, much of the Chocolate Hills is protected as a Natural Monument (Urich et al. 2001). Quaternary coastal limestones are conserved within the Tubbataha Reefs National Marine Park. In 1992, the Philippines adopted a Strategic Environmental Plan for Palawan, "A comprehensive framework for the sustainable development of Palawan compatible with protecting and enhancing the natural resources and endangered environment of the province…"(Government of the Philippines 1992, p.4). In total, about 29% of the Philippines karst is designated as protected areas.

20.6 Lessons About Karst Protection in the Developing World

Overall, 16% of Central America and the Caribbean's karst landscape is afforded at least nominal protection under the auspices of protected area status. The 166 karst-protected areas total 46,357 km^2, with the majority in the Central American isthmus and the islands of the Greater Antilles. There are extensive karst-protected areas in the Yucatan, Belize, Honduras, Cuba, and the Dominican Republic, with lesser areas elsewhere. With the exceptions of Nicaragua, El Salvador, and Guadeloupe, every regional territory has designated at least some karst landscape as protected area, but in countries such as Guatemala and Jamaica, the proportion of protected karst is low, and in the smaller Central American countries and Caribbean islands, both the total area of karst and the proportion protected are minimal.

Similarly, a modest 12% of Southeast Asia's karst landscape is designated as protected areas. The 154 karst-protected areas total about 51,000 km^2, with the largest area, 22,000 km^2 (52%), in Indonesia. There are also extensive karst-protected areas in Malaysia, the Philippines, Thailand, and Vietnam, and small areas in Burma and Laos. Cambodia and Papua New Guinea have yet to designate any karst landscapes as protected areas. Overall, the total area of karst and the proportion designated as protected areas are minimal.

In the broader conservation context, the karst-protected area percentage for Central America, the Caribbean, and Southeast Asia slightly exceeds the figure of 10–12% that is sometimes suggested as the near-term land area protection target for nations and ecosystems (Noss 1996). The relevance of such low numerical targets is, however, questionable (Soule and Sanjayan 1998) and the regional situations mask considerable internal variation, some of which gives rise to concerns. Much karst is poorly recognized at the national level and many sites of scientific importance have not been included in protected areas because their significance has not been brought to the attention of the governments concerned (Williams 2008). Also, although the focus here is on the karst itself, it is important not to lose sight of the holistic scenario of protected areas, of which karst is but a part (Day 2009). Regional-protected area percentages (with karst-protected percentages for comparison) are as follows: Caribbean 11.7% (14% karst), Central America 24.8% (18%), Southeast Asia 14.8% (12%) (IUCN 2003; Day and Urich 2000; Kueny and Day 1998, 2002).

Much of the karst is protected because of its biodiversity, its natural resources, and its cultural and archeological significance, often without explicit recognition of its distinctive geomorphology and hydrology (Thorsell 1985a, b; Vermeulen and Whitten 1999; Wong et al. 2001; Clements et al. 2006). One exception to this is in Cuba, where the scientific merit of karst lands is a central focus of government and education (Parise and Valdes Suarez 2005). A similar situation pertains in Southeast Asia, where only in Gunung Mulu, in Sarawak, is karst science stressed. Governments have an important role to play in karst protection, although other entities and factors are also involved. The high levels of karst protection in Cuba are a direct reflection of government priorities, and in Belize, they reflect a national focus on ecotourism and a national commitment to protected area establishment. Another important factor is Belize's low population density, which stands in marked contrast to that of other developing countries. Although detailed analysis of the factors influencing the differing levels of karst land protection has not yet been undertaken, population pressure would appear to be an important factor.

One concern is that little consideration has been given nationally or regionally to the protection of different or representative karst types, and much of the protected karst is in interior, upland locations, such as the Vaca Plateau in Belize, the Cockpit Country of Jamaica, Lorentz National Park in Indonesia and Cuc Phuong in Vietnam, which in part reflects the relative isolation of those areas. Polygonal or cockpit karst appears to be quite well represented in protected areas, but doline and dry valley karst is less well represented and lowland karst, including poljes and tower karst areas, which is a target for agriculture, industry, and urban growth, is underrepresented in protected areas. Even where such karst is incorporated into protected areas, such as in HaLong Bay, there remain serious conflicts between competing interests, such as urban development, mining, shipping, and tourism (Lloyd and Morgan 2008). An international survey of karst World Heritage sites (Williams 2008) reveals similar gaps in geographical and environmental coverage, with the Southern Hemisphere poorly represented, especially in South America, Africa, Australasia, and the South Pacific, and North, Central, and South Asia and the Middle East underrepresented in the Northern Hemisphere. Environmentally, there is relatively poor representation of arid, semiarid, and periglacial environments. IUCN recommends that these gaps be filled, but the global socio-political scale is not, however, easily reconciled with national, and local priorities, which are themselves highly contested.

So far, there has been little international cooperation between developing countries in the designation of trans-boundary karst-protected areas. This is increasingly necessary for World Heritage designation because humid tropical karst is already well represented (Williams 2008) but its precursors include stable and friendly governments, effective national legislation and precise identification of suitable sites. The proposed international-protected area in the Gran Petén would encompass extensive karst in Mexico, Guatemala, and Belize, and there are possibilities elsewhere in Central America in Darien (Panama and Colombia) and La Amistad (Costa Rica and Panama). In mainland Southeast Asia, there is considerable trans-border potential, although in the insular Caribbean and Southeast Asia the possibilities are more limited: across the borders between Haiti and the Dominican

Republic and between Indonesia and Malaysia in Borneo. There is increasing emphasis on protection of marine karst, for example on the Belize Barrier Reef and in Thailand and the Philippines, and there is considerable scope for integration of marine and terrestrial karst-protected areas. The potential for regional karst designation, for example in the Caribbean or Southeast Asia, appears remote, especially with the pending second phase of the South China Karst World Heritage nomination (Williams 2008).

Much protective legislation in the developing world is inadequate, and enforcement is often constrained by inadequate knowledge, economic and personnel conditions and because of conflicting priorities (McNeeley and Miller 1984; Thomas and Middleton 2003; Hockings et al. 2006). Inadequacies arise at policy, planning, and management levels, and there is often inadequate coordination between agencies and individuals, even in countries with integrated protected areas networks, such as Belize. Contemporary threats include forest clearance, agricultural incursion, urban expansion and development, quarrying and mining, water contamination, invasive species, and the looting of archeological materials. Management and policing of karst-protected areas in the developing world is of variable effectiveness and, in some instances, is nonexistent. Some of the largest and most significant reserves are the most vulnerable. More detailed field surveys of the extent of karst lands and protected areas in individual countries are warranted, particularly if the effectiveness of protection "on paper" is to be ascertained. This is particularly true in Nicaragua, Honduras, Burma, and Laos, where there is considerable uncertainty about both the extent of the national karst and the status of the protected areas.

Local populations can be effective custodians of protected karst, particularly where they derive incomes from sustainable use of the karst, but they need to be encouraged and empowered (Urich et al. 2001; Gardner 2009). Local communities and NGOs have been particularly effective in influencing government protection in Belize and Costa Rica, and their efforts are being replicated elsewhere, e.g., in Jamaica, Puerto Rico, Indonesia, and the Philippines. Political instability in countries such as Honduras, Nicaragua, Burma, Thailand, and the Philippines has not helped the situation, and infringement on karst-protected areas remains acute in much of Central America and Southeast Asia.

The establishment of effective boundaries and buffer zones is important, but this is difficult in small island states particularly (Martin and Piatti 2009). Ecotourism offers promise as a sustainable and educational land use, but mass tourism is clearly incompatible with conservation of karst unless it is strictly controlled (Duval 2006). Low-impact activities such as hiking, bird-watching, caving, and water-based recreation are increasing in many developing karst areas, although they warrant monitoring (Perez Jimenez et al. 2004; Parise and Valdes Suarez 2005).

The integrity of many karst-protected areas in the developing world is also a cause for concern. Many karst-protected areas do not encompass the karst as a whole, and their boundaries are poorly located with respect to karst hydrologic watersheds, both surface and underground. Some of them are of inadequate sizes, and others are already degraded or at risk of degradation in the near future. Many karst areas are highly contested, with increasing pressure for mining and quarrying, for example, which clearly are incompatible with the maintenance of protected areas.

There is a clear and growing need for consistent monitoring of existing protected areas (Ward and Harrison 1985)

One other concern is the looming prospect of accelerated anthropogenic environmental change. Much of the karst is inherently vulnerable, and predictions are that anthropogenic climatic change will lead to increasing air and water temperatures, rising sea levels and changing weather patterns, with changing precipitation totals and the increasing frequency of extreme events, such as droughts and hurricanes (Day and Chenoweth 2009). The effects of these will be magnified in the karst, where water resources are limiting, and disruption of the karst hydrological cycle may lead to increasing aridity and desertification, with impacts on geomorphic processes, ecology, and potential land use. Increasing population and economic development will exacerbate human impacts through clearing of remaining natural vegetation, species extinction, or introduction, expanding agriculture, increasing utilization, and contamination of water resources, tourism, urbanization, and industrial activities, including quarrying and mining. Appropriate land management and land use planning, including the expansion and maintenance of protected areas, will play a significant role in combating these impacts (Day and Chenoweth 2009).

Although this account represents only Central America, the Caribbean, and Southeast Asia, these are significant portions of the developing world, containing large areas of karst, high levels of biodiversity, large human populations, and increasing numbers of protected areas. Accordingly, they are probably representative of the situations elsewhere in developing karst areas, although there will, of course, be regional and local variations. The protected areas situation in the developing world is extremely volatile, with reserves being created and disestablished on a regular basis. Even within the past decade the numbers, sizes, and status of many countries' karst-protected areas have changed, in some cases dramatically. The numbers presented here will almost certainly be outdated by the time of publication. The current levels of protection may increase in terms of area, proportion, and efficacy, or they may decrease as other pressures on natural resources increase. Protected areas in the developing karst represent important resources and buffer against environmental change but, despite considerable progress, the future remains uncertain.

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Chapter 21
Karst in UNESCO World Heritage Sites

Paul W. Williams

Abstract This chapter discusses the requirements that must be met and the processes that must be followed before a natural area can be accepted as being worthy of World Heritage status under the UNESCO World Heritage Convention. Particular attention is paid to karst and cave sites. Various types of karst are defined and their existing representation on the list of World Heritage properties is discussed. This review finds 43 sites to have internationally significant karst features, with 24 of these to have outstanding universal value. But, it is also evident that numerous important karst areas do not feature on the World Heritage List, especially in the Middle East and Central Asia. Major gaps in coverage occur in arid, semiarid, and periglacial environments, and evaporate karsts are not represented at all. With these gaps in coverage having been identified, attention then turns to the process of application for World Heritage status and the various requirements that must be met, including conditions of integrity, management, and the responsibility of the host state. However, in 2007, the World Heritage Committee noted that karst systems (including caves) are already relatively well represented on the World Heritage List, and so there is increasingly limited scope for recommending future karst nominations. It follows, therefore, that only the best of the best are worthy of putting forward for consideration.

21.1 Introduction

In 1972, member states of UNESCO adopted the "Convention Concerning the Protection of the World Cultural and Natural Heritage." This is known as the World Heritage Convention, and it was adopted to try to ensure the proper identification, protection, and conservation of the world's heritage. The Convention established the "World Heritage Committee" and a "World Heritage Fund" and both have been

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in operation since 1976. The World Heritage Committee has developed guidelines concerning the implementation of the Convention, and these are revised from time to time (UNESCO 2008). This was accomplished with the professional assistance of the International Union for the Conservation of Nature (IUCN), which was founded in 1948 to encourage societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable. IUCN has a formal role as the Advisory Body to the UNESCO World Heritage Committee and makes recommendations concerning World Heritage nominations.

World Heritage is concerned with conserving the best that the planet has to offer. It applies to both cultural and natural features, and the properties on the World Heritage List can be seen on http://whc.unesco.org/pg.cfm?cid=31. However, this chapter considers only natural heritage and, specifically, karst landscapes, which occur mainly on carbonate rocks that cover about 15 million km^2 of the planet.

At a meeting of the World Heritage Committee in 2007, it was formally noted that caves and karsts are well represented on the World Heritage List and that in the interests of maintaining credibility of the List there is increasingly limited scope for recommending further karst (including cave) nominations. Therefore, it is important to assess carefully the potential for nomination of new cave/karst sites by identifying significant gaps in existing coverage. This chapter will examine that issue and also consider management concerns relevant to the success of any future nominations. It draws on previous publications by Hamilton-Smith (2006) and Williams (2008, 2009).

21.2 Karst Landscapes

From the point of view of the World Heritage Convention, where does karst start and end? The landscape takes its name from a stony limestone region known as *Kras* (later Germanicized to *Karst*) across the border region of Slovenia and Italy (Gams 1991; Kranjc 2001). This was the place where karst was first scientifically studied and so is referred to as the "classical" karst. But in reality, it is part of a much larger limestone region with a similar style of landscape, known as the Dinaric Karst, that extends continuously southeast along the Adriatic coast to Montenegro and beyond. It is the paramount karst of Europe and the type-site of many karst features. Landforms in other parts of the world that are similar to those found in the Dinaric Karst are by extension known as karst phenomena.

Karst is found on particularly soluble rocks, especially limestone, marble, and dolomite (carbonate rocks), and is also developed on gypsum and rock salt (evaporite rocks). Carbonate rocks outcrop across about 11% of the land area, but subsurface carbonate rocks involved in karst groundwater circulation considerably extend the active karst realm to perhaps 14% of the ice-free continental area (Ford and Williams 2007). Maps and statistics of areas of carbonate rock outcrops around the world are available from http://www.sges.auckland.ac.nz/sges_research/karst.shtm

Karst is produced by rainwater dissolving rock, but other natural processes often intervene, such as river erosion and glaciation, which modify the karst forms and produce intermediate landscape styles such as *fluviokarst, glaciokarst,* etc. Most caves form by dissolution by normal meteoric waters, although some are dissolved by thermal waters enriched by CO_2 and occasionally acidified by oxidized H_2S. These are known as hypogenic caves, and they are considered to be about 10–15% of known caves (Palmer 2007). Other caves form by dissolution at the interface of fresh and salt water along the coast.

Quartzite fluviokarst is developed on quartzites, dense siliceous sandstones, and conglomerates and occupies part of the continuum between karst and normal fluvial landscapes. In thermal waters, the solubility of quartzose rocks approaches that of carbonate rocks and so solutional caves may form, but this is not the case at normal temperatures and pressures. In some quartzite terranes, caves develop along the flanks of escarpments or gorges where deep fractures permit the ingress of water, and hydraulic gradients are steep. But development of a permanently saturated zone with water-filled caves and significant water storage (a typical characteristic of active carbonate karst) is generally precluded. The landforms and drainage characteristics of these siliceous rocks are therefore a style of *fluviokarst*, i.e., a landscape and subterranean hydrology that develops within the aerated zone as a consequence of the essential combined effects of dissolution, mechanical erosion, and transport by running water.

Outstanding landscapes in quartzites or quartz sandstones and conglomerates feature on the World Heritage List. These include Purnululu (Australia), Wulingyuan (China), Meteora (Greece), and Canaima (Venezuela). In addition, there are sandstone landscapes with impressive meshes of joint corridors, canyons, and ruiniform towers elsewhere, such as the “Ruined City” in Arnhemland, Australia and Danxia in China. Wray (1997) provides a review.

Pseudokarst is made up of karst-like landforms produced by processes other than dissolution or dissolution-induced subsidence and collapse. An example is *vulcanokarst,* which comprises tubular caves within lava flows. The roofs of such caves often suffer mechanical collapse, which creates enclosed depressions and provides access underground. An outstanding example on the World Heritage List is Jeju Volcanic Island and Lava Tubes (Korea).

Glaciers also have sinking streams, caves, collapse depressions, and large springs, but the karst-like features are produced by melting rather than dissolution, so the landscape is a *glacial pseudokarst.* Enclosed collapse depressions can be formed at the surface when patches of permafrost melt, the pitted karst-like landscape being termed *thermokarst*. This will become more prevalent with increased global warming.

From the standpoint of the World Heritage Convention, the paramount issue is not the precise designation of the landscape being considered -whether it is karst, fluviokarst, or pseudokarst- but its quality: whether or not it is a superlative natural landscape and the best of its kind. The convention is concerned above all with conserving landscapes that can be considered as possessing *outstanding universal value* to mankind in general: the best of the best. To achieve this, IUCN needs to be informed of what is available to ensure coverage and protection of the best that the planet has to offer. However, the nomination of suitable sites is not planned as a whole; it is an *ad hoc* process driven by individual sovereign states (States Parties). Consequently, the most outstanding sites are not necessarily the first to be brought to the attention of IUCN, and many superb karsts languish without recognition of their outstanding values and international significance. We are still discovering the world of karsts and caves and are sometimes waiting for individual states to make nominations, because it must come from the top with the highest-level political support and not from grass-root scientists, who can only do their best to press the case.

Karsts around the world also have unusual biological values, because of the interplay of surface and subsurface environments in the context of widely differing biogeographical zones (Culver and Pipan 2009). Although the focus of this chapter is on *geodiversity*, one must recognize that karsts often have outstanding *biodiversity* above and below the ground with markedly different species assemblages in different parts of the world. Endemicity and diversity are the rule, especially in isolated karsts in the tropics (Clements et al. 2006). The case of East Asia, for example, has been described by Vermeulen and Whitten (1999).

21.3 World Heritage Coverage of Karst

Under the World Heritage Convention, sovereign states notify UNESCO if they are considering making a nomination for specific areas within their territory. The properties so named are then placed on a Tentative List of potential World Heritage sites. Once on the Tentative List, they then become eligible for later nomination for World Heritage status. If after its nomination, a property is judged to have outstanding universal value, then it has the potential to achieve World Heritage status provided the other legal and administrative requirements are also met.

Karst properties, including caves, on the World Heritage List have been reviewed by Williams (2008), who identified 43 sites with internationally significant karst features (Fig. 21.1), of which 24 were considered to have karsts of outstanding universal value. Many of these sites were nominated for their biodiversity values rather than their karst, but as is the case in the Lorentz National Park of Indonesia, for example, it also happens to contain karst of international significance.

In addition to sites inscribed on the World Heritage List, there are also 29 properties on the Tentative List with important karst values. Tentative List properties can be seen on the World Heritage Center website http://whc.unesco.org/en/tentativelists/.

There are also numerous important karsts that do not feature on either the World Heritage or the Tentative Lists. For example, huge areas of karst occur in the Middle East, but are seldom included in nominations because the States Parties concerned have focused on cultural sites; the well-known Cockpit Country of Jamaica also does not feature, just to illustrate another case.

World Heritage is concerned with *outstanding universal value*, which means that the features of the site are so exceptional that they have a universal significance to all of mankind, far surpassing their significance to the host country alone. We are dealing

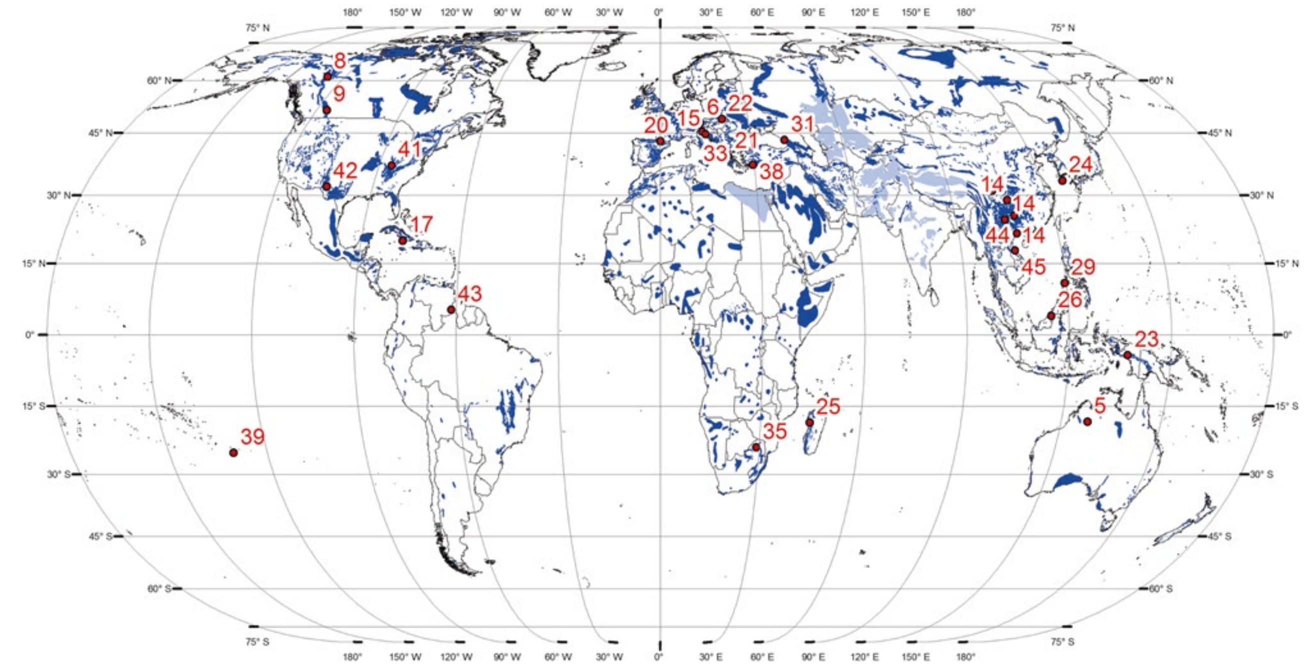

Fig. 21.1 The geographical distribution of World Heritage properties with outstanding karst values plotted on a world map depicting the distribution of carbonate rocks, the principal host rock for karst. *Solid color* indicates that carbonates are relatively continuous; *pale color* depicts areas in which carbonates are abundant but not continuous. Number *14* occurs 3 times and shows the location of sites in a serial property. For convenience four sites with fluviokarst in quartz rocks (numbered *5*, *12*, *21*, *43*) are also plotted on this map (Modified from Williams and Ford 2006)

Fig. 21.2 Karst towers in the Ha Long Bay World Heritage property, Vietnam. They have been flooded by a combination of tectonic subsidence and post-glacial sea-level rise. The partially drowned tower karst results in a landscape of hundreds of sheer-sided islands

with the premier rank of natural and cultural features on the planet such as the Grand Canyon of the USA, the Pyramids of Egypt, and the karst of the Bay of Halong in Vietnam (Fig 21.2). World Heritage sites are simply "the best of the best."

There is no reason why regions possessing sites of outstanding universal value should be spread evenly across the world. Consequently, there is no reason to expect a uniform coverage of World Heritage sites. This applies particularly to karst where potential distribution is directed by the outcrop of karst rocks. Nevertheless, there are large gaps in the geographical distribution of World Heritage karst sites that may not be because there is no excellent karst in the regions concerned. It may simply be because it has not been brought to the attention of IUCN. Some countries are more proactive than others in nominating their sites, often for altruistic reasons but sometimes because of the lure of the dollar: World Heritage status is an important, widely respected and marketable brand for international tourism.

As is evident from Fig. 21.1, there are relatively few World Heritage karst sites in the southern hemisphere, especially in South America, Africa, Australasia, and the South Pacific and also in parts of the northern hemisphere, notably Eurasia and the Middle East. But in addition to gaps in geographical coverage, there are also significant gaps in natural environmental distribution. Thus, for example, karst World Heritage sites are poorly represented in arid, semiarid, and periglacial environments.

There are numerous World Heritage properties with significant karst in humid temperate and tropical regions, and many of the existing properties include outstanding caves with rich and varied biota, superb speleothem decoration, and fossil-rich cave sediment accumulations, and the hydrogeological conditions under which they evolved encompasses a wide range of genetic conditions. Thus, there is little scope for justifying inscription of new sites in those environments. Nevertheless, the *ad hoc* process of nomination and inscription has led to a suboptimal representation of karst values.

This is regrettably obvious when considering the Dinaric Karst of Europe, the features and values of which are completely inadequately represented by three moderate-to-small sites: Plitvice Lakes (Croatia), Durmitor National Park (Montenegro), and Skocjan Caves (Slovenia). This is the region from which *karst* derives its name: the region in which the ground-breaking research of Jovan Cvijić (Cvijić 1893, 1901, 1918) was undertaken at the turn of the nineteenth and twentieth centuries and which gave rise to modern karst science. What areas of the Dinaric Alps would Cvijić have selected to represent the natural heritage of the "Classical Karst"?

Although karst is best developed on carbonate rocks, it is also found on other highly soluble lithologies, notably gypsum and rocksalt. These evaporite lithologies are highly soluble compared to limestone, and so significant landscapes in them occur in drier parts of the world. This is particularly the case for rocksalt, which yields distinctive and spectacular karst landscapes in the arid zone, notably in parts of Iran (Bosak et al. 1999; Waltham 2007) where salt "glaciers" or *namakiers* are the spectacular surface expression of salt domes as they are extruded by lithostatic pressure and flow across the surface. There are 130 salt domes of 1–10 km across in the Southern Zagros mountains and the "glaciers" extruded from them can extend to several kilometers. Karst features including caves are well developed where salt glacier flow is not too active. A carefully selected group of sites that together demonstrate the evolution of namakiers and their landforms could make an excellent World Heritage nomination.

Gypsum is less soluble than rocksalt and underlies many karst landscapes in areas that are relatively dry but not necessarily arid (Klimchouk et al. 1996). The second longest cave in the world, Optimistychna (214 km), in Ukraine, is developed in gypsum and a well-developed landscape of doline karst is found across the surface above it. Yet, despite the scientific and scenic importance of many of these sites, karsts on evaporite rocks are totally unrepresented on the World Heritage List.

Other important karsts contribute to outstanding cultural landscapes, which are the combined works of nature and man. The Hallstatt-Dachstein/Salzkammergut Cultural Landscape in Austria provides a good example already inscribed on the World Heritage List. Meriting further investigation in this context are Les Cevennes et les Grands Causses (France), the Burren (Ireland), and some sites in China that could be included in the second part of the South China Karst serial nomination. The Classical Karst (Slovenia) is of this type and could also contribute to a transnational serial karst nomination.

21.4 Filling the Gaps

From the above discussion, one can conclude that the highest priorities for completion of a comprehensive range of World Heritage karst sites (including caves) are: (a) to cover more adequately the karst type region of Europe, (b) to fill gaps in cold, arid, and tropical oceanic regions and (c) to nominate evaporite karsts.

Several properties on the Tentative List appear to have the potential to fill some of the gaps noted. These include: Band-E-Amir (Afghanistan), Canyon du Rio Peruaçu (Brazil), and Gewihaba (Botswana). The Lijiang River Scenic Zone (China) and Velebit Mountain (Croatia) might best be presented as parts of serial nominations within their respective regions (a serial nomination comprises a series of physically separate sites that are related through the unique contribution that each makes in conveying the outstanding universal value of the property as a whole; like chapters in a book that contribute essential parts of the full story).

21.5 Proposing an Area for World Heritage

Nominations of sites for inscription on the World Heritage List are made to UNESCO by the government of the country concerned (the State Party). This is because the highest level of guarantee and commitment is required for the safeguarding of World Heritage properties. The process is represented schematically in Fig. 21.3. So those who consider that they have identified an area of outstanding universal value worthy of World Heritage status must make a case through formal channels in their country and request their government to send a nomination proposal to UNESCO.

Sometimes the importance of a karst area is first recognized by scientists and cavers on an expedition in a foreign country, and the local people and authorities may be unaware of the considerable heritage value of the property within their territory. In cases where the features of an area are of outstanding importance to geoscience and are accessible and comprehensible by civil society (and not just of a specialized scientific value), then such sites could merit inclusion on the Tentative List of the country concerned, as a precursor to nomination and consideration for World Heritage. Alerting the government about the significance of such sites is best done using formal channels provided by government departments and scientific associations, such as the local academy of science or through the services of international scientific unions (such as the International Geological Union, the International Association of Geomorphologists, the International Association of Hydrogeologists, the International Union of Speleology, and the International Union of Biological Sciences). These are the best sources of objective authoritative scientific information on such sites, and these unions are well placed to judge impartially the importance of their scientific values compared to other properties on the World Heritage List and Tentative List. These unions have international standing and so

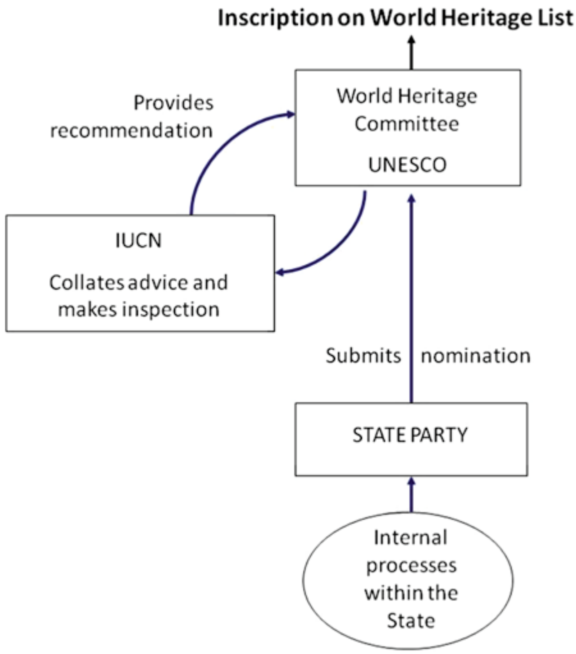

Fig. 21.3 Steps in the process of proposing and assessing a property for world heritage inscription

their opinions and support will be taken seriously by government authorities. They can also open formal channels of communication.

International scientific unions should therefore be encouraged to convey well-documented advice on potential Tentative List sites to the IUCN who, after evaluation of the case and the documentation, would convey the advice to the appropriate State Party for further consideration and possible implementation. International scientific unions would be expected to communicate fully with appropriate national scientific organizations prior to submitting their proposal to the IUCN.

21.6 Requirements for Natural World Heritage Inscription

Advice on what is required for a successful nomination is offered in the publication by Badman et al. (2008), "Natural World Heritage Nominations: A Resource Manual for Practitioners."

World Heritage sites must possess *outstanding universal value*, i.e., have a significance that extends far beyond the confines of the country in which the property is located, being of importance to the whole of mankind. The landscape features concerned must, by comparison with other similar sites, have significance at least equal to the world's best. For a potential World Heritage site to be deemed of outstanding universal value, it must meet UNESCO's conditions of *integrity*, which is a measure of the wholeness and intactness of the natural heritage and its attributes, and it must also have an adequate protection and management system to ensure its safeguarding, including formal legal protection.

World Heritage sites must be accessible to the public: accessible both in terms of physical access and in terms of mental accessibility. People should be able to view, comprehend, and appreciate the significance of the site, because successful long-term conservation and management depends upon public understanding of its outstanding universal value and upon on-going political support. Consequently, small areas of specialized features, the significance of which is really only understood by scientists or other specialists are not appropriate for World Heritage, even if they are extremely rare, fragile, and scientifically important. To use two analogies from physical and cultural landscapes, we want the whole mountain not just the rare plants or endangered animals that it contains; we want the whole cathedral not just its exquisite stained-glass windows. These special and perhaps unique phenomena may well be eminently worthy of conservation, of course, but their safeguarding is better achieved using another convention, such as Geoparks (UNESCO 2007) in the case of geological features. Recognition of geological and geomorphological heritage outside the World Heritage Convention is discussed by Dingwall et al. (2005). We should also remember that the national park system in many countries provides excellent management and robust legal protection; so, World Heritage status may bring little or no enhancement to protection, only prestige.

World Heritage is an important brand with considerable international prestige and importance for tourism. So, while we may have high altruistic ideals about conservation for posterity, the principal motivation of some proponents for trying to secure World Heritage status for a site is often economic and has little to do with conservation for the sake of our children, let alone our grandchildren. Nevertheless, we must be realistic, because in poorer countries, this may be the only way in which investment in the management of an area and the securing of its legal protection can be obtained. This is a kind of enlightened self-interest, and tourism can raise public awareness of the importance of a site and thus can contribute to its protection, provided tourist activity is well managed and carried out in a sustainable manner.

A property nominated for inclusion in the Natural World Heritage List will be considered to be of outstanding universal value if the World Heritage Committee finds that it meets one or more of the following criteria, provided it also meets the conditions of integrity (UNESCO 2008, Clauses 77 and 78):

(vii) To contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance
(viii) To be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms or significant geomorphic or physiographic features
(ix) To be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, freshwater, coastal, and marine ecosystems and communities of plants and animals
(x) To contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation

Many scientists recognize that in some karst areas biodiversity has been damaged through a process of progressive devegetation and soil erosion, termed "rocky desertification," which turns a region into an ecological wasteland (see case studies by Gams et al. 1993 and Yuan 1993). Thus, inscription will most likely only be considered in relation to criteria (vii) and (viii) above, although exceptionally criteria (ix) and (x) may apply, especially underground.

21.7 Conditions of Integrity

Paragraph 78 of the *"Operational Guidelines for the Implementation of the World Heritage Convention"* (2008) requires that for a property to be deemed of outstanding universal value it must meet the conditions of integrity and must have an adequate protection and management system to ensure its safeguarding.

Integrity is defined in Paragraph 88 as a measure of the wholeness and intactness of the natural heritage and its attributes. However, it is appreciated (Clause 90) by the World Heritage Committee that no area is totally pristine, that activities of traditional societies often occur in natural areas, and that these activities may be consistent with the outstanding universal value of the area where they are ecologically sustainable.

The *level of integrity* is also an important consideration, because World Heritage is concerned with best that planet Earth has to offer. Thus, inscribed properties are expected to meet the highest international standards.

An area nominated for Natural World Heritage may have many superb features and values, but are the conditions of integrity met? That judgment requires an assessment of the following:

(a) *The wholeness and quality of the natural heritage and its attributes*. In the nominated area, are the features above and below ground the best examples available? Does the range of features fully represent the karst of the region as a whole? Are the karst attributes so exceptional as to transcend national boundaries in their significance and be worthy of being designated as of outstanding universal value? Do they stand up readily to international comparison and could they be described as the "the best of the best"?
(b) *The intactness of the natural heritage and its attributes*. To what extent has the property suffered from the adverse effects of human development or neglect, and does the impact now render the property unable to meet the condition of integrity? Is there on-going environmental rehabilitation that will lead to effective repair of any damage? Does on-going human activity in the area or in the region around it threaten the long-term sustainability of the natural ecosystem?
(c) *The adequacy of the size of the property*. Is the size of the nominated area sufficient to ensure that on-going natural processes will continue uninterrupted, so that the region's significant features and values will be maintained for the foreseeable future? Is there a sufficient buffer zone that might absorb the impacts of human activities in the surrounding region?

(d) *The prospect of maintaining integrity into the future*. Is the World Heritage area optimally delimited for management? Are the boundaries appropriate for effective protection of the important karst features of the area: both surface and underground; both physical and biological? Is the area adequately protected by effective legislation?

The boundaries of nominated properties require very careful consideration. In any given country, sites may involve areas of different legal status – National Parks, Geoparks, MAB sites, etc. – and the already defined boundaries of these properties may be used as boundaries of core zones in areas nominated for World Heritage inscription. However, nature does not recognize administrative boundaries, and sometimes areas of equal quality to the proposed core zone extend beyond it. Where possible boundaries should follow natural watersheds (including groundwater divides), because that will facilitate catchment management, especially through the control of water quality in recharge zones and the maintenance of high-quality habitat for subterranean species. The largest area practicable should be demarcated to ensure living space for endangered species above and below ground. If necessary, legal boundaries should be adjusted to ensure high-level legal status and protection of the core World Heritage area. This will help obviate future problems and thus facilitate effective environmental management.

21.8 Management Requirements and Structure

This is an important issue for successful World Heritage nomination, because a property will only be inscribed on the World Heritage List if there is assurance that it can be safeguarded appropriately both by formal legislation and by adequate management. For a property to be deemed of outstanding universal value, it not only must meet UNESCO's conditions of integrity but also must have an adequate protection and management system to ensure its safeguarding (UNESCO 2008).

"The purpose of management of a World Heritage property is to ensure the protection of its 'outstanding universal value' for the benefit of the present generation, and its transmission unimpaired to future generations" (Thomas and Middleton 2003, p. 65). World Heritage status often brings considerable tourist pressure that may threaten the integrity of the site, but with good planning and appropriate practices, tourism in protected areas can be managed sustainably, as explained by Eagles et al. (2002).

21.9 Responsibility of the State Party

The inscription of a property on the World Heritage List implies that the State Party will carry the ultimate responsibility for management of the site to the highest level of international conservation practice. It also has responsibility for honoring and implementing any transboundary agreements.

Management of World Heritage properties requires clear unambiguous authority. This does not necessarily sit readily with established interests that may operate at national, provincial (state) and local levels and may involve planning and environmental agencies sometimes with competing and conflicting interests and sensitivities. Thus, when the World Heritage property is first nominated for inscription, the State Party should already have made it clear where final responsibilities will rest.

21.10 Management Structure

Within any given country, three interlinked levels of administration are usually required (Williams 2008):

Policy level: One overarching national authority ultimately responsible for all World Heritage properties with policy-making power that operates within the laws of the country and requires international standards to be applied even-handedly to all properties.

Planning level: a governing body charged with the implementation of national policies applying to all World Heritage sites in the country. It approves management plans for policy implementation at individual property level and delegates authority to individual site managers for their implementation. This body ensures that national policies and standards are applied to all World Heritage sites in the country, this being particularly important in the case of serial nomination sites in different provinces.

Management level: site managers of individual World Heritage properties are responsible for implementing management plans approved by the governing body and should have a role in the development of the plan. Effective implementation to appropriate standards requires strong leadership with clear authority and responsibility, as well as support from the governing body. Park management committees must include representatives of the local people who should also have a significant role in the development of the plan.

A review of options for effective management of protected areas, including assessing management effectiveness and guaranteeing protection, has been undertaken by Thomas and Middleton (2003) and Hockings et al. (2006). Specific guidelines for karst and cave protection are provided by Watson et al. (1997). Management planning starts with the present situation and asks: where are we now? It then proceeds to consider a vision for the area: where do we want to be? Management involves a sequential process of planning, implementation, and outcome, at each step there being a process of evaluation. The management cycle is perpetually implemented with a view always to making improvements and getting closer to an ideal outcome. Figure 21.4 illustrates this process.

A management plan should consider such topics as: documentation of the present situation concerning principal values for conservation, land use, visitors and legislation; documentation of the scientific and aesthetic values of the World Heritage area, threats to them and actions necessary to preserve them; strategic directions for the next 10 or 20 years; monitoring reserve values and the efficacy

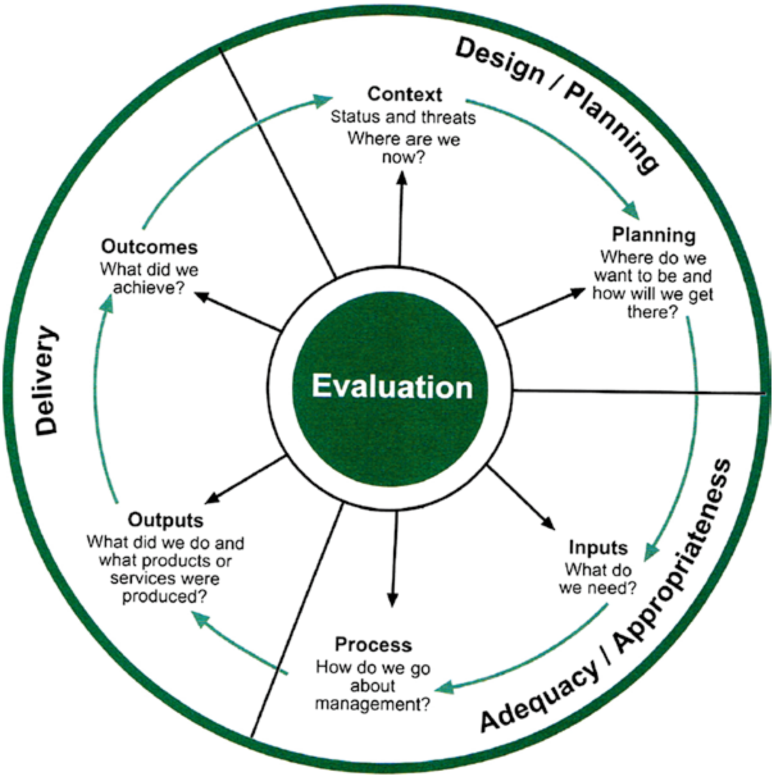

Fig. 21.4 The management cycle proposed by the World Commission on Protected Areas. This illustrates a framework for assessing management effectiveness of protected areas (From Hockings et al. 2006). The cycle starts by reviewing the present context (where are we now?) and then considers management objectives (where do we want to be? and how are we going to get there?). The inputs refer to what is needed in terms of staff, assets, and budget; and the management process asks: how do we go about achieving our aims? The delivery stage identifies outputs (what did we do or provide?) and then reviews outcomes (what did we achieve? For example, were the outstanding universal values of the site protected?)

of management practices; visitor services, facilities, and visitor management; communicating reserve values via interpretation and education; new proposals and their impact assessment; staff management and development; and measuring progress towards attaining goals.

21.11 Management Issues in Karst

The management of karst in general is discussed in such publications as Watson et al. (1997), Vermeulen and Whitten (1999), and Ford and Williams (2007). The focus here is narrower: on karst in and around World Heritage properties. Issues in the maintenance of integrity and adequate management of values in World Heritage karst areas are discussed in the context of the Asia-Pacific region in Wong et al. (2001).

When compared to other landscape styles and ecosystems, Williams (2008) pointed out that karst has a number of unusual characteristics that must be taken into account if management is to be appropriate and effective:

1. Karst is unusually complex because it comprises both surface and subterranean features and values and integrates surface and subterranean processes, both biological and physical. Karst also has natural archives of its own history, because paleokarst features and cave deposits record stages in the evolution of the karst and of the environment and ecosystems around it.
2. Karst ecosystems are fragile because environmental conditions can be extreme. They are usually calcareous (or highly saline in evaporite rocks), periodically arid at the surface (because rainwater sinks quickly underground) and dark and remote from food sources underground while subject to periodic flooding. The subterranean ecosystem is particularly fragile being dependent mainly on energy flows transmitted by water, the quality of which is critically important for survival.
3. Karst integrity depends above all on hydrological conditions, because solar energy input is moderated mainly through the hydrological cycle which powers the karst system (by corroding rock, transporting organic detritus underground, nutrients to plants, etc.) and integrates its various parts.
4. Most water passing through karst is introduced by sinking streams. Many of these are derived from impervious catchments that lie beyond the boundary of the karst area (these are termed *allogenic* streams, as opposed to *autogenic* streams that are derived entirely from karst rocks). Consequently, conditions upstream beyond the karst boundary can have a critical influence on the integrity of the karst. Recharge zones are of critical importance and need to be identified and managed. Fragile subterranean species are particularly at risk, and serious damage can occur unwittingly because the major effects are underground and out of sight.
5. Karst drainage areas are not easily delimited. The drainage basins and routes followed by karst water are not obvious, because drainage paths are largely subterranean. Large springs are a feature of karst, but groundwater basins do not necessarily follow surface divides, and headwaters may be derived from sinking surface streams located many kilometers away.

Runoff from upstream areas: It is not an overstatement to assert that water quality management of allogenic streams draining into karst is *the* key issue of environmental management in any karst area. It is critically important in Natural World Heritage properties because so much is at stake. The deleterious effects of water pollution, particularly underground, can be widespread and insidious. Its effects can also be long lived and difficult to remove, because the residence time of polluted water underground can be long and storage can occur in inaccessible places, not only below the water table (in the *phreatic zone*), but also just below the surface (in the *epikarst*).

The transport of water-borne pollutants by an allogenic river sinking at Skocjan Cave World Heritage property in Slovenia was once a very serious problem but has been largely resolved. It is a potential problem requiring careful management at Libo World Heritage property in the South China Karst because of agricultural and urban land upstream. Only community education and involvement, agreement to work together, and strict enforcement of standards will ensure the problem is kept under control. Contaminated runoff from the land is affecting values in the Bay of Halong World Heritage site in Vietnam and shipping lanes through the Bay pose a continuing threat.

The difficulties confronting park managers in such areas are not to be underestimated, because pollution frequently comes from areas over which they have no direct jurisdiction. In terrestrial sites, the best way to deal with the problem is to ensure in the first place that the nominated area boundary is manageable by following the natural watershed. This leaves catchment supervision in the hands of park management. However, sometimes, that is impractical because allogenic catchments can be very large and may contain agricultural, urban, and industrial centers. In such cases, effective partnerships have to be established with authorities responsible for management of the upstream area with a view to reaching agreement on a total catchment plan of the highest possible standard, effectively enforced and monitored. The maintenance of high water quality is a common good that is in everyone's interests. This also applies to sea waters, as in the Bay of Halong.

To reduce to acceptable levels the danger that uncontrolled allogenic runoff poses to the ecosystems of World Heritage sites, it is absolutely essential to enforce strict and effective water quality management in the catchments of streams and rivers flowing into inscribed areas. No untreated waste water from cities, towns, and industries must be permitted to enter waterways that ultimately drain into World Heritage properties. High water quality standards must be set and regular monitoring must be undertaken, both of dissolved materials and aquatic indicator species of water quality.

Monitoring stations should be established at input and output points in the karst system, i.e., where rivers flow into inscribed areas and at springs, because spring water integrates the effect of all contributing water sources in the catchment. Monitoring plans should be public documents and results of monitoring should be published annually.

A key tool for the management of karst areas: Because of the paramount importance of catchment management in karst areas, the most important tool for the manager is a hydrogeological map. It should cover the World Heritage property and any surrounding areas that impinge upon it, especially allogenic catchments draining to the karst. An excellent example of this is provided by the hydrogeological map of the Mammoth Cave World Heritage area in the USA. It maps all sinking streams and springs and shows proven paths (by water tracing and cave survey) followed by underground water through the National Park. Cave plans are superimposed on the map. Thus, if there is an accidental spillage of a pollutant inside or outside of the park, then managers can see where the pollution is likely to go and plan appropriate remedial action. Every World Heritage property with karst of outstanding universal value should have a hydrogeological map of this kind.

Restoration of Impoverished Ecosystems: Another important issue that arises in many karst sites is environmental rehabilitation, particularly restoration of natural vegetation and improvement of faunal habitat. Improvements of this sort also restore natural karst process conditions. Problems of biological restoration are not a major issue when inscription is on the basis of World Heritage criteria (ix) and (x), which are concerned with biodiversity, but may arise when inscription is on the basis of criteria (vii) and (viii), which deal mainly with geodiversity (UNESCO 2008), because outstanding physical landscapes may have suffered considerable human impacts on their ecosystems with the result that environmental rehabilitation may have become a high priority of management.

In the Dinaric Karst and the South China Karst, the world's two most important karst type areas, there have been thousands of years of human occupation. As population pressure has increased, demand for natural resources has exceeded the capacity of nature to renew itself, and so natural plant and animal systems have become progressively degraded. Nevertheless, World Heritage sites may be nominated for their geodiversity values, even when their biodiversity is damaged, provided the impact on vegetation is not too severe and there is real prospect of significant environmental restoration. Land should be retired from agriculture, and the recovery of natural vegetation should be encouraged. The aim is to restore the core zone of the World Heritage area to as natural a condition as possible: to restore the damage inflicted in the past for the benefit of future generations.

In extreme cases, human impact has led to an induced ecological desert, the process being called *rocky desertification*. Thousands of square kilometers are affected in this way in both the Dinaric Karst and the karst of Southern China (Gams et al. 1993; Yuan 1993). Impact of the severity that leads to advanced rocky desertification renders it impossible to find large areas with recoverable ecosystems, and the karst process system is severely damaged. Consequently, the best that can be done is to save what remains and actively encourage environmental rehabilitation.

Occasionally, rocky desertification has occurred naturally with progressive biological adjustment as climatic zones shifted over geological time. Thus, karst landscapes in the arid subtropics often show the legacy of development under more humid conditions in the geological past. These are important sites, because they contain a record of major stages in Earth's history and may provide refugia of ancient endemic species, especially in the groundwater system.

21.12 Management of Caves

21.12.1 Tourist Caves

Cave management within World Heritage locations must be to international standards and should be a model for commercial tourist caves elsewhere. Special skill is required to develop a tourist cave to the standards worthy of a World Heritage location.

A balance is required between the engineering required to facilitate access and the minimization of engineering for the sake of access. In a World Heritage site, this balance must err on the site of conservation: minimization of impact on natural conditions must take precedence over engineering for mass public access. Further, to maintain a cave in excellent condition, management is required not just of the cave but also of the area above and around it.

The main environmental objectives of cave management should be to keep temperature, humidity, and atmospheric carbon dioxide (CO_2) conditions within the natural range of variation, to minimize light available for photosynthesis, and to maintain water quality and quantity. This will safeguard the subterranean ecosystem. Natural vegetation conditions must be maintained directly above and around the cave to protect the quality of infiltrating water and the epikarst habitat (i.e., no buildings or car parks should be located there). Tourist cave lighting sources should be high efficiency lamps to minimize heat input into the cave atmosphere and to minimize light wavelengths suitable for photosynthesis. The duration and spectral quality of lighting should be such as to restrict the development of plant and algal growth (*lampenflora*) around light sources. A green halo around cave lights is a clear indicator of poor environmental management. In a World Heritage site, it is more appropriate to reveal natural colors than to impose artificial tints through colored lights.

Tourist caves are particularly susceptible to damage both during development, when paths and lighting are installed, and during tourist operation. Decisions made during the development of the cave and during its operation for tourism should always try to ensure the maintenance of natural hydrological and ecological processes and the preservation of cave values and natural resources. If significant variation to measured baseline conditions occurs after tourist visitation commences, then maintenance of World Heritage values must take precedence over tourism, with tourist traffic being modified to reduce human impact to acceptable minimal and sustainable levels, even to the extent of closing the cave. A precedent for this is found at Lascaux World Heritage site in France.

Tourist routes through the cave should be designed to have minimum impact on delicate cave formations (speleothems) and on biological habitats within the cave. Cave sediment floors should be protected by raised pathways to preserve their habitat value, fossil record, and sediment history. Cave entrances may be important archeological sites and so require special protection. Tourist guides should be aware of these special features, should help protect them, and should explain to visitors the significant features of the cave that led to its inscription on the World Heritage List.

Materials used for tourist infrastructure (paths, etc.) should be nontoxic to biota and largely removable, so that, if necessary, the cave can be returned almost unspoiled to nature.

There is considerable international experience on tourist cave development, cave conservation, management, ethics, and restoration of damage. A rich source of ideas on these topics is available in Hildreth-Werker and Werker (2006).

21.12.2 Wild Caves

Many natural (or "wild") caves are found in World Heritage properties with abundant karst. Park managers need to recognize that even the most experienced, careful, and environmentally conscious cavers cause inadvertent damage underground, especially in caves with abundant speleothem formations and fossil deposits. Thus, cave exploration needs careful management. The most important principle here is to insist that an experienced speleologist leads the group and that the party size is small, usually not more than six, but this depends on the nature and size of the cave. Only electric lights should be used and all rubbish must be carried out.

There is a need to manage access to wild caves to ensure that at least 50% of the known caves or parts of caves within a World Heritage property is protected from random recreational access – including recreational research. Access to special sites should only be for research that cannot be conducted elsewhere, and the research should explicitly contribute to the management of the protected area.

Results of cave exploration and survey are important sources of information for park managers as they help to complete part of the hydrogeological picture and provide data on natural resources within the area; thus, careful exploration by experienced cavers should be encouraged, provided impact is minimal and results of exploration are reported back to management.

Scientific sampling within the cave should be by permit only, having been well justified and kept to a minimum. Speleothems may take tens to hundreds of thousands of years to grow but can be removed in minutes. The same approach should be taken to excavating archeological and fossil deposits that are frequently found near cave entrances. They should only be excavated by experts and for good reason; only part of the deposit should be removed and taken to a mutually agreed safe repository, and results of the research should be reported back to park management. Ecological survey and sampling requires a similar approach and conditions.

21.12.3 Monitoring

To be reassured that management activities have been effective, there needs to be a method of evaluating progress. Monitoring measures change over time, and it is required to provide objective evidence of the effectiveness of the implementation of management practices. It is an essential management tool and is designed to provide reliable information on the current situation that can be compared to "baseline" conditions, i.e., to the situation that existed before management commenced. By monitoring before, during, and after developments, changes can be recorded, and there is objective evidence of impacts and improvements.

Sensitive sites and sensitive indicators should be chosen for monitoring. In karst, for example, stream-sinks and springs (input and output sites) should be used as water quality monitoring stations. Apart from a range of chemical and physical measures (e.g., dissolved oxygen, temperature, suspended solids), presence and abundance of sensitive species with a low tolerance to pollution should be monitored. For instance, at the surface and in caves, endemic snails, arthropods, and plants are examples of sensitive species that can be monitored. Invasive species should also be noted.

Water quality monitoring should cover a range of extreme conditions from drought to flood. Baseline climatological and ecological conditions should be established in the cave *before* development for tourism starts, a year being required to obtain reliable representative records. Climate and atmospheric measurement in tourist caves requires a professional weather station approach. Monitoring stations should be set up at sensitive sites, and climatological and ecological surveys should be conducted regularly with results published annually. Automatic monitoring should be undertaken where possible. The objective of management should be to keep temperature, humidity, and atmospheric CO_2 conditions as close to the natural baseline values as possible, while at the same time keeping the cave free from invasive species, vandalism, rubbish, and wear and tear.

Photo monitoring should be used extensively and regularly at established key sites, especially along tourist routes (above and below ground), because it is an effective way of showing up wear and tear from tourist pressure.

Methods and measures used in monitoring should be readily understood and applied by trained staff. Results of monitoring should be published annually. In a few years' time, we will want to know if the World Heritage site is in at least as good a condition as when it was first inscribed. Objective monitoring will provide the evidence. Although tourist pressure creates the potential for environmental impact, it is the park management that can prevent or, at least, limit serious impact – or permit it to occur.

21.13 Conclusions

Managing a World Heritage site is a responsibility of global significance undertaken in trust for present and future generations. Therefore, it must be carried out to the highest international standards and with the cooperation and support of the local people.

The State Party is ultimately responsible to UNESCO for the success or failure of management of World Heritage properties within its borders. Thus, to assist managers and avoid competing or conflicting interests, legal authority and lines of responsibility must be clearly established. To ensure grass root support, local people must have a say in park planning and management and should share in the benefits of having a World Heritage property in their neighborhood.

The boundaries of Natural World Heritage properties should capture all the outstanding universal values of the area that they represent. The boundaries should also be logical, manageable and agreed to, and respected by the local community. Thus, for example, if a property has been nominated for its natural beauty (criterion vii), then it is essential to maintain all areas essential for maintaining the aesthetics of the area.

Water quality management of allogenic streams draining into karst is *the* key issue of environmental management in any karst area. Hence, protected area boundaries in karst areas should follow natural watersheds wherever possible. In many cases, allogenic stream catchments are required to be included in the managed zone to ensure that karst values are safeguarded. If this is not achievable, because of the large size of the allogenic basin, then an effective cooperative agreement for total catchment management must be achieved between park management and the wider community that will protect the World Heritage site from water-borne pollution. This is critical.

All decisions within Natural World Heritage properties must be compatible with conservation, its value to posterity being more important than short-term economic gain. Thus, most economic infrastructure should be located outside the World Heritage property rather than inside it, exceptions being those related to reasonable, low-impact tourist access, especially in tourist caves.

Tourist and development pressure tends to increase when a property is inscribed on the World Heritage List, and if not managed and adequately controlled, it may threaten the very values that led to the inscription of the property in the first place. The Bay of Halong is a case in point: an outstanding karst World Heritage property that is being damaged by pressures stemming from activities beyond the control of park management.

Objective monitoring at key sites should be undertaken as frequently as necessary to assess the effectiveness of policies and management. Results of monitoring should be publicly available and published regularly. Publication should be by the State Party or its delegated authority. External reviews should be conducted periodically under the auspices of the IUCN to evaluate the state of conservation of the World Heritage property and the effectiveness of management. The overall objective will be to ensure that the property is in at least as good a condition as when it was first inscribed in the World Heritage List.

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