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Karst: the foundation for concepts in hydrogeology

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Abstract Few citizens of the world would have trouble understanding the terms springs, ground water, geology, or hydrology. Newer water terms that are more familiar include bottled water, spring water, sparkling water, or mineral water, all of which now come in vessels of different shapes, sizes, colors and labels. It is interesting to note that a glass of cold, refreshing tap water will cost about 1 cent, whereas the same glass of sparkling cold bottled water will cost 50 or more times that price, and is even more than a gallon of gasoline. On the other hand, the term karst is not as well known, and it is the most pertinent objective of this congress to bring about a better knowledge and understanding of karst. 'The past is a key to the future.' A wise statement; however, serving as an editor of the international journal of *Environmental Geology* gives frequent reminders that some younger and perhaps a few older scientists, particularly those in the consulting area, are not well aware of the stepping stones inherited from the past. This is evidenced by the use of phrases such as, 'development of a new concept, method, or solution' which was published many years before. A suggestion: 'do the homework' and adequately reference research while preparing project proposals, and acknowledge primary contributors on the subject. Sometimes a list of carefully selected references is more important to a fellow scientist than the paper itself. Historically, the use of karst spring waters dates back to the earliest civilizations. Cuneiform tablets provided the first written records of hydrological research that describes an expedition in 852 BC by the Assyrian King Salmanassar III to the headwaters of the Tigris. The source of the Tigris is a karst spring. Inscriptions near the entrance to the cave from which the spring discharges state that it is the source of water to the Tigris and immortalizes Salmanassar III. It is the first known reference to the formation of stalagmites. Other examples from the Bible include the principal sources of water for the ancient city of Palmyra in Syria where a spring called Efca discharges water that is warm (33°C), sulphurus, and radioactive. It was believed by some to have curative powers. In Biblical times, karst-caves or systems provided water in Sinai and at Shobek, Kirhareshet, Lachish, Jerusalem, Hazor, and Gezer. In China, a book, *Annotation on Water Scripture*, by Li Daoyuan, published during the second century AD describes hot springs, and the water from Lisban Spring, in China, is recorded in 1134 BC as being used for medical purposes by many monarchies. In Europe, one of the most famous springs is Bath in England. It is the site of an early spa during Roman

times, where soldiers enthusiastically visited these hot springs for rest and relaxation. This source became contaminated and represents one of the earliest recorded problems with pollution of spring waters. Hot springs were famous throughout the Roman Empire, and many remain today as health resorts. In 2004, Dorothy Crouch, in her books, *Water Management in Ancient Greek Cities* (1993) and *Geology and Settlement Greco-Roman Pattern* presents two of the most comprehensive texts on interrelationships between water supplies and development of civilization in karst. The books illustrate that many of the basic hydrogeologic concepts of karst were developed by early philosophers of ancient Greece and were used in the sighting, planning, and construction of Syracuse Corinth, Delphi, Miletus, Ephesus, plus five other sites that were studied and compared representing 1400 years of urbanization by the Greeks and Romans.

Keywords Karst spring waters · Karst · Hydrogeology

Introduction

Karst areas and thus springs from limestone, dolomite, marble, gypsum, and salt have in the past been sites of earliest settlements and religious shrines. They have been sources of water supplies, as well as mysterious natural phenomena subject to man's great curiosity and wonder. Karst areas have abundant resources, including water supplies, rock quarries, minerals, oil, and natural gas. Many karst terrains make beautiful housing sites and there are major cities throughout the world underlain by karst; for example, St. Louis, Missouri; Nashville, Tennessee; and Chicago, Illinois. There are also negative aspects to the development in karst including insufficient and easily contaminated water supplies, poor surface-water drainage, and catastrophic collapse. There are ways, however, to live safely, comfortably, and productively in karst areas.

Karst areas produce a diverse topographic expression by weathering under varied climatic conditions. Carbonate terrains in some areas are underlain by broad, rolling plains, whereas in others they are characterized by steep bluffs, canyons, sinks, and valleys. Owing to the variability of the solubility of limestone under different climatic and geologic conditions, man's inhabitation and development of limestone areas has often been difficult. In some areas the limestone is covered by fertile soils; in others soils are missing. For example, areas underlain by relatively pure chalk may be barren like the famous white desert near Bahariya Oasis in Egypt that is in contrast to a large area underlain by limestone and covered by a very productive, rich soil in the Midwest of the USA, an area that is literally 'the breadbasket of a nation.'

Carbonate rocks in some areas are a source of abundant water supplies, like the largest artesian flowing well in the world from the Edwards Aquifer near San Antonio, Texas, or the many wells that supply water from the Floridian Aquifer for commercial, industrial, mining, and public water supplies in central Florida. Even though there are many blessings associated with carbonate terrains, there are also problems in some areas. Because of this complexity, the evolution of concepts related to the movement and occurrence of ground water in karst, methods of exploration and development of water, safe engineering practices in construction of all kinds, and adequate environmental safety precautions cannot be based one set of uniform rules. Each karst area requires detailed research and analysis.

The interesting history of karst research

Today, karst regions of the world are a continuing source of interest to scientists of many disciplines other than geology, hydrology, and speleology. In karst there are also problems that require the latest techniques from biology, botany, geochemistry, and radiology to list a few. Solving karst problems requires a multidiscipline approach. At a recent Karst Water Institute conference in Denver on the subject of micro-biological aspects of karst is a good example. Karst studies, however, have a much larger history than might be expected.

During Greek times, underground rivers and springs were a part of Greek mythology and the subject of much discussion by Greek and Roman philosophers. The earliest hydrologic concepts of the hydrologic cycle, water source, occurrence, and quality were based on karst settings. Some examples of early references to karst, karst springs, and geomorphic features include:

- Cuneiform tablets provide the first records of karst hydrological research as known and described during an expedition in 852 BC by the Assyrian King Salmanassar III to the headwaters of the Tigris. The source of the Tigris is a karst spring. Inscriptions on the cave state that the source of water to the Tigris immortalizes Salmanassar III.
- The Greek geographer Skilax of Karyanda (500 BC) reported on the karst springs of Timavo.
- The early Greek philosophers theorized on the movement of ground water from springs as related to the water cycle—some examples include Empedocles (490–430 BC) and Aristotle (384–322 BC).

- Eratosthenes (276–194 BC, as reported by Strabo in Book 8) described the hydrologic connection between Katavothra (Ponors) in Pheneos polje to Ladon Spring in the Peloponnesus of Greece—spring rains and discharge.
- Poseidonios (135–50 BC) reported on the springs of Timavo and describes the River Timavius where it disappears in a cave underground.
- Strabo (60 BC–28 AD) devoted his eighth book of 17 volumes, 'Geographica' to the *Karst Phenomena of the Poljes* (underground streams), as well as other karst phenomena.
- Lucius Annaeus Seneca (4 BC–65 AD) was perhaps the most important Roman philosopher and writer regarding karst springs; his book III *Naturales Questiones* describes solution processes, the development of large underground caves, and explains the disappearance and reappearance of streams and springs.
- *An Encyclopedia of Knowledge* was compiled around 970 AD by members of the Arabian Order of the 'Brothers of Purity'. In these documents Arabian Monks wrote about caves inside of mountains and springs discharging the water stored in caves. There were many new ideas and concepts relating to hydrology and geology developing in the Arabian culture at this time; unfortunately however, these materials are hard to acquire. One example is the writings of the famous Arabian Abdul Hasan Ali Masudi.
- Xu Xiake (1586–1641 AD—Ming Dynasty) made extensive field trips into South China karst—the Guilin area—to study the geomorphology of caves. He described tropical karst features, including fenglin, or peak forest karsts and springs. He is known as 'the father of karst studies in China.'
- Karst research in the late seventeenth and early eighteenth century in Europe began with observation and description, for example, Melchior Goldast from Germany who described the Blautopf, one of Germany's largest karst springs.
- In the mid-1700s Hackuet in four volumes described karst in Europe. Perhaps he should hold the title, 'Father of Karst Hydrogeology.'
- 1856, the Frenchman Abby Paramelle was the first to attempt to study the extent of underground karstification and identify the path of ground-water movement in karst.
- 1872, F. Pfaff explained limestone solution. He determined that a limestone slab exposed to weather erodes 0.177 m per year or 1 m in 72,000 years. This value remains valid today.
- 1873, E. Tietze, studying karst in the vicinity of Triest, was the first to reference a 'karst formation'; and in 1876, K. Wessley was the first to mention the new meaning of the word 'karst' for a rocky, barren area that was typical near the city of Triest.
- The large greatly variable flow of the spring of Vancluse, France that lends its name to this type of spring has been measured at regular periods since 1854.

By the twentieth century, much qualitative work had been accomplished, and the early beginning of quantitative methods for determining ground-water velocity, and permeability was witnessed. However, these tools required better definition of the physical character and thickness of karst rocks to make these quantitative studies more reliable. During the period beginning in the 1940s with the need for water during the war years, one of the most difficult problems facing the development and management of ground water was application of quantitative methods to karst rocks.

Tracing studies in karst

In addition to meeting demands for more water of acceptable quantity, it became necessary for protection against pollutions to trace the movement of water from recharge to storage to discharge in karst systems. Tracing ground-water movement in karst required some innovative thinking. Petar Milanović describes the use of 'geobombs' as a unique approach. A couple of early examples include the following.

In 1878, the first large, quantitative karst-water tracing experiments by injecting sodium fluorescein and potassium chloride were performed into sinkholes of the Danube. These were followed by studies in November 1908 while investigating sinkholes in the Danube near Fridingen, at which time large amounts of sodium chloride were injected.

An early basis for quantitative ground-water research became available in 1935, when Theis published his equation describing non-steady ground-water flow. In 1935, Stringfield interpreted regional ground-water flow with a potentiometric map of the Floridian aquifer. In 1959, Cooper reported on the dynamic balance between freshwater and salt water in the Biscayne aquifer in Florida, and applied pumping test methods using the Theis equation to a large-scale pumping test on the Floridian aquifer, a very important karst system, at Fernandina, Florida. Following these early successful quantitative approaches to younger cocina limestone beds (Miocene-Eocene), the same methods were applied successfully in the Huntsville, Alabama area in 1960 with major pumping tests on hard dense, karstified limestones of Mississippian Age. These older limestones were faulted, folded, and extensively karstified. Pumping discharge rates were as much as 10,000 gpm and impacted water levels and spring flows over a large area monitored at over 100 points. Measurements were made at springs, streams, and wells. Results were used to develop and expand the municipal water supply at Huntsville.

New techniques

Many new techniques and equipment have evolved during the later part of the twentieth century that can be used to describe more precisely the physical character of the karst geologic systems so that quantitative methods can be more accurately applied to soluble and fractured rocks. Some of the most important of these include sequential satellite imagery, a sophisticated series of air photography, air and ground remote sensing (resistivity, sonic, radar); far more accurate and detailed chemical laboratory analysis; and the availability of computers to record, store, evaluate, and recover data for tabular and graphic portrayal. This more detailed knowledge of the geologic system provides more meaningful results from pumping tests on karst aquifers.

Over the past 20 years there has been an amazing diversity of multidisciplined scientific talent that has become aware of the complex problems in karst settings over the world. During the later part of the twentieth century, engineers, hydrologists, speleologists, chemists, geologists, biologists, botanists, and mathematicians began to tackle these problems. Karst panels—commissions and institutes—have been organized and there have been at least 250 special congresses, meetings and symposia held, more than 60 book-length publications written, and hundreds of technical articles published. One of the biggest problems today is maintaining a knowledge and good reference source to all karst research. An *Annotated Bibliography of Carbonate Rocks* of the Karst Commission of IAH was one attempt to keep current on what was being done in karst areas, but was dropped after four issues of a bulletin. It is a task that must be done, and is presently being attempted at several Karst Institutes and perhaps on a lesser scale at many karst research centers at universities.

Good examples of current karst research are contained in *Acta Carsological* of the Academy of Science of Slovenia; another international journal with regular papers on karst is the journal of *Environmental Geology*, published by Springer (see volume 47, May 2005 for an article on karst database development). Three new, very comprehensive, extremely well prepared illustrated books include:

1. *Encyclopedia of Caves* by Culver and White. Elsevier.
2. *Encyclopedia of Caves and Karst Science* (2004) by Gunn J. Taylor and Francis, New York.
3. *Las Aquas Minerales en Espaňa* (2001) by the Institute Geology and Minerals of Spain. History, hydrogeology, and utilization. 454 pp with hundreds of analyses, photographs, etc.

Regional symposia, many resulting in published monographs, have been organized worldwide over the past 20 years by IAH, IASH, FAO, and UNESCO within the International Hydrologic Decade (IHD) and International Hydrologic Programme (IHP), and by university groups. For example, the IHD included a Commission for the study of carbonate rocks in Mediterranean countries, and since 1970 a permanent Commission for karst hydrogeology exists within IAH. The International Association of Hydrogeologists (IAH) promotes cooperation between scientists who are working on hydrogeologic problems, and is affiliated with the International Union of Geological Sciences (IUGS), to name a few. This problem of communication is becoming more complex because other sciences, such as chemistry, physics, biology, botany, and speleology, are becoming involved.

This congress

The Yugoslavian scientist Jovan Cvijić became interested in karst and collected much valuable information for his doctoral dissertation 'Das Karstphanomen' (1883). The dissertation was followed in 1900 by the book *Karst Poljes of Western Bosnia and Herzegoviana* and in 1926, *Geomorphology*. In his volume, *Geomorphology*, Cvijić studied water tables, karst springs, seepages, and estavellas and separated karst into three morphologic types of limestone terrains: Holokarst, Merokarst, and Transition karst.

At the beginning of the twentieth century, Cvijić's research provided systematic treatment of karrens, dolines, karst river, karst valleys, poljes, and other types of karst phenomena associated with the Adriatic coast area and the Dalmatians. Cvijić also provided definitions and terminology. He was the greatest contributor at the beginning of the twentieth century, providing over 60 literature items on the subject. This congress honors his name and contributions, and provides further emphasis to the important role karst plays in modern society. All present are urged to make the maximum use of this opportunity.