

A Disturbance Index for Karst Environments

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ABSTRACT / Karst environments, unique from other environments, require their own disturbance index. Karst resources are increasingly disturbed by a variety of pro-

cesses related to social, physical, and economic factors. Recent studies have begun to qualify and quantify these disturbances, yet their focus has been limited to one or two factors such as biotic, geomorphic, or economic impacts. A more holistic approach, addressing economic, scientific, and cultural factors, is needed, to effectively assess the threats to karst areas. Currently, there is no efficient method to measure, compare, and contrast the disturbance of karst environments. We propose a hierarchical and standardized environmental disturbance index as a tool to measure regional impacts and highlight the areas of the karst system that require more protection or study. Addressed categories of disturbance include cultural, biotic, atmospheric, hydrological, and geomorphologic impacts.

The need to identify and protect threatened cave and karst systems is gaining increased attention. Karst is a landscape typified by soluble rocks, such as limestone, gypsum, and dolomite, where solutional processes are dominant, forming sinkholes, depressions, caves, and enhancing underground drainage. Caves and karst resources are non-renewable (Gunn and others 2000) and are increasingly being disturbed by a variety of physical, social, and economic activities. Notable projects that have recently begun to describe and quantify disturbances include the now defunct Karst Waters Institute Top 10 list of Disturbed Karst Ecosystems (Myroie and Tronvig 1998), the International Union for the Conservation of Nature and Natural Resources' Guidelines for Cave and Karst Protection (Watson and others 1997), and a series of regional assessments of karst throughout the world (Day and Ulrich 2001; Kueny and Day 2002, Kueny and Day 1998; Day 1996; Ulrich and others 2001). While many articles address the conservation and protection of caves and karst, their focus has generally applied to one particular factor such as a cave's biotic, geomorphic, or economic value. A more holistic approach is needed, however, to effectively assess the threats to karst areas. This article outlines an environmental in-

dex to measure risk and serve as a standard tool for karst scientists to measure, compare, and contrast the degree of disturbance in their particular region. Its use could help organizations that have investigated protection of a karst region by evaluating the region's disturbance level and identifying areas of the karst system that require more protection or more study. Karst environments differ from other environments and require their own disturbance index. Their uniqueness comes from the solutional processes acting on carbonate and other rocks, generating unusual surface and subsurface landforms. Pseudokarst is considered to be voids in basalt, ice, soil, and sandstone (Gillieson 1996) and will not be considered in this article. Sinkholes and caves generate rapid surface-aquifer transmission of water, sediments, and pollutants. Caves biota is highly adapted and fragile unlike any other. Caves also store and protect sediments and precipitates, allowing scientists new opportunities for research into past climates and archaeology (Watson and others 1997). However, the processes that disturb the karst environments are not unique, such as agricultural practices, deforestation, quarrying, and pollution.

The assessment of karst disturbance can be very difficult and subjective. A complicating factor is the natural variation between and within karst systems, such as wet and dry seasons, differing cave and formation growth rates, and changing diversity of resident species over time and space. Although an index to assess disturbance requires some interpretation of the state of the karst environment, most subjectivity can be

KEY WORDS: Caves; Karst; Index; Human impact; Environmental indicators

Published online June 9, 2005.

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removed through the measurement of a common set of variables and use of a predefined scoring system. This model also improves the ability to directly compare the degree of disturbance in different regions.

Methods

Environmental Indices

This article takes a holistic, ecosystem approach to karst systems, and recognizes that the vegetation, soil, and biota both influence and are influenced by karst processes. Hence, disturbance of any component of the ecosystem is considered part of the impact of karst systems. This is done through the development of a hierarchical index consisting of broad categories divided into narrow attributes.

To date, no study has produced a comprehensive, objective method for measuring karst disturbance. The Karst Waters Institute's top ten list of endangered karst ecosystems (Myroie and Tronvig 1998) created a list of criteria for measuring the disturbance of karst, which allows comparison among locales but little information was provided on how the disturbance was measured, thus it is difficult to objectively compare the degrees of disturbance. Drew (1996), in the study on disturbance of the Burren karst of Ireland, created an index of vulnerability of groundwater to leachate pollution for individual sites. Various surface features, both natural and human-made, were ranked according to the degree of protection they offered against groundwater pollution. While this allowed an objective comparison among sites, it only looked at one component of the system.

The most complete work on the disturbance of karst comes from the International Union for the Conservation of Nature and Natural Resources' Guidelines for Cave and Karst Protection (Watson and others 1997). This international coalition of scientists established an extensive list of both the impacts on karst systems and guidelines for their protection. The various aspects of surface and subsurface karst are extensively covered in this report. Although Gunn and others (2000) examined one cave system in England, they utilized a fairly comprehensive approach to examine the external and internal human impacts on a cave system. Myroie and Tronvig (1998) based their endangered karst ecosystem list on three criteria: (1) biological significance; (2) actual threat to karst community; and (3) relevant local groups interested in the protection of threatened karst. In addition, they emphasized the importance of considering the type of threat to karst regions and the involvement of the local community.

Although neither deals with karst, the indices presented in Spencer and others (1998) and the National Parks Conservation Association (Nations 2004) were used as examples to construct karst environmental disturbance index. Spencer and others (1998) created a rapid appraisal condition index for wetlands in south-eastern Australia. They used four attributes of wetlands—soil, riparian vegetation, aquatic vegetation, and water quality—to assess the health of permanent floodplain wetlands. Certain indicators were chosen for each of these attributes to measure how well each of the components of the wetland was functioning. These indicators were measured and scored according to the condition of the indicator. The wetland condition index provided accurate estimates of the wetland condition when compared with other studies of the same wetlands (Spencer and others 1998). The second study was conducted by the National Parks Conservation Association to assess the state of the national parks in the United States (Nations 2004). The study focused on two broad categories: ecosystem measures of extent, i.e., function, species composition, and condition, and measures of biotic health, i.e., water resources, air quality, climate, and soil resources in the parks. Each of these measures had various indicators that could be analyzed and “scored” with respect to the condition of the components. High scores suggested little disturbance while low scores suggested high disturbance (Nations 2004). These two approaches were used to create an index of disturbance for karst systems.

Application of the index is based upon several inherent assumptions. The first assumption is that for any given indicator, it is theoretically possible to collect the data needed to rate a disturbance. We recognize that data availability will vary from region to region, dependent on the depth of research undertaken for that locale. The second assumption is that the index can be applied to all karst regions. Naturally, its application to highly heterogeneous regions should be done so with caution and over-simplification of the parameters should be avoided. A final assumption is that the karst system is stable and any change to that system is caused by human disturbance. However, all effort should be taken to differentiate obvious natural variability from anthropogenic changes.

Categories and Attributes

The karst environmental disturbance index presented in this report is divided into five categories, each recognizing a distinct part of the natural and human system. These categories incorporate both the physical, biological, and social interactions with those parts. Geomorphology encompasses the surface land-

forms, soils, and caves; atmosphere deals with air quality; hydrology concerns the quality and quantity of the water; biota deals with vegetation disturbance and subsurface biota; social includes human artifacts, stewardship issues, and the human-built infrastructure. This categorical framework provides a systematic approach for the evaluator to review the karst system reducing the system to easily studied elements and identifying lines of study where the relevant information may be collected and ranked.

Scale

When looking at environmental disturbance, there are various scales to consider. The first is the karst region as a whole, classified here as the “macro” level. At the macro level, a regional view is necessary to evaluate the large-scale processes that can impact the entire karst region. Phenomena such as massive opencast mines, hydroelectric dam reservoirs, acid rain, deforestation, and over-pumping of groundwater from karst aquifers or their contamination are macro-scale processes. The second level in the index scale is called the “meso” scale and is more localized to recognize more concentrated, small-scale impacts. Examples of these include impacts on sinkholes, soil pollution, buildings that cover karst features, and the destruction or removal of historical artifacts unique to that particular karst region. The final level is the “micro” scale. This incorporates individual cave biota and conditions. Measurement in the micro scale is limited to the extent that it can only incorporate the conduits accessible to and explored by humans.

Indicators

Previous studies (Spencer and others 1998; Nations 2004; Drew 1996) employed indices to evaluate the health of particular environments, and used the term indicator to denote a measure of some function or component of an ecosystem. The indicator, whether it is an individual species or a measure of an environmental variable such as water turbidity, can be quantified to determine the degree of perturbation. The index we propose uses the term somewhat differently as it tries to measure directly how human practices have impacted a karst system. Hence the term *indicator* as it applies to the karst disturbance index is that it *indicates the degree of disturbance for a certain parameter*. This avoids questions as to which species are the best indicators to use or which environmental variable the best to measure.

Data Collection

Information about the state of the environment can be obtained from field observations, published and

unpublished research articles, and government reports on the karst region under study. While the evaluator should be an expert in an area of karst studies, and have the experience to interpret the data, the index and indicator scoring is designed to be relatively simple and avoid the pitfalls of personal subjectivity. Use of pre-established indicators removes the need for the evaluator to determine what is important to measure. For example, a biospeleologist might concentrate on biota, but ignore the quality and quantity of water in the karst aquifer. Likewise, a geomorphologist might not be concerned with the decline of a cave species over time. This index outlines all the areas of data that should be collected, rather than focusing on a specific, disciplinary viewpoint. However, it must be stressed that no index can encompass every subtle nuance for every karst region of the world.

The evaluator will be expected to know, based on previous research, what is considered an undisturbed karst system for a particular region. This “undisturbed ideal” represents a baseline or a frame of reference for determining the degree of disturbance. For some indicators this should be obvious, as in the case of water quality, degree of deforestation, extent of quarrying or cave destruction. The loss of biodiversity, however, requires knowledge of what existed before human perturbation. The specificity of certain cave biota to only a few but not all caves could also complicate the determination of this parameter. That would require finding locations far from the influence of humans, which for some areas could be fairly difficult. Most locations should nevertheless have some areas with minimal human impact, which can serve as a frame of reference for the evaluator.

Rationale for Scoring System

The scoring system for the disturbance indicators utilized in this study is similar to the model presented by the National Park Conservation Association (NPCA) in their annual assessment of the National Parks of the United States (Nations 2004). Each indicator is assigned a score from 0–3 based on the evaluator’s interpretation of the extent and severity of the variable being considered. A score of 0 means no human impact/karst disturbance. If disturbance is apparent, then the evaluator must judge if the impact is catastrophic (rating = 3), severe and widespread (rating = 2), or localized and not severe (rating = 1). To enhance the comparability between different case studies using this index, guidance as to how these values are assigned is provided in the following section. Heeding the recommendation of the NPCA (Nations 2004), limiting the scores to four possibilities removes

much of the uncertainty and subjectivity associated with more detailed scales. For example, with a scale spanning 0–10, the difference between assigning a value of 5, 6, or 7 can be very subjective. In addition, four levels prevent the evaluator from consistently choosing a middle level and forces him/her be more decisive.

If an indicator is not applicable to a certain karst environment, then that indicator is dropped from the evaluation. This is not to be confused with “no impact,” which would still be part of the index. For example, if the caves of a region have never been occupied by humans, then some social indicators could be discarded. Deletion of an indicator decreases the total possible sum. The degree of disturbance metric, however, is based upon a ratio (total score divided by number of indicators) rather than the simple sum of index variable scores. If there is no information for an index variable, but it is still relevant in the region, then the variable is assigned with a “Lack of Data” (LD). The number of LDs can be tabulated at the end of the study and expressed as a percentage of the total, thereby providing a measure of adequacy of the information and highlighting regions that are in direct need of study.

Index studies often use weighted indices, giving more importance to certain indicators than others. We chose not to use this approach because it is often difficult to determine which indicators are most important. For example, it is not possible to determine which is more important, water quality or water quantity. If both are adversely affected, the subsurface environment suffers. Karst systems are highly interconnected, hydrologically due to the rapid passage of water and energy through the system. One of the main purposes of this index is to allow comparability between different regions. Such comparison would be difficult if evaluators altered weighting schemes due to regional differences in the importance of certain indicators. Consequently, this index does not use weighted indicators.

Scores for each indicator are not modified further, and are only used in determining the final disturbance value for the area being evaluated. The allocation of scores for individual indicators required either quantitative analysis or qualitative evaluation, therefore not every indicator has the same quantitative, incremental divisions between the scores. Statistical analyses of individual scores will distort the overall significance of the determined level of disturbance, and should be avoided.

The Indicators

Details regarding the scoring of indicators are summarized in Table 1.

Geomorphology

Surface Landforms

Surface karst throughout the world has been disturbed by several large-scale human processes, including quarrying, residential development, agriculture, and deforestation. Surface karst includes surface features created by karst processes that can be found in areas where carbonate evaporates and quartzite rocks are predominant, either at the surface or close to the surface. Such features include tower karst, *poljes*, sinkholes, and those of a smaller scale, namely, karren, pavements, and tufa deposits.

Quarrying/mining. The most destructive practice for surface karst is large opencast mining that can remove all notable features from the landscape. Aw (1978) was one of the first researchers to bring attention to THE disturbance of karst landforms with his study of Malaysian Limestone Hills. In this early example, quarrying of the limestone hills destroyed significant religious and archaeological artifacts, habitats of rare flora (orchids and ferns) and fauna (mollusks and wild goats). Great Britain also has abundant limestone quarries, with 124 Mt of rock removed during 1987 alone (Gunn and Bailey 1993). Humans removed more rock during the last century in the United Kingdom than nature removed during the last 10,000 years. Quarrying can reduce spring discharge, cause drawdown of the water table, produce sinkholes, and destroy caves. It also enhances the rate of epikarst development by altering the hydraulic gradient. Tailing ponds can introduce toxic chemicals to the local water supply if they leak or collapse. While quarrying is the most destructive impact, it is usually localized. Landscapers also remove small-scale surface karst features such as limestone pavements for use in gardens in Great Britain (Goldie 1993). This small-scale quarrying became so prevalent that the British government afforded special protection for surface karst under the Wildlife and Countryside Act in 1981.

Flooding. Flooding takes numerous forms, from total inundation of a valley for filling a reservoir for hydroelectric power generation to building small reservoirs on farms. The Three Gorges Dam in China is probably the most extreme example of flooding of a karst terrain. Flooding alters the hydraulic regime of karst systems by saturating the vadose zone (air filled) and, in extreme cases, as in the Vaiont Dam in Italy (Ford and Williams 1989), can destabilize slopes by increasing hydraulic pressure within the bedrock. Natural flooding occurs in karst environments when precipitation exceeds the drainage capacity. This is a short-term occurrence, however, and should not be considered as contributing to karst disturbance.

Stormwater drainage. Sinkholes are a surface window to the karst aquifer and allow rapid drainage. Engineers recognize this property, and use sinkholes as drainage points for stormwater. Much of this stormwater comes from road and parking lot runoff. In such cases, car oil and gasoline spills wash into sinkholes, thereby polluting the aquifer. Increased water flow can also lead to artificial enlargement of the sinkhole. In most states in the United States that have karst, this practice is common (Crawford 1984; White and others 1984; Keith and others 1997). The scoring system depends on the percent of stormwater funneled into sinkholes in the study area.

For this indicator and any other indicator that deals with sinkholes, the sinkholes to be investigated are only those that appear on 1:24,000 scale topography maps, such as those produced by the United States Geological Survey. To measure impacts on sinkholes requires knowledge of where they are, and topographic maps provide that ability. The selection of this universal scale removes evaluator subjectivity as to what is the minimum size of sinkholes that should be included in the index. If a depression or sinkhole appears on this scale of map, it can be included. Two limitations of this approach are that (1) very small sinkholes will not be included and (2) topographic maps usually do not identify sinkholes in wetlands.

Infilling. In urban areas, surface karst features can be obstacles to development and are often covered or infilled. Sinkholes are the most common feature to suffer such destruction, and are the basis of this indicator. This changes the natural drainage of a karst system and often leads to surface flooding. Another unfortunate side effect of this process is that if infilling is not correctly done, buildings atop a sinkhole can break apart when the fill suffuses (fill sinks into enlarging fissures below the surface). Catastrophic collapse of the sinkhole can also occur. This problem is common in west-central Florida, USA (Sinclair and others 1985). Caves are also filled with concrete or covered, leading to destruction or isolation from surface conditions. The scoring used here is based on the number of sinkholes infilled as a percentage of the total number of all sinkholes present in the study area.

Dumping. Sinkholes and caves are convenient locations for disposal of neighborhood or farm garbage. The shape of sinkholes makes them natural traps for windblown garbage as well. Farmers sometimes use sinkholes as “mini landfills” for anything from animal carcasses to old vehicles. The Kentucky Sinkhole Plain is an excellent example of this problem (Quilan and Ewers 1985). A sinkhole should only be counted if the

material dumping in the sinkhole is of a quantity or quality that will impact the karst system through clogging, pollution, and aesthetics.

Soils

Karst areas typically have only a thin veneer of soil cover. Hence, soil conservation is important for vegetation and the continued natural development of karst features. Soils produce carbonic acid that is essential to chemical weathering of the limestone.

Erosion. Poor agricultural and forestry practices can lead to accelerated soil erosion. Distinguishing between natural erosion rates and moderate rates can be difficult. Land-use practices in the karst region may help determine whether erosion is natural or the result of human activities. A dilemma is to whether to include past erosion events that are no longer active today. These events could have been human-induced and may still have an impact on the karst system through infilling of sinkholes and caves. However, hundreds or thousands of years may have passed since that event and its extent may be impossible to determine. Consequently, we limit the measurement to erosion events that are occurring at the time of measurement. In arid regions, this indicator may be dropped from the index.

Compaction. Soil compaction can occur when the soil is trampled by livestock or compressed through farming activity. A compressed soil reduces water percolation by decreasing pore space between the grains. This can lead to surface flooding, anoxic conditions in the soil, and decreased water flow to the epikarst. This can alter the aquifer recharge rate and speleothem deposition in caves.

Subsurface Karst

The subsurface realm includes vadose and semi-phreatic (alternating between vadose and phreatic) zones and caves. The permanently saturated karst is categorized as part of the aquifer and is addressed in the hydrology section.

Flooding. Flooding in the subsurface realm has different causes compared to flooding on the surface and, therefore, has its own indicator. Karst systems are unique in that they enable the rapid transmission of water from the surface to the subterranean environment. Construction of dams on the surface will permanently flood conduits upstream of the dam, thereby destroying terrestrial environments and causing cessation of speleothem deposition. Permanent inundation is the most extreme form of flooding, however, human alteration of the system within or beyond the karst catchment can lead to differing degrees of inundation. Consequently, the degree of flooding is the determin-

Table 1. Disturbance index for karst environments indicators

Category	Attribute	Scale	Indicator	3	2	1	0
Geomorphology	Surface landforms	Macro	Quarrying/mining	Large open cast mines	Small working mines	Small scale removal of pavement	None
		Macro/meso	Flooding (human-built surface structure indirect effect)	Total flooding of valley for hydroelectric dams	Flooding of fields for irrigation	Small scale reservoirs built for farming	Natural precipitation-induced flooding
		Meso	Stormwater drainage (% of total stormwater funneled into sinkholes)	>66%	34–66%	1–33%	None
		Meso	Infilling (% of infilled caves and sinkholes)	>66%	34–66%	1–33%	None
		Micro	Dumping (% of sinkholes affected)	>66%	34–66%	1–33%	None
		Macro	Erosion	Severe	High	Moderate	Natural rate
		Micro	Compaction due to livestock or humans	Widespread and high levels	High Widespread but low levels	Few isolated concentrated areas	None
		Macro	Flooding (human-induced cave flooding due to surfaces alteration)	Permanent cave inundation	Increased intermittent flooding & > 50% filling	Increased intermittent flooding & < 50% filling	Only natural flooding due to high rainfall
		Micro	Decoration removal: vandalism	Widespread destruction	~50% of speleothem removed	Some isolated spots of removal	Pristine
		Micro	Mineral and sediment removal	Most of material removed	~50% of cave affected	Some isolated spots	Pristine
Atmosphere	Air quality	Micro	Floor sediment compaction-destruction	Most of floor sediments and decorations affected	~50% of floor sediments and decorations affected	Small trail through cave	Almost pristine, mostly rock surface
		Macro	Desiccation	Widespread and high levels	Widespread but low levels	Isolated and very low levels	Pristine
		Micro	Human-induced condensation corrosion	Widespread and high levels	Widespread but low levels	Isolated and very low levels	Pristine
		Meso	Pesticides and herbicides	Leakage of concentrated chemicals into aquifer	Heavy spraying of crops/weeds on surface	Little use of chemicals	None used
Hydrology	Surfaces Practices	Micro	Industrial and petroleum spills or dumping	>20 Brownfields	10–19 Brownfields	1–9 Brownfields	0 Brownfields

Table 1. Continued.

Category	Attribute	Scale	Indicator	3	2	1	0
Water quality	Springs	At all scales	Occurrences of algal blooms	Only aquatic life is algal growth	Occasional or seasonal short-term blooms	Nutrients concentrations just above background levels in water	Pristine water
		Macro	Changes in water table (decline in meters)	> 35	15	<5	Only natural variability
Biota	Vegetation disturbance	Micro	Changes in cave drip waters	Total cessation	Long dry spells (not seasonally related)	Slight reduction	No change
		At all scales	Vegetation removal (% of total)	>66%	34–66%	1–33%	0
	Subsurface biota, cave	Micro	Species richness (% decline)	50–75	20–49	1–19	0
		Micro	Population density (% decline)	50–75	20–49	1–19	0
	Subsurface biota, ground water	Micro	Species richness (% decline)	50–75	20–49	1–19	0 or increase in numbers
		Micro	Population density (% decline)	50–75	20–49	1–19	0 or increase in numbers
Cultural	Human artifacts	At all scales	Destruction/removal of historical artifacts	>50	20–49	1–19	0
Stewardship of Karst region	Regulatory protection	At all scales	Regulatory protection	No regulation	A few weak regulations	Statutes in place but with loopholes	Region fully protected
		At all scales	Enforcement of regulations	Widespread destruction, no enforcement	No policing, but little damage done	Some infrequent enforcement	Strong enforcement
	Public education	At all scales	Public education	None, public hostility	None, public indifference	Attempts through NGOs	Well-funded government programs
		Macro	Building of roads	Major highways	Some two lane roads	Some country lanes	Minor trails
Building infrastructure	Meso	Building over karst features	Large cities	Towns	Small rural settlements	No development	
	Micro	Construction	Major modification	Major tourist cave	Cave trail marked	Pristine	

ing factor for scoring this indicator. Hydroelectric dams release torrents of water periodically that can lead to regular flooding of conduits downstream of the dam. Stormwater drainage also leads to flooding in caves when sinkholes are used for surface water removal, although this type of flooding is more intermittent. Karst systems tend to evolve to cope with natural flows and flooding does occur, although less frequently.

Decoration removal or vandalism. Not all visitors to caves treat them with respect. Stalagmites and stalactites are broken off as souvenirs, or graffiti is sprayed on cave walls. Some caves have had every single natural decoration removed and the walls are covered in graffiti. Speleothem removal can be distinguished from natural breakage. If only a stump remains, then the speleothem was removed. If, however, the broken speleothem is found near the stump, then breakage was natural.

Mineral and sediment removal. Some cave biota promote accumulation of unusual deposits on cave floors. Economically valuable deposits include products such as phosphates and nitrates (White 1988). For example, bat guano is high in sodium and potassium nitrates, commonly known as saltpeter and has been mined to manufacture gunpowder (as in Mammoth Caves, Kentucky) (De Paepe and Hill 1981). Guano deposits also serve as food sources for certain cave organisms and mining of these deposits can remove their food sources and habitats. Another mineral to be mined in caves is Galena (lead sulfide), a mineral that was used in early amateur radiosets. However, because it is often associated with silver, miners were quite interested in this mineral. It is commonly found with calcite and dolomite; therefore, caves are a common place to find it. Finally, not only valuable minerals are removed but also ordinary sediments for enlarging passages or building new entrances in tourist caves. All three activities will impact cave biota (habitat removal), cave climate (changed air flows), and cave aesthetics (destruction of calcite precipitates growing on mineral/sediment).

Floor sediment compaction/destruction. Some organisms live in cave sediments and walking on the sediments can destroy the animals' habitat (Gillieson 1996). Some caves have had almost total sediment compaction, resulting in a hard, smooth, concrete-like surface. Some parts of caves are more challenging to explore, and prevent the visitor from entering, therefore, less compaction has occurred. The most challenging or isolated caves are entered by only experienced cavers, who want to keep the cave as pristine as possible and have taped off narrow trails through the cave, thereby

reducing compaction. However, even with the best conservation intentions, once a cave is discovered, it is no longer pristine (Silverwood 2000; Donahue 1990). Although caves with mostly rock floors will not suffer sediment compaction, other types of damage can be done to floor materials. Carbonate precipitates such as flowstone, rimstone dams, or moonmilk are examples of cave sediments that could be damaged by people moving through a cave. Consequently, both compaction and damage will be included in this indicator.

Atmosphere

Air Quality

Human alteration of the atmosphere above and within caves can be detrimental to karst rock or secondary deposits. Baker and Genty (1998) found that cave speleothems are also at risk, due to changing drip water chemistry and increasing volumes of visitors changing cave atmosphere composition. Cigna (1993), however, argued that careful management of human activity can reduce the disturbance of cave decorations and biota. Cigna's thesis is somewhat contrary to several of the studies already discussed (Baker and Genty 1998; Silverwood 2000; Donahue 1990).

Desiccation. To facilitate the flow of people in and out of a tourist cave, many tourist caves have modified or artificial cave entrances. A common consequence of these entrances however, is a drop in the relative humidity, below the usual 99% relative humidity. Increased evaporation results and cave decorations can lose their surface moisture and dry out. Body heat from tourist parties and cave lights will also increase evaporation within the cave (Villar and others 1986). Cave organisms that rely on high humidity can also suffer. Glowworms in Glowworm Cave in Waitomo, New Zealand (Pugsley 1984) began declining when a new entrance was created. Because glowworms were a major attraction for tourists, the decline in the glowworm population was remedied by placing an airlock at the new entrance. Tourist caves can also close off entrances, which can decrease wind flows and increase humidity. While this may change the climate of the cave, we do not see this as detrimental to the cave. A way to investigate the mechanism of desiccation is to measure alterations in relative humidity. However, the researcher would have to make an assumption of what the relative humidity level was before human alteration. It would also require an instrumental setup in the cave. Instead, we decided it would be simpler examine the decorations in the cave to determine the

extent of the problem. Comparing more isolated areas of the cave with the main passages should allow the evaluator to make this assessment of desiccation levels.

Human-induced condensation corrosion. Humans affect the atmosphere of a cave simply by breathing and introducing additional heat. As humans respire carbon dioxide, it concentrates within the cave (Villar and others 1986). This carbon dioxide combines with water to form carbonic acid. As cave decorations are often covered with a thin film of water, the respired CO₂ can form carbonic acid on speleothems. This causes condensation corrosion of cave speleothems. This problem is fairly common in tourist caves and has led operators to decrease the number of visitors. Scoring is the same as that used for desiccation.

Hydrology

Water Quality

Springs that flow from karst regions and wells that tap karst aquifers have traditionally been heavily used for potable water supplies. With growing human population and alteration of the environment, the quality of these water sources has steadily deteriorated, and in some cases they no longer supply safe drinking water. Two ways to examine disturbance of karst waters are through either detrimental surface practices or the quality of water once it emerges at springs. This index will not use predefined concentrations of pollutants or even types of pollutants in the waters as a measure of disturbance. The examples of phosphorous and nitrate demonstrate our reasoning. Both are nutrients essential for growth of all organisms, but when elevated by human activity, they become *pollutants* due to the detrimental effect they can have on water quality (Waterhouse 1984; Wheeler and others 1989). However, various locales have vastly different concentrations of these nutrients. Therefore, it is difficult to use exact concentrations in the water to create a ranking. What may be elevated for one region may not be elevated for another, consequently exact concentrations cannot be used. Additionally, what may be deemed safe in one instance may not be for another. For example, Florida's drinking water standards allow nitrate levels of 10 mg/L (Florida Department of Environmental Protection 2005). However, 7.5 mg/L will cause algal blooms (Champion and DeWitt 2000). Consequently, measuring the severity of the disturbance of certain practices or what changes are occurring to the components of the water, and not their concentrations, overcomes these problems. The following indicators will illustrate our approach.

Surface Practices

Pesticides and Herbicides. Both agricultural and residential areas are characterized by heavy use of herbicides and pesticides. Pesticide and herbicide use can lead to organophosphate, fenamiphos degradates, triazinones, carbamates, cypermethrin, and other chemicals in the aquifer (Choquette and Sepulveda 2000; Gunn and others 2000). Urich (1993) also observed the negative impact of specialized agriculture in Bohol, Philippines. Wet rice cultivation combined with the heavy use of pesticides and herbicides contaminated surface karst waters. Determination of pesticide and herbicide concentration, as well as their derivation, is difficult. Consequently, the frequency and quantity of their application can provide guidance as to the severity of the resultant pollution. However, we must stress that not all the chemicals sprayed on the surface will accumulate in the groundwater, due to the filtering effect of soil.

Industrial and petroleum spills or dumping. Volatile organic compounds (VOCs) and dense non-aqueous phase liquids (DNAPLs) are common industrial chemicals deposited on the surface, but often end up in the karst (Loop and White, 2001). VOCs would normally evaporate quickly, however, the water's rapid transmission through karst rocks (Vesper and White 2003) allows much of the pollutant to remain in liquid form. Consequently, evaporation is more difficult when VOCs are in the cool saturated zone of the aquifer. The frequency and severity of spills and dumping and the degree of cleanup are factors to be considered when scoring this pollution indicator. Of course, there are many heavy metals and solvents that have also been dumped, buried, or spilt at industrial complexes (Quinlan and Ewers 1985; Vesper and White 2003). In the United States, these sites are known as Brownfields: abandoned, heavily polluted factories. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and its 1986 amendment, the Superfund Amendments and Reauthorization Act (SARA), requires the cleanup of these polluted site. However, many sites have received no remediation and remain sore issue for communities. The number of such sites in a region forms the basis of this indicator. Such sites are common across the world and their identification by evaluators should be possible.

Spring Water Quality

Occurrence of algal blooms. Algal blooms in surface waters are a result of elevated nutrients caused by indirect contamination on a diffuse front. Human and

animal waste is often disposed of onto or into the soil and, percolation carries it to the bedrock where transmission to the aquifer may be via the rock matrix or through fissures contained with it. In some parts of the developing world, raw sewage flows from villages through the soil into sinkholes. From there it enters the aquifer, polluting the water that is often used for human consumption. A common practice in the developed world is to spray animal effluent onto pastures. This promotes vegetation growth and disposes of the effluent at the same time. While this practice may be more diffuse, it still pollutes the aquifer. This problem is most severe when the soils are saturated and yet spraying must continue. A more prevalent issue is leaking septic tanks. Leaking septic tanks allow human effluent to seep into the groundwater, thereby increasing coliform bacteria counts and nitrogen levels. Both effluent spraying and leaking septic tanks have been documented by Drew (1996), and can lead to eutrophication of waters and a decline in aquatic species. While the use of reclaimed water for irrigation can decrease demand for aquifer water, the reclaimed water can also contaminate the aquifer. The same effects can come from nitrogen and phosphate fertilizers are commonly used in agriculture to promote crop growth. Phosphorus is the most common nutrient producing algal blooms in surface waters (Schindler 1978). The main problem in Florida is the anthropogenically increased nitrate levels (Champion and DeWitt 2000). An important point is that both nutrients are present in nature and may be present in high concentrations. However, either nutrient can be considered limiting if its concentrations are too low to stimulate growth of organisms in surface waters. Additionally, if phosphate levels are naturally high, then the environment is adjusted to those levels, but enhanced high nitrate levels can lead to eutrophication and resultant algal blooms in surface waters fed by the aquifer. The rapid transmission and poor filtering ability of karst rocks allows agricultural fertilizers to pass freely into the aquifer. The severity and longevity of eutrophication of surface waters fed by karst aquifers is the basis of this indicator.

Water quantity. Approximately 25% of the world's population receives its water from carbonate rocks (Ford and Williams 1989). This resource is, therefore, under increasing pressure. Many karst aquifers are experiencing rapid draw-down due to over-pumping and have become brackish as saltwater intrusion occurs

Changes in water table. Excessive pumping of an aquifer will lead to a decline in the water table. The increasing human population and the demand it generates for water is the most common cause of aquifer

over-pumping. Mining and quarry operations also remove groundwater to extract ore from mines. They create a draw-down cone in the water table to provide access to the desired mineral. Both practices can have catastrophic effects, with increased sinkhole activity being the most common outcome. Sinkholes can also be created by water loading at the surface, when tailing ponds exceed the weight the underlying bedrock can support. Lowering the water table removes buoyant support of rock/sediment overburden above cavities in the bedrock. Collapses can result, as in central Florida (Tihansky 1999). Water table lowering also contributed to the collapse of a tailings pond in Olkusz, Poland, which polluted the town's drinking water supply (Ford and Williams 1989). Natural short-term variability due to seasonal changes in precipitation or drought conditions should be separated from the human-induced lowering to accurately ascertain how much the water table has fallen. All water management districts or authorities should record the natural variability of water levels as part of their management procedures. Therefore, this information should be readily available.

Changes in cave drip waters. Pumping of the aquifer and wells can alter the natural flow of groundwater. This can affect the flow of water to conduits and the precipitation of cave deposits (Baker and Genty 1998). Another major contributor to such alteration of flow is change in surface land use. The construction of large paved areas can lead to a disconnect between the surface and conduits in the bedrock. Consequently, the indicator to be used is the degree of change in the amount of water reaching the cave through the above bedrock.

Biota

Vegetation Disturbance

In most karst environments, vegetation is an important component of the karstification process. As mentioned earlier, pure limestone does not produce abundant soil, and it is often the decay of vegetal litter that helps build the soil. The soil helps provide carbonic acid for the dissolution of the limestone, thereby increasing the generation of karst. The disturbance or removal of vegetation, therefore, disrupts the natural evolution of karst (Harding and Ford 1993; James 1993). Vegetation also prevents soil erosion and maintains the purity of the groundwater.

Vegetation removal. The removal of trees or natural vegetation for agriculture or logging will have a detrimental effect on the karst system. Sauro (1993) showed the impacts of long-term agriculture and deforestation

on the surface karst and how this affected subsurface waters in the Venetian Fore Alps of Italy. Boreal forests intercept up to 80% of precipitation, thereby decreasing rain splash, the major erosion-causing component. Tree removal decreases interception, allows more surface erosion, and consequently infilling of conduits as was evident on Vancouver Island, Canada, where deforestation and burning caused major soil erosion and the exposure of bedrock on karst landscapes (Harding and Ford 1993). The limestone bedrock suffered more severe erosion than nearby deforested volcanic rocks. Agents of deforestation can either be through clear cutting or fires. Fires indirectly promote soil erosion by destruction of soil organic matter. Soot from fires ends up in percolation waters, and can discolor cave deposits. Deforestation, the basis of this indicator, applies to any removal of substantive vegetation that would lead to impacts on the karst system.

Subsurface Biota

As this index is highlighting karst environments and not just any type of landscape, only disturbance in the subterranean realm will be investigated. Surface biota in karst areas differ little from non-karst areas, hence we will exclude disturbance of surface species. Subsurface biota includes species living within caves and those that exist in groundwater and the following indicators can be applied to both realms.

Much of the work on human disturbance of cave environments has focused on biota. Bats are the most commonly associated cave biota in the minds of the public. Their study (Richter and others 1993; Petit 1996; Parson and others 2003) has shown that, with the changing ambient conditions in caves, the destruction of feeding grounds, and the perception of bats as pests, their numbers have declined in many areas of the world. Sharratt and others (2000) provided a comprehensive list of endangered endemic species in sandstone caves in the Cape Peninsula of South Africa. These authors highlighted a common aspect of cave biota: bats can be found exclusively in only one or two caves. This makes their monitoring and conservation all the more urgent.

The decline and preservation of the biodiversity of highly specialized species found in caves 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 have contributed to a loss of diversity. Gunn and others (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. Wood and others (2002) also illus-

trated the impact of agricultural pollutants on cave invertebrates and highlighted the importance of long-term monitoring of groundwater to detect pollution.

Species richness. This is a measure of the number of species present in a given area. It is one of the most common, standard measures used in human impact studies and provides a way to determine more subtle change that may not be evident in the above indicators. This indicator requires regional species richness studies that are separated by decades and would, therefore, show disturbance most clearly. Consequently, the information for this variable can only be found in the literature, and, therefore, does not require the researcher to actually measure this variable. If the data do not exist, then a second approach would be to undertake a species richness study of "pristine" areas with disturbed sites for a region to determine how richness has declined. We recognize two problems with the second approach. First, certain species may only inhabit one or two caves and not elsewhere. Consequently, the researcher may surmise incorrectly that the caves where this species does exist may have been somehow negatively impacted. Second, what is considered "pristine" may be difficult to ascertain. Some regions could conceivably have no pristine caves, and the only alternative left is to use the least impacted caves as a guide, while recognizing the limitations of the study.

Population density. This is a measure of the number of individuals within a population. Species richness by itself can provide a misleading picture of the health of an environment. Certain karst regions may have a large number of different species. However, the number of individuals for each species may be very low and even under the threat of extinction. As with the species-richness indicator, the researcher is reliant on the literature or field measurements to determine how this variable has changed over time.

Cave environment. Species richness will not be great in caves due to the lack of food, but the species present may have healthy population numbers (Gillieson 1996). If caves are accessible, then sampling their biota should be fairly straightforward. The problem occurs when parts of the cave are flooded or too small to access, which is a common situation for most caves. Only the latter is a major obstacle as the former can be overcome through the use of cave divers. For more detailed information about measuring these indicators in caves, researchers are encouraged to consult Schneider and Culver (2004) and Culver and others (2004). While conducting species-richness studies, the measurement of individual population densities is a common practice and would not require much added work.

Groundwater. There are two ways to access the organisms living in the groundwater, either via flooded caves or through boreholes. Humphreys and others (1999) and Boulton and others (2003) discuss sampling in the aqueous environment. Boulton and others (2003) showed that groundwater pumping in arid karst areas has adversely impacted the biodiversity of groundwater species in Australia. Furthermore, water table lowering, sedimentation, and pollution are causing the extinction of certain aquatic species. Even subtle disturbances such as cave diving can alter the physicochemical profiles in water columns on which certain species depend (Humphreys and others 1999). Knowledge of this realm, however, is very fragmentary and few policies protect the biota. Over 3,000 cave dwelling species of crustaceans live in the groundwater of Australia but their low densities make monitoring difficult.

A potential criticism of this approach is that the index does not use individual species as indicators of ecosystem health. Much debate exists over which species are suitable indicators (Lawton and Gaston 2001) as some species may be present in certain regions and not others. Using species richness and population density eliminates this problem because the person collecting data does not have to decide which species to choose, but instead must determine if there has been a decline in the number of species or individuals. This approach requires more work than using a single indicator species, but in some cases this type of information may already be available.

If such studies are beyond the expertise of the researcher, then the "Lack of Data" demarcation can be used. We recognize that to measure this indicator is a major undertaking if it has not already been done and may be beyond the expertise of the karst scientist. However, as stressed earlier, highlighting areas that require more research is an important part of this index.

Cultural Factors

An aspect of karst environmental disturbance that is often neglected is the human-built environment. Karst regions are some of the earliest landscapes that were populated by humans. Evidence of early occupation include hominid remains in caves in the Middle East, Neanderthal art in European caves, and aboriginal art in caves of Australia. The Dinaric Plateau in the Balkans is a famous karst region, with old Roman structures built from locally quarried limestone. One of the most heavily plundered karst regions is the Mayan area of Mesoamerica. These locales all show the unique interaction of humans and the karst environment.

Human Artifacts

Destruction/removal of historical artifacts. This form of disturbance has indicators incorporating all three scales. *Macro-scale* disturbance is best exemplified by the looting of Maya ruins in Southern Mexico and Central America. The removal of carved limestone tablets (stelae) and the destruction of old temples by looters is so widespread and is categorized as a macro-scale disturbance. An example of *meso-scale* disturbance is the localized removal of columns or small parts of temples or the digging of trenches by looters to find buried treasures. *Micro-scale* is individual cave impacts, such as those with paintings peeling off walls due to humans altering cave climates, a problem that plagued Altamira Cave (Cigna 1993). The scoring system for all these indicators is based on how much of the artifacts has been removed, on a percentage scale.

Stewardship of Karst Region

The degree of recognition and protection of human and environmental value of karst regions is a measure of human stewardship. Stewardship can occur at all three scales, i.e., at the *macro* or regional level. The *meso-scale* could involve a single cave system such as the Mammoth Cave-Flint Ridge system in Kentucky, and *micro* may refer to individual karst features. Whether the local population recognizes that their karst landscape is unique can determine whether steps are taken to reduce disturbance. Implementation of protections may also be affected by population density: a low density reduces the amount of economic conflict between those interested in development versus protection (assuming that these processes are in conflict). If the environment is unique and warrants protection, then a possible positive economic outcome could be increased regional tourism.

Tensions arise because of the competing interests among those who want to preserve, manage, and utilize karst regions and resources in many developed countries. The United Kingdom has taken steps to protect its karst resources and probably has the strongest legislation and enforcement in the world, though some local farmers were not happy with the law. It designated karst regions as Sites of Special Scientific Interest (SSSI) and protection is given under the Wildlife and Countryside Act of 1981 (Gunn and Hardwick 1996). This official status controls resource use on both public and private land. In contrast, the United States protects some caves on some federal land under the Federal Cave Resources Protection Act of 1988 (Huppert 1995). This legislation does not cover private land, nor does it cover all federal land, but only some caves un-

der the authority of the Departments of Agriculture and Interior (Carpenter 1993), something that cave protection advocacy groups find lacking. These groups also dislike the fact that oil and gas exploration is not illegal in karst regions on federal lands. Certain states within the United States have been more accommodating in the creation of protected areas (e.g., Katcher Caverns, Arizona) (Wiley 1989). In this instance, the legislature, governor, and landowners worked together and used the cave as a rationale to create the state park.

Regulatory protection. The most obvious form of stewardship and protection of a karst area is legislation that bans disturbance, or regulates land use. The United States used the creation of National Parks, e.g., Carlsbad Caverns, New Mexico, National Monuments (e.g., Oregon Caves), and US National Landmark status (Marengo Cave, Indiana) to protect distinctive karst. The United Kingdom protects its karst through the Wildlife and Countryside Act of 1981 (Gunn and Hardwick 1996). In Australia, the state of Tasmania has guidelines that must be followed in dealing with karst areas under the Tasmanian Forestry Practice Code (Gillieson 1996). Studies from the Caribbean, Central America, and Southeast Asia illustrate the protection of karst regions in developing countries, through national parks, national forests, nature reserves, and on private property (Day and Urich 2000; Kueny and Day 2002; Kueny and Day 1998; Day 1996; Urich and others 2001). El Salvador and Nicaragua have no protected karst regions. From these studies, it appears the density of human population is inversely correlated to the areal extent of protected karst (Kueny and Day 2002). The ranking of this indicator is governed by the amount of protection given.

Enforcement of regulations. While it may seem encouraging to have a suite of regulations protecting a locale, they count for little if they are not enforced. Legislators may placate concerned groups by creating protective laws but not enforcing their statutes. Several countries in Central America provide examples of this problem. Where national forests have been created to protect karst areas, logging, looting, and agriculture continue unabated (Kueny and Day 2002).

The designation of "Protected Land" does not mean that the land is off limits to human development. National forests are still logged and illegal agriculture is very common in developing countries. Urich and others (2001) state that the creation of a National Monument in Bohol, Philippines, generated much local opposition, due to what the locals perceived to be illegal "takings" of their land. The government failed to educate the public as to the benefits and importance

of such nature preserves, and how their current agricultural practices were detrimental and unsustainable. This study highlighted the importance of public support and local education to preserve a protected area.

Public education. Gillieson (1996) suggests that the best way to prevent disturbance of karst features is through public education. The worst-case scenario would be no public education in a region where the public is hostile to protection because they feel it could impair their earning potential. Such is the case in Bohol, Philippines (Urich 1993). From this scenario, there is a gradation of possible situations: no education provided but public indifference, attempts through non-governmental organizations such as local caving groups to educate the public, or well-funded government education programs.

Building Infrastructure

While historic or prehistoric human interaction with karst environments may add to their uniqueness, as discussed above, modern development can create widespread karst disturbance. Rapid human population growth in karst areas is leading to increased disturbance. The best example is China, which has the highest percentage of its total land surface categorized as karst (Ford and Williams 1989). Its growing population is increasing urban sprawl, thereby impacting both surface and sub-surface features. In China, the most extreme case of disturbance due to human-built structures is the Three Gorges Dam, being built in a karstified valley to provide hydropower to the ever-growing population.

Building of roads. To allow movement of people between cities and from workplaces to homes requires road building. The largest are the multi-lane highways that can cut right across karst regions. These constitute the largest disturbance because they cover the most area and provide significant quantities of contaminated stormwater runoff that can pollute the groundwater. As the size of the roads and traffic progressively decrease down to minor trails, the level of disturbance also diminishes.

Building over karst features. The expansion of cities requires new development that can lead to infilling of caves (as in Israel) or sinkholes (as in Florida). The larger the city, the greater the impact will be and, consequently, the higher the score for disturbance.

Construction within caves. The most common installations within caves are walkways and lights in tourist caves. Major infrastructure, however, can be built, such as the famous washrooms in Mammoth Cave, Kentucky, or the Brewery near La Chaux de Fonds, Switzerland. Using caves for storage or industrial purposes

Table 2. Classification of disturbance

Score (tally/total possible tally)	Degree of disturbance
0.8–1.0	Highly disturbed
0.6–0.79	Moderately disturbed
0.4–0.59	Disturbed
0.2–0.39	Little disturbance
0–0.19	Pristine

is another type of major modification, while tourist caves with walkways and lights and trail markers in wild caves have a more minor effect.

Compilation of Scores

Karst Environmental Disturbance Index

Once all the indicators have been scored according to Table 1, scores can be summed. This total is then divided by the highest possible score to attain a value between 0 and 1. Interpretation of this value is summarized in Table 2. The higher the value, i.e., the closer number is to 1, the greater the degree of disturbance. Five categories have been created and range from 0.8–1.0 (highly disturbed) to 0.0–0.19 (pristine).

Only those indicators applicable to a study area can be used. The variety of index indicators is provided to encourage the broadest possible measure of the karst disturbance. Some indicators, however, will be applicable in certain locales and not others. For example, the social indicators of human artifacts may be appropriate for the karst regions of the Middle East, but not for the Canadian Rockies. If an indicator is removed, a lack of data (LD) notation should not be used.

LD Rating System

Lack of data (LDs) indicates insufficient data to classify the indicator. The simplest and most effective way to highlight this problem is with a rating system (LD rating) that accompanies the karst environmental disturbance index. This rating enables one to evaluate the credibility of the index as applied in any particular study area. The LD rating is the number of LDs listed in the index divided by the total number of indicators used in the study. The higher the rating, the less confidence one can have in the determined degree of disturbance. For example, if 40 indicators were applicable to the study area and 10 had LDs, then the rating would be 0.25. A value of 0.25 means that a quarter of the indicators had insufficient data to allow scoring, which would equate to only moderate confidence in the index. Ratings of <0.1 would inspire high con-

fidence in the index. Values >0.4 suggest that more research is required before the index can be applied in that location.

Conclusions

Karst systems, like many environments around the world, have come under increasing pressure as human population grows. These pressures have created a need to evaluate the extent of human impact on the environment. The development of the karst environmental disturbance index is a response to this need. This study focused on the karst environment because it is one of the most susceptible to human disturbance. The index provides a quantitative measure of human impacts and can be applied to any karst region, enabling comparisons among locales.

The next step in the development of this index is its testing and application in a single karst environment. A study of the karst environmental disturbance of Central Florida will begin in 2005. This is a first attempt to produce a definitive index for measuring disturbance in karst landscapes. We hope that the publication of this index will provoke discussion and further index refinement.

Acknowledgments

The authors thank William White for his helpful thoughts and comments on this article and especially thank John Mylroie for suggesting the idea of a karst disturbance index and commenting on the completed text.

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