Environ Manage (2007) 39:261–277
DOI 10.1007/s00267-005-0393-x

ENVIRONMENTAL ASSESSMENT

Application of a Karst Disturbance Index in Hillsborough County, Florida

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Received: 15 December 2005 / Accepted: 16 July 2006

Abstract Hillsborough County, Florida, is a karst region that is heavily urbanized, yet no study has been undertaken measuring the degree of human disturbance. Van Beynen and Townsend (2005) created a hierarchical and standardized disturbance index specifically designed for karst environments. To address the problem of determining human disturbance in the county, the above index was successfully applied and it was found that Hillsborough was highly disturbed (disturbance score of 0.69 of 1.0) because of its predominant urban and rural land use. Furthermore, the application of the index allowed for its refinement and the highlighting of environmental aspects in need of remediation such as soil compaction, deforestation, disturbance of archaeological sites, and the expanding urban footprint. Several minor issues arose during the application: the need for broader indicator descriptions that encompass a variety of scenarios, the need for a revised water quality indicator, inadequate data on sinkholes, and a lack of data for species richness and species population density. The utility of the index to resource managers arises from emphasizing certain areas of the environment that require immediate attention and determining temporal changes in environmental quality. Future application of the index requires potential retooling of the biota indicators, tightening of scoring descriptions for certain indicators, and further examination of the scale at which the index can be applied.

Keywords Florida · Karst · Index · Human impact · Environmental indicators

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Introduction

Karst is a type of terrain formed largely on and in carbonate rock, such as limestone, where groundwater has solutionally enlarged openings to form subsurface drainage systems (Ford and Williams 1989). Surface karst has been impacted through quarries, dams, urban development, landfills, and drainage network disruption (Tihansky 1999; Keith and others 1997; Gunn and Bailey 1993; Goldie 1993; Ford and Williams 1989; Sinclair and others 1985; Quilan and Ewers 1985; Crawford 1984; White and others 1984). Caves are probably the most highly identifiable feature of karst environments; they are also among the most impacted because of surface and cave human activities (Silverwood 2000; Gunn and others 2000; Baker and Genty 1998; Gillieson 1996; Harding and Ford 1993; James 1993; Donahue 1990). However, karst aquifers are also negatively impacted through human agricultural and industrial processes (Boulton and others 2003; Wood and others 2002; Loop and White 2001; Arfib and others 2000; Drew 1996; Sauro 1993).

The problem addressed in this article is how to measure both quantitatively and qualitatively the degree of human disturbance in a unique karst landform, such as Hillsborough County, Florida. In 2005, van Beynen and Townsend created an index to measure and compare the disturbance of karst environments based on cultural, biotic, atmospheric, hydrological, and geomorphologic facets of karst. The application of this theoretical index to Hillsborough County provides a solution to the outlined problem. An index approach to measure environmental quality is useful because of its holistic nature incorporating many different components of the environmental system encompassing the physical, ecological, and social, as well as their interrelationships. Environmental indices enable comparisons of the state of the environment over time and space through the collation of common, pertinent data (Murray and Legget 1997). In 1991, the Organization for Economic Co-operation and Development (OECD) created guidelines to help determine which indicators are appropriate for environmental indices. These criteria included 1) relevancy—serve a clearly defined purpose; 2) reliability—of sound scientific basis; and 3) reasonability—can be measured by available data (OECD 2004). In this vein, the Canadian International Development Research Center (IDRC) suggested that indicators should be sensitive to interventions, demonstrate change over time, be reproducible, and permit examination through the disaggregation of data (Murray and Legget 1997). Environmental indices can be constructed with composite indicators to assess the overall environment within a defined geographical location. Examples of this include Spencer and others' (1998) index of wetlands, the National Parks Conservation Association (Nations 2004) annual index of the state of the federal parks in the United States, and Pauleit and others' (2005) index of urban land use and land cover change in Merseyside, United Kingdom.

Index utility to county or regional resource managers arises from 1) the ability to compare different counties or municipalities within a region, thereby highlighting areas that require remediation, and 2) the facilitation of year-to-year comparisons of environmental quality for the same region. Although the holistic approach of the index is a major strength, individual indicators can be disaggregated, thereby providing pointers for environmental components that require the attention of the manager.

The van Beynen and Townsend (2005) index applies a holistic, ecosystem approach to karst systems, recognizing that the vegetation, soil, and biota all influence and are influenced by karst processes. The broad categories assessed by the karst index are the cultural, biotic, atmospheric, hydrological, and geomorphologic impacts. These are then subdivided into the macro, meso, and micro scale of environmental disturbance. Indicators were selected to represent discrete, relevant, and measurable environmental disturbances to a karst environment. Each indicator receives a score indicative of the level of disturbance: the higher the score, the greater the disturbance. The importance of the disturbance index is threefold: 1) the index provides a tool for measuring human disturbance in an environment where no previous systematic method existed; 2) the holistic approach of the index incorporates many different facets, providing a more scientifically rigorous approach than any previously undertaken; and 3) the concentration on karst highlights a landscape with many unique features and directs attention to the high degree of interconnectedness, particularly of the karst hydrologic systems. Consequently, this index provides a tool to determine the degree of human disturbance in Hillsborough County, but also allows for a methodological refinement in this initial application of the index.

Study Area

Hillsborough County is located on the west coast of central Florida (Figure 1). In 2003, Hillsborough County had a population of ~1 million and an annual population growth rate approaching 20% (US Census 2005a). Hillsborough County has 2644 km^2 of land (US Census 2005b) and 62 km^2 of inland water (Hillsborough County 2005a). In 2003, urban areas covered approximately 45% of the land area of the county, whereas the majority of Hillsborough, 55%, is rural (Hillsborough County 2005b). Tampa is the largest city. Hillsborough County is currently undergoing rapid development and urban sprawl. An average of 9100 new homes was built in the county from 2000 to 2004 (US Census 2005b). Most of this new suburban construction is in the eastern portion of the county.

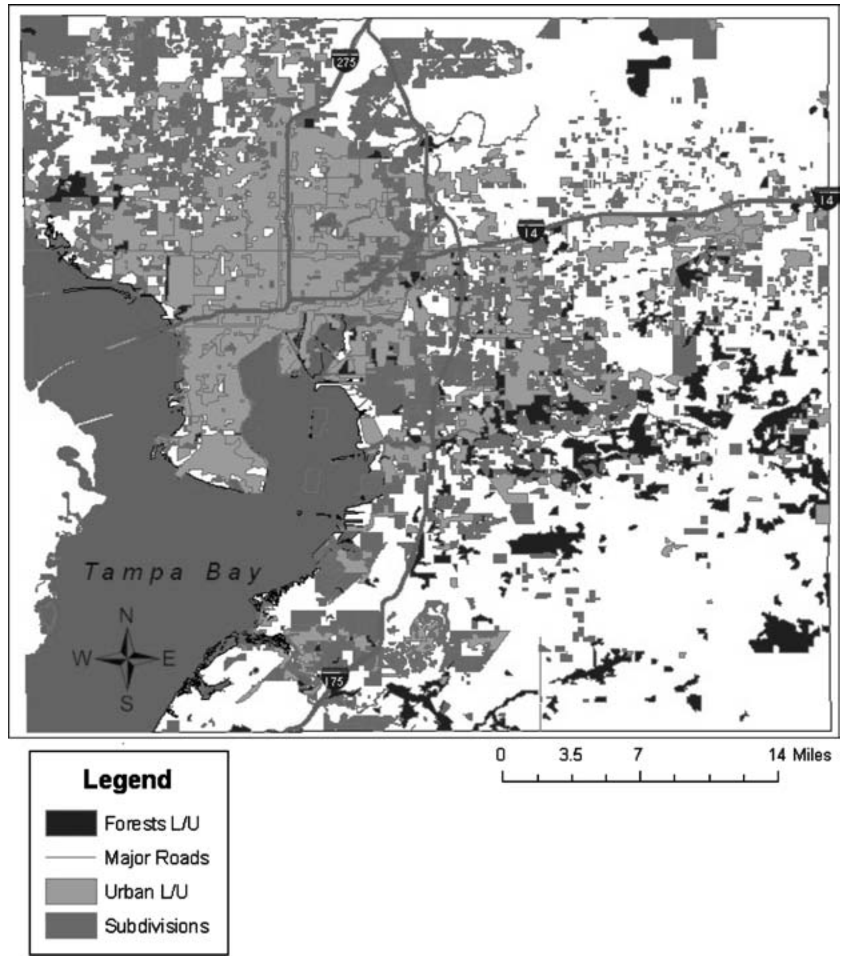


Fig. 1. Map depicts Hillsborough County, illustrating the extent of deforestation, urban and agricultural development. L/U, landuse

The county lies within the Gulf Coastal Lowlands physiographic unit (Randazzo and Jones 1997), which is characterized by low relief, with a mantle of clay, sandy clay interspersed intermittently with some calcareous rock (Hawthorn Group) overlying the Ocala-Suwannee Limestone Groups. The Hillsborough River dissects the county as it meanders on a NE–SW trending course. Small sinkholes commonly puncture the surface, especially in the NW portion of the county. Below, the surface flooded caverns that help generate sinkholes exist within the highly porous Floridian Aquifer.

Methods

An overview of indicators measuring the karst environment is given in Table 1. Most of these indicators were used with the exception of those not applicable to the region. The indicators of subsurface karst and subsurface atmosphere were not applied because of the absence of air-filled caves in Hillsborough County. Those deleted indicators are not included in Table 1.

Data sources included information collected from websites, topographic maps, Southwest Florida Water Management District reports, Hillsborough County Government Geographic Information System (GIS) department, field surveys of sinkholes in the county, and during interviews with local and state officials. Table 2 is an overview of the data sources used for each indicator used in this study. Data collection was conducted from February to December 2005.

The field surveys involved visiting 30 randomly selected sinkholes in Hillsborough County from the Florida Department of Environmental Protection Sinkhole Database. For discussion on what defines a sinkhole, see van Beynen and Townsend (2005). The randomly generated locations were created using the ESRI ArcView program. Seven other sinkholes were examined because of their close proximity to the randomly selected ones. The total 37 sinkholes were a representative sample (~11.5%) of the known sink-

Table 1 Disturbance index for Karst environments indicators as applied to Hillsborough County, Florida (van Beynen and Townsend 2005)

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
		Macromeso	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 %	1–34%	None
		Meso	Infilling (% of infilled caves and sinkholes)	>66%	34–66 %	1–34%	None
		Meso	Dumping (% of sinkholes affected)	>66%	34–66 %	1–34%	None
	Soils	Macro	Erosion	Severe	High	Moderate	Natural rate
		Micro	Compaction due to livestock or humans	Widespread and high levels	Widespread but low levels	Few isolated concentrated areas	None
Hydrology	Water quality i) Surfaces Practices	Meso	Pesticides and herbicides	Leakage of concentrated chemicals into aquifer	Heavy spraying of crops/weeds on surface	Little use of chemicals	None used
		Micro	Industrial and petroleum spills or dumping	>20 Brownfields	10–19 Brownfields	1–9 Brownfields	No Brownfields
	Water quality ii) Springs	At all scales	Concentration of harmful chemical constituents in springs	Concentrations harmful year round	Concentrations harmful for short periods	Concentrations just above background levels in water	Pristine water
	Water quantity	Macro	Changes in water table (decline in meters)	> 35	15	<5	Only natural variability
Biota	Vegetation disturbance	At all Scales	Vegetation removal (% of total)	>66%	34–66 %	1–34%	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 (% taken)	>50	20–49	1–19	0
	Stewardship of Karst region	At all scales	Regulatory protection	No regulation	A few weak regulations	Statutes in place but with loopholes	Region fully protected
		Micro	Enforcement of regulations	Widespread destruction, no enforcement	No policing, but little damage done	Some infrequent enforcement	Strong enforcement
		Micro	Public education	None, public hostility	None, public indifference	Attempts through NGOs	Well funded government programs
	Building infrastructure	Macro	Building of roads	Major highways	Some two lane roads	Some country lanes	Minor trails
		Meso	Building over karst features	Large cities	Towns	Small rural settlements	No development
		Micro	Construction within caves	Major modification	Major tourist cave	Cave trail marked	Pristine

NGOs, non government organizations

Table 2 Data sources used to score the disturbance indicators in Hillsborough County, Florida

Indicator	Data source
Quarrying/mining	USGS topographic maps (1990)
Flooding (due to human-built structures)	Florida Department of Agriculture and Consumer Services
Stormwater drainage	Florida Administrative code: Chapter 62-522.300(3)
Infilling	1940s and 1990 USGS topographic maps
Dumping	Florida Dept of Environmental Protection (DEP) Sinkhole Database
Erosion	Soil Survey, Hillsborough County, Florida USDA
Compaction	Hillsborough County GIS Geodata Directory; Florida Department of Agriculture's 2002 Census of Agriculture
Pesticides and herbicides	Lantigua (2005), Florida Department of Agriculture and Consumer Services, Florida Dept of Environmental Protection
Industrial and petroleum spills or dumping	Florida EPA
Concentrations of harmful chemical constituents in springs	Southwest Florida Water Management District
Changes in the water table	Southwest Florida Water Management District.
Vegetation removal	Florida Geographic Data Library (USGS Landuse)
Groundwater biota—species richness	No data found
Groundwater biota—population density	No data found
Destruction/removal of historical artifacts	Florida Division of Historical Resources website
Regulatory protection	Florida Statutes; Florida Administrative Code; Florida Forever Program
Enforcement of regulations	Office of the General Council (OGC) Enforcement, Florida DEP
Public education	SWFWMD website; FL DEP website
Building over karst features	Hillsborough County GIS Geodata Directory
Building of roads	Hillsborough County GIS Geodata Directory

USGS , *USDA* , *GIS* , *EPA* , *OGC* , *SWFWMD* Acronyms for Abbreviations

holes for the county that were investigated for the dumping indicator.

Scoring System

Each indicator was assigned a score from 0 to 3 based on the extent and severity of disturbance. A score of zero indicates no human impacts had occurred to the environment. When a disturbance was apparent, the following scores were given: 1–localized and not severe, 2–highly disturbed and widespread, 3–severe disturbance. The sums of all the indicator scores were then divided by the highest possible score to attain a value between 0 and 1. The karst disturbance index provides five categories ranging from 0.8 to 1.0 (severely disturbed), 0.6 to 0.79 (highly disturbed), 0.4 to 0.59 (disturbed), 0.2 to 0.39 (little disturbance), and 0.0 to 0.19 (pristine). The closer the value is to the number 1, the greater the degree of disturbance. According to the index guidelines, if an indicator is applicable to Hillsborough County, but no data are available, a Lack of Data (LDs) score is given (van Beynen and Townsend 2005). 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. As such, ratings of <0.1 would have high confidence in the index, whereas values >0.4 suggest that more research is required before the index can be applied in that location.

Results

All the applicable indicators were measured during 2005 for Hillsborough County, Florida. Only 2 of the 20 indicators lacked sufficient data to be scored and for the remaining set, some field work was required to complete the index. What follows is a description of the application of each indicator, complete with any issues that arose from their use.

Geomorphology: Surface Landforms

Quarrying

The disturbance level for this indicator is rated on its coverage across the county. U.S. Geological Survey (USGS 2004) topographic maps from the 1990s to 2000 were utilized to indicate the type and prevalence of quarrying and mining that occurs in Hillsborough County. These topographic maps revealed that Hillsborough County has active medium-scale strip mines and reclaimed mines that are no longer active. In addition, information from the Hillsborough County

Planning and Growth Management Development Service was used to add any new mines not covered by the topographic maps. Data on the phosphate mines were collected from the Florida Institute of Phosphate Research. In total, from the above sources, Hillsborough County has 1 limestone quarry, 7 active or recently inactive phosphate mines, 9 fill quarries, 13 small sand pit mines and numerous reclaimed mines. Although there are numerous mines in Hillsborough, covering 64 km^2 of the 2644 km^2 of the county (2.4% of total area), most produce little in the way of toxic tailings. Only the very south end of the county, where the phosphate mines are located, are there acidic ponds. Because of the nature of the mining–quarrying in Hillsborough County and its areal coverage, a score of 2 indicates a high degree of disturbance.

Flooding of Surface Karst

In Hillsborough, agricultural irrigation systems are used to grow watermelons, strawberries, squash, and citrus (McGovern 2004). Flood control mechanisms, however, are in place to protect the crops and indirectly prevent agricultural flooding of the karst system (FDEP 2004a). As such, flooding occurs on a meso scale in Hillsborough County and was scored at 1, indicating a low level of disturbance.

Stormwater Flow into Sinkholes

The indicator calls for determining the percentage of sinkholes utilized for stormwater drainage. In Hillsborough County, the Florida Administrative code, Chapter 62-522.300(3), prohibits the use of sinkholes for stormwater retention ponds as well as drainage points. However, the sinkholes utilized for drainage before the passing of the law have not been re-piped (Awad 2005). The number of sinkholes (five) used for stormwater drainage (Awad, personal communication 2005) was divided by the total number of sinkholes (321) found on the 1990s–2000s USGS topographic maps. Consequently, only 1.6% of the known sinkholes are used for stormwater drainage sites. A score of 1 was given because of the low percentage of sinkholes utilized.

Infilling of Sinkholes

Construction projects within Hillsborough require sinkholes to be covered or filled-in for development, a meso scale disturbance. If the sinkhole is not properly filled, buildings on the surface are vulnerable to subsidence, a problem common in Hillsborough and elsewhere in Florida (Sinclair and others 1985). This indicator was used to determine the percentage of filled sinks in the county. USGS 1:24:00 topographic maps of Hillsborough County were utilized to assess the number of filled sinkholes by comparing 1940s maps to updated 1990–2000 versions. The 1940s quadrangle maps contained 871 sinkholes, compared to only 321sinkholes on the 1990–2000 topographic maps. Consequently, 63% of the sinkholes present in 1940 had been filled by 1990.

The sinkholes were assumed filled if the area containing the sinkhole was previously shown as non-residential on the 1940s maps, but subsequently that same area was shaded residential (purple) on the 1990–2000 maps. For example, a mall that appeared on the 1990 map was in the same location of a sinkhole on the 1940 map, so it is safe to assume the sinkhole was filled. Ground-truthing was undertaken to check the validity of this assumption. A sample of 30 of the proposed filled sinkhole sites, which was 30 sites that were colored purple on the 1990 map, were visited throughout Hillsborough County. These ‘‘infilled’’ sinkholes were separate from those selected from the dumping indicator. All were no longer present because of urban development. As such this indicator received a high disturbance rating of 2. Underestimation of sinkholes infilling may arise because not all sinkholes filled since the 1940s are removed from the later versions of topographic maps (Moore 2001). Another limitation is that new sinkholes appear and are filled but are not captured by these two sets of topographic maps.

Dumping in Sinkholes

Intentional and incidental dumping into sinkholes is a meso-scale disturbance. Only sinkholes with materials dumped into them of a quantity or quality to impact karst through clogging, pollution, and aesthetics were included in this study (van Beynen and Townsend 2005). A visual inspection of the 37 randomly sampled sinkholes was conducted for the types and amount of garbage in each locale. In Hillsborough County, dumping within the sampled sinkholes included but was not limited to soda cans, hangers, and boxes. Blue Sink, one of the largest sinkholes in Hillsborough, became clogged when a dumpster from a neighboring car dealership fell into the sink. The level of dumping throughout Hillsborough County received a score of 2.

Soil Erosion

Soils are a vital part of karst processes because they produce carbonic acid essential to weathering the limestone rock. Soils that have developed in situ in karst regions are often very thin; however, certain karst regions have a veneer of sediments deposited on top of the karst, which is the case in Hillsborough County. Increased development and continuing urban sprawl in the county has led to the increase of deforestation practices and an associated increase in erosion rates. Higher erosion rates also occur in areas with steep gradients. Because Hillsborough county is part of the Gulf Coastal Lowlands, the underlying Suwannee–Ocala Limestone is covered with a mantle of ~5 m sandy clay (Randazzo and Jones 1997). Figure 1 shows the current location of forested areas in Hillsborough County and the current locations of urban and subdivision growth. However, the county has very low relief to escalate the erosion processes. In fact, 63 of the 74 soil classifications within Hillsborough County had slopes between 0 and 2% (Leighty 1958). In construction areas, weed mat prevents soil washing from the site. In rural areas shelter belts are used to decrease aeolian erosion. Therefore, the erosion indicator received a score of 1.

Soil Compaction

Disturbance of a karst environment through soil compaction leads to reduced water percolation, accumulation of water on the surface, and increased flooding of the area. It also increases anoxic conditions in the soil and can alter the aquifer recharge rate. Compaction of soils can be caused by livestock, farming activities, or urbanization. The sandy soils in Hillsborough are not greatly compacted by agriculture, and the scoring of this indicator was established mainly by determining the amount of urban lands in comparison to the total land area of Hillsborough County. Figure 1 shows the current land use for urban areas. Compaction is occurring throughout the county in high levels due to building of roads, housing, and commercial and industrial infrastructure. Urban lands account for 38% of the county's total land area (Floyd 2003) and the county is ranked seventh in the state for population density in 2002 (Floyd 2003). Based on these figures as well as the construction of new urban areas, compaction of the soils was rated a 3.

Hydrology: Surface Practices

Pesticides and Herbicides

Agricultural and residential properties, alike, are typified by the intense use of pesticides and herbicides (van Beynen and Townsend 2005). This indicator was determined by analyzing the frequency and quantity of pesticide and herbicide application within the county as opposed to specific concentration levels. Because of the widespread nature of agricultural fields in Hillsborough County, pesticide and herbicide use is considered a macroscale disturbance. However, with the rapid conversion of rural to urban areas within the county, this indicator will probably become a mesoscale disturbance over the next decade. Tampa Bay Water only measures pesticide levels at its well fields which are not in urban areas (Troutt, 2006 personal communication), and consequently there no data available to assess its use or impact in urban areas and consequently it cannot be included in this index.

Hillsborough County agriculture is largely horticultural, which uses large amounts of pesticides and herbicides, with Florida being the largest users of these products in the nation (Lantigua 2005). Small cattle farms can also be found scattered throughout the county, but there is no record of pesticide or herbicide use on these farms. The Florida Department of Agriculture Bureau of Pesticides regulates pesticides, maintains a chemical laboratory for the monitoring of ground and surface water for excessive pesticide or herbicide concentrations, registers pesticide products, and conducts scientific reviews on the environmental and health risks of pesticide use in any particular region. However, the Florida Department of Agriculture and Consumer Services has only one inspector who is responsible for 300 farms in Hillsborough (Lantigua 2005). Farms are inspected once every 2 years, and farmers are usually told a week in advance of an impending inspection.

Some encouraging steps have been taken in Hillsborough County to prevent the dumping of old or banned pesticides into the karst environment. Operation Cleansweep, run by Florida Department of Environmental Protection (FDEP 2004b), has collected 60,600 pounds of cancelled, suspended, and unusable pesticides between years 2000 and 2006, for safe disposal. Because of the high use of pesticides in Hillsborough for agricultural purposes and the sporadic enforcement of the pesticide regulations, this indicator was ranked a 2.

Industrial and Petroleum Spills or Dumping

The Environmental Protection Agency (EPA) defines brownfields as "real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" (USEPA 2003). These sites generally have high contents of volatile organic compounds (VOCs) and dense or light nonaqueous phase liquids (D- and LNAPLS) due to their former industrial use. From these sites, the VOCs leach into the groundwater.

Hillsborough has a history of contaminated sites. Honeywell International had a major spill in 1982 but has yet to take measures to clean the site, and the company is resisting DEP orders to undertake certain remediation measures (Salinero 2005). Although Honeywell has not disclosed what chemicals were spilled at the site, it manufactured circuit boards that contain, or use in the production of, compounds such as polybrominated diphenyl ethers (possible endocrine 7disrupter), ferric chloride (corrosive, irritant, and mutagen), numerous acids and many others. Another example of industrial pollution is the Helena Chemical Company contamination of soils and groundwater with wettable dusting sulfur and formulated pesticides, herbicides, fungicides, and liquid and dry fertilizers. This site is adjacent to another spill, the Alaric Area Groundwater Plume Site, which is commingling with the Helena pollution plume (USEPA 2005).

Thus, when determining the ranking score for this indicator, the number of known brownfields in Hillsborough County was considered. In van Beynen and Townsend (2005), this indicator had a microscale disturbance designation, because of the relatively small and localized nature of brownfields. However, because of the rapid hydrologic flow characteristics of karst and the potential for spreading plumes, we have changed this scale to meso. To date, the EPA has classified four brownfields in Hillsborough County, giving this indicator a score of 1.

Hydrology: Spring Water Quality

The spring water quality indicator is a new addition to the karst disturbance index. The original indicator, *Occurrence of Algal* Blooms, was too imprecise and would miss important aspects of pollution in individual karst areas. Consequently, the *Occurrence of Algal Blooms* is no longer being used, and has been substituted for the following indicator.

Concentration of Harmful Chemical Constituents in Springs

Elevated levels of harmful chemicals in the outflows of karst areas, namely, springs, is a measure of the human impact on water quality over the karst. An example of harmful chemicals includes excessive nutrients from leaking septic tanks, improper disposal of animal waste onto pastures, or nitrogen and phosphate fertilizers. More toxic chemicals that can occur in springs are arsenic, cyanide, lead, chromium, DNAPLS, LNAPLS, polychlorinated biphenyls and other synthetic organic compounds. For this indicator, it is impossible to give an exact list of which chemical constituents to measure because the list would be vast and highly specific to each karst region. Consequently, we suggest that the expert applying this index should be most familiar with the pollution problems in the area and which chemicals constitute the problem compounds.

In Hillsborough county, nitrates and phosphates are problematic in inducing environmental eutrophication. An example of this is that the seagrass population dropped dramatically in Tampa Bay due in part to increased nitrogen loading (Lewis and others 1985). Evidence for these increased nitrate loads is shown in the spring data obtained from ''The Hydrology and Water Quality of Select Springs in the Southwest Florida Water Management District'' (SWFWMD 2001). The report stated that normal nitrate and total phosphorus levels should be <0.01 mg/L; however, levels of nitrate, from inorganic fertilizers, have increased, leading to the increased occurrence of the algae *Lyngbya*. All springs in Hillsborough County had >3.0 mg/L of nitrate, with Bell Creek Spring having >10 mg/L, as the result of local animal waste. Total phosphorus levels ranged from 0.01 to 0.05 mg/L throughout Hillsborough County. The report concluded that Sulphur Springs had a nitrate level of 0.89 mg/L and a phosphorus level of 0.11 mg/L. In addition, Lettuce Lake Spring, mostly covered by algae blooms, had nitrate levels of 3.05 mg/L and phosphorus levels of 0.06 mg/L. Other more toxic chemicals have been introduced to the groundwater as mentioned previously, but these are more meso-scale events. All of this information was combined to create a score of 2.

Hydrology: Water Quantity

Changes in Water Table

The overpumping of water from an aquifer, for public or commercial use, can create a drop in the water table. In Hillsborough County, excessive pumping of water serves as a mesolevel disturbance. Water table levels often have natural variability due to seasonal changes in precipitation or drought conditions. These changes were disregarded when determining the score for this indicator in order to better reflect the level of human-induced water table changes.

Although central Florida has several water-bottling companies that extract spring water for commercial use, these companies are located in neighboring counties and not in Hillsborough County (Samek 2004). As of November 16, 2005, water levels had decreased an average of 0.25 m in Hillsborough County in the month of October alone, despite the county having record amounts of rainfall during the same month (SWFWMD Hydrologic Data Section Operations Department 2005). In the same report, 43 of 52 Floridan aquifer wells monitored by the SWFWMD were noted with lower water levels in October 2005 than in October 2004; however, these water levels varied only by 1.54 m. This trend is in addition to a decline in the Floridian Aquifer underneath Hillsborough of 3–6 m since the 1930s and in some areas as much as 13 m (SWFWMD 1988; 1993; 2001; 2005). Overall, this indicator was given a score of 2.

Biota: Vegetation Disturbance

Vegetation Removal

Vegetation removal from clear cutting or fire, for agricultural or logging practices has an adverse affect on karst systems (Harding and Ford 1993). Thus, this indicator was based on the total percentage of deforestation, or the total percentage of substantive vegetation removal that could adversely impact a karst system and is considered a macroscale disturbance. Dividing the total number of forested lands, 17 km^2, by the total land area, 339 km^2, indicates that 95% of Hillsborough County forested lands have been destroyed. These numbers were determined from GIS data collected from the Hillsborough County Government Office; Figure 1 illustrates the remaining forest cover in the county. Based upon this analysis, vegetation removal was given a disturbance ranking of 3.

Biota: Subsurface Biota

Species Richness

Only subsurface biota, that is, species living inside caves and species living in groundwater, were considered in this indicator (van Beynen and Townsend 2005). Disturbances to the subsurface karst biota in Hillsborough County are difficult to research because of natural flooding of the caves. Consequently, there is a significant lack of data concerning Hillsborough County subsurface species richness, so this indicator received a ‘‘Lack of Data’’ (LD).

Species Population Density

Population density is the measure of the number of individuals of each species. Population density is a microlevel indicator, because of the individuality of species variance and living conditions within each cave environment. As with species richness, this calculation requires extensive research spanning large periods of time. Because these data concerning Hillsborough County do not exist, the indictor was assigned a LD.

Cultural: Human Artifacts

Destruction/Removal of Historical Artifacts

Hillsborough County has small, concentrated areas containing historical artifacts; thus, this indicator is a microlevel disturbance. The destruction or removal of historical artifacts is important from the viewpoint that karst locations can provide unique locations for burial sites, religious shrines, or even prehistoric dwellings. Although unflooded caves are not found in Hillsborough County, surface sites are still important because sinkholes are common archaeological sites. The removal and destruction of the artifacts from karst environments determined the scoring for this indicator.

The database for historical artifacts, on The Florida Division of Historical Resources website (Florida Department of State 2005), was utilized to determine the areas throughout Hillsborough County where artifacts were discovered. Thus far, 355 archaeological sites have been uncovered, with 38 middens, 58 mounds, 38 settlements, 2 burial sites, and 1 fishing site (de Montmollin 1983). The database did not indicate that any of the sites were protected, nor did it describe what happened to the artifacts after their discovery (Florida Department of State 2005). However, Deming (1980) stated 40% of these sites had been destroyed, a number deemed very low by Dr. Brent Weisman, a University of South Florida anthropologist who conducts research in the county. He suggested that sites situated on developments described as having regional significance (>20 ha) would not be protected (with the exception of a large burial mound). For a site to be protected, it must meet the eligibility requirements for listing in the National Registry of Historic Places. No archaeological sites in Hillsborough County have been through this long, rigorous process. The most significant site was a large settlement–burial mound complex in what is today's downtown Tampa, though very little remains of the site because of commercial development. Such a situation exists for all the significant settlements–mounds in the county (Wiesman, 2006. personal communication). Only when a site is located within a state or county park is it safe from development. Admittedly, most of the artifact sites would not meet the requirements of the National Registry of Historic Places, but those destroyed may represent a high degree of urban development (45% of county) and major roadways dissecting the county (Wiesman 2006, personal communication). Overall, the disturbance to the artifacts scored a disturbance level of 3.

Cultural: Stewardship of Karst Region

Human stewardship is measured by the regulatory protection, enforcement of regulations, and public education about the unique characteristics of karst environments regions. Stewardship can occur at all scales from the protection of a single karst feature to the complete protection of an entire karst region.

Regulatory Protection

Regulatory protection consists of laws that either prohibit or limit the amount of disturbances to karst areas as well as laws that regulate aspects of karst systems. Under the Federal Cave Resources Protection Act of 1988, caves and cave resources (such as animal and plant life, paleontological deposits, minerals, and speleogens and speleothems) on federal lands are protected as an ''invaluable and irreplaceable part of the Nation's natural heritage'' (United States 1988); however, Hillsborough County does not have any caves on federal lands that receive this statutory protection.

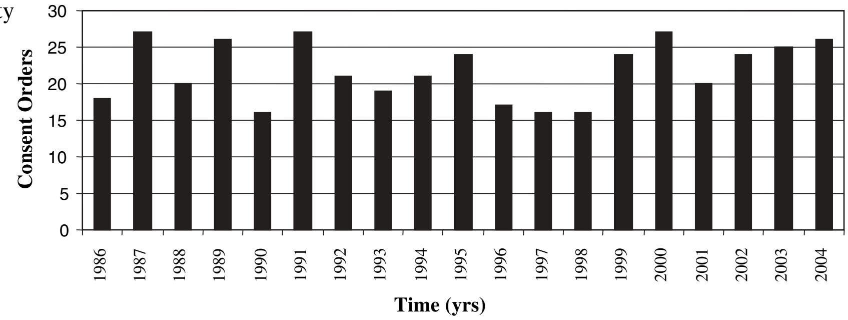
The Florida Administrative codes have several statutes that directly or indirectly protect karst systems. The administrative code, Chapter 62-522.300(3), prohibits any discharge through sinkholes that will have direct contact with class G-I groundwater (single-source aquifer with dissolved solids of <3000 mg/L), or G-II groundwater (dissolved solids of <10,000 mg/L). Chapter 62-610.523(9) states that the physical characteristics of unconsolidated materials overlying the bedrock shall be such that direct rapid movement of reclaimed water to underlying aquifers does not occur unless requirements of 62-610.525 of the F.A.C. are met. These requirements state that total nitrogen should be less than 10 mg/L, there shall be filtration for suspended solids, water shall not contain more than 5 mg/L of suspended solids, and water should meet a minimum of secondary treatment and receive a high level disinfection. Broadly, the Florida Administrative Code does not allow any materials of concern to be discharged to karst features (Administrative Code 2005). Florida Statute 810.13 also makes it a misdemeanor crime to vandalize, deface, or remove any cave, cave life, sinkhole, speleogen, or speleothem on public or private property without the written permission of the owner (Florida Statute 810.13 1998). The sale of speleothems is also not permitted under this law, nor is the storage of any chemical or other material hazardous to the ''waters of the state'' within a cave.

According to the Department of Environmental Protection, a karst risk analysis is conducted when any area of planned collection or channelization of storm water, reclaimed water, or other effluent could become introduced to karst systems (K.T. Moran, personal communication, 2005). Similar to an Environmental Impact Statement, if these reports conclude that damage is incurred to the karst system, the planned construction will not be able to proceed.

In 1999, the Florida Legislature established the Florida Forever Program. The main mission of this program is to restore damages to environmental systems, including Florida's springs, as well as to increase the amount of land protected by the acquisition of conservation areas. Ideally, by setting aside more areas for recreational parks, karst environments would benefit. In Florida, the selection of land for conservation is based upon nomination and population demands, not on any environmental criteria, although the Hillsborough County Department of Parks mission is to provide recreation and preservation of resources (Hillsborough County 2005b).

Despite the presence of these rules and procedures, the indicator of regulatory protection receives a disturbance score of 1 because the regulations at both state and local levels are not specific to karst. Instead, they indirectly regulate karst systems. These regulations are not ironclad and there are possible means to legally violate them. In 1995, the U.S. Environmental Protection Agency authorized the Florida Department of Environmental Protection to implement the National Pollutant Discharge Elimination System to permit surface water discharges mainly from industrial and domestic wastewater facilities. Although Florida has reduced the discharges to surface waters by 32% as of March 18, 2004 since receiving the authorization, the release of these discharges would disturb karst systems (USEPA 2003).

Fig. 2. Consent Orders for Hillsborough County pertaining to the karst environment, 1986–2004



Landfill regulations can be considered as indirect protection for karst areas because the discharge material can pollute the groundwater and the aquifer. There are 162 abandoned landfills that are not monitored by the state in Hillsborough, because Chapter 403.0885 of the Florida Statute (2001), which promotes the establishment and authorization of a state-administered National Pollution Discharge Elimination System program, has not been passed at the time of their abandonment. However, Hillsborough County does monitor groundwater for 16 of the landfills, and the City of Tampa is responsible for monitoring 49 landfills. Ninety-seven landfills are not considered the responsibility of either the City of Tampa or Hillsborough County (R. Cope 2005, personal communication).

Enforcement of Regulations

It is important to evaluate the level of enforcement that occurs to determine whether the karst region is being protected against human disturbance. In 2004, the Florida Department of Environmental Protection (FDEP) released a report on the agency's statistics of civil and criminal enforcement of environmental laws. This report was based on statewide data and included violations not directly affecting karst. According to the report, in comparison to the four previous years, regulatory enforcement throughout the state increased by 35% from 2000 to 2004 (FDEP 2005). An almost 10 million dollar increase in penalty accumulation was also acquired during this time period. Consent orders, an agreement between the violator and FDEP enforcement, increased by over a thousand orders statewide compared to previous years.

To learn about the enforcement level specifically in Hillsborough County, the authors collected consent order data for Hillsborough County karst violations from 1986 to 2004 to determine whether an increase in enforcement did in fact occur (FDEP 2005) Figure 2 indicates an increase in the number of consent orders during the time frame 2001 through 2004. However, in comparison to previous years, a low number of consent orders from 1986 through 1999 could indicate either that fewer violations occurred or that enforcement was not as strict. Comparing the increase in enforcement from 1986 to 1999 with the period from 2000 to 2004, the earlier period had an annual average of 20.9 consent orders whereas the 2000–2004 period had 24.4, a 14% increase in enforcement. Because there was not an increase as stated in the report and because no year reached higher than 30 orders, enforcement of regulations received a score of 1 for the disturbance index.

Public Education

Public awareness of karst and protection practices is vital to the maintenance of karst systems. This indicator examines the roles of nongovernmental organizations (such as local environmental organizations) and governmental programs in their public education efforts that either directly or indirectly protect the karst environment in Hillsborough County (van Beynen and Townsend 2005). Hillsborough County has several programs in place to protect various aspects of the local karst environment. The Southwest Florida Water Management District (SWFWMD) currently funds area community groups to increase groundwater protection. One project, The Linked Resources for Community Education in Hydrogeology, teaches about sinkholes, the hydrologic system, stormwater runoff, and Florida-friendly vegetation (SWFWMD 2005). SWFWMD also coordinates the Waterwise Florida Landscape Program that provides education to the public on the type of landscape that best protects Florida's springs and provides many brochures on water pollution and conservation.

The City of Tampa Solid Waste Department is very active in its public education efforts, producing brochures listing hazardous waste materials to educate the public on proper disposal methods (City of Tampa 2005a). To further encourage local participation, the department created The Neighborhood Environmental Action Team to conduct waste cleanup, report any environmental violation, and conduct the collection of nonhazardous materials that may degrade the quality of karst environments. The University of South Florida is home to the Karst Research Group, a group comprising interdisciplinary faculty and students who are dedicated to researching karst environments and promoting awareness of the importance of karst (Karst Research Group Website 2005).

Several television programs directly and indirectly educate the public about the need to protect the local karst environment. Focused specially on the local karst environment, SWFWMD produced a documentary called ''Water's Journey: The Hidden River's of Florida'' (Karst Productions Inc. 2004) that has been repeatedly shown on the local WUSF-TV public television station. The City of Tampa Water Department runs water conservation programs for K–12-grade students. The city also funds CTTV Water Conservation Plays, which educate children on the importance of water conservation (City of Tampa 2005b). The Florida DEP Hydrogeology section also offers an interactive video on human threats to Florida's springs and the impact to the aquifer (FDEP 2005). The site also promotes an educational program for third to fifth graders to develop a model of how pollutants can alter water quality.

A limitation of these public educational efforts is that the agencies are not strongly promoting the programs, and many of these programs only reach people who actively seek the information or who might already be conscious of disturbances to the environment. Thus, Hillsborough County receives a score of 1 with regard to public education.

Cultural: Building Infrastructure

Building of Roads

Modern development, because of increased population and urban sprawl, is a form of macro-disturbance to karst areas that can create widespread karst disturbance. Figure 1 shows the major roads and highways in Hillsborough County. There are three interstate highways in the county and 34 major roads have up to eight lanes divided by a median (Hillsborough County 2005c). Based on the data, as well as the maps generated through ArcGIS software, the ever-increasing road construction in Hillsborough County rated a 3, indicating highly disturbed.

Table 3 Classification of disturbance

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

Building Over Karst Features

Through the building of large apartment complexes, malls, and residential developments that typify Florida's rapid urban expansion, many karst features will be impacted. In 2002, Hillsborough County had a population density of more than 405 people/km^2 and a 5.9% increase in home construction was recorded between 2000 and 2002 alone (Floyd 2003). Because of the increasing construction of urban areas over karst features, the building over karst features received a score of 3 on the disturbance index.

Construction Within Caves

This indicator will not be used in this application of the index because all the caves are submerged in Hillsborough and construction is impossible.

Degree of Disturbance: Hillsborough County

A total score of 37 of a possible 54 was calculated for the geomorphology, cultural, biota, and hydrogeology categories applied to Hillsborough County. The overall score for the entire index that measures the total level of karst disturbance was then calculated at 0.68, which according to Table 3 is *highly disturbed*. It is worth noting some of the indicators that scored a 3: quarries, urban development, and disturbance of archaeological sites in Hillsborough. Only two of the indicators that could be applied to Hillsborough County had insufficient data and were given the ''Lack of Data'' designation: *Species richness* and *Population density* under the biota category.

The final aspect of the index to calculate is the confidence we have in its application to Hillsborough County. For Hillsborough County, 20 indicators were applied, with only two LDs. Thus, the rating was 0.1, providing a high degree of confidence in the estimation of the level of disturbance of this region.

Discussion

The application of the Karst Disturbance Index to Hillsborough County provided a valuable opportunity to assess the degree of human disturbance but also allowed for the index's refinement.

Human Disturbance in Hillsborough County

The index application to Hillsborough yielded a result that the karst environment was highly disturbed. However, the wide scope of the index does highlight certain aspects of the environment that are under great stress. Soil compaction, deforestation, archaeological sites, and urban development (building of roads and cities) indicators were scored a 3, providing pointers to areas of concern for the region. This concern is generated by the large increase in population of Hillsborough County in recent years. The growth of new suburban development is spreading the human imprint on the landscape, increasing environmental impact. Although agriculture preceded much of this urban sprawl, it generated a somewhat lesser impact or alteration of the natural karst environment.

Results from the index can be used by resource managers to create a baseline for the level of human disturbance, and with repeated applications of the index, resource managers or county officials can assess how the overall state of disturbance (i.e., environmental quality) has improved or worsened. Through disaggregation of the index, the indicators that scored a 3 (severely disturbed) would be good candidates for investigation by the managers to provide guidance as to where resources may be allocated to improve environmental quality or lessened human disturbance. For example, in Hillsborough County, urban sprawl is rapidly increasing the housing over karst, leading to increased soil compaction, deforestation, and decreased water quality. Insufficient consideration of the underlying karst environment is leading an increase in problems of sinkhole development beneath houses, leading to rising insurance rates for homeowners. Restrictions placed on conversion of farmland or scrubland to new residential–commercial developments and instead promoting urban renewal projects accompanied with reforestation–conservation projects would reduce human disturbance. Examples of these types of projects have been undertaken in Aurora, Illinois; and Irvine and Anaheim, California (Jackson and others 2006). However, providing recommendations on reducing human impact is not within the scope of this article.

Regional managers could also use the index to compare counties within Central Florida if the index were to be applied to neighboring counties. Such an approach may highlight hot spots within the region that require remediation as identified by certain indicators. Pasco County, to the north of Hillsborough, is experiencing rapid urban development, which is accompanied by environmental deterioration which the index can quantify.

Refinement of the Index

Of the indicators that could be used in the index, 90% of indicators had sufficient data to measure the disturbance levels. This led to a high degree of confidence in the validity of the index. Only two indicators pertaining to biota could not be scored because of a lack of data.

However, the use of the index did reveal some important points about the quality of data and refinement of certain indicators. Starting with the quality of data held by state and local agencies for both sinkhole locations and their status increased the difficulty of accessing the level of disturbance. Previous funding for recording sinkhole locations allowed the creation of the Florida Sinkhole Research Institute at the University of Central Florida (FSRI 1985). This program dissipated because of insufficient funding, but during its tenure, the Institute provided the only data on sinkhole occurrence in the state. The Florida Geological Survey has continued this database, although most of the sinkholes reported are from insurance claims. There has been much debate as to whether many of the "sinkholes" are really sinkholes or merely subsidence of sediment beneath the house resulting from poor building practices. For insurance purposes, sinkhole formation is preferable to the homeowner because claim reimbursement is more lucrative than from subsidence.

Topographic maps were utilized to determine the amount of infilling that has occurred in Hillsborough County. Unfortunately, these maps are not modified completely when revisions occurred, and contour lines were not changed after the filling of sinkholes. Examining aerial photographs would be a better way to determine whether sinkholes present in previous years had in fact been filled. Recent aerial photographs would also help locate open sinkholes for the field testing of the dumping and filling of sinkholes indicator. Such a project is currently under way at the University of South Florida.

Indicator score descriptions were found to be constraining in certain instances. This problem can be resolved by broadening the descriptions to encompass more scenarios. For example, the descriptor for providing a score of one for the *Public Education* indicator identified only nongovernmental organizations; however, Hillsborough County's governmental agencies play a large role in the education of the public regarding the karst environment. Similarly, the *Quarrying/mining* indicator only called for an examination of large-scale strip mines whereas reclaimed mines were not taken into account. However, every karst region will have its own unique characteristics that should be included in the assessment of disturbance level. Consequently, when determining a score for an indicator, it is important for the evaluator to not rely only on the indicator descriptor but also on the characterization of what the score means: a 3 is for severe disturbance through to a 0 for pristine environments.

Determining what laws and public awareness programs pertained to karst stewardship was problematic because the regulations and programs usually did not apply directly to karst environments. Even though many regulations were not specifically written for karst areas, they do provide protection to sensitive karst systems.

The *Occurrence of Algal Blooms* was the only indicator that was entirely replaced through the application of the index. It was deemed that to test water quality more holistically, an indicator should be more adaptable to individual situations. Consequently, a new indicator, *Concentration of harmful chemical constituents in springs*, was created to highlight elevated levels of harmful chemicals in the outflows of karst areas. Each karst region will probably have a different set of harmful water constituents, and the new indicators leave it up to the expert to determine which ones are particularly problematic for that locale and how severely that impact is to the water quality. We believe this is a better approach than the more narrowly focused *Algal Bloom* indicator.

Species richness and species population density received a score of lack of data. This represents a general problem with karst research in that little is known about biota of karst systems. This is not a shortcoming of the index, but more an indication of a lack of biospeleological research in certain areas. However, if we refer to the OECD's and IDRC's indicator guidelines, they state that indicators should be consistent and reproducible. Thus, the insufficient data for species population density pose a problem for the consistent and comparable application of the index. The inclusion of biotic data is ideal; should this information be readily available, we believe the indicator should remain in the index, even though this it will commonly receive a LD when the index is applied.

In conducting this study, we discovered that the wording of the rating system should be changed from what is shown in the original karst disturbance index. We recognized that there is a need to use clearer words to describe the scale of disturbance and a need to be more consistent in usage between the individual indicator ratings and the final index score. For instance, to many people ''catastrophic'' disturbance may convey a preconceived notion of completely destroyed with no chance of repair. Thus, a score of 3 was changed to mean ''severe'' disturbance. Also, we believe that the label of ''severe'' disturbance can be correlated more easily with the total degree of disturbance, which has categories named ''highly disturbed, moderately disturbed, disturbed, little disturbance, and pristine.''

Future Application of the Index

There are certain factors that must be considered before applying the index to another region. First, there is a need to retool the biotic category to revise the species richness and population density indicators to increase the category's utility. Only certain karst regions in North America and Europe have the data available to support these indicators. Van Beynen and Townsend (2005) stated that selecting individual indicator species would be problematic because of disagreements about which species to use. However, on viewing what little literature exists for Management Indicator Species (MIS) for Karst (Doran and others 1999), the list of possible candidates used could be as few as three to five species, such as certain bats species, blind fish, salamanders, or equivalent organisms. Consequently, for future applications of the index, the viability of MIS will be investigated to increase the utility of the biota category. Second, with the future application of the index, the indicators will be reviewed for tightening their quantitativeness to reduce any likelihood of evaluator subjectivity. Most of the indicators applied to Hillsborough County were quantitative, but qualitative indicators were pesticide and herbicide use and those pertaining to cultural values and protection. Finally, through the refinement of the index, the aim is to increase its applicability to resource managers. Part of that refinement is the index application resolution, which involves determining what level of spatial resolution has the greatest utility to managers.

Conclusions

A holistic approach of an environmental index combining both quantitative and qualitative indicators was applied to the karst landscape of Hillsborough County to assess the degree of human disturbance. The successful application of the index resulted in a ranking of ''highly disturbed'' for the county. Areas of most concern were soil compaction, deforestation, archaeological sites, and urban development (building of roads and cities). With all but two of the applicable indicators being measurable, a high degree of confidence in the results of the index was achieved.

The index is useful for regional resource managers to not only assess temporal changes in the environmental quality of their jurisdiction, but also to highlight components most in need of remediation. For Hillsborough County, the rapid urban development is clearly responsible for the high degree of disturbance. Conversion of scrubland–agricultural pastures to new suburbs is leading to vegetation clearing, soil compaction, disruption of archaeological sites, and building over the karst environment. Hillsborough County has the capability to reduce such impact by taking measures such as urban renewal projects to minimize the urban footprint in the county.

Recommendations that arose from the application of the index include the following: 1) deficiencies in current data held by state and local agencies for both sinkhole locations and their status complicated the application of certain indicators; 2) the use of aerial photographs would be the most accurate method to determine the fate of sinkholes rather than relying on topographic maps; and 3) indicator score descriptions should be broadened to encompass a greater diversity of possible scenarios. However, we stress that when determining an indicator's score, the evaluator should not only rely on the indicator descriptor but also on the overall characterization of the score; and 4) biota category indicators of species richness and population density require retooling to reduce the likelihood of continual ''lack of data'' designation.

Acknowledgments We thank Dr. Brinkmann for his thoughtful comments of the manuscript prior to submission and the anonymous reviewers' comments, which helped improve the quality and context of the article.

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