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Hydrogeologic Constraints on Yucatán's Development

The peninsula's water resource is threatened by man-induced contamination.

Donald O. Doehring and Joseph H. Butler

The northern Yucatan Peninsula, once the site of some of the most impressive expressions of Mayan civilization, is now a region undergoing rapid cultural and economic modernization. Implementation of national health programs over the past few decades, particularly programs controlling malaria, has lowered the death rate and resulted in unprecedented levels of population increase on the peninsula. The federal government has sponsored colonization of sections of the peninsula, bringing in families from other, more densely populated parts of central Mexico. It has also organized and supported a program of building low-cost, all-weather roads to connect remote villages with other towns and cities of the region. The dramatic lowering of real transportation costs for goods and people, together with the availability of inexpensive transistor radios, is increasing the mobility and changing the cultural patterns of the people in all but the remotest Mayan villages of central Quintana Roo.

Increased population, in-migration to the peninsula, and new levels of mobility all combine to increase stress on the hydrologic environment. The territory of Quintana Roo, for example, is expected to double its urban population during the period 1971 to 1976 (*1*). In order to meet the needs of the burgeoning population, governmental policies and programs have been sponsored to encourage and assist the economic development of the peninsula (*2*). Emphasis has been placed on municipal water supply systems, irrigated agriculture, and industrial water supply. Tourism is fast becoming a leading source of revenue. All of these activities tend to create new spatial concentrations of requirements for fresh water in towns, cities, irrigated agricultural districts, and resort areas. This new configuration of water demand is very different from the dispersed pattern of the past. The only natural source of fresh water on this karstic platform is a fragile aquifer system consisting of a freshwater lens floating on saline water. Evidence strongly indicates that the spatially concentrated demands on the freshwater lens are creating a new and serious set of environmental problems.

In this article we will attempt, on the basis of field evidence and within the bounds of existing data, to assess two of these problems: (i) pollution of the freshwater lens by the diffusion of basal saline water due to high-discharge pumping of wells and the attendant drawdown and brine-coning, and (ii) increased danger of waterborne disease due to contamination of low-discharge wells by pathogens. Both of these problems are directly related to the hydrogeologic environment and threaten to act as constraints on the economic improvement and well-being of the residents of the study area. A further objective will be to suggest strategies designed to lessen the long-range potential threat of these problems; we believe that such strategies will be applicable to other developing tropical karst regions with similar problems.

Dr. Doehring is an environmental geologist and geomorphologist in the department of geology and geography, University of Massachusetts, Amherst 01002. Dr. Butler is a geographer and civil engineer in the department of geography, State University of New York, Binghamton 13901.

Hydrogeologic Environment

The Yucatán Peninsula is located in southeastern Mexico, where it protrudes into the Gulf of Mexico and the Caribbean Sea. It is composed of part of the state of Campeche, the state of Yucatán, and the territory of Quintana Roo (Fig. 1A). Figure 1A shows Mérida, the capital of Yucatán, which has a population of some 250,000; Valladolid, the second largest city, with approximately 50,000 inhabitants; and Peto, a town with about 8,000 inhabitants, which served as a base for much of our fieldwork. The study area consists of the state of Yucatán and the northern two-thirds of the territory of Quintana Roo, and comprises approximately 70,000 square kilometers.

The peninsula lies between latitudes 20° and 21°N and, for the most part, has a tropical climate (type Aw in the Köppen classification). Monthly mean temperatures vary from about 20°C in November and December to 30°C in May and June. Temperatures below 10°C are exceedingly rare. Rainfall is not evenly distributed in space or time. Figure 1B is an isohyetal map showing mean annual rainfall in meters. Most of the area receives 1.0 to 1.4 m annually, with the rainfall diminishing northward toward the coast and with one region in the northeastern part of the peninsula receiving anomalously large amounts. The wet season normally begins in May or June and extends to November. Severe and sometimes localized droughts are not uncommon on the peninsula. The northern Yucatán Peninsula may be characterized as having relatively mild dry winters and hot wet summers. The warm, even temperature of the region is conducive to the viability of microorganisms.

Geologically, the peninsula may be

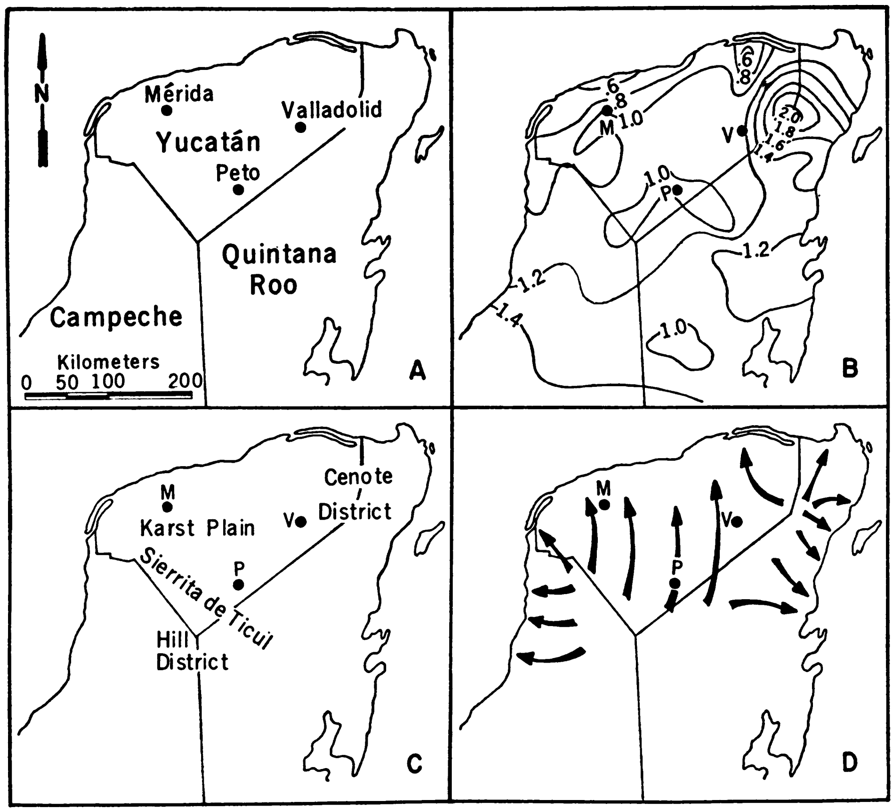

Fig. 1. Maps of the Yucatán Peninsula showing (A) place-name geography, (B) isohyets of mean annual rainfall in meters, (C) geomorphic provinces, and (D) interpreted pattern of groundwater flow.

characterized as a Cenozoic carbonate platform. The flat-lying limestones have been subdivided into biostratigraphic units (*3*); they are largely cream to white crystalline limestones, which in places are marly, silicified, or dolomitized. Intergranular, fracture, and solution porosity make these rocks extremely permeable (Fig. 2). Pump-down tests on aquifers yielded transmissibilities ranging from 4 million to more than 13 million gallons per day per foot (*4*). These extreme transmissibilities are high even for limestone aquifers.

The rocks of Yucatán are nearly horizontal across the region, except in the southern part of the study area, where they are folded and faulted to form a low range of hills named the Sierrita de Ticul. The geomorphic subdivisions of the peninsula are shown in Fig. 1C. Most of the study area consists of an undulating karst plain which slopes from sea level at the coast to an elevation of approximately 30 m at the base of the Sierrita de Ticul. The two most prominent landforms in this region of subdued topography are the low subconical hills, termed hums by geomorphologists, and the sinkholes or depressions which dot the karst plain. The sinkholes or dolinas are of two general types, the steep-walled cylindrical type shown in Fig. 2, and the bowl-shaped depressions locally called *bajos*. These features are formed by solution and by collapse of cavern ceilings. The development of a particular type of sinkhole depends, in part, on the relative volume of rock in the former roof, and on the degree of modification to the sinkhole by subsequent slope processes. The term cenote (from the Mayan *dzonot*) is used in Yucatán to refer to any natural subaerial exposure of groundwater. Hence, caves and sinkholes which intersect the water table are given this name.

The Sierrita de Ticul has a maximum relief of approximately 100 m and trends northwest to southeast for some 200 km. South of the Sierrita is the Hill District, a region of rolling hills at a somewhat higher elevation than the karst plain to the north. In the northeast part of the peninsula, corresponding approximately to the area of anomalously high rainfall, is the Cenote District. In this region the density of cenotes is considerably greater than in the remainder of the peninsula. The northern Yucatán Peninsula may be characterized as a platform of extremely permeable carbonate rocks which have been faulted and folded to produce one low range of hills and which have been etched to form a karst topography.

The insoluble fraction of the limestones produce the soils of Yucatán. They are thin, residual, terra rossa soils and are commonly rich in the mineral halloysite. The natural color of these soils is chocolate brown, but oxidation of organics due to the burning of vegetation in connection with shifting agriculture has turned the soils bright reddish brown (*5*), which prompted early workers to misclassify them as laterites. Isphording and Wilson (*5*) have mapped and studied the soils of the peninsula. In the study area, soil thickness rarely exceeds a few centimeters, and most of the terrain consists of bedrock outcrops with thin accumulations of soil in topographic lows (Fig. 3) (*6*). The thin soils of Yucatán do little to impede the rapid infiltration of meteoric water. Even during intense summer storms surface detention is rarely observed.

The high infiltration characteristics of the surface, high permeability of the rocks, and low relief of the area combine to produce a regional aquifer with a very low hydrologic gradient. For example, at Chichén Itzá, some 80 km from the coast, the elevation of the

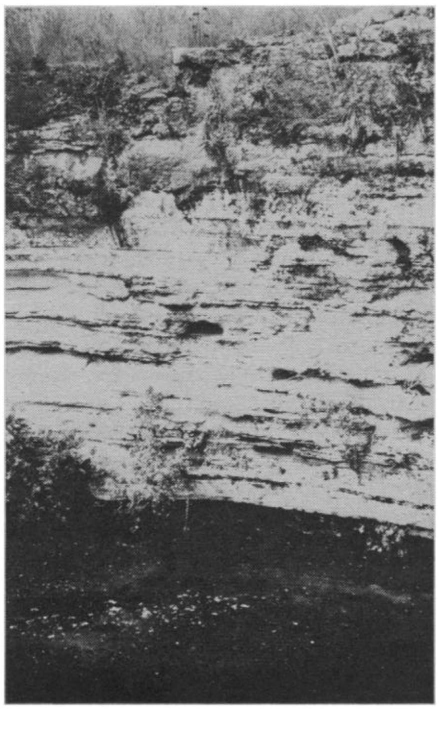

Fig. 2. A 30-m exposure of the Piste member of the Chichén Itzá Formation exposed in the wall of the Sacred Cenote at Chichén Itzá. The cavernous nature of this rock is typical of Yucatán's carbonate substrate.

water table has been measured at 1.2 and 1.4 m above mean sea level (*7*). Figure 1D shows the general pattern of groundwater flow as interpreted from the regional topography and distribution of precipitation. Summer storms of high yield and high intensity have been known to produce a mound on the water table. These perturbations move down the gradient and have been detected by the water levels of wells many kilometers away (*8*). Figure 4 is a diagrammatic cross section which summarizes the geological and hydrological setting of the peninsula. It shows the cavernous limestone with its relatively thin, freshwater aquifer floating on salt water. This condition was first documented by Lesser-Jones (*9*). The thickness of the fresh water can be estimated from the elevation of the water table by using the Ghyben-Herzberg relation. At Chichén Itzá, where the elevation of the water table can be taken as approximately 1.3 m above mean sea level, we estimate the thickness of fresh water at 52 m. The zone of fresh water may be considered as somewhat thicker owing to diffusion near the boundary with the saline water. Back and Hanshaw (*7*) estimated the thickness at no more than 70 m.

The high infiltration of the surface and high permeability of the rock are also responsible for the nearly total lack of surface water. There are virtually no streams or rivers in the study area. Subaerial water is found only in sinkholes which intersect the water table, in several relatively small lakes of brackish, nonpotable water, and in a number of scattered swampy areas locally called *aguadas*. Most of the *aguadas* contain perched water (elevated by a localized lack of permeability), and many were created by the ancient Maya, who used stone blocks and clay to decrease surface infiltration (*10*).

Yucatán's only major source of potable water is the thin, fragile aquifer which underlies the peninsula. In most rural areas water is extracted from the aquifer by means of a rope, bucket, and hand-dug well; in urban centers both high- and low-discharge pumps are used. In Mérida water is commonly acquired from low-discharge pumps, from windmills (at one time the city had more than 20,000 windmills), and from the city network of piped water obtained from 20 high-discharge wells located about 12 km south of the city (*9*).

Pollution by Dissolved Solids

A high concentration of dissolved solids impairs the quality of water for human consumption and industrial use and, if the concentration is extremely high, for agricultural purposes. A total amount of dissolved solids in excess of 500 parts per million (ppm) renders a water supply undesirable for drinking (*11*) because of the potential physiological effects, the extent of which are not completely known, and because of taste (*12*). The conductivity and hence the corrosiveness of water increase as the amount of dissolved solids in-

Fig. 3. Thin, terra rossa soil (foreground) accumulates between low bedrock hillocks (middle ground) in a cleared field or milpa. Note the lack of fluvial features (foreground and middle ground) and the natural vegetation and flatness of the karst plain (background).

Table 1. Total dissolved solids (TDS) and fecal coliform bacteria (*E. coli*) in well samples from various locations in the study area. The 1966 results are from Back and Hanshaw (*7*). The results for 1972 and 1973 were obtained by the authors, using conductivity measurements for TDS and the Millipore method for *E. coli*.

Sample No.	Location	1966 TDS (ppm)	1972 TDS (ppm)	1972 *E. coli* (per 100 ml)	1973 TDS (ppm)	1973 *E. coli* (per 100 ml)
1	X-Can	418	461		708	500
2	Chickén Itzá	338	338		416	1500
3	Hoctun	371			481	1100
4	Leona Vicaria	503			507	2100
5	Libre Unión	687			601	1000
6	Valladolid	755	786		650	2700
7	Mérida, municipal supply	865	878		878	0
8	Muná	1640			1170	900
9	Puerto Juárez	1170	1462		1040	
10	Cocoterros	3500			618	
11	Isla Mujeres	4340	1430		1398	2200
12	Holactun		218	100		
13	Isla Mujeres		988		1170	500
14	Chétumal		894	0		
15	X-Hazil		471	2200	637	200
16	Carillo Puerto		384	3300	471	4200
17	Peto		991	0	1235	800
18	Cozumel				910	
19	Cozumel				796	0
20	Dzonotchel				552	1400
21	Telchiquillo				578	600
22	Mami				845	700
23	Petolillo				436	1400
24	Antun				784	
25	Kilometró 50				682	
26	Tzucacab				663	2200
27	Laguna de Chichabkanab				2860	
28	Oxkutzcab				780	200
29	Mérida, San Sebastian Church				611	200
30	Mérida, San Jóse Church					3200

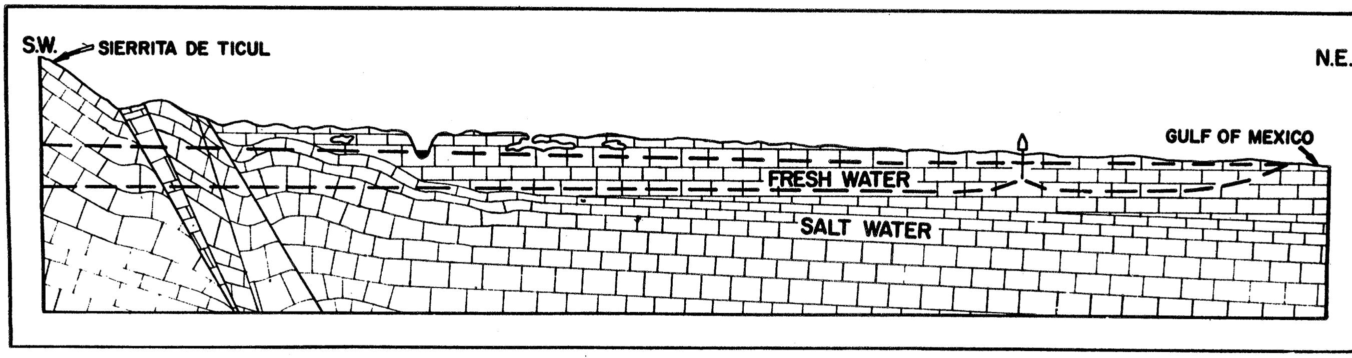

Fig. 4. Diagrammatic cross section of the northern Yucatán Peninsula, after Lesser-Jones (*9*). Note the coning of the brine into the fresh water in response to high-discharge pumping.

creases, making the water less suitable for use in textile, plastics, and paper manufacturing as well as for the operation of steam boilers and many other industrial uses.

In the study area the concentration of total dissolved solids in the groundwater ranges from 200 to more than 4000 ppm. High concentrations of dissolved solids are associated with high-discharge pumping of wells, with wells located near the coast, and with areas underlain by rocks that are relatively soluble. As shown in Fig. 4, the drawdown of the water table by high pumping rates causes coning of the saline water below. The upwelling of the brine follows the Ghyben-Herzberg relation in that the height of the cone is approximately 40 times the drawdown. The boundary between the two water types is a zone of diffusion, and instability of this zone increases the degree of diffusion. All high-discharge wells sampled in the study area yielded water with total dissolved solids above 800 ppm. Low-discharge wells located in the vicinity of high-discharge wells reflect the mixing of saline water into the aquifer. Samples 7, 8, and 17 in Table 1 are examples of high-discharge wells. Samples 9, 10, 11, and 13 exemplify the type of water obtained in coastal areas. Sample 27, from Laguna de Chichabkanab, owes its high dissolved solids content to an underlying bed of gypsum. A similar condition exists south of the Sierrita de Ticul where groundwater has been contaminated by gypsum. During the normal dry season or periods of drought, fresh water continues to flow seaward and the thickness of the aquifer is reduced. During these times increased mixing of the fresh and salt water will occur and water of lower quality will result.

At present the dissolved solids content of Yucatán's water places constraints on industrial development and may be affecting public health. Irrigation with water containing approximately 1100 ppm of dissolved solids has increased soil salinity and has contributed to difficulties with operations of an experimental farm which we visited at Santa Rosa. Yucatán's problem of pollution by the underlying brine is common to many carbonate aquifers (*13*) and can be eliminated or alleviated by careful location of wells, appropriate well spacing and pumping rates, and, in some cases, the use of lateral shafts for extracting water with a minimum of drawdown and associated brine-coning.

Contamination by Pathogens

Many of the low-discharge wells tested contained significant amounts of fecal coliform bacteria (Table 1) and several (samples 4, 6, 11, 15, 26, and 30) exceed 2000 coli per 100 ml, the maximum permissible for treatment to produce a safe water supply according to the U.S. Federal Water Pollution Control Administration (*12*). Water from the wells we tested is not receiving any treatment before consumption. The high infiltration of the surface, high permeability of the substrate, general lack of soils to filter liquids passing through them, and warm climate of Yucatán favor the growth and dissemination of pathogens. The major sources of the biological contaminants are sewage and domestic animals. In rural areas the yard near or adjacent to the living quarters is used for latrine purposes and commonly to contain domestic animals. In urban areas the same practices are followed by some, while others use cesspools. In the entire study area only one barrio, in Mérida, has a public sewer system; the remainder of the population rely on less formal means of waste disposal. Practices such as locating cesspools within a meter or two of wells, disposing of sewage in the same cenote system that serves as a water supply, and draining storm runoff from the streets by drilling holes through the pavement tend to increase the spread of biologic contaminants and are not uncommon in the study area. In many cases only the coarse particulate matter is filtered out in the sewage recharge of wells. According to Romero (*14*), "Studies involving the viability of bacteria in porous media report that under favorable living conditions some forms of bacteria, includ-

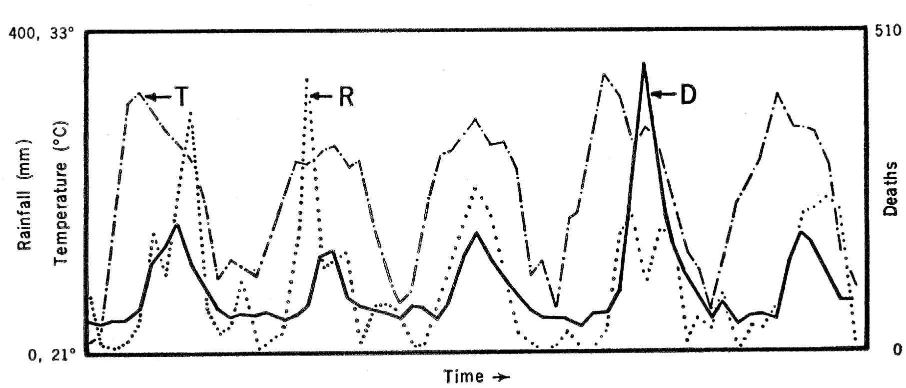

Fig. 5. Plot of monthly mean temperature (*T*), monthly mean rainfall (*R*), and total monthly deaths due to intestinal causes (*D*) for 60 consecutive months (1924 to 1928) in Mérida. After Hilferty and Maher (*17*).

ing the types [*Escherichia coli*] mentioned in this report, may survive up to five years. It should be mentioned that such conditions are extreme (tropics) and that 60 to 100 days might be the maximum life in temperate climates. Most investigators agree that the nature of the soil in contact with the source of contamination plays a dominant role in the subsequent life and travel of bacteria." While some viruses behave much like bacteria, other types are more resistant and may be expected to travel farther in the groundwater. In Yucatán the amount of fecal coliform bacteria found in a given water supply seems to be controlled by local population density, amount of precipitation during the preceding few weeks, and local soil conditions.

Escherichia coli constitute a prominent portion of the normal flora found in the large intestine of humans and other warm-blooded animals. Some serological strains are pathogenic and are responsible for gastroenteritis, infantile diarrhea, meningitis, and urinary tract infection. The *Klebsiella* genera are potentially the most dangerous for they contain the *Klebsiella pneumoniae* strain, which are highly fatal, resistant to penicillin, and associated with a host of serious diseases including sinusitis, pharyngitis, liver abscesses, and endocarditis (*15*). The presence of fecal coliform bacteria also indicates the potential presence of pathogenic viruses; the viruses are responsible for various diseases including infectious hepatitis, which is endemic in Yucatán.

The relative importance of diseases due to waterborne pathogens could be evaluated if the appropriate public health data were available. Unfortunately, we have been unable to acquire reliable data of the proper form for the entire study area. The Pan American Health Organization's summary of principal causes of death in Quintana Roo for 1971 (*16*) lists enteritis and other diarrhetic illnesses as the number one cause of death, and more than 40 percent of the deaths with identifiable causes are due to pathogens which may be transmitted through groundwater. For the most part, mortality data for the peninsula are incomplete and of questionable accuracy. Hilferty and Maher (*17*), using mortality data for 1924 to 1928 from the districts of Mérida, Valladolid, Ticul, and Peto, found that typically 40 to 60 percent of the total deaths were due to intestinal disorders. Rates of death due to intestinal disorders were markedly higher in urban than in rural areas. They noted that "epidemics of malaria and intestinal diseases occur in all districts of Yucatán" and that the number of deaths due to intestinal causes tends to follow fluctuations in temperature and rainfall (Fig. 5). Higher amounts of rainfall give pathogens added mobility and temporarily increase the rate of flow in Yucatán's aquifer system. Lags between peaks in rainfall and mortality may reflect the travel time of the pathogens and the duration of the terminal illness. Higher temperatures during the wet summers are thought to provide a slightly less hostile environment for the pathogens and have a debilitating effect on the ill. We conclude that the warm, periodically wet climate, the extremely high transmissibility of the bedrock, the lack of substantial soil cover, the low hydrologic gradient, and the local sanitation practices taken together tend to optimize the spread of waterborne disease.

Conclusions and Recommendations

The Republic of Mexico has an ambitious and effective national water program. The Secretaria de Recursos Hidraulicos (SRH), whose director has cabinet rank in the federal government, is one of the most professionally distinguished government agencies of its kind in the Americas. Resources for the Future, Inc., has been assisting the World Bank with a water planning study which the Bank is undertaking jointly with the Mexican government. The study is intended to provide guidelines for the development of government policies and projects designed to bring about the most efficient use of Mexico's water resources. However, to date, their study has not been directed toward the growing problems of the northern Yucatán Peninsula which are discussed here.

LeGrand (*13*) suggested that man has inherited a harsh environment in carbonate terranes. In the case of the northern Yucatán Peninsula, the physical environment creates a set of hydrogeologic constraints to future economic and social development. Planning for intermediate and long-range land use on the peninsula must be related directly to the limited and fragile groundwater source. Continued contamination will make future aquifer management a difficult challenge for federal, state, and territorial agencies. We conclude that any strategy for long-range land use in the study area should include establishment of a regional aquifer-monitoring network for long-term measurements of key hydrogeologic parameters, including precipitation, evapotranspiration, water table elevations, and water quality. Information from this network would flow into a central facility for storage, interpretation, and analysis. At present the SRH is collecting some of these data. Expansion of the existing program to provide sound information for regional planning will greatly benefit present as well as future generations. If such a program is implemented, it will represent a model for regional planning in other tropical and subtropical karstic terrains.

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