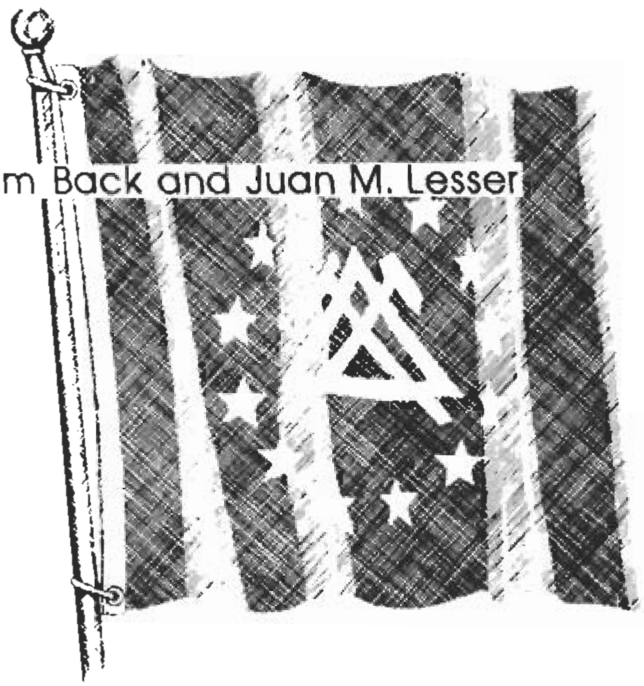
Chemical Constraints on Ground-water Management in the Yucatan Peninsula, Mexico



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CHEMICAL CONSTRAINTS ON GROUND-WATER MANAGEMENT IN THE YUCATAN PENINSULA, MEXICO

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Abstract

Two critical objectives of water management in the Yucatan are (1) to develop regional groundwater supplies for an expanding population and tourism based on the Mayan archeological sites and excellent beaches and (2) to control groundwater pollution in a chemically sensitive system made vulnerable by geologic conditions.

The Yucatan Peninsula is a coastal plain underlain by permeable limestone and has an annual rainfall of more than 1000mm. Such a setting should provide abundant supplies of water; however, factors of climate and hydrogeology have combined to form a hydrologic system with chemical boundaries that decrease the amount of available fresh water.

Management of water resources has long had a major influence on the cultural and economic development of the Yucatan. The Mayan culture of the northern Yucatan developed by extensive use of groundwater. The religion was water-oriented and the Mayan priests prayed to Chac, the water god, for assistance in water management primarily to decrease the severity of droughts. The Spaniards arrived in 1517 and augmented the supplies by digging wells, which remained the common practice for more than 300 years. Many wells now have been abandoned because of serious problems of pollution resulting from the use of a sewage disposal well adjacent to each supply well.

The modern phase of water management began in 1959 when the Secretaria de Recursos Hidraulicos (SRH) was charged with the responsibility for both scientific investigations and development programmes for water supply and sewage disposal systems for cities, villages, and islands.

Résumé

Deux objectifs critiques de la gestion de l'eau dans le Yucatan sont (1) de développer des approvisionnements regionaux d'eau souterraine pour une population accroissante et un tourisme basé sur les sites archéologiques maya et sur d'excellentes plages et (2) de controler la pollution des eaux souterraines dans un système chimiquement sensitif rendu vulnérable par des conditions géologiques.

La presqu'île du Yucatan est une plaine côtière sous laquelle gît du calcaire perméable et reçoit une pluie annuelle de plus de 1000mm. Un tel milieu devrait fournir d'abondants approvisionnements

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d'eau; cependant, des facteurs climatiques et hydrogéologiques se sont réunis pour former un système hydrologique avec limites chimiques qui diminue la quantité disponible d'eau fraîche.

La gestion des ressources d'eau a eu depuis longtemps une influence majeure sur le développement culturel et économique de Yucatan. La culture maya du nord du Yucatan se développa par vaste usage d'eau souterraine. La religion était orientée vers l'eau et les prêtres maya priatient Chac, le dieu de l'eau, demandant assistance dans la gestion de l'eau, principalement pour diminuer la rigueur des sécheresses. Les Espagnols arrivèrent en 1517 et augmentèrent les approvisionnements en creusant des puits, qui est restée la pratique courante pour plus de 300 ans. Plusieurs puits ont maintenant été abandonnés a cause de sérieux problèmes de pollution résultant de l'usage d'un puits de disposition d'eaux d'egout adjacent à chaque puits d'approvisionnement.

La phase moderne de la gestion de l'eau commenca en 1959 quand le Secretaria de Recursos Hidraulicos (SRH) fut chargé de la responsabilité des investigations scientifiques et aussi des programmas de développement pour l'approvisionnement d'eau et pour les systèmes de disposition des eaux d'égout pour les villes, villages et iles.

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INTRODUCTION

Management of water resources has long had a major influence on the cultural and economic development of the Yucatan. Two critical objectives of groundwater management in the Yucatan are (1) to develop regional groundwater supplies for the increased demand resulting from an expanding population and a governmental programme to promote tourism based on the Mayan archeological sites and excellent Caribbean beaches and (2) to control groundwater pollution in a chemically sensitive system made critically vulnerable by climate and geologic conditions.

The Yucatan peninsula in south-eastern Mexico projects northward between the Caribbean Sea on the east and the Gulf of Mexico on the north and west. It contains the states of Campeche on the west, Quintana Roo on the Caribbean Sea, and Yucatan in the north central portion. Merida is the capital of Yucatan and principal city of the Peninsula. Scientific investigations are being conducted to understand the hydrologic functioning of the Yucatan by means of a most successful institutional arrangement. It involves federal agencies and universities under the auspices of Consejo Nacional de Ciencia y Tecnologia (CONACYT) and National Science Foundation (NSF) under an agreement for scientific collaboration signed by Mexico and the United States in June 1972. The project staff and collaborators are scientists from the Secretaria de Recursos Hidraulicos, University of New Orleans, University of Kansas, University of South Florida, University of South Alabama and U.S. Geological Survey.

In order to identify the alternatives available to resolve the modern problems of developing water supplies and disposing of sewage, the geologic and chemical controls on the hydrologic regime must be clearly understood. For this purpose both detailed and reconnaissance studies are underway to evaluate the interrelation between chemistry, hydrology and geology. These include determination of a water budget (Lesser, 1976), mapping of tectonic features and stratigraphy (Weidie, 1976), studies of sedimentology (Brady, 1976; Ward and Brady, 1976), mapping the water table and flow patterns (Lesser, 1976), mapping the areal and vertical distribution of chemical parameters (Lesser 1976), and studies of processes such as mineral disgenesis (Ward, 1976; Choquette, 1976), weathering, soil formation (Isphording, 1976), and karst formation (Stringfield and LeGrand, 1976; Back and others, 1976). Other papers on related topics are being prepared and will be published as part of the CONAYCT-NSF project.

The purpose of this paper is (1) to summarise the hydrogeologic controls, with an emphasis on the chemical constraints which influence management practices in the Yucatan, and (2) to provide a brief historical perspective of the use and management of the water resources of the Yucatan from the time of the Maya of Precolumbian time through that of the Spaniards during the Colonial period and the Mexicans during later history, and up to the present.

HYDROLOGIC CONDITIONS CONTRIBUTING TO MANAGEMENT PROBLEMS

The northern third of the peninsula, about 150km wide, is an almost level karst plain underlain by nearly horizontal Tertiary formations consisting chiefly of limestone, marl and gypsum. It ranges in elevation from sea level along the coast to slightly more than 30m above sea level in the interior. Bare, fluted limestone is exposed over large areas and generally it is pitted and scarred by solution depressions and small ridges (Stringfield and LeGrand, 1976). The rough surface and many sink holes make travel across country very difficult despite the apparent flatness. This northern coastal plain is bounded on the south by a range of low hills (the Sierrita de Ticul or Puuc Hills) with an elevation of about 150m above sea level.

The great degree of karstification has caused environmental and ecological problems similar to those in karst areas of other parts of the world (LeGrand, 1973). Karst develops because limestone is soluble in water charged with carbon dioxide gas. Climate is an important control on the solubility of limestone (Trainer and Heath, 1976; Drake and Wigley, 1975; Harmon and others, 1975). For example, limestones in cold or arid regions often form ridges because vegetation, a major source of carbon dioxide gas, is absent in cold regions and water is scarce in the arid zones, limiting solution of limestone. In humid areas of temperate-to-tropical temperature the limestones are readily dissolved, as in Appalachian areas of the eastern United States where the folded limestones typically are eroded to elongated valleys (LeGrand, 1973).

Structure, topography and presence or absence of other geologic formations play an important role in the development of hydrogeologic conditions in a karst area because these, along with the climatic factors, control the permeability and the soil formation which strongly influence the type of water management required for any area. For example, a pure limestone, such as that of the Yucatan, can dissolve and leave essentially no residue; and also, owing to the lack of other geologic formations that would produce clay or sand, the soil is essentially non-existent. In addition, the permeability developed from the solution of the limestone remains high with the concomitant porosity in the form of open channels in the Yucatan because other sediments are not available to decrease the permeability and porosity by filling the solution channels. If the limestone above the water table had lower permeability in the Yucatan as a result of containing sediments in the solution channels the head would be higher and the fresh water-salt water interface would be appreciable farther below sea level. In addition, the presence or absence of sediments is a major control on the development of surface drainage and river systems. No rivers have developed in the Yucatan because the absence of sediments permits the rainfall to infiltrate rapidly to the water table.

In the Yucatan peninsula these factors have combined with the regional geologic and physiographic setting to produce long-term difficult problems of water management. Although the rainfall is high-as much as to 1500mm per year – it is seasonal and requires storage for use during the extended dry season. The type of storage usually provided in non-karstified areas by rivers and aquifers to maintain base flow of streams, virtually does not exist in the Yucatan. There, the extreme permeability of the limestone causes rapid infiltration of rainfall and nearly simultaneous discharge of groundwater to the ocean. The limestone is so permeable and movement through the system so rapid that not enough head is developed in the groundwater body to provide adequate storage in the aquifer.

Not only does the high permeability decrease the amount of fresh water available, it also makes the aquifer particularly susceptible to contamination by domestic and municipal sewage, barnyard wastes, and the natural decomposition of the abundant vegetation in the warm, humid environment. If the limestone were overlain by less permeable sediments as in Florida (Back and Hanshaw, 1970), the sediments could serve as a filtering medium. This would tend to purify the water by decreasing the flow rate and providing longer residence time, thus permitting the decomposition of the organic contaminants. In addition, the warm climate is particularly conducive to the growth of bacteria in polluted water. Widespread pollution has generated a host of endemic water-borne diseases (Doehring and Butler, 1974).

Encroachment of salt water from the ocean that surrounds the Peninsula on three sides is another serious problem. The large hydraulic conductivity along with the lack of high heads permits an extensive body of salt water to underlie the entire northern third of the Peninsula. Estimates based on the Ghyben-Herzberg principal indicate that the freshwater lens has a maximum thickness of about 160m (Lesser, 1976) in the southern part of the Peninsula, thinning to zero near the coasts.

The only naturally occurring bodies of water in the Yucatan are those situated in openings formed by solution of limestone or by tectonic activity. The most numerous bodies of water are the cenotes (from the Mayan word d'zonot) or sinkholes; sources of water also occur in other solution features such as caves and shallow, clay-lined depressions called aguadas. Tectonically controlled bodies of water occur along the east coast as bays in an elongated, faulted and fractured depression. Also, the groundwater level in this zone is shallow and occasionally comes to the surface resulting in a series of small lagoons called "sabanitas".

The chemical character of groundwater of the Yucatan is controlled primarily by three processes: (1) mixing of the rain water with the subsurface salt water, (2) solution of limestone and gypsum and (3) contamination by organic material and sewage (Back and Hanshaw, 1967).

In summary, such a setting as the Yucatan should provide abundant supplies of water; however, factors of climate and hydrogeology have combined to form a hydrologic system in which fresh water is scarce and whose chemical environment decreases even that restricted supply. These factors include (1) extensive karstification that permits rapid infiltration to prevent formation of rivers;

rapid discharge that precludes development of enough head to provide adequate storage; also low head permits sea water to permeate the aquifer; (2) uneven seasonal distribution of rainfall and (3) long-term pollution and contamination from organic and inorganic sources.

HISTORICAL DEVELOPMENT OF WATER USE AND MANAGEMENT

The northern part of the Yucatan, no doubt, presented an environmental challenge to the first people who came to the area, and it has continued to do so ever since. The paucity of fertile soil, the scarcity of potable water and shortage of other natural resources make this one of the most inhospitable regions in which a sophisticated civilisation has ever developed (Thompson, 1966, p. 26). The small plots near the family settlements that grew beans, squash and corn were often constructed by transporting the soil from areas of accumulation, sometimes underground, to where it was more convenient to plant the crops. Nonetheless, plentiful small game of both birds and animals, accessibility to the oceans, easily quarried limestone for building material, and the knowledge of maize cultivation combined to permit a livelihood. At times it was quite pleasant, requiring a minimum amount of effort to provide for the family and thus permitting leisure time to be used, in lieu of paying taxes, for the construction of public buildings, public roads, and public water sources (Morley and Brainerd, 1956, p. 14). The need for water is constant and its uneven distribution, both seasonally and spatially caused both the priests and the common people to spend time and effort in providing reasonably ample and secure supplies. The constant effort to obtain water is suggested by the numerous village and place names that end in "chhen" (well) "ha" (water), or "d'znot" (cenote). For example, Kanachhen means "the necessary well"; Tamchen means "very deep well"; Nacheha means "place where water is distant"; Yocdzonot means "at base of the cenote."

Stephens (1843), gives many examples of difficulties the people encountered in obtaining water, ". . . the same scarcity of water still continued. The rancho was entirely destitute; it had no pozo or well of any kind, either ancient or modern, and the inhabitants procured their whole supply from the village of Sabachshe, two leagues, or six miles, distant! This supply, too, was brought daily on the backs of Indians; but again in this arid and destitute region was still another evidence of ancient population – another desolate and ruined city" (p. 19, Vol. 2).

Because of the absence of rivers and with the exceptions of a few brackish lakes along the east coast, the Yucatan would be a waterless plain if it were not for the cenotes and caves containing groundwater and the scattered aguadas intermittently containing rainfall perched above the water table. The Maya were one of the few early civilisations to utilise a groundwater supply extensively. Many of the early cities developed around cenotes. For example, the archeological site at Dzibilchaltun, about 15km north of Merida, has a beautiful, deep cenote hundreds of square metres in areal extent, and a water level only a few centimetres above sea level on which floats a thin layer of fresh water (Back and Hanshaw, 1974, p. 47). This was the source of the entire water supply for a center of several thousand inhabitants. Surface elevation at Dzibilchaltun is only 2 or 3m above sea level. In contrast the scared sacrificial cenote at Chichen Itza is elliptical with diameters of about 50m and 70m and has a water level about 20m below its rim. The great distance to water and the vertical walls made the water in this cenote essentially unobtainable for use by the Maya. For water supply the people used another nearby cenote which has sloping sides into which steps were carved. These natural wells, seasonally supplemented by aguadas, were the source of water throughout much of the northern Yucatan that supported a considerable population (Thompson, 1966). Had it not been for the groundwater supply, northwestern Yucatan would have been largely uninhabitable.

As with many early people, the Maya practiced water management through religion and simple engineering tasks. Water management involves some human activity to make the spatial and temporal occurrence compatible with the spatial and temporal need for the water. The religion and much of the culture was water-oriented and the Mayan priests prayed, and performed rituals and sacrificed to Chac, the water god, for assistance in water management – primarily to decrease the severity of droughts. Chac is represented with a large elephant-like nose in the Maya glyphs and codices (the books of picture writing that tell much of the history and culture) and is sculptured on many buildings and painted in many murals. His "T" shaped eyes, full of tears, symbolically represent the rain. In the Dresden Codex, Chac is seated on a coiled snake enclosing a deposit or reservoir of water from which he dips water to sprinkle on the earth in the form of rain (Thompson, 1966, p. 192).

The hydraulic works of the Maya are among the first engineering efforts to control water in the Americas (Irigoyen, 1970, p. 18). In a few places small aqueducts and canals were constructed to carry the water from the hills to the areas of settlement. The Mayas constructed aguadas (reservoirs) and chultuns (cisterns) of both large and small scale to store water supplies, particularly in the southern part of the peninsula.

Aguadas are natural shallow depressions some of which the Mayas lined with stones or impermeable clay. Stephens (1843) observed aguadas whose bottoms were covered with layers of large flat stones and the interstices were filled in with red and brown clay (p. 140, Vol. 2). Cisterns or wells in the limestone were built in the bottom of the aguadas to furnish water during the season of no rain when the aguada itself was dry (Vol. 2, p. 150, fig. 9).

The chultuns or cisterns with collecting platforms and house foundations are scattered throughout the southern part of the Yucatan. Although the area is agriculturally rich there is no available water there for six months of the year. Chultuns are usually hemispheroid with a flat bottom and a hole about 40cm in diameter at the top. They often show signs of an interior coat of plaster and underlie the remains of a plastered floor sloped so as to drain into the cistern. The chultuns are found in major numbers under the plazas of ceremonial centres and are also characteristic of the small domestic sites; they are not found on the northern Yucatan plain. The capacity of many chultuns is about 30,000 litres. According to computations based on monthly rainfall figures for the Puuc and upon the water consumption of individuals in the area, a chultun could have comfortably supplied about 25 people with drinking and cooking water for a year. The number of chultuns in one of the larger centres could have supplied between 2,000 and 6,000 people (Morley and Brainerd, 1956, p. 264–265).

The chultun at Kabah is about 6m deep and consists of two spherical chambers, each about 2m in diameter. One chamber is above the other and they are connected by a 2m long vertical shaft which is about a metre in diameter. This chultun is dug into solid limestone and holds water without special lining. It gathers water from about 100m^2 catchment area (Back and Hanshaw, 1974, p. 48).

The first people to the Yucatan migrated from the south and crossed the Puuc Hill region to reach the northern coastal plain. In this region the caves and caverns were the source of water, and the Maya examined every cave they found in the hope it would lead to a permanent source of water. "Much of the earliest archeology of the country seemed to depend upon the question of what the first-comer did, before wells were dug and cities and cisterns built, to get water. As original immigrants coming in the dry season could not have found a satisfactory supply on the surface, it is certain that they must have discovered and ransacked these caves, and this fact gave the wet underground passages a new meaning. No matter how remote they were, no matter how difficult of access, they were natural and original sources of water supply at certain times" (Mercer, 1896, p. 43–44).

The Maya have been speleologists for the past 2,700 to 3,000 years (Thompson, p. IX, in Mercer, 1975). They developed water supplies from the many caves and caverns by constructing steps and ladders from the entrance to the deep water levels and water was carried out in clay jars or lifted by rope and bucket from the land surface. On many occasions Stephens (1843) told of descending into caves to observe the Indians' water supply, ". . . . .at the foot of the ladder there was a rude platform as a resting place, made to enable those ascending and descending to pass each other. A group of naked Indians, panting and sweating under the load of their calabashes, were waiting till we vacated the ladder above; and in this wild hole, with loads on their backs, straps binding their foreheads and panting from fatigue and heat . . . the distance, as we traversed it, with ladders, ascents and descents, winding and crawling passages . . . was not quite fifteen hundred feet . . . It was the regular and only supply of a living population." (p. 18, Vol. 2).

As with many primitive religions, the art and ceremonies are either to honour or appease the gods, or to imitate them. The Maya honoured Chac with the paintings and sculpture; they appeased him with offerings of jewelry, art objects and human sacrifices in sacred cenotes. An example of honouring and imitating Chac is given in the following account by Thompson (1966, p. 275). The Maya had a special reverence for corn that was part of their religion. The agricultural practice of "slash and burn" in which a field was cleared of trees and the crops were planted for a few years until the soil lost its fertility and then lay fallow. Special religious rites precede clearing the land and burning off the scrub when it is dry. Typical of the religious context of the agricultural year are the ceremonies to the Chacs still held in villages of the Yucatan when rain is needed. Every man in the village attends. The first task is to obtain water needed in the preparation of food offerings. This has to be the virgin water from a sacred cave or cenote where women never go. Once this has been brought, no one must return home, for if anyone had intercourse with a woman during the ceremony the rains would not come. Accordingly, the men sling their hammocks within a cleared area usually on the outskirts of the village. Following two days of preliminary ceremonies, at dawn of the third day the shaman offers 13 tall gourds and two shallow gourds of balche (fermented honey) to the Chacs and to the guardians of the corn fields. Boys are used to represent frogs which are the attendants and musicians of the rain gods. As the ceremony proceeds they croak in imitation of frogs announcing the approach of a storm. An older man selected to impersonate the chief Chac is reverently carried to a cleared space a few yards east of the altar. He is provided with a calabash and a wooden knife to simulate the calabashes carried by Chacs and water sprinkled from them causes rain. The wooden knife represents the implement with which they produce the lightning. From time to time this impersonator makes sounds like thunder and brandishes his wooden knife.

The water for the religious ceremonies was obtained from the caves because it was believed that the water dripping into the caves was virgin fresh and uncontaminated by not having been touched by man. Water jars were placed in the caves to catch the drips and the more inaccessible the source, the more sacred was the water. Even now we find water jars in remote niches of a cave covered with the calcareous dripstone where the jar was abandoned many centuries ago. The floors of the caves and the deposits in the caves contain many sherds of the broken water vessels. Caves were used throughout the Maya area as ossuaries and for religious rites particularly in honour of the God of the interior and of the earth and of the rain God. The most hidden and dampest of the rooms of the cave often contained huge numbers of complete or broken pottery and stone vessels often sheathed in lime from dripping stalactites (Thompson, p. 268).

The three great accomplishments of the Maya civilisation were the design and construction of temple centres, their development of an accurate perpetual calendar and, independently of the Hindus, the use of the concept of zero. Water is a dominant theme in all these accomplishments. For example, aqueous symbols and creatures, such as turtles, conch shells, and water jugs are common architectural embellishments. The Maya had an understanding of the concept of "water year." Their impressive calendar based on knowledge of astronomy permitted the priests to foretell the beginning and ending of the rainy season, so that maize could be planted and harvested at the best possible time (Back and Hanshaw, 1974, p. 46).

Like the Mayans, the Spanish conquistadores faced serious water problems when they arrived in 1517. The long period of time required for the conquest of the Yucatan, almost 20 years, was due in large part to the terrain and notably to the tremendous difficulties of obtaining adequate water supplies (Irigoyen, 1970, p. 57). The Spaniard came from a land of rivers and lakes and did not know how to cope with water supplies that were to be obtained only from below the surface. During the conquest, much of the warfare was of guerilla type, and for defence, the Mayas would burn their houses and fill the wells with stones. Carrying water jars, they would take their wives and children into hills where they obtained water from caves. The Spaniards, often wounded and fatigued from travelling across the difficult terrain would suffer greatly during the three or four days it often took to clean and repair the wells. During and after the conquest, the Spaniards constructed wells of their own, some of which are still in operation today. The construction of wells by digging with pickaxe and shovel and using a bucket to remove the broken rocks continued through the many centuries up to modern times.

Some of the wells were equipped with large wooden wheels with attached buckets for lifting the water. A burro or ox was used to rotate a wheel that was geared to the vertical wheel containing the buckets (Irigoyen, 1970, p. 66). Mercer (1896, p. 65) tells of observing such a well at Muna, which was similar to ancient Persian wells. The water fell into a tank from which groups of village girls filled water jars.

Introduction, by the Spaniards, of these wells was practically a revolution in the agricultural system because it permitted irrigation and the development of a cattle industry. Construction of wells made water available throughout the Yucatan coastal plain and permitted development of numerous haciendas owned by wealthy landholders which were worked by the Maya descendants, somewhat similar to serfdoms. This form of society based on economic development of cattle and henequen led to the centuries-long oppression of the Indians and was largely overthrown by the Mayan revolt between 1847 and 1855 (Reed, 1964).

The first public water supply was organised in the village of Tekax on 22 November 1825, and resulted the construction of a public well. The water from public wells was lifted by rope and bucket, generally by the individual using the water, except, of course, where he had the help of a burro.

In the late 19th century, increases in population resulting primarily from the world demand for sisal, prompted the digging of thousands of wells. The first mechanical pumps, driven by steam engines, were introduced in 1865. In 1880 the first windmill was installed in the patio of a private home in the city of Merida. This was a most important historical event in the use of water in the Yucatan, because the windmill became an extremely popular way to obtain the water. Wells equipped with windmills became so numerous in Merida that as recently as 30 years ago more than 20,000 windmills existed within the city limits, and Merida was known as the "city of windmills." These have now been abandoned because of the pollution resulting from the use of a sewage disposal well adjacent to each windmill.

In 1903 the city of Merida began making plans to install a public water supply under contract to a New York firm. The work began in 1906 and immediately ran into serious obstacles because the first site selected for the storage tank was the highest hill so that distribution pressure could be maintained. In this flat, topographically featureless plain, the only hill was a temple mound built by the Maya which failed to support the weight of the huge concrete cylinder. Excavations were dug, and concrete foundations were then used to support the water tank. For many years much of the city was supplied by horse-drawn buggies carrying a water barrel from which the people obtained their domestic water supplies. In 1946 planning began for the modern water supply, and Merida today has a city well field with electric pumps and a distribution system for the potable water.

MODERN PHASE OF WATER USE AND MANAGEMENT

The modern phase of water management began in 1959 when the Secretaria de Recursos Hidraulicos (SRH) was charged with responsibility for both scientific investigations and development programmes.

In order to provide the hydrologic information required to manage this difficult supply, studies were undertaken to (1) map the thickness of the lens of fresh water by making conductivity traverses in wells and cenotes; (2) determine temperature, rainfall, and evaporation by installation of 43 meteorological stations; (3) map the water table by first establishing topographic controls for elevations above sea level and then measuring depth to water; (4) map the chemical character of water by collecting samples for chemical analysis and interpretation; and (5) estimate the amount of water use. From these studies, the mean annual precipitation was determined to be 1,050mm; and the evapotranspiration, approximately 900mm. Assuming that the difference between rainfall and evaporation of 150mm provides a basis for estimating recharge, this value multiplied by 62,240km^2, the area of the higher middle part of the Yucatan, gives a value of about 9,000 million m^3/yr. Pumpage was estimated to be 350 million m^3/yr on the basis of population, number of wells, and individual water use. The difference between recharge and use suggests a large volume is being wasted to the ocean and could perhaps be developed for additional supplies (Lesser, 1976).

One of the principal problems that confront the peninsula is identifying areas for the disposal of municipal sewage, which infiltrates into the freshwater aquifer by means of cenotes, shallow wells, or septic tanks at each house. The disposal of sewage often contaminates the aquifer that is the only source of water for human consumption. On various occasions, the possibility has been considered of transporting the sewage of Merida to the sea by means of pipeline and then depositing the residues several kilometres from the coast where the sea has a sufficient depth. This has been considered to be too expensive.

The solution considered most feasible to solve this problem is treating sewage and injecting the residue into disposal wells that have sufficient depth to reach areas where the water has a salinity greater than 2,000mg/l; the sewage, because of its high density, would be lost below. Construction of these wells is more feasible in the coastal area downgradient from the town. Similar systems are being developed for other towns with the basic policy that within populated areas the aquifer will supply water for uses other than human consumption and that an additional supply for drinking and cooking will be imported from sparsely populated recharge areas.

In general, the subterranean water of the peninsula has an acceptable quality with respect to the organic material content except near cities and villages where the municipal sewage has infiltrated to the aquifer. The degree of contamination added by the population is large, and in Merida in 1960, 41 percent of the diseases of children less than 6 years old were water-borne. This has diminished since the city obtained a system for providing potable water.

The major part of the pumpage of the water in the coastal zones, principally in the state of Quintana Roo, is by means of wells with openings in the casing at certain depths that correspond to the position of the fresh water. The lower part of the well, which is completed in the salt water zone, is sealed and serves somewhat as a cistern for the collection of fresh water. By using a low pumping rate, it is possible to avoid salt water moving into the well.

CONCLUSIONS

From the historical perspective of a paper such as this, it is obvious that people had problems of ground-water use and management long before the first well was drilled. It should be equally obvious that such problems will continue. In addition, the contamination of groundwater in an area like the Yucatan dramatically demonstrates the chemical control and constraints on the system. The management problems evolve largely from hydrogeologic conditions resulting from chemical processes of (a) solution of limestone to form karst, which controls the hydrology; (b) seawater contamination to form a chemical boundary at the base of the fresh-water system; and (c) organic decomposition that hosts viruses and deleterious bacteria.

What can hydrogeologists do to help manage the inflow of contaminants in an area such as this? First, identify the dominant hydrogeologic controls and significant chemical conditions and processes; second, focus attention on parts of the system other than the porous media, such as aquitards, the unsaturated zone, areas of fracture permeability, and areas of deeper formations; third, integrate their studies more thoroughly, with knowledge from other disciplines, such as organic chemistry, bacteriology, virology, and carbonate petrology, plus reaction kinetics (Back and Cherry, 1977).

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NOTE.——The page numbers for the original printing were G18 to G29.