PROCEEDINGS

OF THE THIRD SYMPOSIUM

ON THE GEOLOGY OF THE BAHAMAS

Editor

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Production Editor

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Sponsored by CCFL Bahamian Field Station

June 6 - 10, 1986

Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

Articles in this volume should be cited as follows:

Author(s), 1987, Article title, in Curran, H.A., ed. Proceedings of the Third Sympoisum on the Geology of the Bahamas: Fort Lauderdale, Florida, CCFL Bahamian Field Station, p. xx-xx.

ISBN 0-935909-24-9

Printed by Don Heuer in the U.S.A.

OCCURRENCE AND DEVELOPMENT OF WATER RESOURCES IN THE BAHAMA ISLANDS

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ABSTRACT

The population of the Bahama Islands relies almost exclusively on groundwater for its freshwater supply. The amount of precipitation available for groundwater recharge varies from year to year and from north to south across the islands. The size of the individual islands also influences the amount of rainfall. More than 75% of the precipitation is evapotranspirated, and extended droughts lasting more than three years have been known to occur.

Runoff, however, is limited due to the permeable karst terrane, and infiltrating freshwater will form a Ghyben-Herzberg lens floating on the denser, underlying saltwater. Uniform, fine grained sediments are conducive to stable lens formation, but they will yield only limited amounts of water. Aquifers with extensive solution channels will yield large quantities of water but may have thick mixing zones. In areas where the depth to the water table is deep, good lens formation is encouraged because the infiltrating water is not intercepted and evapotranspirated, and the longer flow path will result in slower but more continuous recharge.

Large diameter, widely spaced wells or trenches pumped at low rates are less likely to cause upconing than are small diameter, deep wells. Safe yields may be estimsted by considering withdrawal as a reduction in recharge. Pollution from domestic sewage, chemicals, leaking tanks, hazardous wastes, and stormwater runoff is an increasing problem and needs to be controlled.

INTRODUCTION

Freshwater in the Bahamas is derived from three main sources. Some is collected from rooftops and artificially constructed catchments on the land surface, and some is produced by desalinization of brackish or seawater. The greatest volume, however, is extracted from lenses of freshwater that occur below the ground's surface. The quantity (Lloyd, 1980) and quality of water in the lenses is dependent on the amount and distribution of the rainfall, the amount of this precipitation that percolates down to the water table, the hydrogeologic characteristics of the the aquifer, and the impacts of withdrawal and pollution by human activity.

CLIMATE

The climate of the Bahamas is generally classified as marine subtropical with warm, wet summers from May to October and dry, cooler winters from November to April. The amount of rainfall varies widely from year to year, and from north to south along the length of the archipelago. Rainfall also varies from island to island at the similar latitudes, and even between different locations on the same island.

The large, northern islands, which are influenced by weather systems moving off the continental North America, have average annual rainfalls on the order of 50 to 60 inches (1200 to 1500 mm) per year (Little and others, 1977). The smaller southern islands, in contrast, average as little as 25 to 38 inches (640 to 1000 mm). These averages can be greatly distorted if slow moving hurricanes or tropical depressions reach the islands; or when prolonged periods of dry weather occur. At the U.S. Air Force Base on San Salvador, for example, the average annual rainfall from 1948 to 1954 was 34.57 inches (878 mm) (U.S.G.S. 1958). In 1954 however, 15.94 inches (405 mm) of rainfall fell in October alone and raised the annual average to 53.43 inches (1357 mm). At the other extreme, droughts having less than two-thirds of the average rainfall and lasting for at least three successive years have been known to occur (Mather, 1975).

Local variations in precipitation can also be the result of the sizes of the islands. Islands with large east-west dimensions are big enough to generate their own weather. The warming of the land mass can cause moist air to rise high enough to condense and fall as rain. The small or long, thin islands often do not have enough land mass to develop significant convection cells. Cat Island, for example, receives about 15% less rainfall than Andros on about the same latitude line. Sometimes, even if the air does rise high enough to condense, the cloud may have moved off the lee shore of the island before it begins to rain.

The precipitation that reaches the island may run off to the sea, infiltrate into the ground, or return to the atmosphere by evapotranspiration. The intermittent nature of many of the rain showers and the warm, sunny climate of the Bahamas causes the majority of the precipitation to follow this latter course. In fact, it has been estimsted (Little and others, 1977) that more than 75% of the annual precipitation that falls on the islands returns to the atmosphere by evaporation and evapotranspiration.

The amount of runoff, by comparison, is extremely limited. The permeable nature of the soils, sediments, and rocks precludes the development of any major streams or rivers. Only in places where residential or commercial developments near the shore have resulted in large areas being covered by pavement or buildings, for example downtown Nassau or Freeport, is runoff significant.

GROUNDWATER

The remainder of the precipitation infiltrates to recharge the groundwater. The fate of the infiltrating water is largely controlled by the permeability of the sediments and rocks.

Fresh Water Lens

All of the islands are underlain at some depth by saltwater with approximately the same salinity as the surrounding ocean. Freshwater is less dense than sea water ($1.08 m/cm^3$). If the permeability of the aquifer is very high, the freshwater will simply spread out on the saltwater as an infinitely thin layer or mix with it to form a brackish zone as it does in the open sea. If the rocks and sediments offer some resistance to the water's movement, however, the freshwater will displace the saltwater and form a lens-shaped body known as a Ghyben-Herzberg lens. In order to be in hydrostatic equilibrium, the pressure exerted by the freshwater must be equal to the pressure exerted by the saltwater. In a uniform, porous medium, the depth of the saltwater/freshwater interface below sea level will be equal to about 40 times the height of the water table above ses level measured in the same vertical plane. Although the lens shape may remain constant, the water in the lens is not static. Rather the amount of water being added to the top of the lens by precipitation must be equaled by the amount that flows out through the discharge face along its edges (Kohout, 1960).

Aquifer Characteristics

The nature of the aquifer has a major influence on the extent and stability of the freshwater lens, the quality of the water, and the potential for water resource development. Sediments and rocks with relatively low permeabilities may encourage the formation of deep, stable lenses with thin mixing zones. Such formations, however, may have such low transmissivities that only a limited amount of water can be extracted without causing excessive drawdowns and upconing. Rocks that have undergone extensive solutioning resulting in high hydraulic conductivities, on the other hand, may allow only limited lens development and can have thick, brackish water zones. The extensive buried ancient soil horizons and karst terranes that were developed during Pleistocene low sea level stands have high horizontal transmissivities, but may be separated from the saltwater zone below by less permeable aquitards. In cases where these horizons are extensive, large quantities of good quality water may be extracted.

The size of an island and the distance of a specific site from the sea can also influence the size and shape of the fresh water body and the quality of the water it contains. Some smaller islands contain ideal formations for lens development, but because of the limited surface area to receive precipitation, and the proximity of the shorelines, only small lenses can develop. Near the middles of the larger islands, however, even highly solutioned limerocks with large open channels may still contain thick lenses of freshwater with thin mixing zones.

It is often noticed by people living and working in the Bahamas (personal communication) that some of the thickest freshwater lenses occur beneath the highest parts of the islands, even in close proximity to the sea (Kuntz, 1984). In the author's opinion, there are two main reasons for this phenomenon. First, more water reaches the water table in these areas because the infiltrating precipitation can percolate past the bottom of the root zone and will not later be evapotranspirated by the plants or be drawn by capillary action to the ground surface where it can be evaporated. Similarly, the water quality below the deep areas is better because this lack of evapotranspiration will prevent the concentration of salts near the ground surface that could be washed back by subsequent rains.

The second main reason for the greater thickness of the lens is also a result of the length of the flow paths the infiltrating water must travel before reaching the water table. During short duration rainfall events, the wetting front may only progress a relatively short distance into the ground before all the water adheres to the dry passage walls. The next event will then move down on top of the previously infiltrated water either pushing it down farther, or passing between the wetted grains to a deeper depth. This process will continue following each event, until finally water begins to reach the water table.

This delay between the rainfall events and the arrival at the water table means that the rate of recharge per unit of time is reduced, but the duration over which recharge occurs is extended. As a result of this slower but steadier recharge, the amount of fluctuation in the elevation of the water table surface is reduced. Hence, the height of the water table and, therefore, the gradient between the points of recharge and discharge will not be greatly increased following each event so the rate of water movement out from the lens will not be accelerated. Similarly, the reduced amount of fluctuation in the elevation of the water table will cause less fluctuation in the position of the interface at the bottom of the lens, which will result in less mixing of the fresh and salt waters.

WATER RESOURCE DEVELOPMENT

The generally shallow depths to the fresh, groundwater lenses in the Bahamas has facilitated tbe use of this resource since the arrival of the earliest inhabitants. The methods of extraction have ranged from simply finding a convenient sinkhole and scooping the water out in a bucket or bowl, to drilling deep wells and installing pumps. The small amount of water withdrawn by bucketing will usually cause only minimal changes in the freshwater lens unless it is very thin. Deep wells yielding large quantities of water to population centers or for irrigation, however, can quickly upset the lens's stability, resulting in saltwater intrusion and upconing.

Sustainable Yield

Intuitively, it may appear that it is safe to extract from a lens any quantity of water up to the amount that naturally flows out of the lens along the discharge zone, since this water is being lost anyway. Because the lens is in dynamic equilibrium, however, any change in either the amount of recharge to the lens or the rate of discharge from it, will alter its shape.

Mather (1975) has suggested that a practical method of estimating the amount of water that can be withdrawn from a lens without destroying it as a viable source of potable water, is to consider all withdrawals as being equal to a comparable reduction in the amount of recharge. Mather showed that, for a given lens, the depth of a point on the saltwater/freshwater interface below sea level (z from Fig. 1) is approximately proportional to the square root of the rate of uniform vertical recharge per unit area (W). Therefore, if the rate of recharge is reduced, the depth to the interface will be lessened by an amount proportional to the square root of the recharge reduction. For example, if the annual amount of recharge is 400 mm (15.8 in.) and a point on the interface of the original lens is 10 meters (32.8 ft.) below sea level, a reduction of 100 mm (3.9 in.) in the amount of recharge will result in a decrease in lens depth of about 1.3 m (4.3 ft.) to 8.7 m (28.5 ft.) below sea level.

Each lens will react somewhat differently to these changes, but Mather suggested that

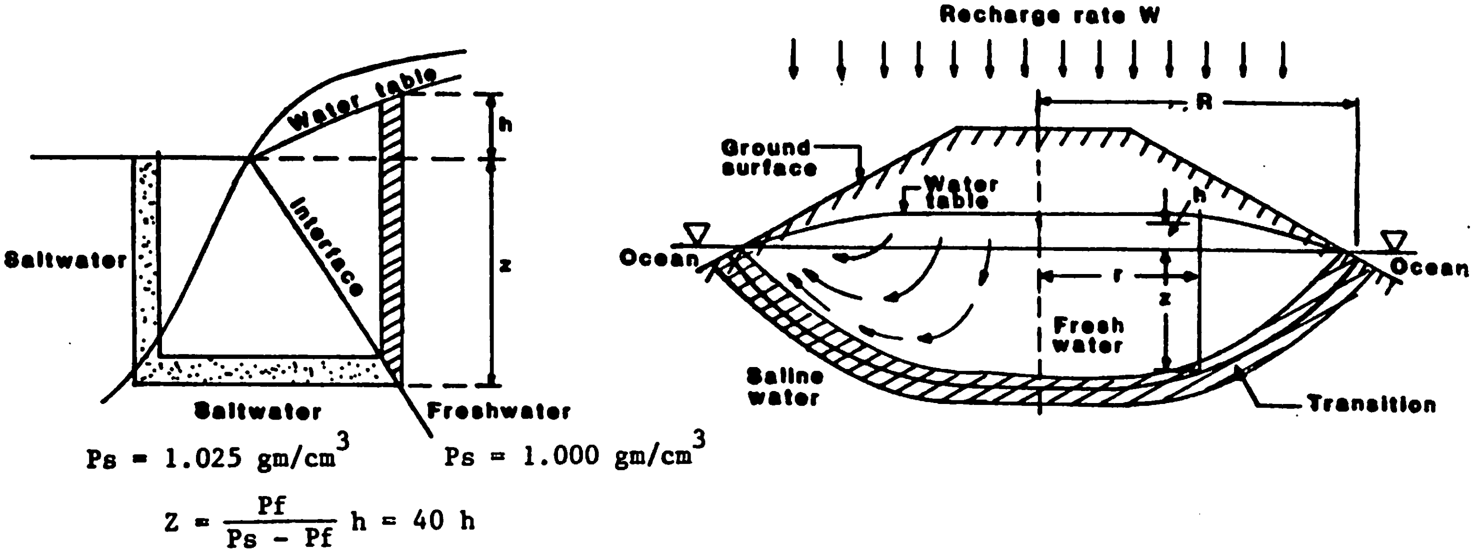

Fig. 1. Ghyben-Herzberg lens in an oceanic island.

a first approximation of a safe pumping rate will be one that decreases the natural lens thickness by one-half. Using the example above, if the 10 meter thick lens is to be reduced to five meters, the equivalent of about 300 mm of recharge will be available for abstraction. This amount, however, should be reduced by almost half to allow for drought conditions (Mather, 1975), resulting in a safe yield of 160 mm, or only about 4.275 liters/day/hectare (457 gallons per acre per day).

After withdrawal has begun, the change in position of the interface should be monitored, and the pumping rate reduced if necessary or increased if allowable. It must be realized, however, that a lens can take years to re-establish equilibrium after extraction has begun, so a lack of change in interface position should not be interpreted too quickly.

Methods of Extraction

It is important to note in the example above, that the safe yield from the 30 ft. thick lens is less than 460 gallons per day per acre. Problems have arisen when well construction techniques and pumping rates commonly used on the mainland are transported to the islands.

These methods typically use a minimum number of relatively small diameter, deep wells pumped at high rates. Such practices can cause upconing of the saltwater below the well. According to the Ghyben-Herzberg relationship, a drawdown of only 0.1 meters (0.33 ft.) in the well will theoretically result in a local rise of four meters (13.1 ft.) in the saltwater/freshwater interface. (Actually, the phenomenon of upconing is more complex, see Todd, 1980.)

For many years in the Bahamas, it was thought that the lens would re-establish itself during the "resting" time between periods of pumping (Riddel, 1935). In reality, however, the fluctuations in the water levels only resulted in a thickening of the transition zone.

Unless the freshwater lens is thick and the permeability of the aquifer is high enough to yield a lot of water with very little draw down, a much safer practice is to use shallow, large diameter, widely spaced wells pumped at low rates for long periods of time. In locations where enough land is available, and the water table is not too deep, long trenches can be excavated (Watson, 1980). By pumping from these trenches, large quantities of freshwater can be skimmed without causing significant upconing.

GROUNDWATER CONTAMINATION

Degradation of the freshwater lenses in the Bahama Islands by saltwater intrusion resulting from inappropriate water extraction methods has long been recognized as a major cause of contamination. As the islands experience increasing development, other potential sources of contamination must be recognized and controlled. Some of these include domestic sewage, agricultural chemicals, spilled petroleum and industrial chemicals, buried wastes, leaking tanks, and stormwater runoff.

The permeable nature of the soils and bedrock facilitates the use of buried sewage effluent disposal systems. When properly sited and constructed, such systems provide an effective, environmentally sound means of sewage effluent disposal. As the population increases and the number of such systems multiply, however, contamination of the underlying groundwater can occur. Therefore, it is imperative that suitable guidelines and regulations be enforced.

Similarly, the sewage effluent disposal practices of municipal systems and community treatment plants at residential and commercial developments should be strictly controlled. Offshore discharge should be discouraged, not only because the nutrient, chemical, and particulate loads from these plants can do irreparable damage to ecology of the nearshore and reef environments, but also because such discharges waste valuable freshwater. Rather, the possibilities of effluent disposal by spray irrigation on golf courses, lawns, landscaping, and agricultural crops should be fully explored. The fate of agricultural chemicals in the groundwater must also be fully understood before their use is widely permitted in the vicinity of potentially productive fresh groundwater lenses.

The consequences of past practices regarding the use, storage, and disposal of hazardous wastes and chemicals are becoming recognized as a major threat to the quality of groundwater throughout the world. In the Bahamas, this threat is even more pronounced because of the fragile, shallow nature of the "sole source" aquifer. Because of the karstic nature of the terrane, the population must be made aware of the dangers of even such seemingly inconsequential practice as discarding used motor oil or paint solvents down the nearest convenient sinkhole. Pilots should also be required to discard even the small amounts of aviation fuel they routinely withdraw from wing tanks into suitable containers rather than onto the ground surface.

Leaking storage tanks, especially those holding petroleum products should be inventoried and checked to insure that they are not leaking. The shallow, fluctuating, and often somewhat salty groundwater can cause even relatively newly buried metal tanks to begin to leak, and even minor levels of contaminants in the water supply can be carcinogenic.

Stormwater running off parking lots and roads can also carry significant quantities of pollutants with it. This is especially true of the first one-half inch or so of rain that falls after an extended period of dry weather. Studies should be undertaken to mitigate the potential damage this runoff could do to the groundwater.

CONCLUSIONS

Fresh groundwater in the Bahama Islands occurs in a unique climatic and hydrogeologic setting that makes this resource difficult to develop safely and susceptible to contamination and degradation. Only by fully understanding its mode of occurrence and the risks of pollution can this valuable resource be fully utilized for the benefit of the Bahamian population.

REFERENCES CITED

Cant, R.. 1980, The operation and management of groundwater supplies in the Bahamas: Proceeding of the Seminar on Water Resources Assessment, Development and Management in Small Oceanic Islands of the Caribberan and West Atlantic: United Nations, Bridgetown, Barbados, p. 703-711.

Davis, C.C., 1980, Water resources legislation and administration: Proceeding of the Seminar on Water Resources Assessment, Development and Management in Small Oceanic Islands of the Caribbean and West Atlantic: United Nations, Bridgetown, Barbados, p. 488-501.

Klein, H. and others, 1958, Geology and groundwater resources in the vicinity of the auxiliary air force bases, British West Indies: U.S. Geological Survey. Tallahassee, p. 142.

Kohout, F.A., 1960, Flow patterns of fresh and saltwater in the Biscayne Aquifer of the Miami area, Florida: IASH General Assembly of Helsinki, Pub. No. 52, p. 440-

448.

Kunze, A.W.G. and Burke, J.C., 1984, A resistivity survey of Sandy Point, San Salvador, Bahamas: Proceedings of the Second Symposium on the Geology of the Bahamas: San Salvador, Bahamas, CCFL Bahamian Field Station, p. 97-111.

Little, B., and others, 1977, Land Resources of the Bahamas: A Summary, Surrey England, 133 p.

Lloyd, J.W., 1980, Problems of the quantitative assessment of fresh groundwater resources on small limestone islands: Proceeding of the Seminar on Water Resources Assessment, Development and Management in Small Oceanic Islands of the Caribbean and West Atlantic Water: United Nations, Bridgetown, Barbados, p. 337-351.

Mather, J.D., 1975, Development of the groundwater resources of small limestone islands: Quarterly Journal of Engineering Geology, v. 8. pp. 141-150.

Mather, J.D., and Buckley, D.K., 1973, Tidal fluctuations and groundwater conditions in the Bahamian Archipelago: Estratto da: Atti Del 2nd Convegno Internzionale Sulle Acque Sutterranee, Palermo.

Riddel, J.O., 1935, Excluding saltwater from island wells, a theory of the occurrence of groundwater based on experience at Nassau, Bahama Islands: Civil Engineering, v. 3, p. 383-385.

Todd, D.K., 1980, Groundwater Hydrology, 2nd Ed.: New York, New York, John Wiley & Sons, 535 p.

Watson, D., 1980, Gravity flow versus pumped extraction from water production trenches in the Bahamas: Proceedings of the Seminar on Water Resources Assessment, Development and Management in Small Oceanic Islands of the Caribbean and West Atlantic: United Nations, Bridgetown, Barbados, p. 360--372.