Figure 1. Atoll Diego Garcia

Figure 2. Typical Atoll Lagoon Beach

Fresh Water on the Coral Atoll Island

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WITHIN the tropical oceans of the world lie some 330 coral atolls which encompass thousands of islands. With few exceptions, such as Midway in the central Pacific and the Dry Tortugas and Hogsty Reef in the Bahamas, they are all in the Indo-Pacific tropical area. The largest emergent atoll is Kwajalein, 75 miles long and up to 15 miles wide, in the Marshall Islands of the South Pacific; most of the atolls are much smaller. An atoll rises abruptly from the ocean depths and typically encloses a shallow lagoon in the center. The outer wave-washed rim of the atoll has a configuration which is frequently angular or elliptical (Figure 1). The entire atoll may be awash, but it is more frequently marked by low islands on its rim. These islands of coral and sand are ever-changing features, born and destroyed at the whim of the sea.

One of the most intriguing geologic questions of the past century has been the origin of the coral atoll[1]. While it is probable that no single theory can account for all the existing atolls, it seems likely that most of them are the result of coral growth maintaining itself on the surface of a subsiding platform. This theory was first postulated by Charles Darwin in 1842 as a result of his historic voyage on the HMS *Beagle*.

According to the theory, the original platform may be either a peaked volcanic island or a truncated island whose fringing coral overgrew it as it sank. This basic theory has been somewhat modified by considerations of eustatic sea level change and the cooled water brought on by glacial activity, but it is generally accepted as the most plausible yet presented. That atolls rest ultimately on buried non-coral foundations has been confirmed with the discovery of basalt at Eniwetok Atoll at depths of 4,158 and 4,610 feet, and at Bermuda at a depth of 560 feet.

The usual atoll island projects some 5 to 30 feet above sea level, although the dune hills of the Bermudas are up to 200 feet high. Except for the Bermudas, the reef rock platform is usually about at the low tide level. In some cases, the core of the island may contain remnants of elevated reef rock from a higher sea level stand or a phosphate rock layer from sea bird droppings of a bygone era. Also, the island detritus may spill off the reef rock platform and build up on the lagoon side, creating a significant difference in permeability. Many variations occur because geologically the islands are an ephemeral feature with great changes sometimes wrought by a single typhoon or tsunami.

The primary hydrologic characteristic of the atoll island is its extreme permeability. Even on beaten paths, rainfall seldom travels more than a few feet before sinking into the ground. Generally, the ocean side of the island is made up of large pieces of rock ripped from the reef and worked up during storms. The lagoon side is composed of finer material and consequently is less porous than the seaward side. On either beach, relatively impervious beach rock may develop from the chemical changes as fresh ground water merges with sea water at the beach line. Because of the transitory nature of the shoreline, old beach rock strata may also be found in the interior, which is generally depressed in elevation from the shoreline ridges of boulders and sand. On some islands, sections of the interior may contain a relatively impervious layer of phosphate rock, the extent of which may be sufficient to create a hardpan immediately below the ground surface. Marshy areas may form in such regions during rainy periods.

CLIMATE

Precipitation is the first consideration in evaluating the possibility of finding fresh water on an island, and this varies greatly throughout the atolls. Large differences in precipitation rates are attributed to the various geographical locations of the islands and the inconsistent rates of annual precipitation. Rainfall records over a period of years would be most valuable, but a certain determination of probable rainfall can be made from a study of rainfall patterns within an area.

Considering sea level stations only, the heaviest oceanic rainfall is north of the equator in the Pacific —in a belt between 1°38′ north and 8°30′ north, stretching from Palmyra Island (160° west) to Kayan-

[1]See "Coral Reefs of the South Pacific," by Hobart E. Stocking [M.E. Aug. 1944].

gel Island (134° east). Rainfall diminishes north and south of this zone and also, very markedly, eastward. Palmyra Island, at about 8° north, averages some 150 inches annual rainfall while Canton Island, lying only 3° south, averages 17 inches annually. Most atoll precipitation is dependent on oceanic air convection and occasional cyclonic depression activity which is coincidental to the location of the island.

VEGETATION

Atoll islands have a plant cover of strand type vegetation which at first appears very uniform, but closer inspection shows wide variation and zoning of flora species. Major differences in vegetation character occur between islands in dry and wet climates. Dry islands have a sparse desert type of vegetation consisting of a few grasses, herbs, and dwarf shrubs which contrast sharply with the luxuriant jungles on atoll islands in the Central and Eastern Carolines and Southern Marshalls. Another important difference exists between the vegetation on small or narrow islets and on larger land masses, the vegetation of islets being much sparser because of the close contact with sea water.

On most atoll islands vegetation varies by zones from the outer beach to the inner, or lagoon, beach. The outer zone contains a scrub reaching a height of 6 to 15 feet with smaller plants interspersed. On very narrow islets this may extend the full width of the land. Next, there is a salt-tolerant (halophytic) forest zone, which is ordinarily a narrow belt. The greater part of the interior is occupied by a more normal tropical growth depending on the freshness of available ground water. On populated atoll islands this area is often made up of coconut plantations. On wetter islands, the breadfruit tree is frequently grown in the interior. If the interior consists of marshes or swamps, mangroves and planted taro may be found. On the inner lagoon shore is a narrow strip of scattered trees and herbaceous growth approximating that found on the ocean side (Figure 2).

Certain common types of vegetation may provide indications of the nature of ground water. The presence of halophytes, for example, may indicate saline ground water. The hardiest large indigenous growth found on the atoll island is the Pisonia tree. Large dense groves of these trees are found on islands of moderately heavy rainfall (80 to 110 inches per year), but they seem to survive even on islands so small that an identifiable fresh-water lens does not exist. Such an island is Rose Island, about 200 by 240 yards in size. The Pisonia tree, with creamy white bark, large light green leaves, and twisted stems, attains heights of 85 feet and girths of 25 feet. These trees may be found where lack of fresh ground water precludes the existence of coconut trees. The Pandanus tree, with medium dimensions and long, slender leaves, also has a greater tolerance to drought and salinity than the coconut palm.

The familiar coconut palm is the most frequent and useful indication of marginal ground-water conditions. It is a tenacious plant with enough salt tolerance that brackish water will enable it to survive a drought. Palm trees mark drought by narrowing their trunks during the dry period. When good conditions return, the new growth above is expanded. Thus the continuity of trunk thickness may indicate the drought history of a tree. On wet islands, the palm thrives

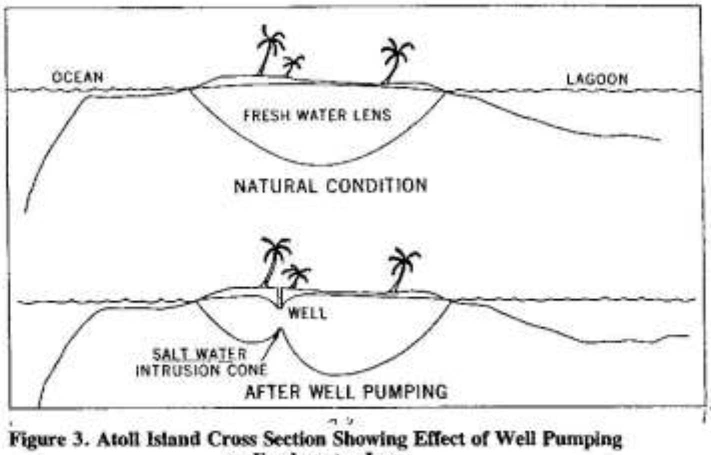


Figure 3. Atoll Island Cross Section Showing Effect of Well Pumping on Fresh-water Lens

on sandy shores up to the beach line. The distribution of other common island food trees is closely related to the ground-water salinity. The large split leaf breadfruit tree is much less resistant to drought and salinity than the coconut palm. Banana and papaya trees and taro plants require even fresher ground water than the breadfruit tree. The presence of these plants indicates a ready supply of ground water of very low salinity.

FRESH WATER OCCURRENCE

By far the most important source of fresh water on an atoll island is the ground water. If the rainfall, permeability, and size of the island are suitable, a lens of fresh water "floating" on salt water will develop in the land mass. Characteristically, the lens will be asymmetric, being thicker on the lagoon side than on the more pervious seaward side. On the atoll island, the water table is seldom more than 1 or 2 feet above sea level. It has been theorized[2] that the body of fresh water probably extends no deeper than 40 to 80 feet at the point of highest water table. Also, there is a tide-induced fluctuation in the water table which can vary throughout the island in a rather complex manner depending on the proximity of ocean or lagoon, and permeability of the land mass. Because of the changing elevation of the water table (top of lens) to sea level, the size of the lens may be difficult to determine. In addition, voids and lack of uniformity in the permeability of the land mass material may greatly disrupt the theoretical configuration of the lens. On Onota Atoll in the Gilberts, which has an average annual rainfall of 44 inches, a well in the center of an island wider than 1,000 feet has a good chance of producing a fairly continuous water supply. In islands of the Marshall group, where rainfall is greater than about 54 inches annually, conditions are similar with a permanent lens existing when the island is at least 0.1 square mile in area. Diego Garcia Atoll in the Indian Ocean, with an average annual rainfall of 102 inches, is considered a wet island and exhibits a classic fresh-water lens. In the mile-wide part of the island the water table may stand as high as 3 feet above mean sea level.

When a fresh-water table is found to exist in a land mass, even though the water level be as little as a foot above sea level, it may be assumed that a considerable reservoir of fresh water lies within the ground. But it must be recognized that the reservoir

[2]See "The Ghyben-Herzberg Theory" following this article.

represents a natural balance of hydrologic influences which is affected when an outside influence is introduced (Figure 3). Removal of ground water causes the system to attempt to reach a new balance, and such removal at a rate faster than replenishment results in a lowering of the water table and a rise in the lower lens sea-water/fresh-water interface at a ratio of about 1 to 40. The movement of the interface lags behind that of the water table because of the greater distance involved to reach the new equilibrium; hence, this inevitable result may not be noticed at the time. A rapid, concentrated withdrawal of fresh water will cause a local effect more quickly than a drawdown of the same quantity distributed over the surface of the lens. And the deeper the withdrawal point, the sooner the salt-water intrusion will occur. The safest method of withdrawal from the lens is to remove the fresh water uniformly at the surface.

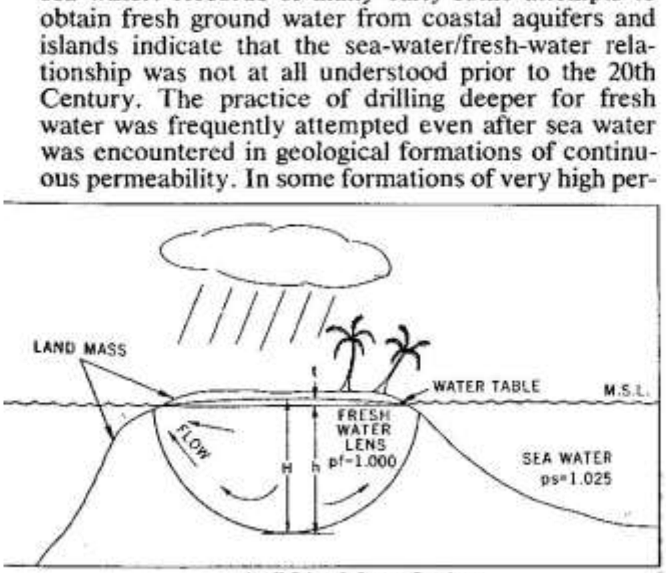
If the need for a large supply of fresh water is immediate, and little importance is assigned to future use of the aquifer, then it may be fully exploited. But once the sea water has permeated the land mass, restoration of a salt-free ground condition may take many months or years.

Ground water may be recovered from atoll islands by dug wells, driven wells, or infiltration galleries. Of these, the dug well is the simplest and was the first to be developed. Because the well should not penetrate more than a few feet below the water table, the hole is not usually deep. The most effective of the ground-water withdrawal systems is the infiltration gallery consisting of a trench or permeable conduit paralleling and intersecting the water table. The system should be placed where the lens is thickest and the water skimmed off over a wide area.

The quality of ground water found in an island lens is usually within acceptable Public Health Service limits. Chlorides range from 50 to 250 ppm, originating from salt in the island formation itself and from the marine atmosphere. Continuous testing for chloride will provide early indication of increasing salt intrusion and withdrawal can be curtailed, enabling the well to restore itself. The water will be hard with carbonates, and may on occasion contain gases such as hydrogen sulfide which must be removed. But in most instances, the water is clear and innocuous, requiring little more than chlorination for safe consumption. In all cases, full chemical analyses of samples should be made to ensure that minimum necessary treatment is being provided.

The Ghyben-Herzberg Theory

In all except the most impervious land masses, rainfall will infiltrate and percolate downward at a rate dependent on the permeability of the geologic material. At some point in its movement through an oceanic island, the fresh water encounters sea water. If rainfall is sufficiently great, a fresh-water lens overlying the sea water will develop within the land mass. Exceptions may be found in extremely pervious low-lying small islands and rock islands containing wide fractures or cavernous openings, but generally the salt-water/fresh-water boundary is well-defined physically within the land mass. Even on a dense bedrock coast, the bay areas are frequently composed of pervious deltaic alluvium or beach sediment which foster similar boundary conditions between fresh water and sea water. Records of many early futile attempts to obtain fresh ground water from coastal aquifers and islands indicate that the sea-water/fresh-water relationship was not at all understood prior to the 20th Century. The practice of drilling deeper for fresh water was frequently attempted even after sea water was encountered in geological formations of continuous permeability. In some formations of very high permeability, the opinion was too easily formed that fresh ground water necessarily terminated at sea level. It was not until 1887 that Badon Ghyben, a Dutch captain of engineers working on the seacoast of Holland, first discovered that the depth of sea water was a function of the height of the water table above mean sea level. In 1900, Baurat Herzberg of Berlin, drilling wells on the East Friesian Islands off the coast of Germany, found the same relations, apparently without knowledge of Ghyben's work; hence, the basic theory for the sea-water/fresh-water relation is termed the Ghyben-Herzberg Theory.



Atoll Island Cross Section

This theory is based on the principle that fresh water, being less dense than sea water, will tend to float on top of the sea water. In a small island or narrow land mass of pervious material, a well-defined lens of fresh water is found below the surface of the ground and on top of the sea water as shown in Figure 1. The flow of the fresh ground water is normally to the edge of the lens as indicated, towards the shoreline.

The total height, H, of fresh water displaces the lesser height, h, of greater-density sea water (a unique application of Archimedes' principle). The difference, t, will be the elevation of the ground water above mean sea level. Assuming the specific gravity of fresh water to be pf and sea water to be ps, then:

$$H\,pf = h\,ps \text{ and } H\,pf = (h + t)\,pf$$

$$\text{combining equations given } h = \frac{t\,pf}{ps - pf}$$

The specific gravity of sea water, ps, varies, but averages about 1.025. The specific gravity of fresh water, pf, may be taken as 1.000. Using these values it is found that $h = 40\,t$. Thus it is found that the lower boundary of fresh water is 40 feet below sea level for every foot above sea level the water table occurs.