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Groundwater flow dynamics beneath atoll islands

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Abstract Based on research of numerous islands within the Indo-Pacific region, a conceptual model of a "typical" atoll island groundwater flow system is proposed. The model depicts an island comprised of unconsolidated reef- and lagoon-derived sediments upon a well-established Holocene-age reef platform. This platform is composed of a reef on the ocean side, a well-indurated reef-flat plate, and unconsolidated sediments deposited in back-reef and lagoon environments. These facies units exhibit significant cross-island differences in hydraulic properties. Deposits of the reef platform rest unconformably upon an older Pleistocene-age limestone that has been solution altered during lower sea-level stands. Large differences in hydraulic properties exist between the Holocene and Pleistocene aquifers that affect the occurrence and movement of freshwater within the flow system. Within the Holocene aquifer, fresh groundwater occurs as an asymmetric lens with the greatest thickness located adjacent to the lagoon shoreline. The lens thins toward the ocean, but extends past the island shoreline where the reef-flat plate acts as a confining layer. A well-developed transition zone exists at the freshwater–seawater interface and is thickest in units of higher permeability. The model includes two flow patterns: a wet-season pattern radiating outward from the unconfined lagoon side of the island, and a dry-season pattern of localized reverse flow where evapotranspiration losses are at a maximum.

Flujo dinámico de aguas subterráneas en atolones

Resumen En base a la investigacion de numerosas islas en la región del Indo-Pacífico, se propone un modelo conceptual para un sistema "típico" de flujo subterráneo en atolones. El modelo representa a una isla conformada por sedimentos no consolidados derivados de arrecifes y lagunas, sobre una plataforma de arrecifes del Holoceno. La plataforma está compuesta por un arrecife del costado del mar, una placa endurecida de arrecifes planos, y sedimentos no consolidados depositados detrás de los arrecifes y en la laguna. Estas unidades independientes muestran significativas diferencias en sus propiedades hidráulicas a través de la isla. Los depósitos de la plataforma de arrecifes reposan sobre una formación más antigua de caliza del Pleistoceno cuya solución se ha visto alterada durante períodos de descenso del nivel del mar. Existen grandes diferencias en las propiedades hidráulicas de los acuíferos del Holoceno y del Pleistoceno, que afectan la ocurrencia y el movimiento del agua dulce dentro del sistema de flujo. En el acuífero del Holoceno, el agua dulce subterránea ocurre como espejo asimétrico, con su mayor espesor adyacente a la línea costera de la laguna. Este espejo se hace más delgado a medida que se aproxima al océano, aunque se extiende hacia afuera del atolón donde la placa del arrecife actúa como estrato impermeable. Existe una zona de transición bien desarrollada en la interfase agua dulce-agua salada, que es más espesa en unidades de mayor permeabilidad. El modelo incluye dos patrones de flujo: uno de estación lluviosa radial desde la laguna no confinada, y otro de estación seca, de flujo inverso localizado, donde encontramos las máximas pérdidas por evapotranspiración.

INTRODUCTION

Atoll islands are common throughout the tropical Indo-Pacific ocean and provide a habitat for a significant portion of the population within the equatorial region. Atolls are unique end products of a continuous series of geological and biological processes that have been at work for tens of millions of years. As viewed from sea level, atolls are characterized by ring-like structures consisting of barrier reef systems that totally or partially enclose a central lagoon. Maximum lagoon depths among atolls range from a few to several tens of metres. Often, but not always, islands composed primarily of unconsolidated carbonate sediment form on top of the reef platform. These islands are variable in size and shape, low lying, and usually vegetated with numerous species of plants. Below sea level, volcanic pedestals supporting atolls may extend upward from the ocean floor for thousands of metres.

The presence of freshwater lenses beneath atoll islands is an important and sometimes the only source of potable water available to the local community. Therefore, it is vital that the flow dynamics of these lens systems be understood so that good decisions can be made regarding the long-term use of groundwater resources within the atoll-island setting. The purpose of this paper is to propose a conceptual model for a "typical" atoll island that describes the occurrence and movement of groundwater with respect to the hydrogeological makeup of the reef platform, and to the climatic regime within which the island is located. This model is based on the results of extensive fieldwork on islands within Micronesia and on the findings of other investigators conducting research on islands throughout the tropical Indo-Pacific region.

HYDROGEOLOGICAL FRAMEWORK

A large number of atoll complexes across the Indo-Pacific ocean exhibit remarkably similar geological characteristics. Based on work conducted on Eniwetok (Ladd & Schlanger, 1960), Bikini (Emery *et al.*, 1954), Tarawa (Jacobson & Taylor, 1981), Nukuoro (Ayers & Clayshulte, 1983), Pingelap (Ayers & Vacher, 1986), Majuro (Hamlin & Anthony, 1987), and elsewhere, it is known that reefs and reef-associated sediments of recent age rest upon an older, pre-emergent Pleistocene limestone. Carbonate units of Pleistocene-age usually differ greatly in their hydraulic properties compared to their Holocene counterparts; higher permeability due to the development of secondary or solutional porosity is the most significant difference. Although depth is variable, the Pleistocene contact is often located between 15 and 25 m below sea level. Recent carbonate sediments overlying the Pleistocene units are mostly unconsolidated to poorly consolidated with occasional thin hard layers of either coralline algae or well-cemented sand and rubble. Numerous facies are present and usually exhibit unique hydraulic properties.

Holocene units overlying the older karstic limestone can be subdivided into two main categories; one is the facies mosaic that comprises the reef and reef-associated complex and the second is the group of surficial units that comprise the island. Figure 1 shows a schematic cross-section of the various units and their relative stratigraphic positions. The main units making up the reef platform are: (a) the reef

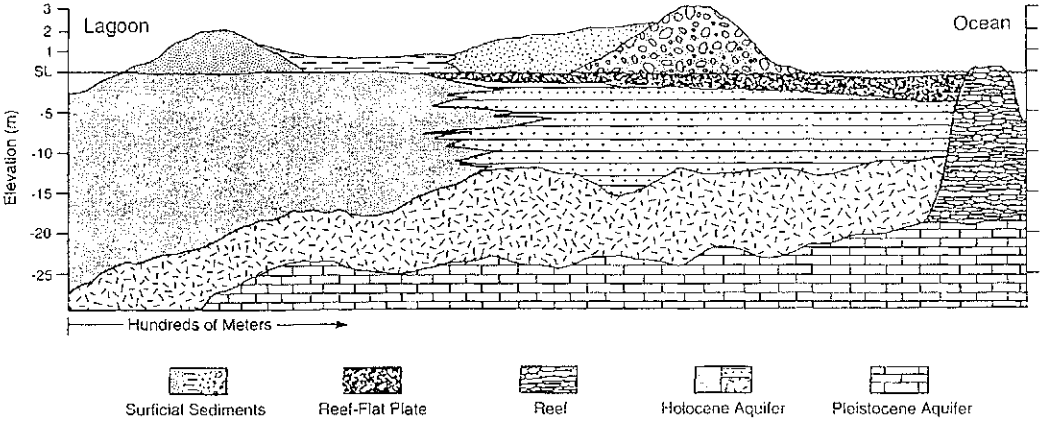

Fig. 1 Schematic diagram of the geological composition of a typical atoll platform.

composed of well indurated *in situ* coral, coral rubble, and coralline algae; (b) a reef-flat plate composed of well-cemented back-reef deposits; (c) a back-reef facies composed mostly of unconsolidated deposits similar to those of the reef-flat plate; (d) a sand apron composed of carbonate sediment derived mainly from the lagoon; and (e) a facies composed of sand and gravel sized sediment and distinctive *Halimeda* (an algae) segments that underlies back-reef and lagoon sediments and overlies the Pleistocene limestone.

Sediments comprising the island rest partly upon the reef-flat plate and partly upon the sand apron. Collectively, these sediments can be grouped into four main components that describe the surficial geology and define the major physiographic features of the island (Fig. 2). These components are: (a) a set of boulder ridges along the ocean shoreline; (b) a series of coalescing wash-over fans; (c) a narrow band of organic-rich soil; and (d) a low berm and beach along the lagoon shoreline. Boulder ridges and wash-over fans are products of erosion and deposition caused by

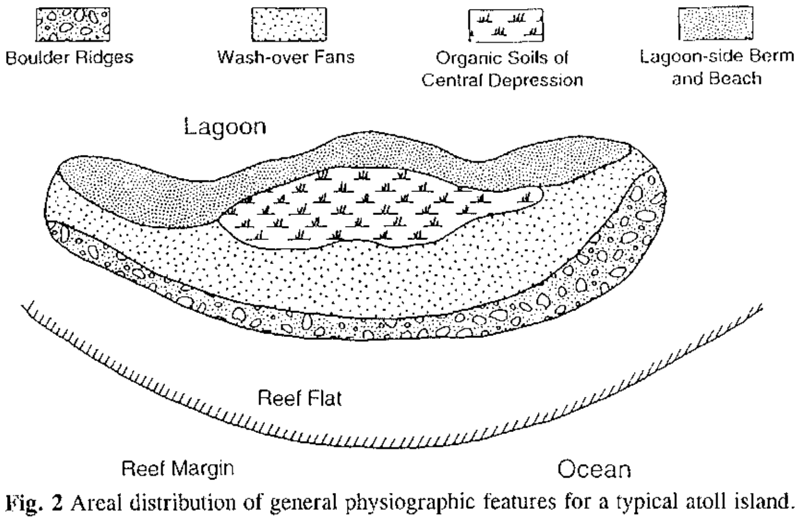

Fig. 2 Areal distribution of general physiographic features for a typical atoll island.

storms during which large amounts of material are transported from the reef margin, across the reef flat, and onto and across the island. Organic-rich soil and very fine-grained sediment usually occur near the lagoon side of the island and normally occupy the lowest elevations. This area is often termed the central basin or central depression and is an important physiographic feature with regard to the hydrology of the lens system. In the central depression where wet conditions often prevail, plant debris tends to concentrate and decay rapidly, forming a black, mucky soil. The low berm and beach along the lagoon shoreline are composed of sediments derived from the lagoon and deposited by wave and wind action.

The occurrence of a freshwater lens on an atoll island depends on a number of factors. First and foremost, the island must be of sufficient size to support the creation of a lens and must be composed of permeable geological material. In addition, there must be frequent and ample rainfall such that groundwater recharge is at least equal to groundwater discharge. In general, four main components comprise the hydrogeological framework of an atoll island. The first of these is the island itself. Its main function is to catch rainfall and transmit it to the freshwater lens. Such processes as plant interception, evaporation, and transpiration operate in this part of the system.

The second component is the reef-flat plate. This feature extends from the offshore reef, partially beneath the island, and eventually grades into lagoon-derived sediments. The well-indurated character of the reef-flat plate provides a stable platform upon which island sediments accumulate. Permeameter tests of plate samples collected from Pingelap Atoll (Ayers & Vacher, 1986) and elsewhere in the Pacific (Buddemeier & Holladay, 1977; Oberdorfer & Buddemeier, 1983) indicate hydraulic conductivities in the range of 0.01–1 m day^{-1}, with most values <0.05 m day^{-1}. Such low hydraulic conductivity suggests that the reef-flat plate is relatively impermeable and acts as a confining or semi-confining layer.

The third component is the facies mosaic that comprises the Holocene aquifer. This component exhibits an areal variation in hydraulic properties, relatively high values for sediments near the ocean and lower values (by an order of magnitude) for sediments adjacent to the lagoon. In addition to this cross-island heterogeneity, hydraulic properties also vary with depth, particularly for ocean-facing units. In general, hydraulic conductivities for the back-reef and lagoon units range between 10 and 100 m day^{-1}, depending on the degree of cementation present.

The last component of the atoll-island hydrogeological system is the underlying Pleistocene-age limestone. This component is characterized by numerous solution unconformities (Schlanger, 1963), secondary porosity, meteoric diagenetic features, and high permeability. Hydraulic conductivity values may be as high as 1000 m day^{-1} (Oberdorfer & Buddemeier, 1983). The contact between the Holocene and Pleistocene aquifers is at shallow depths, usually within a few tens of metres of sea level. As pointed out by Buddemeier & Holladay (1977), the effect of a deeper high-permeability unit is that the tidal signal is propagated relatively unimpeded through the lower more permeable aquifer and then upward through the overlying Holocene sediments. This phenomenon has been documented on Eniwetok (Buddemeier & Holladay, 1977) and Kwajalein (Hunt & Peterson, 1980), where calculated tidal efficiencies increase and observed delay times decrease as a function of well depth, rather than horizontal distance from the shore. Two important implications of this phenomenon should be considered. First, the base of a freshwater lens located near the high-permeability unit will receive a stronger tidal signal compared to a lens system in a single-layered aquifer where the tidal signal is propagated directly from the shore. Therefore, tide-induced hydrodynamic dispersion about the interface between freshwater and underlying salty groundwater is more pronounced. A thicker zone of mixed salinities is formed, and the unblended nucleus of freshwater is smaller. The second implication relates to flow dynamics. Results of numerical modelling by Herman & Wheatcraft (1984) indicate that vertical-flow components may dominate in the interior of the freshwater lens because of the tidal link between the Pleistocene limestone and the overlying sediments of lower permeability.

DYNAMICS OF GROUNDWATER FLOW

Under ideal conditions, where the aquifer is homogeneous and isotropic, the system is recharged uniformly, and there are no external influential factors (such as sea-level fluctuations), a symmetric Ghyben-Herzberg lens should be maintained. This, however, is not the case. Most atoll island lens systems are partially confined, occur within complex geological units possessing disparate hydraulic properties, experience recharge events of variable magnitude, and exhibit the effects of sea-level variations caused by tidal frequencies, barometric pressure changes, and seasonal or long-term ocean-level oscillations.

A conceptual model of the flow dynamics for an atoll island is shown in Fig. 3. The upper diagram represents the flow regime that would exist during wet season conditions and the lower diagram represents the flow regime for the dry season. Important features of the model include: (a) the asymmetry of the lens; (b) the variability in thickness of the mixing or transition zone; (c) the relation between the reef-flat plate and the region of principal recharge; (d) the relation between the zone of discharge and the shoreline; and (e) the differences in lens configuration between the wet and dry seasons.

One of the most obvious features of the model is the asymmetric lens configuration. The main portion of the lens occurs within the Holocene aquifer and the thickest part occurs near the lagoon where the sediments have a relatively low permeability. Resistance to groundwater flow due to the low hydraulic conductivity tends to produce higher heads, which in turn depress the position of the transition zone and thus create a thicker lens. The thickness of the transition zone is less along the lagoon side of the island due to a greater attenuation of the tidal signal caused by the less permeable sediments. In the more permeable sediments adjacent to the ocean shore, the transition zone is much thicker and may exceed the thickness of the unmixed freshwater.

Island physiographic features influence the configuration of the freshwater lens. There are three general regions that have different patterns of recharge and evapotranspiration losses. The first of these is the central depression where the ground surface is near the water table. In this region, groundwater storage losses due to direct evaporation and plant withdrawals can be significant. If these losses are greater than recharge, as they are during the dry season, there can be a localized thinning of the lens beneath the central depression. In contrast, when losses are small relative to recharge, as during the wet season, groundwater mounding may occur.

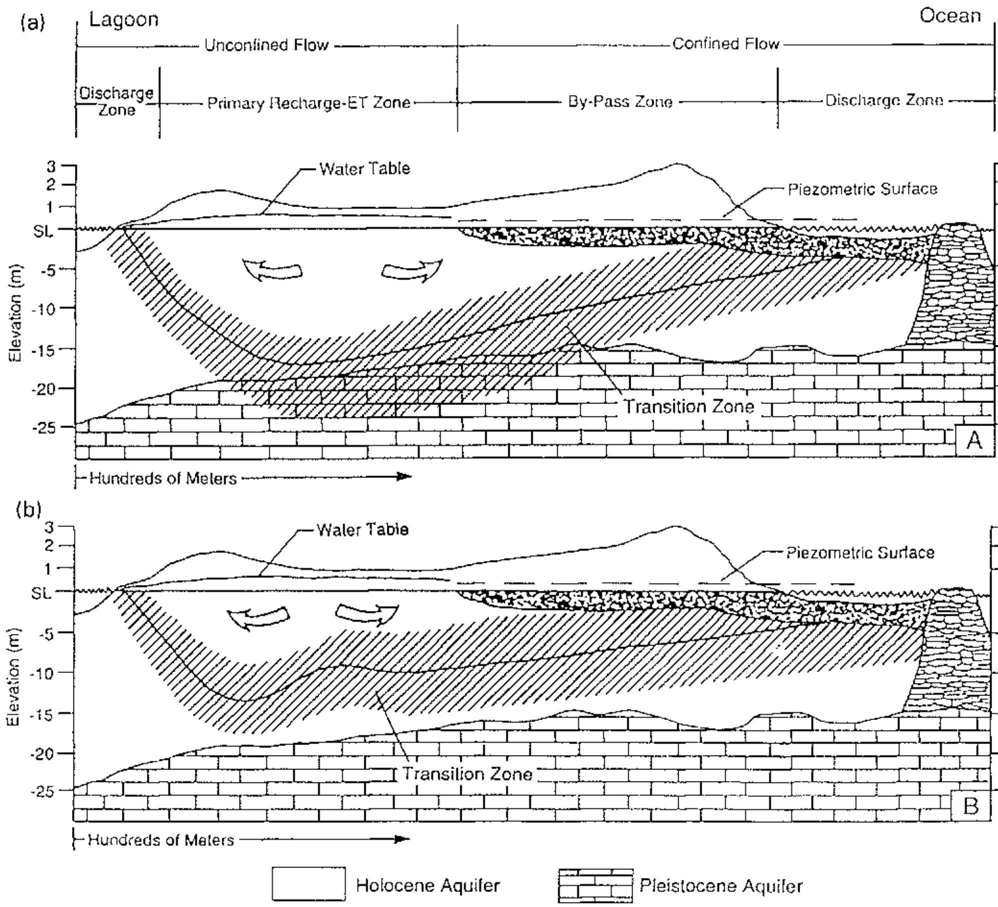

Fig. 3 Groundwater flow patterns for recharge and evapotranspiration conditions prevalent (a) during the wet season and (b) during the dry season.

Thus, the central depression acts as a sink during the dry season and as a source during the wet season.

Across the region underlain by the reef-flat plate, direct recharge to the lens is impeded by the low permeability of the plate. During low tide, water ponds on the surface of the plate and tends to drain downward into the lens. This downward drainage is thought to be largely through fractures (Ayers & Vacher, 1986; Griggs & Peterson, 1993). Even with these fractures, not all of the ponded water drains into the lens before the next high tide. This excess water is probably lost as interflow, exiting the system along the ocean-facing shoreline at the contact between island sediments and the reef-flat plate. With regard to consumptive losses, the plate acts as an effective barrier to direct evaporation from the lens and to deep root penetration by plants, so water losses across the top of the lens are less in this region than elsewhere.

Over the region where the reef-flat plate is absent, recharge water moves unimpeded from the ground surface to the water table. Direct loss of water from the lens is primarily by plant transpiration with lesser amounts lost through evaporation. Depending on vegetation density, plant species, and root penetration depths, transpiration losses may be significant, particularly during the dry season when water consumption is at a maximum. Because of the thicker sediment cover, recharge events and water losses have a less pronounced effect on the configuration of the lens compared to the effects in the central depression.

The reef-flat plate acts as a confining or semi-confining layer over a portion of the freshwater lens. Because of this, it is not appropriate to assume that the ocean shoreline of the island marks a discharge boundary. As demonstrated on Deke Island (Ayers *et al.*, 1984) and Laura Island (Griggs & Peterson, 1993), groundwater can be transported well beyond the island limits to exit either through the reef-flat plate via fractures or along the reef margin itself. A consequence of this situation is that the volume of freshwater within the lens system is greater than would be expected if the island shoreline was the discharge zone.

As a result of seasonal variations in recharge, two distinct groundwater flow patterns develop. During the wet season (Fig. 3(a)), when recharge is at a maximum, the axial mound of the water table is well developed, and flow is directed away from the divide toward both the lagoon and ocean discharge zones. Head elevations and the volume of freshwater within the lens are at their maximum. The flow pattern during the dry season (Fig. 3(b)) is similar except in the region of the central depression. Due to a net water loss over this area, the water table depresses and the transition zone rises resulting in groundwater movement toward the depression from the surrounding lens. In general, there is a reversal of wet-season flow directions in the vicinity of the central depression, a decrease in head within the lens, and a decline of freshwater in storage. However, with renewed rainfall, the rapid recharge rates within the central depression quickly re-establish the axial mound, restore water lost from storage, and initiate the wet-season flow pattern that existed prior to the onset of the dry season.

CONCLUSION

The conceptual model proposed in this paper depicts a complex groundwater flow system that is influenced by the geological composition of the reef platform, by the three-dimensional variations in hydraulic properties of the aquifer, by the seasonal variations in recharge and evapotranspiration, and by the cyclic and long-term fluctuations in sea level. This model should be useful to hydrogeologists, engineers, water resources planners, and others involved in the development and management of groundwater resources on atoll islands. Although the model has not yet been quantified, it does help to explain why some island communities experience certain problems related to the occurrence, movement, supply, and quality of fresh groundwater. Chief among these are seawater intrusion, seasonal water shortages, and water-borne diseases. These problems can be avoided or their effects greatly reduced by applying the concepts represented in the model and by making decisions about resource development and management based on them.

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