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1981

UCRL- 85411
PREPRINT

MASTER

# THE GEOHYDROLOGY OF ENEWETAK ATOLL ISLANDS AND REEFS

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To be presented at the 4th International
Coral Reef Symposium, Manila, Phillipines,
May 18-22, 1981

May 6, 1981

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# The Geohydrology of Enewetak Atoll Islands and Reefs*

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## Abstract

Extensive tidal studies in island wells and the lagoon at Enewetak Atoll have shown that island ground water dynamics are controlled by a layered aquifer system. The surface aquifer of unconsolidated Holocene material extends to a depth of approximately 15 m, and has a hydraulic conductivity K = 60 m/day. From 15 to 60 m (approximate lagoon depth) the reef structure consists of successive layers of altered Pleistocene materials, with bulk permeability substantially higher than that of the surface aquifer.

Because of wave set-up over the windward reef and the limited pass area for outflow at the south end of the atoll, lagoon tides rise in phase with the ocean tides but fall later than the ocean water level. This results in a net lagoon-to-ocean head which can act as the driving force for outflow through the permeable Pleistocene aquifer. This model suggests that fresh water, nutrients or radioactive contaminants found in island ground water or reef interstitial water may be discharged primarily into the ocean rather than the lagoon.

Atoll island fresh water resources are controlled by recharge, seawater dilution due to vertical tidal mixing between the surface and deeper aquifers, and by loss due to entrainment by the outflowing water in the deeper aquifers.

*"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

Estimated lagoon-to-ocean transit times through the deep aquifer are on the order of a few years, which corresponds well to the freshwater residence time estimates based on inventory and recharge. Islands in close proximity to reef channels have more fresh ground water than others, which is consistent with a locally reduced hydraulic gradient and slower flow through the Pleistocene aquifers.

## INTRODUCTION

Enewetak, the northwesternmost atoll of the Marshall Islands chain, was part of the U.S. Pacific Proving Grounds between 1948 and 1958. Numerous nuclear tests were conducted on the atoll, which has been the site of a variety of scientific investigations. This paper presents some of the results of a study funded by the U.S. Department of Energy as part of a program to determine the physical, chemical and biological mechanisms controlling the distribution and transport of fallout radionuclides in the atoll environment.

Enewetak Atoll (see Figure 1) is roughly elliptical in shape, with a reef structure 40 km long by 32 km wide. The lagoon reaches a maximum depth of 60 m, and is connected to the ocean by three openings in the reef. The Deep Channel in the southeast is 1.5 km wide, with a maximum depth of about 60 m. The Wide Passage in the south is 10 km across, with a maximum depth of 30 m and a typical depth of 20 m. The West Passage is little more than an irregular series of interruptions in the surficial reef structure, with typical depths of 2-3 m. The reef supports in excess of 30 small, low-relief islands composed of carbonate sand and gravel; total dry land area is 6.7 km$^2$, with the largest islands being about 1 km$^2$ in area.

The Northern Marshall Islands are in the zone of the northeast trade winds. Enewetak receives an average annual rainfall of 1470 mm, mostly during the August-December period. Rainfall is highly variable; annual totals range from 605 to 2422 mm (Taylor, 1973; this study). Tides are mixed semi-diurnal, with a maximum range of about 1.8 m.

The geology of Enewetak Atoll has been extensively studied, with initial reports by Emery et al. (1954), Ladd and Schlanger (1960) and Schlanger et al. (1963). The islands are unquestionably of Holocene orgin (Tracey and Ladd, 1974), as is the present reef surface (Buddemeier et al., 1975). Recent geological and geophysical investigations of the atoll have been reported by Ristvet et al. (1978). The first solution unconformity, representing the interface between generally unconsolidated Holocene material and the underlying Pleistocene carbonate, occurs at a depth of approximately 15 m below mean sea level (MSL). Below that a series of successive solution unconformities apparently represent a record of emergence during Pleistocene sea level fluctuations. Shallow seismic refraction studies (Ristvet et al., 1978) on representative windward, leeward and transitional islands yielded consistent results indicating the presence of four distinct and reproducible seismic velocity intervals. $V_0$, the velocity in unsaturated soil and surface sediment, is 330-660 m/sec. $V_1$ is the velocity in the saturated unconsolidated sediments and is typically about 1600 m/sec. $V_2$ appears to represent the velocity in the moderately consolidated Pleistocene sediments, usually about 2500 m/sec. The $V_1/V_2$ interface occurs at about 15 m below MSL, is nearly horizontal, and appears to correlate well with the first solution unconformity. In a few cases the experimental methods were able to resolve a deeper velocity interval $V_3$ ($\sim$3000 m/sec) apparently corresponding to well-consolidated sediments at a depth of about 60 m. The velocity interfaces rise sharply as the seaward edge of the island is approached, apparently as a result of increased consolidation associated with the fore-reef structure. Figure 2 is a cross-section of Enjebi Island, showing the major features reported by Ristvet et al. (1978).

Atkinson et al. (1981) have studied the water budget and circulation of water in the Enewetak lagoon. They found that essentially all of the water input to the system comes from wind-driven transport across the windward reef. Since the windward reef crest has a typical elevation close to MSL, wave set-up onto the reef drives water from the ocean into the lagoon at all times except when low tide concides with calm seas, and the reef blocks any return flow. Atkinson et al. estimated a net cross-reef input of ca. 7 x $10^8$ $m^3$ per tidal cycle (12.5 hrs) and found that virtually all of the outflow occurs through the Wide Passage in the south. The Deep Channel has a balanced inflow and outflow of about 3 x $10^9$ $m^3$/tidal cycle in both directions, and other input/output terms (e.g., transport across the leeward reef) are negligible in comparison. The calculated mean lagoon water residence time is about one month, with a maximum of 4 months for water in the Northeast section of the atoll. Although water levels were not directly observed, the circulation pattern requires the existence of a net lagoon to ocean gradient.

Buddemeier and Holladay (1977) reported that well tides on Enjebi Island lagged lagoon tides by amounts which decreased with increasing well depth. The plot of lag vs depth showed a sharp discontinuity between 10 and 20 m depth, and they hypothesized that the effect might be due to the existence of a more permeable aquifer below the first solution unconformity. Wheatcraft and Buddemeier (1981) showed that shallow wells on Enjebi had tide lags, tidal efficiencies, and heads which were uniform and independent of distance from shoreline. They compared these results with predictions based on a mathematical model of horizontal tide signal propagation in the surface aquifer and concluded that the classic Ghyben-Herzberg lens model does not describe the system, which is almost certainly controlled by vertical transmission of tidal signals from the deeper and more permeable Pleistocene aquifer. High permeability in the Pleistocene aquifer is consistent with the observations of Hanshaw and Back (1980) concerning dissolution processes at fresh water/salt water interfaces.

Although the islands of Enewetak Atoll are hydrologically as well as geologically and geophysically similar, some systematic differences need to be explained. Some of these are shown in Table 1 (Wheatcraft and Buddemeier, 1981; Buddemeier and Jansen, 1976) from which it may be seen that the total fresh water content of island groundwater (assumed proportional to surveyed water elevations) is essentially independent of island area and radius, and that the southern islands have approximately 50% more fresh water than the northern islands. In addition to this difference in gross inventory, salinity profiling in deeper wells, shallow well salinity measurements, and the results of pump tests all indicate that the northern islands have thinner layers of potable water and more extensive transition zones than do the southern islands.

This paper examines the factors controlling water movement and residence time in the more permeable Pleistocene aquifer, and advances a conceptual model to explain differences in fresh water resources as a function of island location.

## OBSERVATIONS AND RESULTS

Nearly continuous tide observations from the lagoon side of Japtan Island were made available by Dr. Klaus Wyrtki, University of Hawaii. Sporadic lagoon and reef tide measurements were made at other locations indicated on Figure 1. These measurements were made with Stevens Type A-71 float gauges in stilling wells where supporting piers or structures were available, and with recording bubbler gauges elsewhere.

Although the primary purpose of these relatively short tide records was establishment of a local sea level datum for surveying, records from various locations were both qualitatively and quantitatively compared. During periods when the reef was awash wave setup produced a tide signal on the Enjebi seaward reef which was in phase with the Enjebi lagoon tide but which had a mean water elevation 0.3 - 0.5 m above the mean lagoon level; smaller but still significant differences were observed between the Enewetak Island reef and lagoon gauges. Significant short-term differences in amplitude, timing and tide curve shape were also noted between different tide stations. In order to evaluate possible systematic variations, a good quality tide record from the lagoon side of Biken Island was digitized and subjected to computer comparison with the Japtan Island record. The period analyzed spanned most of the month of December, 1978.

A commercially available Fourier tranform program, SPECTRA (SAS), was used to produce estimates of cross-spectral densities. The results indicated that the Japtan and Biken data were essentially identical in amplitude and in frequency composition. Since no independent common datum was available, the long-term means of both records were set equal, and time series plots were constructed and differences calculated. A representative tide sequence is shown in Figure 3.

It may be seen that, although time-independent means were equalized, the Biken tide signal is distorted relative to Japtan by delay of the falling tide, so that the highs are broadened and the lows narrowed. When differences between same-time measurements are averaged, the result is a net water elevation at Biken relative to Japtan. Calculated over a two-week period, this net difference averaged 6.5 cm.

## DISCUSSION

Net head of lagoon water relative to the ocean represents a driving force which will tend to set up a lagoon-to-ocean flow of water through the permeable reef structure. The results of Atkinson et al. (1981) clearly require that a north-to-south water level gradient exist within the lagoon. The measured elevation at Biken relative to Japtan is clearly a conservative estimate of that gradient for several reasons: 1.) Although the Japtan tide gauge is adjacent to the Deep Channel, it is in the lagoon rather than in the ocean; 2.) Long-term means were set equal, and if any difference does exist it will certainly further elevate Biken water levels relative to Japtan; 3.) Although Biken is about 15 km north of the Wide Passage and 25 km south of Enjebi, it is considerably to the west of the N-S lagoon axis and is adjacent to the shallow West Passage which may tend to reduce the observed head. Based on these observations, I estimate for the purpose of calculation that the net lagoon-to-ocean head near the southern passes is less than 5 cm, and that it may well exceed 20-25 cm in the extreme north.

If we consider the first Pleistocene aquifer (roughly the $V_2$ layer in Figure 2) as a high permeability conduit connecting the lagoon with the ocean, then we may estimate average water throughput according to the equation:

$$v_p = Kn^{-1}\, dh/dl$$

where $v_p$ is the pore velocity, K the hydraulic conductivity, n the porosity and dh/dl the piezometric head.

Lagoon depth contours show a broad shelf on the windward side at a depth of approx. 22-30 m MSL and a sharp drop in the 18-22 m MSL interval. If we consider the shelf to be the lagoonward extension of the first solution unconformity surface and the shallow drop-off to be the end of the overlying back-reef sediments, we can approximate the length (l) of the subsurface aquifer as the distance between the 15 m depth contour and the seaward reef edge. This distance is about 920 m for Japtan and Enewetak, 1690 m for Aomon and 1850 m for Enjebi. The head (h) is taken as 25 cm at Enjebi, 20 cm at Aomon, and 5 cm at Japtan and Enewetak.

K for surface sediments is about 60 m/day (Wheatcraft and Buddemeier, 1981); in order for the Pleistocene aquifer to dominate island well tidal effects its K must be substantially larger, and is estimated for the purpose of these calculations as 600 m/day. The porosity is taken as 20% (Couch et al., 1975).

Once the pore velocity is obtained the transit time of water through the section of the Pleistocene aquifer beneath each island may be calculated as $t = d/v_p$, where d is the effective island diameter (approximate lagoon-reef distance) and $v_p$ is the pore velocity appropriate to that island.

Although the Ghyben-Herzberg model is not strictly applicable to this system, it is useful to estimate the fresh water inventory of each island as $W = 40 \cdot H \cdot n$, where 40 is the approximate Ghyben-Herzberg ratio based on density differences between fresh and salt water, H is the mean fresh water head (Table 1) and n is the porosity; W is then the equivalent column height of the fresh water in the island. Island recharge estimates based on soil moisture profiles, evaporation data and rainfall distribution range from 10 to 50% of the incident rainfall, depending on the exact values used and the temporal distribution of the rain. An average recharge rate (R) of 500 mm/yr (approx. 30% of average annual rainfall) is used; on this basis the residence time of the island fresh water may be calculated as $T = W/R$.

Table 2 summarizes the results of the calculations outlined above for the four islands. The results are necessarily very approximate in view of the assumptions and estimates involved, but it can readily be seen that the freshwater residence times (T) and the Pleistocene aquifer residence times (t) based on flow estimates are of the same order of magnitude and vary in the same sense. This suggests that the Pleistocene aquifer not only controls island well tidal responses and causes vertical tidal mixing of the groundwater, but also that the entrainment of fresh water by the head-driven flow through the aquifer limits the total fresh water inventory. If this is the case, it also implies that tidal mixing between the Holocene and Pleistocene aquifers occurs on a time scale comparable to or shorter than the residence times observed.

Two caveats must be noted in connection with the foregoing discussion. First, the model used neglects any effects of deeper aquifers (e.g., the $V_3$ zone shown in Figure 2) on the system. Second, the calculation implicitly treats the reef plate as impermeable and considers wave-set up onto the reef to be perched water. This is consistent with the reef plate hydraulic conductivity measurement of K = 33 m/day reported by Wheatcraft and Buddemeier (1981); however, if the reef surface is in hydrostatic equilibrium with the underlying Pleistocene aquifer, the details of the water movement may be quite different. Since the reef-lagoon head (0.3-0.5 m at Enjebi) is comparable to the lagoon-ocean gradients, the flow rates would still be comparable to those calculated above, and the conclusions about the budgetary importance of flow through the Pleistocene aquifer as a control on fresh water inventory would be similar. Unfortunately, data available at present do not allow resolution of this uncertainty.

## SUMMARY AND CONCLUSION

Mean net water level differences in the ocean-reef-lagoon system may reach several tenths of a meter, and vary geographically as a result of wave set-up on the reefs in relation to lagoon water level and the location of passes. It is probable that the amount and quality of fresh island groundwater is controlled by the rate of ocean to lagoon head-driven flow through a high permeability aquifer of Pleistocene carbonate which has an upper surface at approximately 15 m below MSL. The calculated island groundwater residence times of a few years are significant from both scientific and resource management standpoints.

## ACKNOWLEDGEMENTS

I particularly appreciate the advice and technical assistance of Stephen Wheatcraft, Stephen Smith and June Oberdorfer. Thomas Cooney performed the computer analysis, Klaus Wyrtki made available the Japtan tide data, and the staff of the Mid-Pacific Research Laboratory provided logistic support.

Table 1: Shallow Well Characteristics

| Island | Effective Area (km$^2$) | Effective Radius (m) | No. of Wells | Mean ± s.d Head (m) | Mean ± s.d. Efficiency | Mean ± s.d. Lag (Hrs) |
|---|---|---|---|---|---|---|
| Enewetak | 0.32* | 305 | 7** | 0.33<br>±0.09 | 0.12<br>±0.07 | 3.28<br>±0.36 |
| Japtan | 0.44 | 302 | 2 | 0.38<br>±0.27 | 0.05<br>±0.01 | 4.28<br>±0.10 |
| Aomon | 0.32 | 275 | 5 | 0.21<br>±0.04 | 0.11<br>±0.06 | 1.69<br>±0.34 |
| Enjebi | 1.11 | 405 | 9 | 0.26<br>±0.05 | 0.09<br>±0.04 | 2.96<br>±0.29 |

* Area of the wide southern portion of island - narrow northern extension is excluded as hydrologically irrelevant

** One seaward well which terminated in consolidated reef plate material was excluded from the calculation

Table 2: Water Flux Estimates

| Island | $dh/dl^1$ (m/m) | $v_p{}^2$ (m/day) | $t^3$ (yr) | $\bar{\tau}^4$ (yr) |
|---|---|---|---|---|
| Enewetak | .05/920 | 0.16 | 10.2 | 5.6 |
| Japtan | .05/920 | 0.16 | 11.0 | 6.0 |
| Aomon | .20/1690 | 0.36 | 4.2 | 3.4 |
| Enjebi | .25/1850 | 0.41 | 5.4 | 4.2 |

Notes:
1. Estimated lagoon-ocean head over estimated aquifer length
2. Pore velocity in Pleistocene aquifer (see text)
3. Pleistocene aquifer water transit time under island
4. Estimated residence time of fresh water in island groundwater (see Table 1 and text)

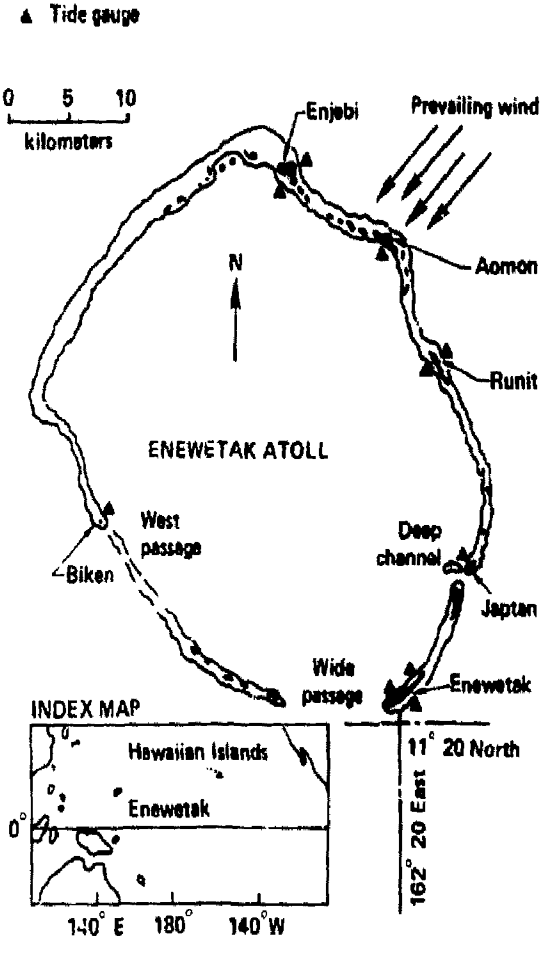

Figure 1: Enewetak Atoll, with locations of lagoon and reef tide observations.

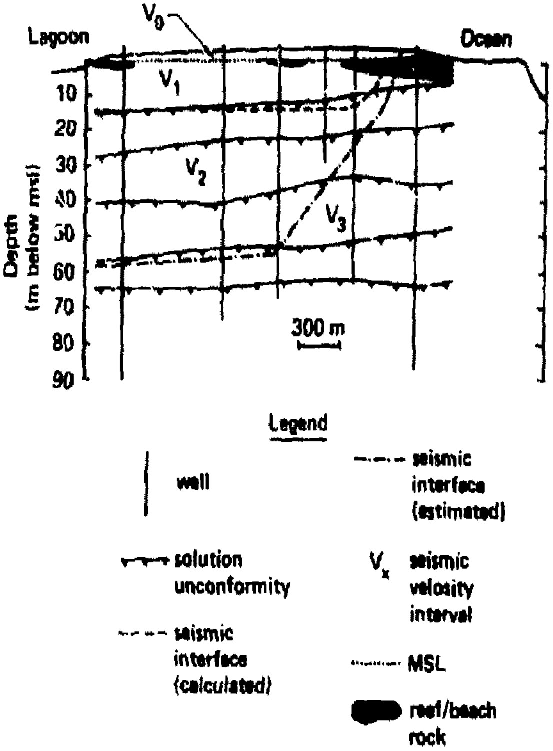

Figure 2: Cross section of Enjebi Island (from Ristvet et al., 1978) with key geological and geophysical horizons indicated. See text for discussion of seismic velocities.

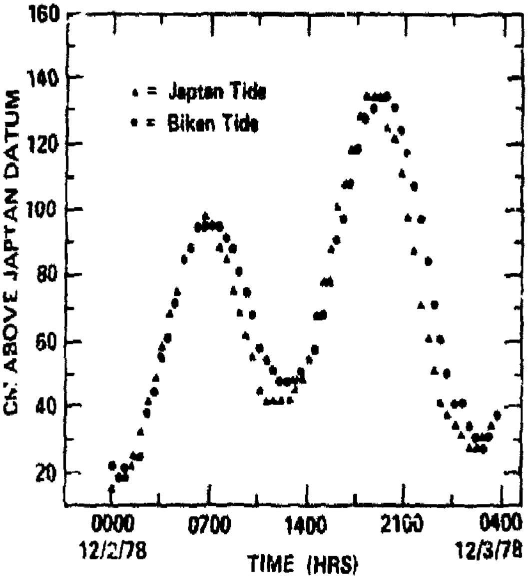

Figure 3: Comparison of tide signals from Japtan and Biken Island lagoon gauges. Long-term means arbitrarily adjusted to coincide.

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