# ESTIMATE OF RECHARGE
# TO THE
# FRESHWATER LENS OF NORTHERN
# GUAM

JERRY F. AYERS

## Water Resource Research Center

## UNIVERSITY OF GUAM

Technical Report No. 21

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By

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Project Completion Report

for

Estimate of Recharge Inferred from the Chloride
Concentration of the Fresh-Water Lens of Northern Guam

OWRT Project No. A-017-Guam, Agreement No. 14-34-0001-0112

Principal Investigator:  Jerry F. Ayers

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## ABSTRACT

*In Guam, as in other oceanic-island environments, rainfall has a significant chloride-ion concentration. As a result, there is a relatively simple and straightforward method of estimating groundwater recharge by considering the chloride ion as a tracer which is concentrated by evapotranspiration-related processes.*

*The chloride-ion concentration of rainwater in Guam is about 4.5 mg/ℓ. The freshest part of the northern lens is about 11.8 mg/ℓ. Taking the 11.8 mg/ℓ value as an indicator of the chloride-ion concentration of recharge, the average annual recharge rate is estimated at 38 per cent of the 218 cm/yr average annual rainfall, or about 83 cm/yr.*

*This estimate agrees very well with previous work which utilized other independent methods of determining recharge rates.*

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# INTRODUCTION

The groundwater hydrology of Guam has been studied by a number of investigators for decades. Because of a lack of funds to conduct comprehensive programs of study and because of limited research facilities in the past, progress toward an understanding of the hydraulic behavior and hydrogeology of the groundwater-flow system has been slow. As a result, certain key parameters need further investigation. One such parameter is the rate of recharge to the fresh-water lens of northern Guam, the main source of potable water for the island community.

It is essential to determine recharge by as many ways as available data will allow, since recharge is one of the variables most difficult to measure. Previous investigators of groundwater occurrence on Guam have used only two of the many available methods to estimate recharge. This is due to primarily two reasons:

1. a lack of reliable and consistent data; and

2. limited research facilities and capabilities.

The purpose of this investigation is to determine the magnitude of recharge to the fresh-water lens of northern Guam utilizing a rather simple and straightforward method presented by Vacher and Ayers (1980). This technique requires only chloride-concentration data for rainfall and groundwater samples and is easily applied where other data are absent or insufficient.

## PREVIOUS ESTIMATES OF RECHARGE

One of the earliest attempts to estimate the magnitude of recharge in northern Guam was made by Peterman et al. (1945) as part of a groundwater

study sponsored by the military. Study results indicated that the northern half of Guam (the study area for this report) received a recharge rate of 100 million gallons per day (mgpd) for the approximate 259 square-kilometer area or about 0.39 mgpd per square kilometer.

In a later study of water resources beneath the Marbo-Dededo area (north-central Guam), Davis (1964) estimated that from 0.73 to 0.89 mgpd of rainfall per square kilometer reached the fresh-water lens. This range of values was determined by two methods. The low end of the range was estimated by assuming that any month with less than 10.2 cm of rainfall is a drought month and therefore no water is available for recharge. Thus, rainfall occurring during the dry-season months of January through June is usually less than the 10.2 cm criteria and thus would not contribute to recharge. Rainfall during the remaining months, less the 10.2 cm/mo value, contributes approximately 101 cm of water to recharge. This latter volume, when multiplied by the area, yields the 0.73 mgpd per square kilometer estimate. Davis obtained data from Blumenstock (1957) for calculating the budget.

The high end of the range of recharge rates was obtained by assuming that runoff in southern Guam is equivalent to recharge in northern Guam (there is no surface drainage in the study area). That is, if the study area was completely drained by streams, then the amount of water leaving the area is equivalent to the amount of water that infiltrates as recharge. Davis found from past records that the average of the total flow for six drainage basins in southern Guam (volcanic terrain) was approximately 0.89 mgpd per square kilometer and the range was 0.73 to 1.00 mgpd per square kilometer.

In an administrative report prepared for the Air Force, Davis and Huxel (1968) estimated the recharge rate over northern Guam to be about 0.97 mgpd per square kilometer. Runoff records for the Pago and Ylig Rivers in southern Guam were used in the determination. Both streams drain basins that receive approximately the same magnitude of rainfall per square kilometer as northern Guam.

In a report of groundwater availability and current water well development, Sheahan (1968) estimated that 50 per cent of the rainfall infiltrates the soil as recharge. His estimate is apparently based on a budget calculation using evaporation data; however, no data was presented in the report and no computational procedures were described.

Austin, Smith and Associates, Inc. (1970), in a report to the Public Utility Agency of Guam (PUAG), presented a set of rainfall-runoff percentages for the wet and dry season months. Rainfall and runoff data were from 1959 through 1966 and included stage records from six streams in southern Guam. For the 8-year period of record, the mean dry season rainfall-runoff percentage was 38 and the mean wet season value was 63. It was assumed that runoff from the six watersheds was a measure of the recharge to the lens of northern Guam; no allowance was made for base flow from groundwater. These percentages convert to a recharge rate of about 1.04 mgpd per square kilometer.

As part of a study on the groundwater resources of Guam, Mink (1976), presented estimates of recharge based on hydrologic budget calculations and rainfall-runoff relationships. Using rainfall and evaporation data he estimated that from 0.52 mgpd to 0.95 mgpd per square kilometer reaches the fresh-water lens if no runoff from the northern plateau is assumed and that from 0.44 mgpd to 0.86 mgpd per square kilometer is available for recharge if 5% runoff is assumed.

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In general, the results of previous studies on groundwater resources of northern Guam have presented a range of recharge rates that center on 0.77 mgpd per square kilometer with a deviation of about 0.20 mgpd. This converts to a rate from 79 cm/yr to 135 cm/yr or, expressed as a percentage of the mean annual rainfall, from 37 to 62 percent (assuming that 218 cm/year is representative of the mean annual rainfall).

## HYDROGEOLOGIC SETTING

The study area encompasses the northern half of Guam and is characterized by a gently undulating limestone plateau bordered by steep wave-cut cliffs. The plateau slopes southwestward from elevations of about 185 meters in the north to less than 30 meters at the narrow midsection of the island. At the southern end of the plateau, the boundary is represented by the east-west trending Adelup-Pago fault which separates the limestones from the volcanic rocks of the mountainous southern half of Guam.

Two formations, the Mariana and older Barrigada, make up most of the rock of the study area and together form the major aquifer (Ward et al., 1965; Mink, 1976). These principal units form a thick sequence of limestone consisting of shoal, complex reef, and lagoonal facies. Permeability within the units is highly variable due to numerous solution channels and fissures and, for the Agana argillaceous member of the Mariana, varying amounts of clay. An average or regional hydraulic conductivity of approximately 610 m/day has been assigned to the northern aquifer (Mink, 1976).

Impervious volcanic rocks of probable Eocene age underly the limestone aquifer (Tracey et al., 1963). Depths to the volcanic basement range from about sea level to several hundred feet over most of the plateau. Volcanic rocks outcrop at three locations forming Mt. Santa Rosa (260 meters in

elevation), Mataguac Hill (210 meters in elevation) and Palia Hill (185 meters in elevation). Where exposed on the plateau, the volcanics are composed of bedded tuffaceous shale and sandstone containing lapilli tuff. On Mt. Santa Rosa, six lithologic units have been mapped (Tracey et al., 1963) which consist of weathered volcanic conglomerate, blocky flow breccia, basic flows and dikes, tuffaceous sandstones and shales, lapilli conglomerate, and boulder conglomerate. The exposed volcanic units have been assigned to the Alutom formation (Tracey et al., 1963).

The topographic relief of the volcanic basement is shown in Figure 1. As inferred from the zero contour line, there is a relatively large area of the northern plateau under which the basement lies at or above sea level. Major features of the basement topography include high relief areas centered on Mt. Santa Rosa, Mataguac and Palia Hills, three buried hills located to the north and southwest of Mataguac Hill, a long slightly arcuate ridge extending from Mt. Santa Rosa southwestward to Barrigada Hill, and a north-east-southwest trending trough between Mt. Santa Rosa and Mataguac Hill. The map of Figure 1 was constructed by Biehler and Walen (1980) from seismic refraction data obtained from a recent geophysical study.

Fresh groundwater occurs as a complex Ghyben-Herzberg lens (Ward et al., 1964; Mink, 1976). Rainfall infiltrates the ground surface and percolates through the highly permeable limestone as recharge. Freshwater reaching the water table, which lies near sea level, displaces the salty groundwater by virtue of the density differences between fresh and sea water and a lens-shaped body of freshwater is formed and maintained. Sea water is approximately one-fortieth greater in density than freshwater; consequently, the depth of a static freshwater lens below sea level would be roughly 40 times the height

of the water table above sea level. The lens is, however, a dynamic system through which water is in constant motion from areas of recharge to zones of discharge, and the energy involved in this movement affects the shape of the lens and the depth of the freshwater. Theoretical aspects of the hydraulics of the fresh-water lens have been discussed in detail by Hubbert (1940), Cooper (1959), Glover (1959), and Bear (1972, 1979).

The boundary between fresh and underlying salty groundwater in northern Guam is not an abrupt interface, but rather a zone of mixing or, as defined by Bear and Todd, (1960), a transition zone. The presence of the transition zone can be attributed to periodic fluctuations of the water table which cause corresponding movements of the theoretical interface (Bear and Todd, 1960; Bear, 1972). Periodic fluctuations in the positions of the water table are due to seasonal variations in recharge and oscillations of sea level. The latter are more important to the maintenance of the transition zone, particularly sea-level oscillations due to the tides (Carrier, 1959) and sea-level changes related to atmospheric pressure variations (Vacher, 1978; Ayers, 1980).

Experiments on dispersion models of the transition zone (Carrier, 1959; Bear and Todd, 1960) have shown that the increase in relative salinity ($\varepsilon$) with depth can be described by an error function (integral function of the bell-shaped curve of statistics); that is, if z is depth below the water table, then

$$\varepsilon(z) = \tfrac{1}{2} \left\{ 1 - \mathrm{erf}\ \frac{z - \bar{z}}{\sqrt{2}\ \sigma} \right\}$$

where
$$\bar{z} = (z)_{\varepsilon} = 50\%$$
$$\sigma = \tfrac{1}{2} \left[ (z)_{\varepsilon} = 84.1\% - (z)_{\varepsilon} = 15.9\% \right] .$$

Thus, the set of values of relative salinity determined at various depths in an observation well can be plotted on probability paper, the regression line drawn, and the value of z corresponding to any relative salinity of interest interpolated easily. Of interest is the position corresponding to $\bar{z}$, as this datum corresponds to the theoretical interface (Todd and Meyer, 1971) defined by the Ghyben-Herzberg relationship.

Figure 2 shows a plot of relative salinity versus depth which represents the transition zone in and near the GHURA-Dededo monitoring well. The monitoring well is located in the north-central portion of the study area and is the only observation well to penetrate the fresh-water lens and bottom in the underlying saltwater (Huxel, 1980). As indicated by the gentle slope of the regression line, the transition zone is relatively thin compared to the thickness of the fresh water column.

Because of the configuration of the volcanic basement, the fresh-water lens is discontinuous in the north-central region of the plateau and along the southern fault boundary. Figure 3 shows diagramatic cross sections through the lens which demonstrate the relationship between the groundwater-flow system and the boundary conditions. Note the large increase in head and the lack of a transition zone over the basement. Wells located in this portion of the aquifer yield relatively high quality water because upconing of seawater beneath the well can not occur. This region is analogous to a coastal aquifer subject to a landward migrating saltwater/freshwater front (e. g. Shamir and Dagan, 1971).

Recharge increases the thickness of the fresh-water lens and causes a downward movement of the transition zone. At times of little or no recharge, the lens thins and the transition zone moves upward as continuing discharge

depletes the amount of freshwater in storage. Major fluctuations in recharge follow the seasonal pattern of rainfall as evidenced by the correlation between water-table response and rainfall events shown in Figure 4. Water-level changes in areas where the volcanic basement is at a higher elevation than the transition zone are greater than those areas where the lens is continuous and show strong effects of recharge during the wet season (Ward et al., 1965).

## METHODS

In the process of evaluating groundwater recharge of Devonshire lens in Bermuda, Vacher and Ayers (1980) found that an estimate of recharge could be made by considering the chloride ion as a tracer which is concentrated by the processes of evapotranspiration. Rainfall in coastal or island environments normally has a significant chloride-ion concentration due to aerosols (Garrels and Mackenzie, 1971, p. 137). Evapotranspiration, which involves fluxes back to the atmosphere with essentially zero chloride, concentrates the rain-derived chloride in the remaining soil-water excess or recharge. In northern Guam, where nearly all rainfall probably infiltrates the soil surface, the ratio $Cl_R^-/Cl_r^-$ (where $Cl_R^-$ is the chloride concentration in rain water and $Cl_r^-$ is the chloride concentration in recharge water) would measure the ratio of recharge to rainfall; i.e., r/R where r is recharge and R is rainfall. As an example, if 2/3 of the infiltrating rain water is transmitted back to the atmosphere as a flux with $Cl^- = 0$, then the chloride concentration of the remainder would be 3 times that of the initial concentration. The rationale is the same as that used to calculate the degradation of shallow groundwater resulting from recycling it as irrigation (e.g., Helwig, 1977).

In northern Guam, the evapotranspiration-related concentrative process can be utilized to determine recharge because the chloride concentration of rainfall is easily measured; the chloride concentration of recharge is approximated by the lowest concentration found in the fresh-water lens; and, the hydrologic circulation is not complicated by surface drainage.

Two rainwater-collecting stations were established (Figure 5), one at the Water Resources Research Center (WRRC), University of Guam, and the other at Ypao Point near the Guam Memorial Hospital. Samples were collected using a prewashed glass bottle with an attached funnel. The collecting apparatus was placed in the open and left on site for approximately 24 hours. A minimum of 250 ml of rain water was obtained for each of the six collection dates.

Ground-water samples were collected from observation wells (Figure 5) penetrating the fresh-water lens. Six wells were selected on the basis of location and accessibility and sampled using a Kemmerer-type water sampler. All samples were taken at a depth of 6 meters below the water table.

Immediately after collection, chloride-ion concentrations were determined in accordance with Standard Methods for Examination of Water and Waste Water (American Public Health Association, 1975).

## RESULTS AND DISCUSSION

Results of chloride analyses on rain-water and groundwater samples are listed in Tables 1 and 2 respectively. Chloride-ion concentrations are given in milligrams per liter (mg/ℓ). Sample collection dates are also listed.

From the data of Table 1, the chloride-ion concentration of rainwater is relatively low. The range of values is from 2.0 to 7.2 mg/ℓ with a mean

concentration of 4.5 mg/ℓ. Although the time interval of collection is fairly short, it is assumed that this mean chloride-ion concentration is representative of rain water. No other chloride data for rainwater have been found in the literature; however, supplemental data from analyses conducted on storm runoff samples add validity to the assumption. These data are shown in Table 3. Chloride-ion concentrations found in storm runoff agree very well with those found in rainwater. These data represent an additional set of rainwater samples. The high value for Site No. 1 is probably the result of some local contamination and probably does not represent the norm.

Inspection of Table 2 indicates that chloride-ion concentrations of groundwater fall within two groups, one with a range of values between 72 and 151 mg/ℓ and the other with a range between 9 and 15 mg/ℓ. The data suggest that concentrations within the range of 9 to 15 mg/ℓ represent the lowest chloride-ion concentrations found in the fresh-water lens. Concentration values within the high range probably represent sea water intrusion on a small scale due to pumping within nearby well fields or local hydrogeologic anomallies.

The interpretation of these results is summarized in Figure 6. With the premise that the mean of the low range of chloride values for samples from the fresh-water lens represents the $Cl^-$ of recharge, then $Cl_r^- = 11.8$ mg/ℓ. From the rainwater analysis, $Cl_R^- = 4.5$ mg/ℓ. Thus $Cl_R^-/Cl_r^- = R/r = 0.38$. With $R = 218$ cm/yr (Mink, 1976), recharge is $r = 83$ cm/yr, and actual evapotranspiration is 135 cm/yr. The result agrees very well with previous estimates.

Table 1.   Results of chloride analyses on rain-water samples.

| Sample No. | Date of Collection | $Cl^-$ (mg/ℓ) |
|------------|--------------------|---------------|
| WRRC – 1 | 6 – 18 – 80 | 6.0 |
| WRRC – 2 | 8 – 19 – 80 | 2.0 |
| WRRC – 3 | 9 –  9 – 80 | 6.0 |
| TAM  – 1 | 6 – 18 – 80 | 4.0 |
| TAM  – 2 | 9 – 22 – 80 | 2.9 |
| TAM  – 3 | 9 – 30 – 80 | 7.2 |
|          |             | Ave = 4.5 |

Table 2.   Results of chloride analyses on ground-water samples.

| Sample No. | Date of Collection | $Cl^-$ (mg/ℓ) |
|------------|--------------------|---------------|
| BPM | 3 – 25 – 80 | 87.6 |
|     | 6 – 18 – 80 | 91.2 |
| A-16 | 3 – 25 – 80 | 125.0 |
|      | 6 – 18 – 80 | 177.0 |
| M-10A | 3 – 27 – 80 | 9.7 |
|       | 6 – 18 – 80 | 9.9 |
| M-11 | 3 – 27 – 80 | 72.2 |
|      | 6 – 18 – 80 | 72.7 |
| M-11A | 3 – 25 – 80 | 10.5 |
|       | 6 – 18 – 80 | 11.7 |
| 107 | 3 – 27 – 80 | 13.7 |
|     | 6 – 19 – 80 | 15.0 |

Table 3.   Results of chloride analyses on rainfall-runoff samples.

| Location | Date of Collection | $Cl^-$ (mg/ℓ) |
|----------|--------------------|---------------|
| Camp Watkins Road | 10– 27 – 80 | 27.0 |
| Airport Parking Lot | 10– 27 – 80 | 6.7 |
| Perez Acres | 10– 27 – 80 | 5.3 |
| Latte Heights | 10– 27 – 80 | 5.6 |
| Barrigada Heights | 10– 27 – 80 | 3.8 |

## CONCLUSION

A relatively simple and straightforward method is utilized to estimate the annual (and long term) recharge rate to the fresh-water lens of northern Guam. The technique requires chloride-ion concentration data from rain-water and ground-water samples. Assuming that the chloride ion is concentrated by evapotranspiration-related processes and that the freshest part of the lens can be identified, a rainfall-recharge ratio can be calculated. Results from the application of this method to the estimation of recharge in northern Guam agree very well with previous work which used other independent methods to obtain recharge estimates.

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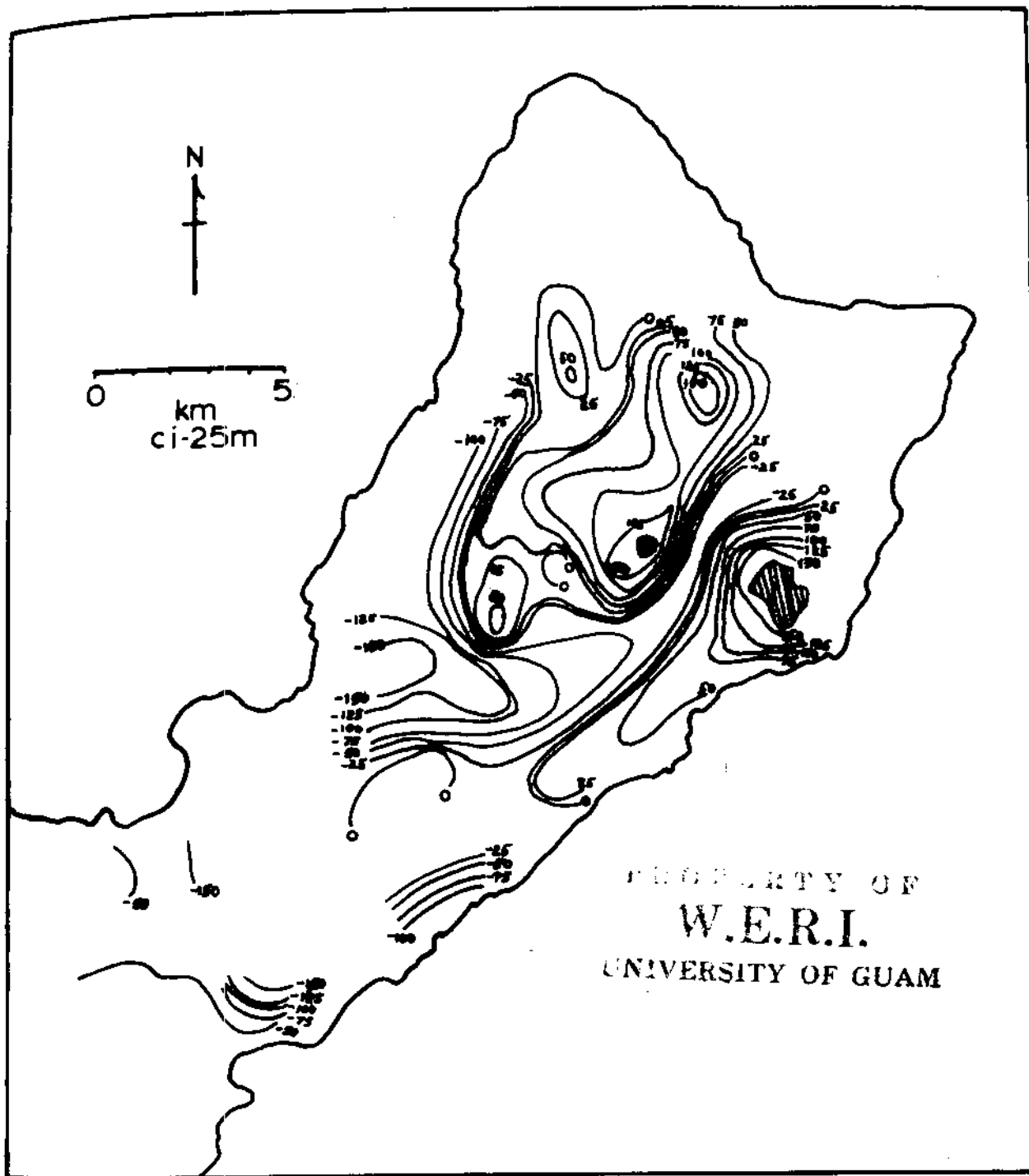
Figure 1. Topographic relief of the volcanic basement beneath northern Guam.
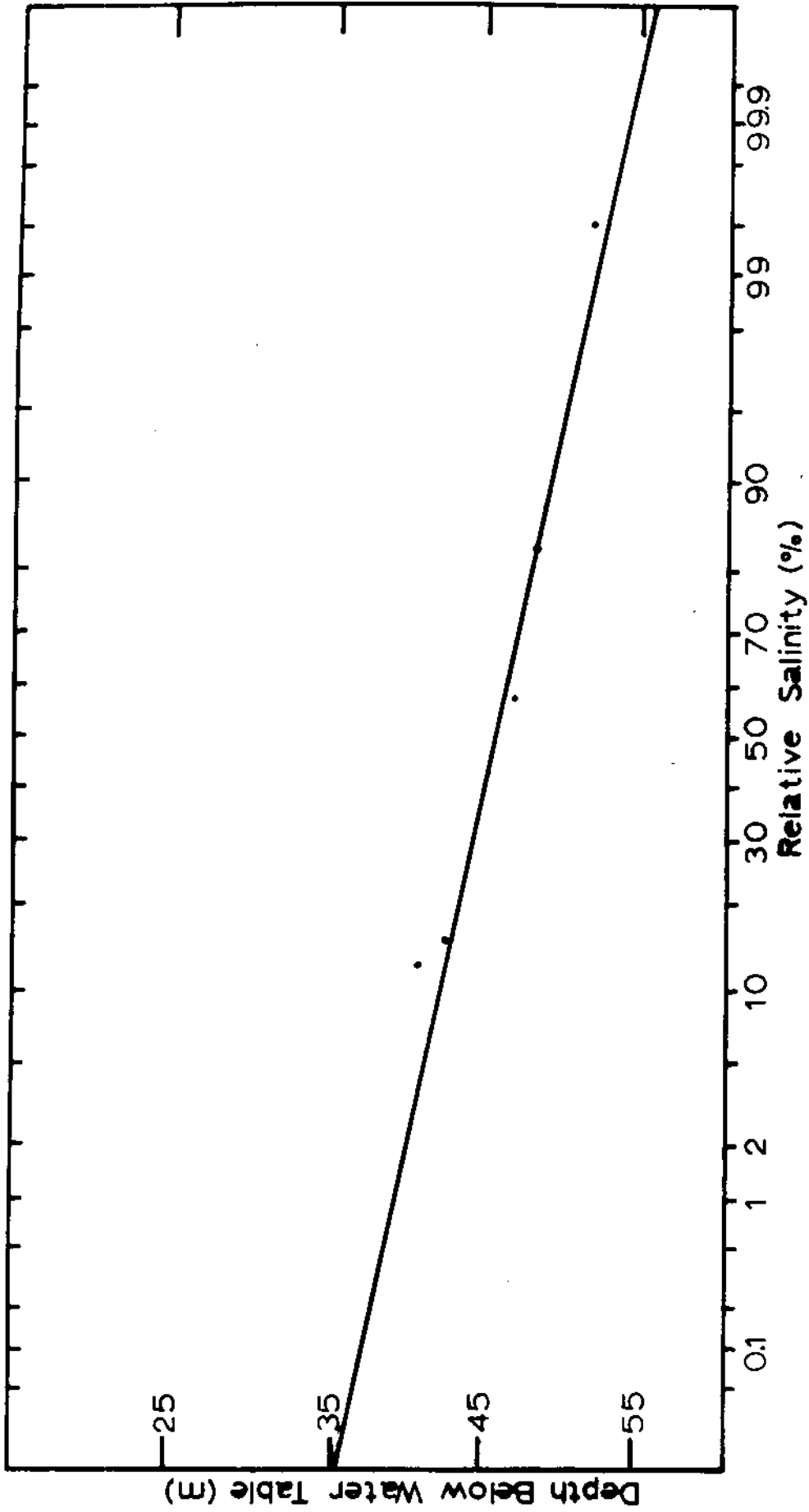
Figure 2.  Relative-salinity profile of the transition zone in the GHURA-Dededo monitoring well.  Data collected in October 1979 and provided by the USGS, Guam office.
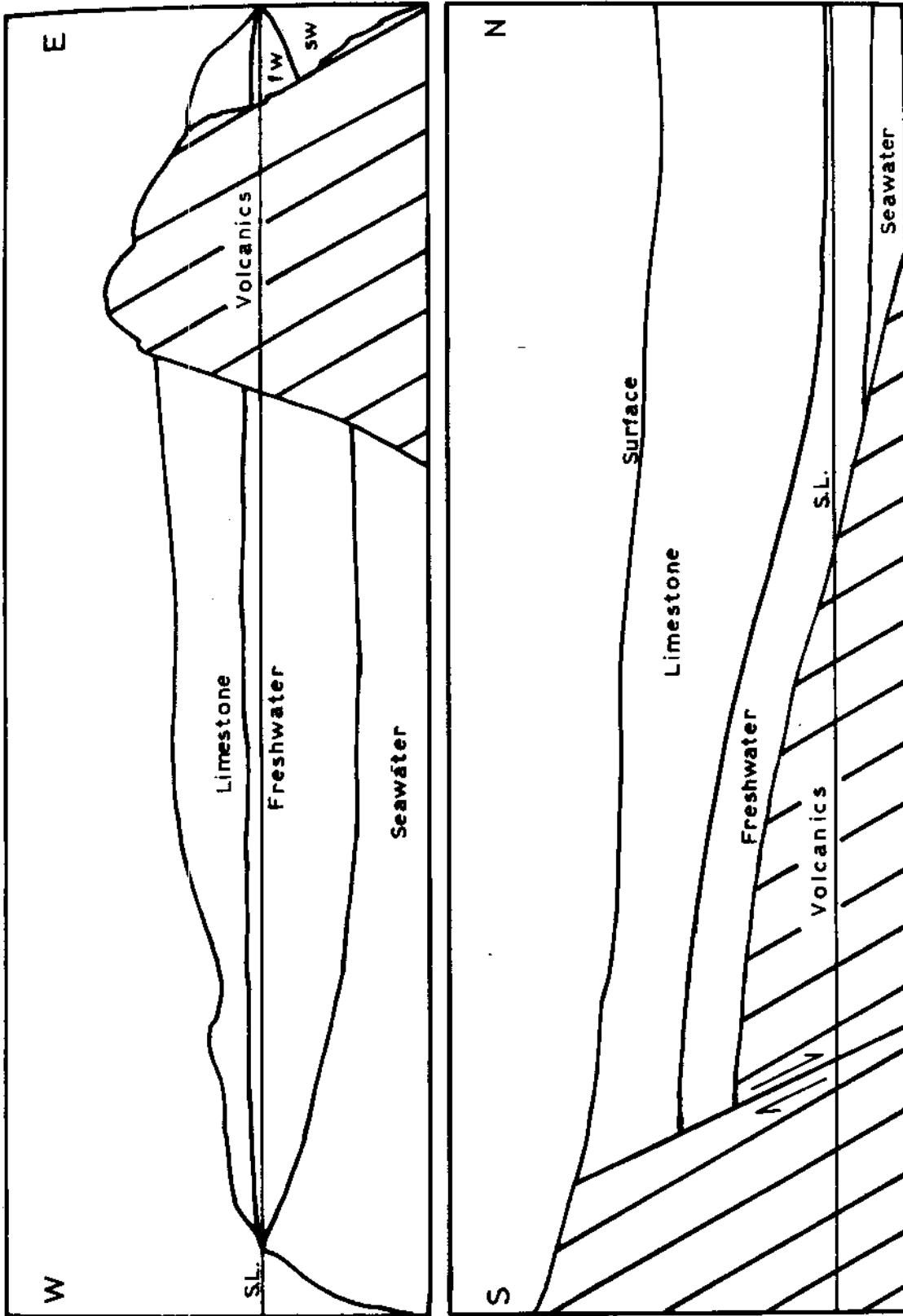
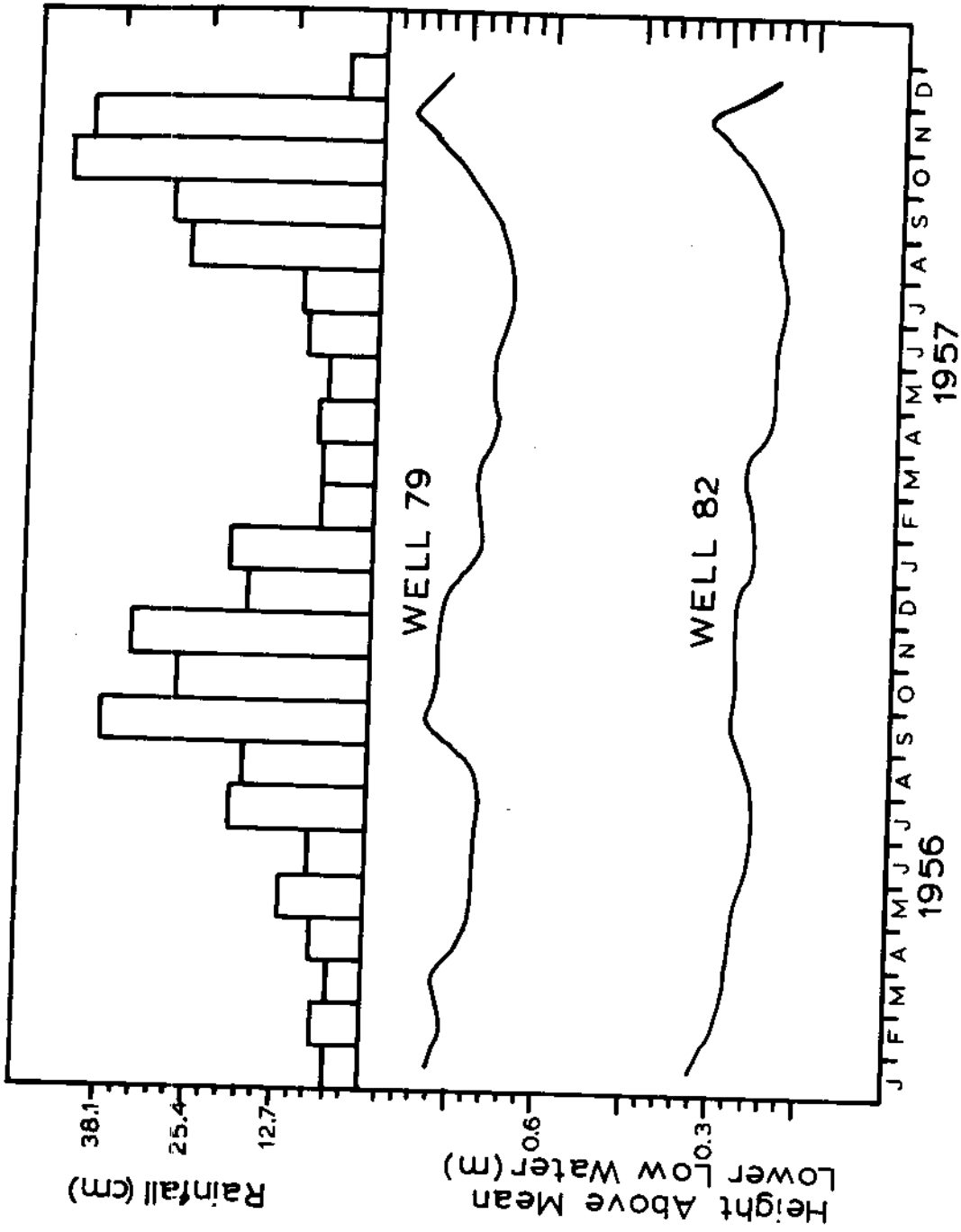Figure 3. Cross sections through northern Guam showing the complex nature of the fresh-water lens.

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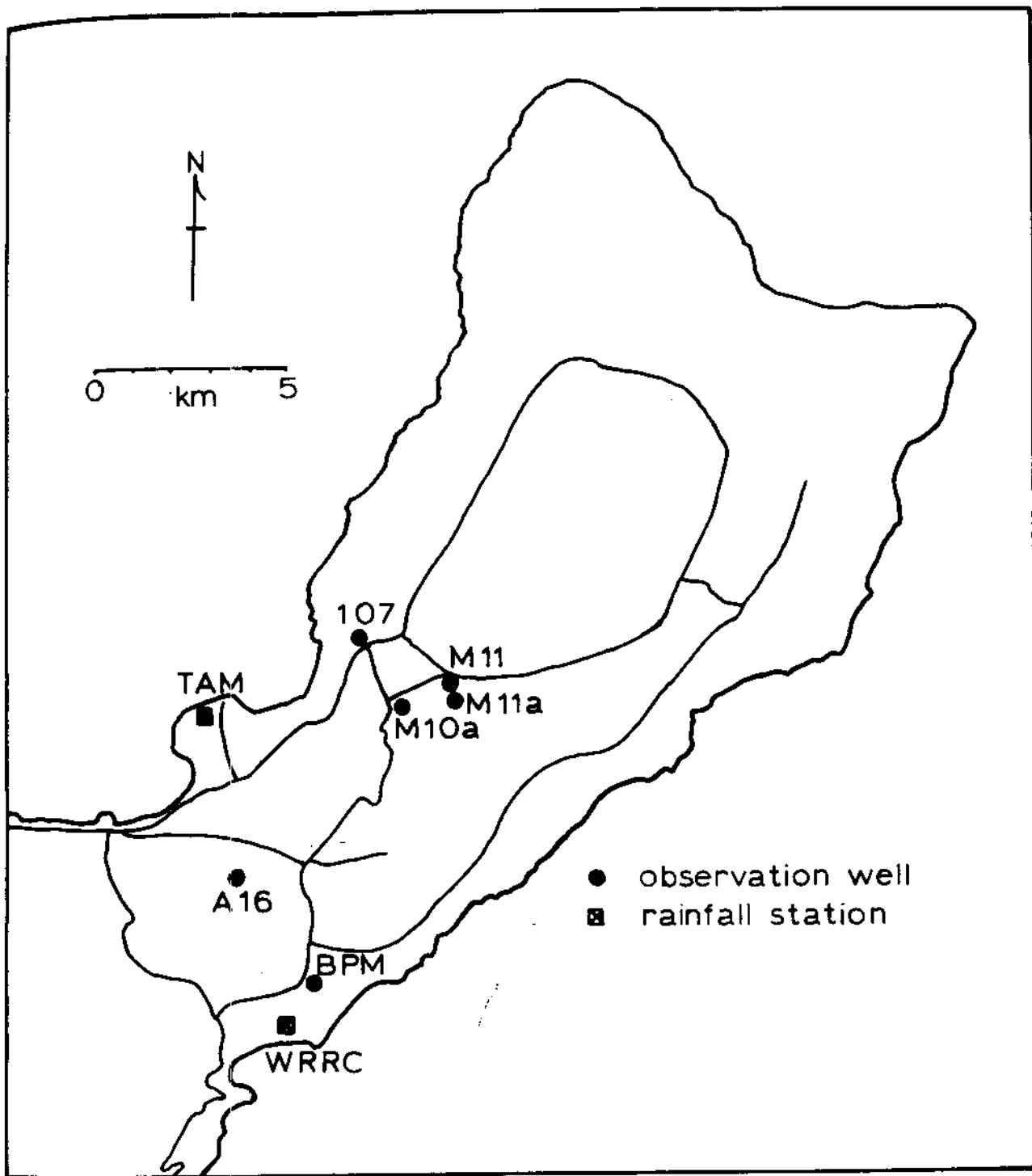Figure 4. Graph of water-table response and rainfall events.

Figure 5.  Map of northern Guam showing sample site locations.

Rainfall =218cm/yr

Evapotranspiration =135cm/yr

Recharge =83cm/yr

Freshwater
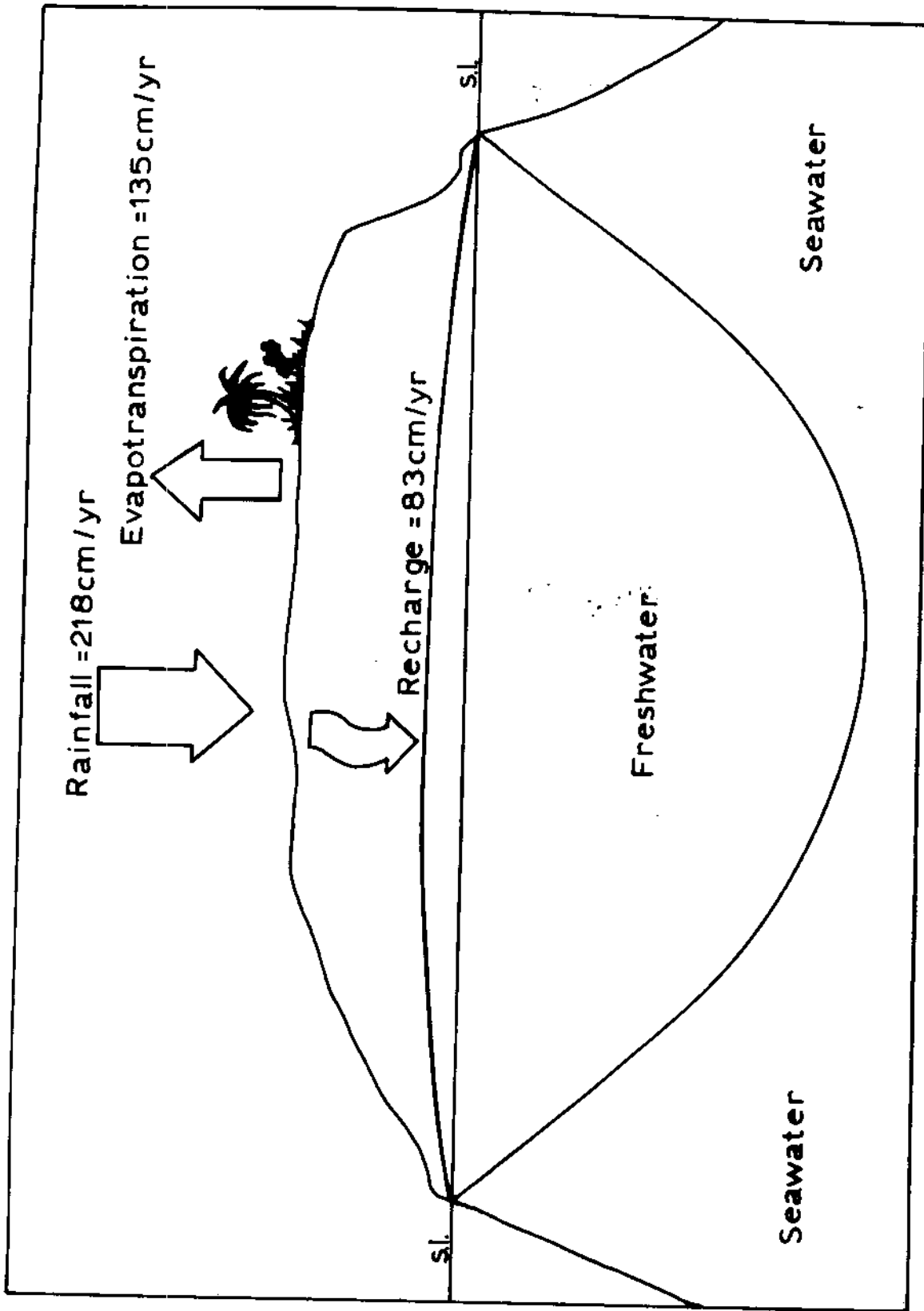
Seawater

Seawater

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Figure 6.  Diagram summarizing the chloride-ion concentration of rainfall and the fresh-water lens of northern Guam.