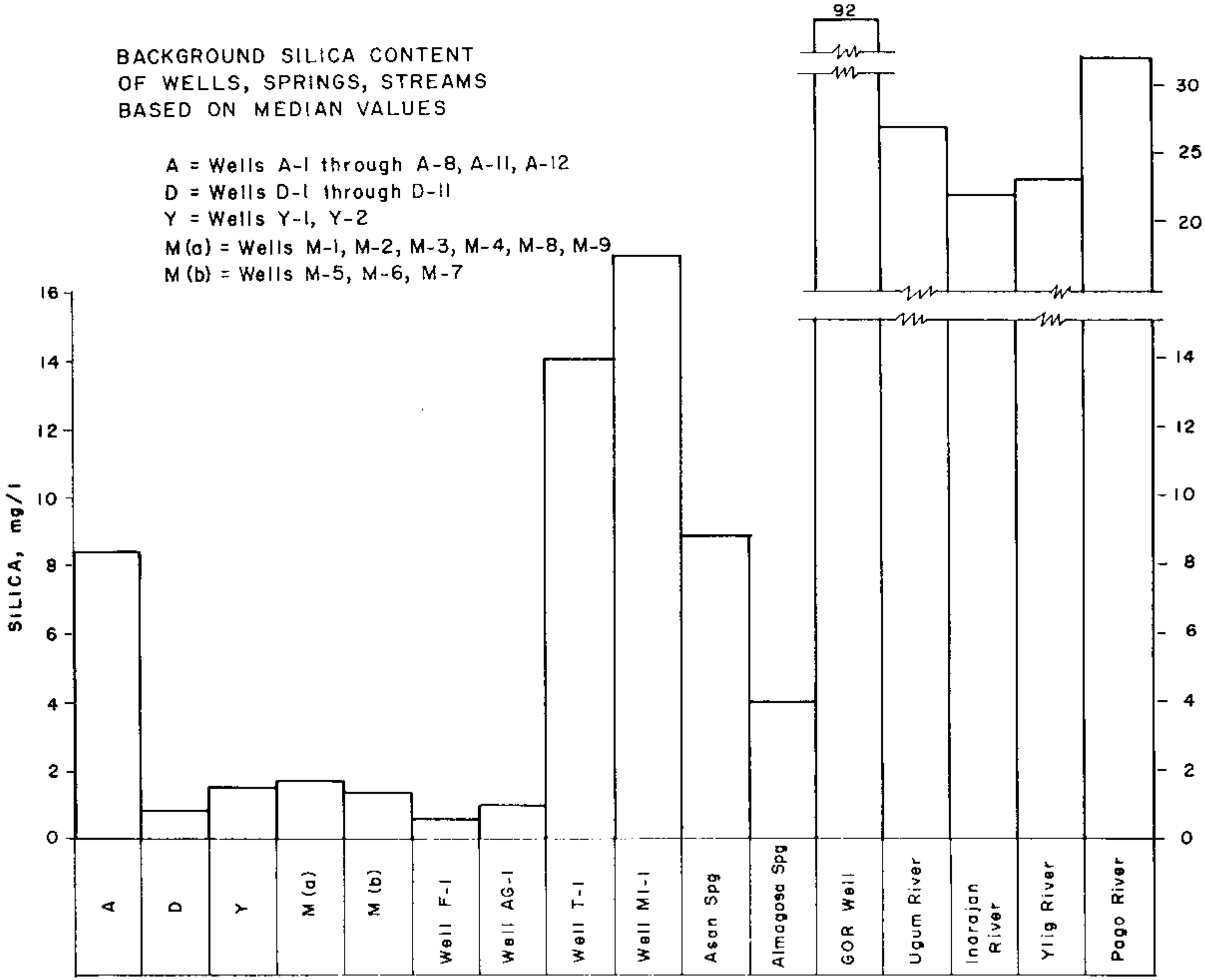

BACKGROUND SILICA CONTENT
OF WELLS, SPRINGS, STREAMS
BASED ON MEDIAN VALUES
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-11
Y = Wells Y-1, Y-2
M (a) = Wells M-1, M-2, M-3, M-4, M-8, M-9
M (b) = Wells M-5, M-6, M-7
SILICA, mg/l
92
0
2
4
6
8
10
12
14
16
20
25
30
A
D
Y
M (a)
M (b)
Well F-1
Well AG-1
Well T-1
Well MI-1
Asan Spg
Almagosa Spg
GOR Well
Ugum River
Inarajan River
Ylig River
Pago River

FIG. 18

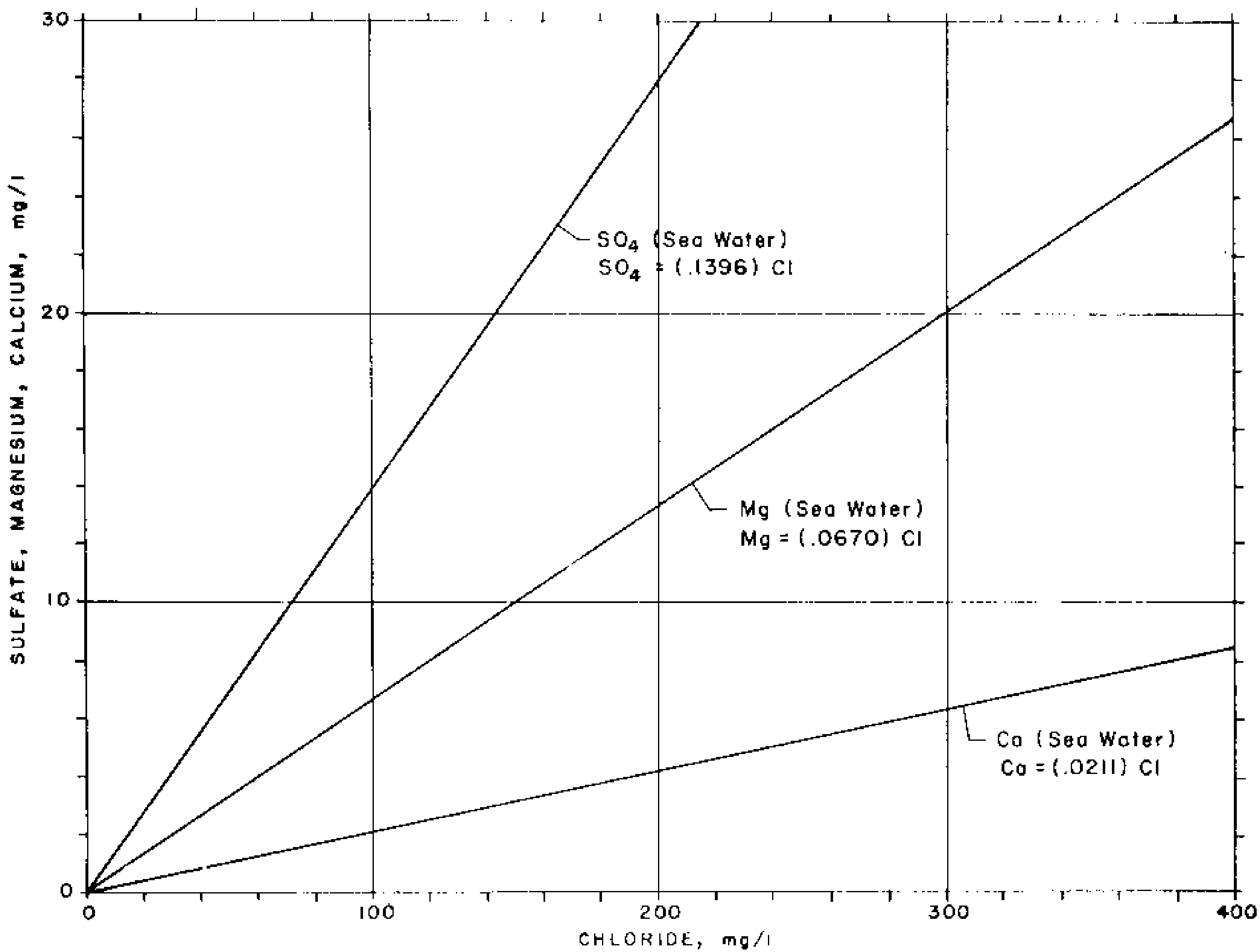

SULFATE, MAGNESIUM, CALCIUM, mg/l
CHLORIDE, mg/l
0
10
20
30
0
100
200
300
400
SO4 (Sea Water)
SO4 = (.1396) Cl
Mg (Sea Water)
Mg = (.0670) Cl
Ca (Sea Water)
Ca = (.0211) Cl

FIG. 19

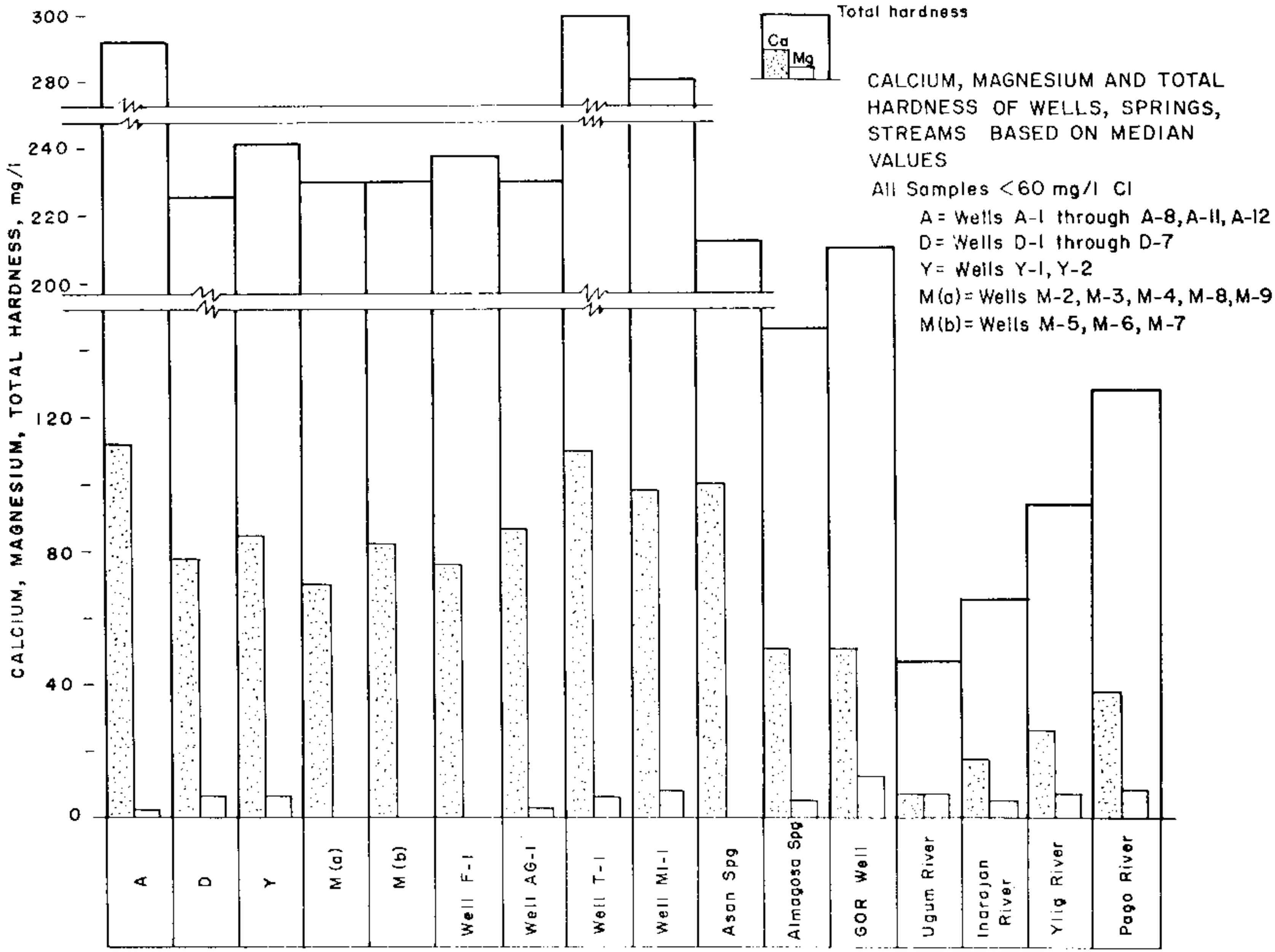
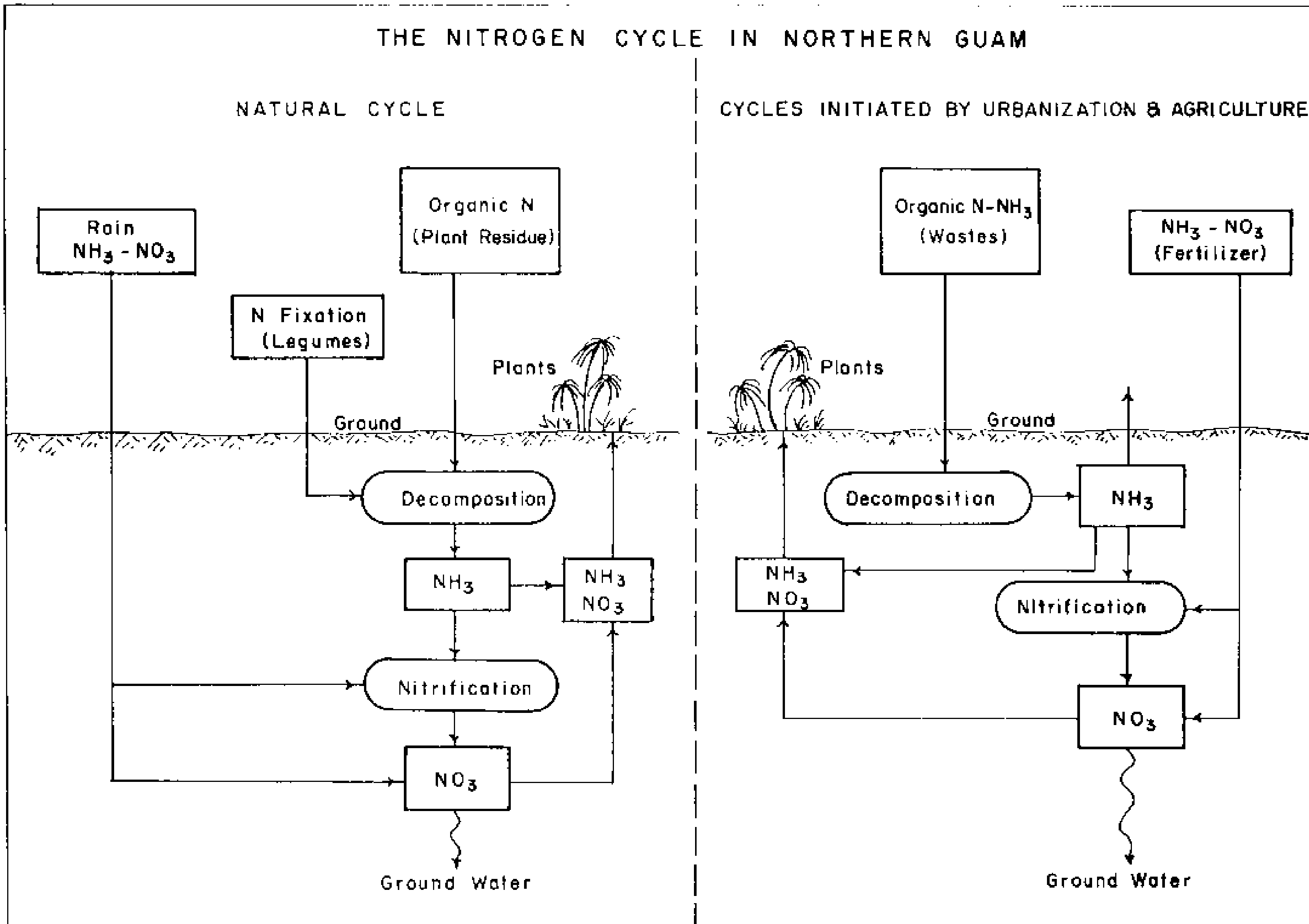

Total hardness
Ca
Mg
CALCIUM, MAGNESIUM AND TOTAL HARDNESS OF WELLS, SPRINGS, STREAMS BASED ON MEDIAN VALUES
All Samples <60 mg/l Cl
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-7
Y = Wells Y-1, Y-2
M(a) = Wells M-2, M-3, M-4, M-8, M-9
M(b) = Wells M-5, M-6, M-7
CALCIUM, MAGNESIUM, TOTAL HARDNESS, mg/l
300
280
240
220
200
120
80
40
0
A
D
Y
M(a)
M(b)
Well F-1
Well AG-1
Well T-1
Well MI-1
Asan Spg
Almagosa Spg
GOR Well
Ugum River
Inarajan River
Ylig River
Pago River

FIG. 20



THE NITROGEN CYCLE IN NORTHERN GUAM
NATURAL CYCLE
Rain
NH3 - NO3
N Fixation
(Legumes)
Organic N
(Plant Residue)
Plants
Ground
Decomposition
NH3
NH3
NO3
Nitrification
NO3
Ground Water
CYCLES INITIATED BY URBANIZATION & AGRICULTURE
Organic N-NH3
(Wastes)
NH3 - NO3
(Fertilizer)
Plants
Ground
Decomposition
NH3
NH3
NO3
Nitrification
NO3
Ground Water

FIG. 21

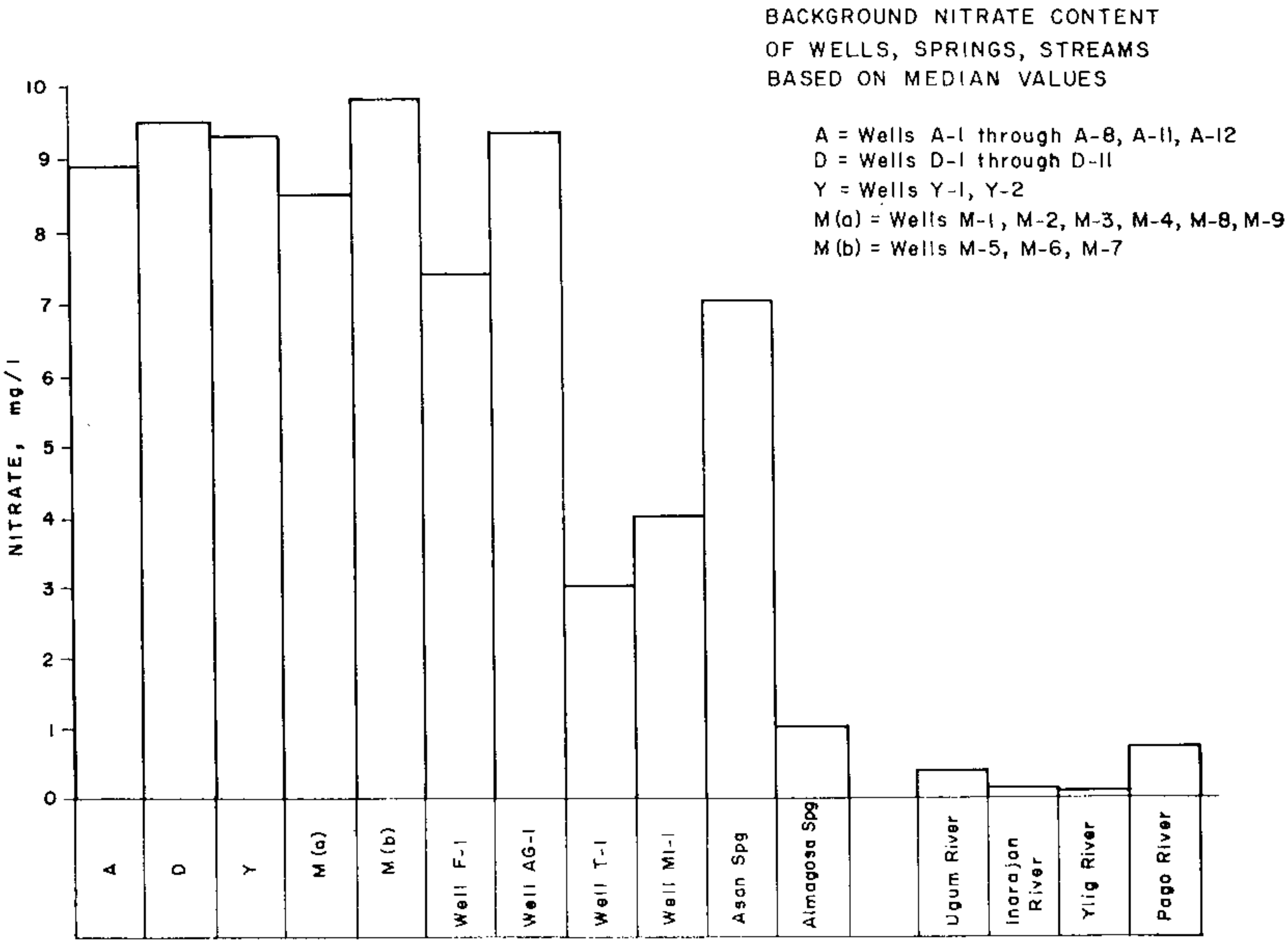

BACKGROUND NITRATE CONTENT
OF WELLS, SPRINGS, STREAMS
BASED ON MEDIAN VALUES
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-11
Y = Wells Y-1, Y-2
M (a) = Wells M-1, M-2, M-3, M-4, M-8, M-9
M (b) = Wells M-5, M-6, M-7
NITRATE, mg/l
0
1
2
3
4
5
6
7
8
9
10
A
D
Y
M (a)
M (b)
Well F-1
Well AG-1
Well T-1
Well MI-1
Asan Spg
Almagosa Spg
Ugum River
Inarajan River
Ylig River
Pago River

FIG. 22

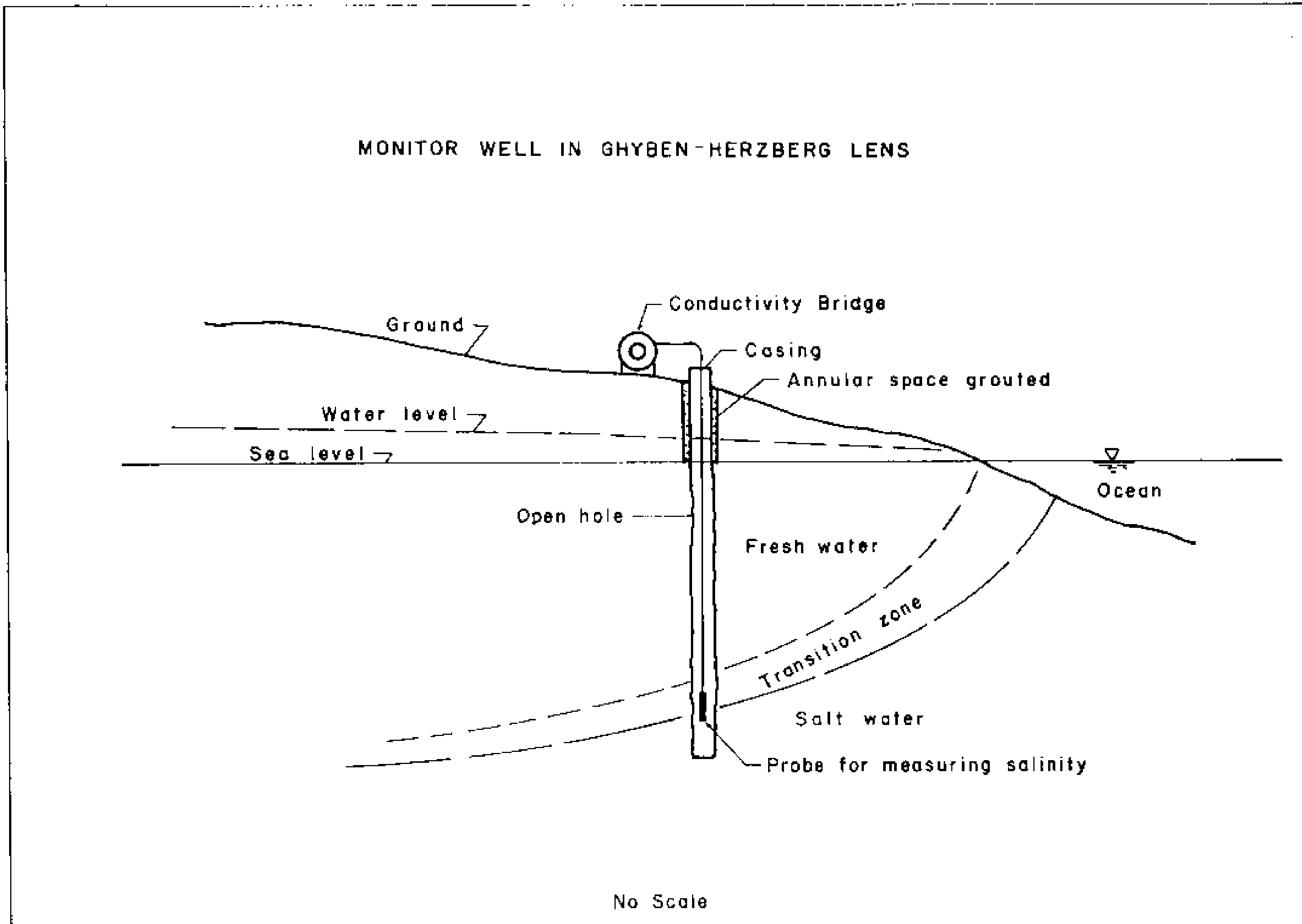

MONITOR WELL IN GHYBEN-HERZBERG LENS
Conductivity Bridge
Ground
Casing
Annular space grouted
Water level
Sea level
Ocean
Open hole
Fresh water
Transition zone
Salt water
Probe for measuring salinity
No Scale

FIG. 23

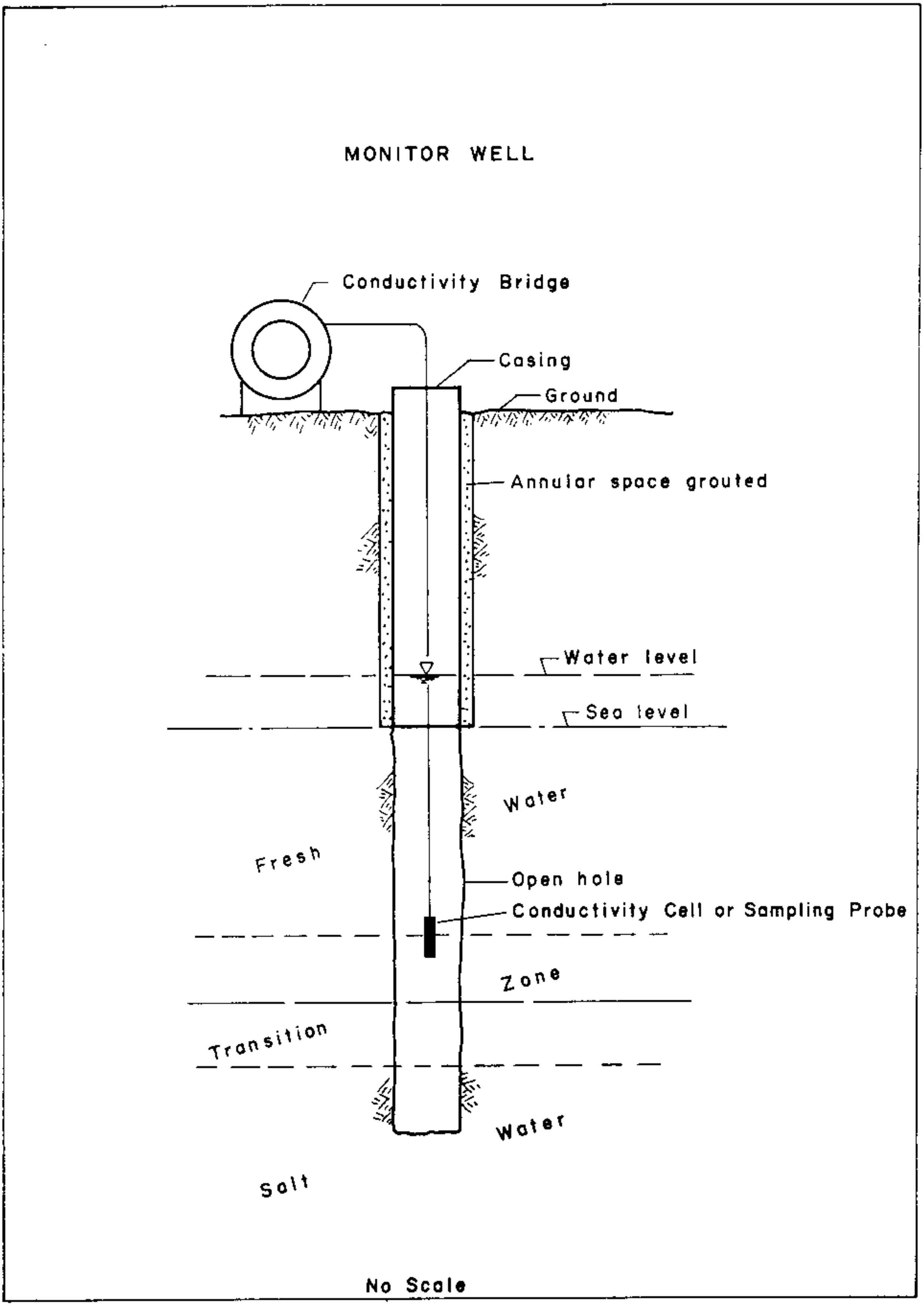

MONITOR WELL
Conductivity Bridge
Casing
Ground
Annular space grouted
Water level
Sea level
Fresh Water
Open hole
Conductivity Cell or Sampling Probe
Transition Zone
Salt Water
No Scale

FIG. 24

APPENDIX A-1

<u>Simple derivation of the Ghyben-Herzberg principle</u>

Throughout most of northern Guam, fresh ground water floats on salt water in approximate buoyant equilibrium, which in combination with the effects of the dynamics of flow of the fresh water results in a body of fresh water with parabolic surfaces at both the fresh water -- air interface and the fresh water -- sea water interface. This body of fresh water is called a Ghyben-Herzberg lens, or a "basal" lens if it is unconfined. Not any of the ground water in the limestone aquifers of northern Guam is "confined," that is, under artesian pressure.

The buoyancy relationship between fresh and salt waters gives a surprisingly good estimate of the thickness of a Ghyben-Herzberg lens. The common rule of thumb that 40 feet of fresh water lies below sea level for every foot above sea level is derived by computing the hydrostatic balance as follows:

(1) $g_f h + g_f z = g_s z$

(2) $z(g_s - g_f) = g_f h$

(3) $z = \left(\frac{g_f}{g_s - g_f}\right) h$

where:

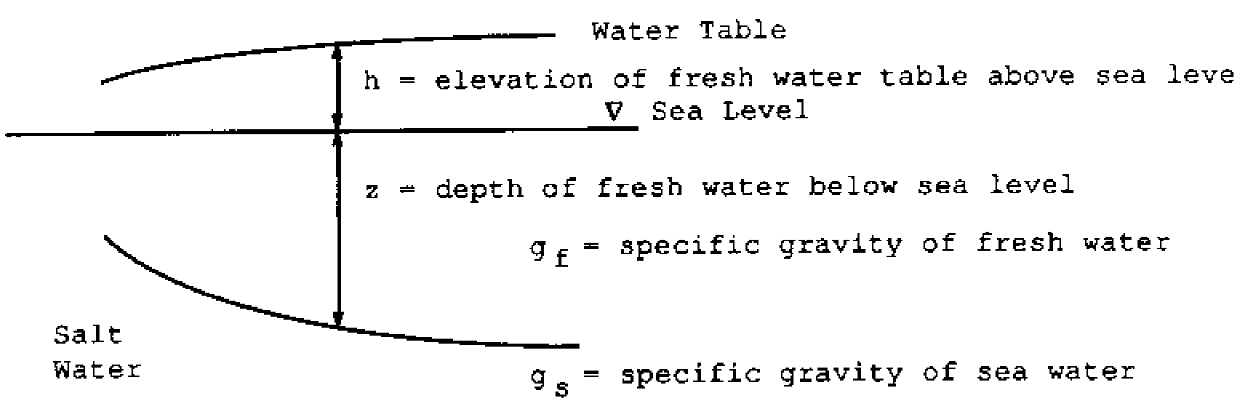


Fig. 1-1

If the normal specific gravity of fresh water ($g_f = 1.000$) and of sea water ($g_s = 1.025$) is used in the above, then:

(4) $z = 40\ h$

The above derivation assumes the existent of a sharp boundary between the fresh and salt waters. The boundary, however, is diffuse because of hydrodynamic dispersion induced by movements of the interface which result from tidal changes, seasonal differences in recharge rates, and withdrawals of fresh water by mechanical means. The diffuse zone of brackish water between the fresh and salt waters is called the "transition zone." Its thickness depends upon the dynamics of flow in the fresh water portion of the lens; if the fresh ground water velocity is high, the transition zone will be narrow. The salt water underlying the lens is generally treated as being static, although it responds to tidal changes and to changes in elevation of the transition zone.

Hydrodynamic dispersion results in a vertical distribution of salt concentrations which follows the symmetry of the error function curve. The concentrations in the transition zone thus change symmetrically from sea water to fresh water such that the mean concentration in the zone is equal to one half that of sea water. Under this condition, hydrostatic balance shows that the 40:1 Ghyben-Herzberg ratio actually applies to the middle of the transition zone rather than to a sharp interface at the bottom of a fresh water lens, derived as follows:

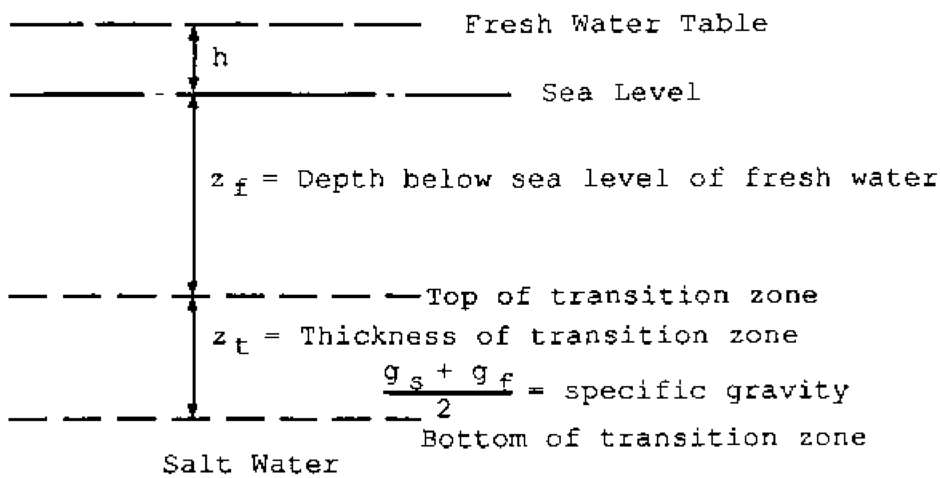


Fig. 1-2

(5) $$g_f h + g_f z_f + \left(\frac{g_s + g_f}{2}\right) z_t = g_s (z_f + z_t)$$

(6) $$z_f = z_t \left\{\frac{g_s - \left(\frac{g_s + g_f}{2}\right)}{g_f - g_s}\right\} - \frac{g_f h}{g_f - g_s}$$

If $g_s = 1.025$, $g_f = 1.000$

then:

(7) $$z_f = 40h - 0.5z_t$$

and:

(8) $$40h = z_f + 0.5z_t$$

which is the middle of the transition zone.

APPENDIX A-2

The Shape of the Ghyben-Herzberg Lens

The derivation of the thickness of the Ghyben-Herzberg lens based on hydrostatics tells nothing about the shape of the lens. The lenticular shape, in which the upper and lower faces are approximately parabolic, is caused by the flow of fresh groundwater toward the coast along a hydraulic gradient. An approximate expression for the shape of the lens may be derived by using Darcy's law for flow in porous media in combination with a continuity equation. Figure 2-1 gives the coordinate system for the derivation in the case of an unconfined lens. Assumptions are that the aquifer is homogeneous and isotropic, and that the fresh water flows along horizontal stream lines above a sharp interface separating the fresh from the underlying salt water.

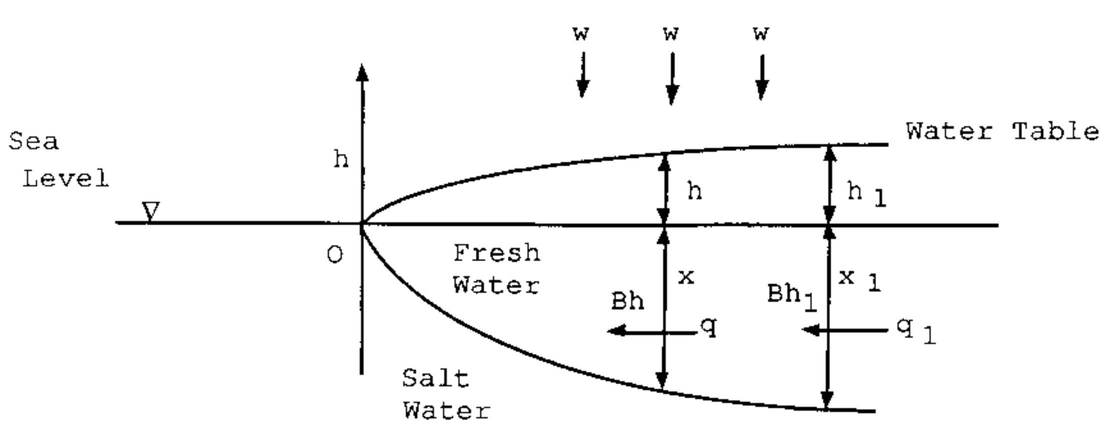


Fig. 2-1

In figure 2-1, h is elevation of the fresh water table above sea level; x is distance inland from the discharge line along the coast; q is specific flux; w is the specific rate of vertical infil- tration considered uniform; and B is the Ghyben-Herzberg constant, $\frac{g_f}{g_s - g_f}$, in which g_f is the density of fresh water and g_s the density of sea water. For normal densities, B = 40.

Continuity requires that:

(1) $q = q_1 + w(x_1 - z)$

For the coordinate system depicted above, Darcy's law is:

(2) $$q = k(B + 1)h\,\frac{dh}{dx}$$

in which k is hydraulic conductivity. This equation is simplified to:

(3) $$q = 41\,k\,h\,\frac{dh}{dx}$$

Equating (1) and (3):

(4) $$q_1 + w(x_1 - x) = 41\,k\,h\,\frac{dh}{dx}$$

which in integrable form with approximate limits becomes:

(5) $$q_1 \int_0^x dx + wx_1 \int_0^x dx - w \int_0^x x dx = 41k \int_0^h hdh$$

and on solution:

(6) $$q_1 x + wx_1 x - \frac{wx^2}{2} = \frac{41kh^2}{2}$$

Expressed as h(x), eq. (6) may be written:

(7) $$h^2 = \left[\frac{2x}{41k}\right] \left\{q_1 + wx_1 - \frac{wx}{2}\right\}$$

If there were no vertical recharge, as in the confined aquifer case, then,

(8) $$q_1 = \frac{41kh^2}{2x}$$

which, since continuity requires that $q_1 = q$, becomes the familiar expression:

$$(9) \quad q = \frac{41kh^2}{2x}$$

Equation (9) is a very useful expression, even though it ignores vertical recharge. If recharge were temporarily sporadic and spatially random, equation (9) would probably be a good approximation to flow in the lens.

Equation (7), because it includes continuous vertical recharge, yields somewhat higher heads and flatter piezometric surface than equation (9), which may explain the relatively low gradients found in the broad inland area north of Dededo. Comparison of heads derived from equations (7) and (9) for the approximate conditions which pertain to northern Guam are tabulated below.

The approximate conditions are:

h_1 = 5 ft; x_1 = 10,000 ft; k = 2000 ft/d

w = .0096 ft/d (42 inches/yr, or 2 mgd/mi^2/d)

Using these values in equation (9) yields a specific flux value of q = 102.5 ft^3/d, the daily discharge per lineal foot of coastline. A solution for q_1 in equation (7) gives a value of 54.5 ft^3/d. Thus the following heads are computed for comparable distances inland:

x	h(eq.7)	h(eq.9)
10000 ft	5.00 ft	5.00 ft
8000	4.68	4.47
6000	4.22	3.87
4000	3.58	3.16
2000	2.62	2.24
1000	1.89	1.58
100	0.61	0.50

APPENDIX A-3

Use of tidal responses to estimate hydraulic conductivity of the aquifers of northern Guam

Fluctuation of the piezometric surface of an aquifer in open connection with the sea is related to tidal action in the sea by the simplified expression:

$$(1)\quad h/h_o = \exp\left(-x\sqrt{\frac{\pi s}{t_o T}}\right)$$

in which:

- h = maximum amplitude of the tide in the aquifer, ft.
- h_o = maximum amplitude of the.tide in the sea, ft.
- x = distance inland from the sea coast, ft.
- s = storage coefficient,or specific yield
- T = transmissivity, ft^2/d
- t_o = period of tidal cycle (approx. 0.5 days)

Equation (1) is strictly applicable to confined aquifers of constant thickness but is a good approximation of an unconfined lens in which the range of tidal fluctuation is much smaller than lens thickness, as in northern Guam.

The sea around Guam has a semi-annual mean tidal range of 1.6 ft. and a mean diurnal range of 2.3 ft. The datum is mean lower low water, and pertinent tidal indices are (Tracey, et al, 1964):

MHHW (mean higher high water) ... 2.3 ft.
MHW (mean higher water) ... 2.2 ft.
MWL (mean water level) ... 1.4 ft.
MLW (mean lower water) ... 0,6 ft.
MLLW (mean lower low water) ... 0.0 ft.

A few measurements of tidal fluctuations in wells penetrating to the basal lens have been reported. These measurements in conjunction with tide tables and certain assumptions can be used in equation (1) to estimate the regional transmissivities of the limestone aquifers. Figure 3-1 illustrates the position of the lens in northern Guam for which calculations can be made. Note that the depth of the water mass in the limestone aquifer includes both the fresh water lens and the salt water lying between the lens and the impermeable basement.

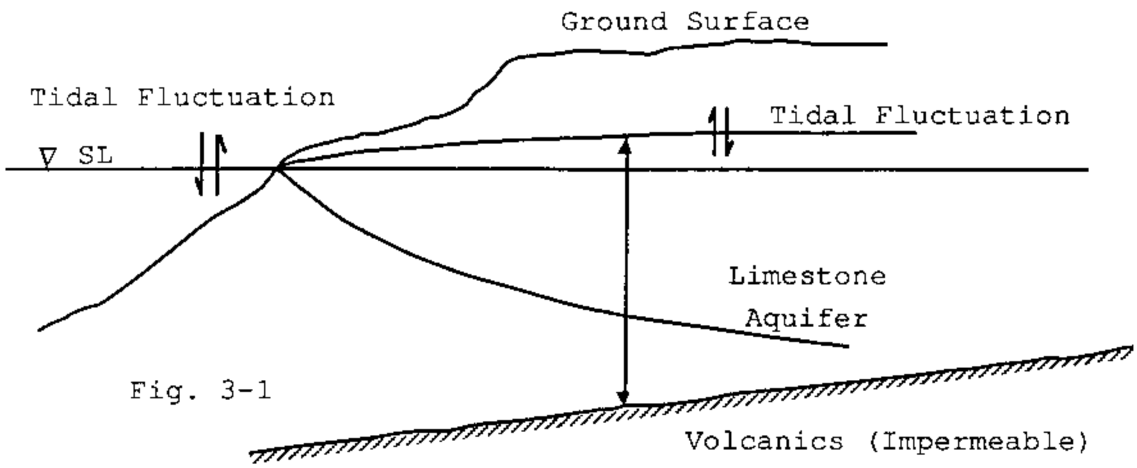


Fig. 3-1

Table 3-1 summarizes the computations based upon the least ambiguous data available from records and in reports. A value of 0.1 was assumed for S, and the average thickness, $\bar{y}$, of the saturated aquifer was approximated by employing a slope of 5 degrees in a seaward direction for the volcanic basement from its known or reasonably estimated position inland. Obviously the configuration of the basement is largely conjectural, but its actual depth is not likely to vary from the assumed depth by a factor of more than two.

Table 3-1

Data source	Well	h_o/h	S/T	T	$\overline{y}$	$k=T/\overline{y}$	Remarks
Stearns (1937)	9	11.0	$6x10^{-8}$	$1.7x10^{6}$	1300	1308	Let h_o=2.2
Stearns (1937)	6	8.5	$7.3x10^{-9}$	$13.7x10^{6}$	1400	9800	Let h_o=2.2
Huxel (1973)	D-13	10.0	$5x10^{-9}$	$20x10^{6}$	1000	20000	Use actual sea tide record
Huxel (1973)	AG-2	13.3	$7.4x10^{-9}$	$13.6x10^{6}$	1200	11333	Use actual sea tide record
Huxel (1973)	107	8.0	$5.6x10^{-8}$	$1.8x10^{6}$	1300	1385	Use actual sea tide record
USGS (1974)	ACEORP	9.1	$8.6x10^{-8}$	$1.2x10^{6}$	1200	1000	Let h_o=2.2
Ward, et al (1965)	82	7.3	$4.9x10^{-8}$	$2.3.x10^{6}$	1200	1717	Let h_o=2.2

The computed transmissivities and hydraulic conductivities vary widely, the highest transmissivity being about 17 times more than the lowest. The very high transmissivities may indeed reflect unusual conditions of permeability, which may help to explain the anomalously high chloride water pumped in some inland wells, such as D-13. However, the lower transmissivities computed for wells 9, 107, and 82 and for the ACEORP tunnel more nearly reflect the expected regional permeabilities as deduced from hydrologic budget studies.

Evidently the factors affecting tidal responses in the aquifer are insufficiently understood to allow refined extrapolations of aquifer parameters from equation (1). The collection of additional and more precise data, however, will eventually allow more sophisticated analyses of tidal responses.

APPXNDIX A-4

Decay of an unconfined Ghyben-Herzberg lens under conditions of no recharge

The following analysis deals with a free floating Ghyben-Herzberg lens to which all recharge has ceased and from which the only discharge is natural leakage at the coastline. The analysis will show that under natural conditions the decay of a Ghyben-Herzberg lens takes place very slowly. Figure 4-1 shows the coordinate system and the geometry of the lens under consideration. The model is applicable to northern Guam.

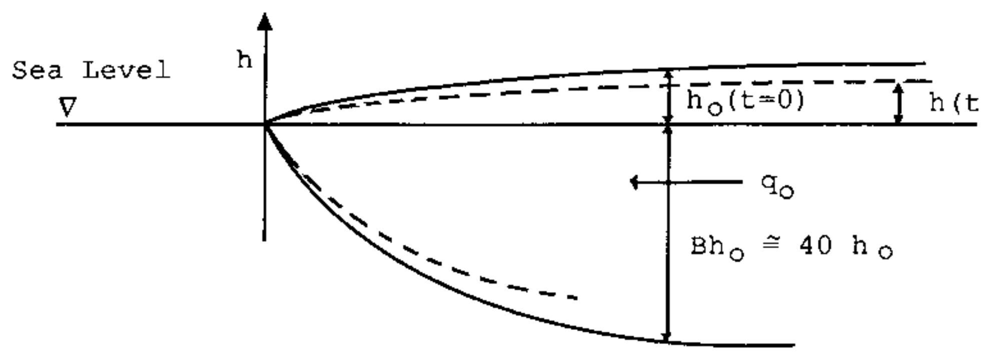


Fig. 4-1

Two fundamental equations of flow may be used to express the discharge of a free basal lens. Drainage from a lens which receives no recharge may be be expressed as:

$$(1) \quad q_o = \frac{41kh_o^2}{2x}$$

in which q_o(ft^3/d) is discharge per unit width of coastline at the start of the decay, k(ft/d) is hydraulic conductivity, and h_o(ft) is the head at a distance x(ft) from the coastline.

The decay equation for drainage from a porous medium into which there is no recharge may be written:

(2) $q = q_o e^{-bt}$

where q is discharge at any time, t, after the initial flow, q_o, and b is the decay constant. From this equation the initial volume of water, V_{ow}, in the porous medium may be determined as:

(3) $V_{ow} = q_o/b$

By restricting the model to a one foot wide strip along the x axis, the flows and volumes become specific values per unit coastline.

The decay constant, b, is unknown, but V_{ow} can be found by determining the volume of the lens above and below sea level, after which b can be computed if q is known. Substituting equation (1) into equation (3):

(4) $$V_{ow} = \frac{20.5\ kh_o^2}{bx}$$

from which:

(5) $$b = \frac{20.5\ kh_o^2}{V_{ow}x}$$

The volume included within the parabolic surfaces of the Ghyben-Herzberg lens may.be computed from the relationship:

(6) $$h = \left(\frac{2q}{41k}\right)^{1/2} x^{1/2}$$

The specific volume, V_{as}, above sea level is:

(7) $$V_{as}\ \left(\frac{2q}{41k}\right)^{1/2} \int_0^x x^{1/2}\ dx$$

where V_{as} is the total volume of the pore space and the solid matrix of the aquifer. Equation (7) becomes:

$$(8) \quad V_{as} = \left[\frac{2q}{41k}\right]^{1/2} \left(\frac{2}{3}\right) x^{1.5}$$

and the specific volume, V_{1s}, below sea level is:

$$(9) \quad V_{1s} = 40V_{as}$$

Thus at the start of the decay the total volume between the parabolic surfaces of the lens is:

$$(10) \quad V_{os} = (41) \left(\frac{2}{3}\right) \left[\frac{2q_o}{41k}\right]^{1/2} x^{1.5}$$

or:

$$(11) \quad V_{os} = 27.33\ h_o x_o$$

Boundary conditions for the normal maximum head in the middle of the island are:

h_o= 5.5 ft; x_o = 12,000 ft; q_o = 103 ft^3/d

from which Vos is computed as 1,803,780 ft^3. However, the volume of water, V_{ow}, contained in V_{os} is:

$$(12) \quad V_{ow} = nV_{os}$$

in which n is porosity, estimated at 0.1, yielding V_{OW}= 180,378 ft^3. Equation (5) can now be solved to give the decay constant, b = .00057.

To determine the loss of head over a given time, equations (11) and (12) may be used to yield:

$$(13) \quad \Delta V_w = 27.33\ nx(h_0 - h_1)$$

in which ΔV_w is the change in water volume resulting from the natural decay of the lens from time t_0= 0 to a given time, t_1. From the decay equation of flow in porous media

$$(14) \quad \Delta V_w = \frac{q_0 - q_1}{b} = \frac{q_0\ (1 - e^{-bt_1})}{b}$$

Equating equations (13) and (14):

$$(15)\quad 27.33\, nx(h_0 - h_1) = \frac{q_0\,(1 - e^{-bt_1})}{b}$$

and solving for h_1:

$$(16)\quad h_1 = h_0 - \frac{q_0\,(1 - e^{-bt_1})}{27.33\, nbx}$$

in which the quantity $\frac{q_0\,(1 - e^{-bt_1})}{27.33\, nbx}$ is the loss in head which occurs from $t = 0$ to t_1 under conditions of natural leakage and no recharge.

The significance of equation (16) can best be illustrated by example. If, for instance, $t_1 = 180$ days, the head loss after this period of time would be 0.54 ft, and the head 12000 ft. inland would be 4.96 ft. rather than 5.5 ft. The specific flow would decrease from $q_0 = 103$ ft^3/d to 84 ft^3/d, illustrating the tendency of the lens to preserve itself. If t_1 were 365 days, the head loss would amount to 1.03 ft, leaving a residual head of 4.47 ft. at the middle of the island.

The equations of flow for a Ghyben-Herzberg lens during natural decay show that the outflow from the lens decreases greatly for a small change in head, and thus even extended periods of drought would not endanger a lens the size of that in northern Guam.

The foregoing analysis does not take into account the effects of draft on the condition of the lens during periods of no recharge. The present rate of groundwater withdrawal in northern Guam is about 15 mgd, equivalent to approximately 10 ft^3/d per ft. of shoreline, or one tenth of the natural leakage when the head is 5.5 ft. in the middle of the island. Constant draft without recharge would, of course, cause the head to fall more rapidly than would natural leakage alone.

A constant draft term may be included in the flow equations by changing equation (2) to read:

(17) $q = q_0 e^{-bt} + D$

in which D is a constant draft. Equation (14) would then change to

(18) $\Delta V_w = \dfrac{q_0 - q_1}{b} + D(t_0 - t_1) = \dfrac{q_0\ (1 - e^{-bt_1})}{b} + Dt_1$

Equation (16) would then become:

(19) $h_1 = h_0 - \dfrac{q_0\ (1 - e^{-bt_1})}{27.33\ nxb} - \dfrac{Dt_1}{27.33\ nx}$

The term $\dfrac{Dt_1}{27.33\ nx}$ is the loss of head caused by constant draft.

If constant draft were equivalent to 10 ft^3/d per foot of coastline after 180 days without recharge the loss in head due to draft alone would be 0.06 ft., and after a year it would be 0.12 ft,

APPENDIX A-5

Ground water in the volcanic rocks of southern Guam as determined from stream flow measurements

The volcanic rock formations of southern Guam make very poor aquifers because of their low hydraulic conductivities but nevertheless they carry appreciable volumes of ground water. Only one well in the volcanic rock, that at Guam Oil Refinery producing 100 gpm, can be said to be an economic success. Unfortunately a good log for this well is not available and the nature of the subsurface in the vicinity is therefore unknown. Other volcanic rock wells show very low hydraulic conductivities, practically always less than 1 ft/d. Even so, the RCA well at Pulantat is being used, regardless of the fact that at 20 gpm drawdown is greater than 300 feet, because of the importance of a water supply to the communications station.

Rain that infiltrates the volcanics eventually seeps to stream channels and then flows to the sea. The infiltrate remains in the ground for a long period of time, following tortuous flow paths through poorly permeable tuffaceous shales and sandstones and somewhat more permeable agglomerates to discharge points in stream channels. Water tables are high, in some areas lying within a few feet of the surface. At Pulantat for instance, the water table is less than 20 feet below the surface, even though ground elevation is about 360 feet.

The exponential flow decay equation may he used to evaluate ground water seepage to stream channels. A channel is treated as a line sink into which uniform seepage per unit length takes place, according to:

(1) $Q = Q_0 e^{-at}$

in which, using convenient units, Q is flow in mgd at time t in days; Q_0(mgd) is flow at t = 0; and a is the recession constant.

Seepage flow must not be confused with total runoff; most of the flow in the volcanic streams of the south is direct runoff of rain over the ground surface. Seepage flow can be estimated by analyzing the daily records of flow over the dry season, starting about December 1 and ending in June, and establishing the decay relationship. It is a matter of some judgement to extract from the daily records flows that do not reflect direct surface runoff; ordinarily if the minimum daily flows from one month to the next decrease monotonically, a decay curve can be constructed.

In the analysis, maximum subsurface storage, and therefore maximum seepage, is assumed to occur at the start of December and to decay over a period of 180 days. Table B-6 (Appendix B) gives the initial flow from storage, Q_0, and the flow 6 months later, Q_6, of the major streams in southern Guam for the period 1953 through 1960 (data for 1959 is missing because it wasn't available when.the analysis was made). From this data, the recession constant, a, the subsurface volume tributary to the stream channel, and the subsurface volume which drains to the stream over the period of 180 days can be computed. These parameters in some measure define the characteristics of ground water occurrence in the volcanic rocks.

Table B-7 (Appendix B) gives a summary of the runoff characteristics of the major streams of southern Guam, emphasizing the ground water contribution. Streams are listed by type of rock formation which they drain. The Ugum, Inarajan and Tinaga (formerly called Pauliluc by the USGS) rivers chiefly drain the Bolanos pyroclastic member of the Umatac formation; this member consists of tuffaceous shale, sandstone and agglomerate. The Umatac River chiefly drains the Facpi volcanic member of the Umatac formation, consisting of pillow basalts overlain by tuffaceous shale and sandstone with lenses of limestone. The Ylig and Pago Rivers drain the Alutom volcanic formation, which is predominantly formed of tuffaceous shale and sandstone. The recession constant, a, of the streams reflects the subsurface geology of the drainage basins in that it is directly proportional to hydraulic conductivity and aquifer thickness, and inversely proportional to effective porosity.

The data in table B-7 clearly show that ground water storage in the Bolanos member is far greater per unit drainage area than in either the Facpi member of the same formation or in the Alutom formation The Ugum drainage basin has especially large ground water storage. The low unit storage for the Tinaga River basin probably results from pirating of subsurface water within its geographic boundaries by the more deeply incised Ugum and Inarajan Rivers. The Ugum may also pirate some of the subsurface flow of the upper drainage region of the Inarajan River. With respect to ground water the basins of the three rivers should be treated as a single regional unit, the subsurface drainage from which comes nearly exclusively from a Bolanos member.

Calculations suggest that the total volume of ground water available for drainage to the three Bolanos basins is 152 mg/mi^2 at the start of the dry season, of which 118 mg/mi^2 actually drains to the streams during the 6 months period. On the other hand, the Alutom formation of the Ylig and Pago basins carries considerably smaller ground water storage per unit drainage area, only about 60 - 65 mg/mi^2, less than half that in the Bolanos member. Also the recession constants for the Ylig and Pago Rivers are nearly twice as great as those for Bolanos streams, reflecting rapid drainage. Still another significant difference between Bolanos and Alutom streams is the ratio of runoff to rainfall, which is about .57 for the Bolanos and .65 for the Alutom, denoting higher total yields from the latter formation.

Because hydrologic conductivities of the volcanic formations are very low, in the normal case producing wells would have to be very deep to provide even small quantities of water. It is improbable that the economics of deep wells equipped with small capacity pumps would justify widespread development of ground water from the volcanics for some time. Local requirements, however, might justify the expense. In locations where volcanic rocks encase limestone lenses, such as at Malolo and Talofofo, immediate exploitation of the limestone aquifers would be appropriate.

Table B-7 also provides important information with respect to surface water exploitation. As an example, for the Ugum River the total ground water seepage over the 180 day dry period is 1109 mg, which averages to 6.16 mgd. This does not include the direct surface runoff component of the rainfall. In effect, the volcanic rocks are porous media reservoirs whose slow seepage rates could be exploited in designing surface reservoirs. For this purpose, the Ugum River basin has the best characteristics, while the Ylig and Pago basins have the poorest. The Ugum River would require a smaller surface reservoir per unit flow than the Ylig or Pago Rivers because substantially more of its total flow consists of ground water seepage. For the Ugum River, of the total average flow of 19 mgd, 6.16 mgd (32.4%) consists of ground water, while of the total average flow of 16.8 mgd for the Pago River, 1.91 mgd (11.4%) consists of ground water.

APPENDIX A-6

WASTE WATER DISPOSAL BY MEANS OF INJECTION WELLS

HYDRAULICS OF INJECTION WELLS

The hydraulics and flow from an effluent well are extremely complicated and defy straightforward analysis, particularly if the boundary conditions are ill-defined. A simple flow model can be evaluated, however, from which the results may provide insight into more complex cases. In the simple model, the aquifer is homogeneous and isotropic, with a definite bottom and discharge boundary. The injection well is assumed to fully penetrate the aquifer, to be uncased, and to receive a constant, continuous effluent flow. In a Ghyben-Herzberg system, the injection well may be designed to discharge the effluent either into the basal lens or the saline water beneath it.

Injection Well in Basal Lens

The lens is assumed to contain fresh water and to have a static bottom coincident with the theoretical interface between fresh and salt waters. The densities of effluent and groundwater are considered identical. Initially, the effluent mixes with the water in the aquifer and becomes highly diluted, but with time the aquifer water is gradually displaced until at steady state the effluent, having totally displaced the ambient water along its path, travels as a slug toward the coast with dilution caused by dispersion occurring only at the margins of the slug. Dispersion, which includes molecular diffusion, is a relatively short-range phenomenon, dwarfed in significance by the slug movement. Eventually, the slug of effluent reaches the coast over a width determined by the aquifer parameters and the flow field of the aquifer under initial conditions. Dilution of the effluent with sea water depends in large measure on the width of the slug where it emerges at the coast and the seaward extent of the discharge front. The steady state case is more relevant than the transient condition in evaluating the effects the effluent may cause in both the aquifer and at the shore because it expresses the expectable long-term environmental status.

As effluent pours into the injection well, it accumulates until its potential is sufficient to force flow into the aquifer against the prevailing aquifer potential field. The effluent will travel radially until its velocity is equal to the velocity of natural flow in the aquifer. When the velocity of the effluent equals the velocity of the environmental water, the effluent will no longer move against the natural gradient, but will follow a path parallel to the flow lines of the aquifer water. Directly up the gradient from the injection well a null point will occur, the distance to which is the minimum radius traveled by the slug. The flow line from the null point will outline an envelope which will move with the natural gradient, its width expanding to a value equivalent to the circumference of the null circle, as will be shown later (see fig. 6-1).

The null radius and the time to reach it can be derived from assumptions of continuous injection into the ideal aquifer model and symmetrical cylindrical flow away from the well. At a constant rate of injection, Q, the volume V, of effluent that flows into the aquifer is:

(1) $V - Qt = n\pi br^2$

where t is time, n is porosity, b is thickness of the fresh water aquifer, and r is radius measured from the well. As the cylindrical volume of effluent expands from the well, its velocity, U_e is:

$$(2)\quad U_e = \frac{dr}{dt}$$

From Equation 1:

$$(3)\quad r = \left[\frac{Q}{n\ \pi\ b}\right]^{1/2} t^{1/2}$$

and thus:

$$(4)\quad \frac{dr}{dt} = \left[\frac{Q}{n\ \pi\ b}\right]^{1/2} \frac{dt^{1/2}}{dt} = \frac{1}{2}\left[\frac{Q}{n\ \pi\ b}\right]^{1/2} t^{-1/2}$$

The natural aquifer particle velocity, Ua, is expressed by:

$$(5)\quad U_a = \frac{k}{n}\frac{db}{dx}$$

in which k is hydraulic conductivity and x is length measured in the direction of flow. By equating U_a and U_e:

$$(6)\quad (k/n)\frac{db}{dx} = 1/2\left[\frac{Q}{n\ \pi\ b}\right]^{1/2} t^{-1/2}$$

$$(7)\quad t^{1/2} = 1/2\left[\frac{Q}{n\ \pi\ b}\right]^{1/2} \frac{n}{\left[k\ \frac{db}{dx}\right]}$$

and:

$$(8)\quad t = 1/4\left[\frac{nQ}{\pi b}\right] \frac{n}{\left[k\ \frac{db}{dx}\right]^2}$$

in which the term $\left[k\ \frac{db}{dx}\right]$ is the Darcy (bulk) velocity.

From Equations 8 and 3 the steady state maximum radius of the slug directly upstream of the well is computable as:

$$(9).\quad r = \left[\frac{Q}{2\ \pi\ b}\right] \frac{1}{\left[k\ \frac{db}{dx}\right]}$$

When r is reached, the particles at r form the outer flowline of the slug which moves along with the natural flowfield. Total flow over any width of the aquifer is expressed as:

(10) $Q = k\ b\ L\ \frac{db}{dx}$

in which L is the width of a section. When the effluent potential becomes indistinguishable from the natural aquifer potential and since the effluent input is constant and continuous, from Equations 9 and 10 the following relationship is derived:

(11) $L = 2\ \pi\ r$

Thus the final steady state width of the slug as it moves toward the coast may be related to the null radius. For some distance on either side of the slug dilution caused by dispersion will occur, but the volume of effluent in this band will be insignificant compared to the primary slug. Figure 6-1 illustrates the flow relationships described by the above analyses.

Discharge at the Sea Coast

The effluent slug moves toward the sea coast initially at a higher velocity than the ambient aquifer velocity and finally in velocity equilibrium with the aquifer environment. The time for the slug to reach the coast depends upon the distance inland of the well, the rate of injection, and the particle velocity of the ambient water in the aquifer. By solving Equation 8, the time before the slug velocity equals the ambient velocity is obtained, and by Equation 9 the distance traveled is calculated. The remaining time of flow to the coast is determined from the standard Darcy relationship.

For instance, in the limestone lens fitting the ideal model, that is, having a regional hydraulic conductivity of 2000 ft/day uniformly distributed, a porosity of 0.1, a thickness of 100 feet based on an average head of 2.5 feet, and a gradient of 5 ft/10000 ft, and receiving a constant rate of effluent input of 0.75 mgd (525 gpm), the time to reach the null radius would be 8 days, and if the sea coast were located 5000 ft. inland, the first coastal discharge of effluent would take place approximately 1.3 years later.

With regard to the quality of coastal waters, the ultimate success of an effluent well is measured by the degree of dilution which occurs where a slug emerges as seepage at the discharge boundary of the aquifer. If the groundwater flows in the form of a basal lens, as is the case along most of the coast of northern Guam, it discharges as springs at the coast and for some distance seaward as submarine seepage. Dilution with sea water depends upon the cross-sectional area through which the slug seeps. The area of discharge in the ideal model is the product of the lateral extent of the slug and the width of the seepage band. However, the real situation at the coast may differ markedly from the model in view of the structure of the limestones that make up the aquifers. In particular, large point sources of discharge, exemplified best by caverns, may in many areas predominate over uniformly distributed seepage.

Under ideal conditions, where no caprock occurs seepage from the basal lens will be uniformly distributed across a strip whose seaward width depends on flow from the lens, hydraulic conductivity of the aquifer, and the density difference between fresh and sea water. The relationship (Cooper, et al., 1964) is:

(12) $$x = \frac{q}{2\ ak}$$

where x is the width of the seepage strip, q is the fresh water flow per unit length of shore line, and a is the difference in density between the sea water and fresh water divided by the density of fresh water, and k is hydraulic conductivity (see Figure 6-2). The narrower the seepage strip, whose extreme minimum would be a line or point as in Figure 6-3, the less dilution that would occur in the immediate vicinity of effluent discharge.

As an example, for an aquifer with a hydraulic conductivity of 2000 ft/day, a gradient of .0005 and a depth of 100 feet, the flow per unit length of shore line would be 100 ft^3/day (748 gpd) and the seaward length of the seepage strip would be just 1 foot. If the width of the effluent slug were 1000 feet, the maximum attained at steady state, the cross-sectional area of seepage would be 1000 square feet, and thus the seepage rate into the ocean would be 100 $ft^3/day/ft^2$, or .52 gpm/ft^2. Dilution of this seepage with sea water would depend on oceanographic conditions over the seepage zone.

Equations 10 and 12 can be manipulated to give a simple algorithm in which seepage rate per unit area is related only to hydraulic conductivity and is not restricted to the steady state formation of the effluent slug. In Equation 12 the value of q is equivalent to Q/L where Q refers to Equation 10. Also, seepage rate per unit are Q/A = Q/LX, and therefore:

(13) $$Q/A = Q/(L)\ \frac{(q)}{2\ ak}$$

and

(14) $Q/A = 2\ ak$

The seepage rate per unit area for the preceding example could have been obtained from Equation 16 as follows:

$$Q/A = (2)(.025)(2000) = 100\ ft^3/day/ft^2 = .52\ gpm/ft^2$$

Neither L nor X need be known; their values are implicitly included in Equation 14.

The above discussion describes a model aquifer, which is at best a first approximation to the limestone aquifers of Guam. Deviations from the ideal work to either enhance dilution of the effluent slug or force it to concentrate along limited flow paths. For instance, the layering in limestones may cause a widening of the seepage zone at the coast, while such structural aberrations as solution caves would serve as conduits to point discharges. A reduction in permeability would enlarge the area of the seepage zone; an increase would narrow it. On a regional basis the model approximates the overall behavior of effluent flow and discharge, but where a local condition, such as a beach is concerned, the geological and hydrological details of the area would have to be carefully appraised to determine, particularly, whether point discharge or normal seepage would more likely occur.

Effect of Injection Wells on Pumping Wells

Among the critical constraints on the location of injection wells is the effect the effluent may have on groundwater that is either being or could reasonably he developed. Most of the northern portion of Guam contains fresh groundwater which has become the principal source of domestic supply. The groundwater is developed chiefly by means of drilled wells.

If an injection well were located within the radius of drawdown influence of a pumping well, the effluent would eventually travel to the pumping well and mix with aquifer water during operation. If the distance of travel were great, the effluent would probably have lost its contaminating characteristics. However. injection wells should not be sited where the effluent would move down the gradient, whether natural or induced, to wells producing water for domestic uses. On Guam such interference could be avoided by considered planning.

An approximation of distance to the groundwater divide from a pumping well can be made by evaluating the steady state pumping regime. The Thiem equation for steady state may be expressed as:

$$(15)\quad \ln(r_o/r_w) = \frac{\pi k\ (b_o^2 - b_w^2)}{Q}$$

where r_o is radius from the well to the groundwater divide; r_w is the well radius; b_o is depth of saturated aquifer before pumping and depth at r_o; b_w is depth of the saturated zone at the pumping well; $(b_o - b_w)$ is drawdown; and Q is a constant pumping rate. For a well in the limestone of northern Guam, let the following apply:

r_w	= 1 ft
b_o	= 100 ft (based on head of 2.5 ft)
Q	= 300 gpm = 57754 ft^3/d
k	= 120 ft/d (local hydraulic conductivity)
$(b_o - b_w)$	= 5 ft (typical aquifer drawdown at a well)

From the above, solution of equation 15 gives r_o = 580 ft.

Thus, if a well were pumping at 300 gpm while another were injecting at the same rate. it would be prudent to locate them at least $2r_o$ apart (1160 ft) to prevent flow of effluent to the pumping well.

Injection in Salt Water Below the Lens

A technique which at first glance would would appear to eliminate the problem of polluting the fresh water zone would be the injection of the effluent into the salt water underlying the Ghyben-Herzberg lens. However, because the effluent would be lighter than salt water, it would tend to rise toward the fresh water zone, and unless the mixing length were great, slugs of effluent would reach the transition zone. In addition, the potential of the effluent would exceed that of the salt water, whose head is close to sea level, thus driving the effluent away from the well, some of it toward the fresh water lens.

An injection well cased throughout the fresh water zone and open only in salt water would require an initial gravity head to overcome buoyancy effects before effluent would move away from the well. The balance equation is expressed as follows (see figure 6-4):

(16) $g_s d = g_f(h_e + d)$

where g_s = density of salt water $\cong$ 1.025

g_f = density of effluent $\cong$ 1.000

d = depth below sea level to bottom of casing

h_e = head of effluent column above sea level

In terms of effluent head,

$$(17) \quad h_e = \frac{(g_s - g_f)}{g_f} d$$

If the head of the basal lens is h, the extra head, h′, required for injection is,

$$(18) \quad h' = h_e - h$$

As an example, if an injection well penetrating a basal lens with a head of 5 feet were cased to its bottom in salt water at a depth 400 feet below sea level, the required gravity effluent head for injection would be 10 feet, or an excess of 5 feet over the natural regional head. Actually, for total injection head the gravity effluent head would have to be added to the well hydraulic head. For instance, in the above example if the specific capacity of a well were 30 gpm/ft, the total injection head needed to force 0.75 mgd (521 gpm) into the formation would be 27.4 feet. This relationship is especially important in locations where surface elevation does not greatly exceed the free water table surface: obviously for an artesian condition it would be impractical to attempt injection by gravity.

The salt water below the fresh water lens is static or nearly so and has a very small gradient. Effluent injected into it would establish a gradient as a result of gravity and the density difference between the two waters. The eventual flow path of the effluent would be upward toward the transition zone and the open sea. Under steady state conditions a slug stream would probably form, which upon reaching the lower portion of the lens would move toward the discharge zone at the coast unless its potential were greater than that of the brackish water of the transition zone, in which case it would mix with the brackish water.

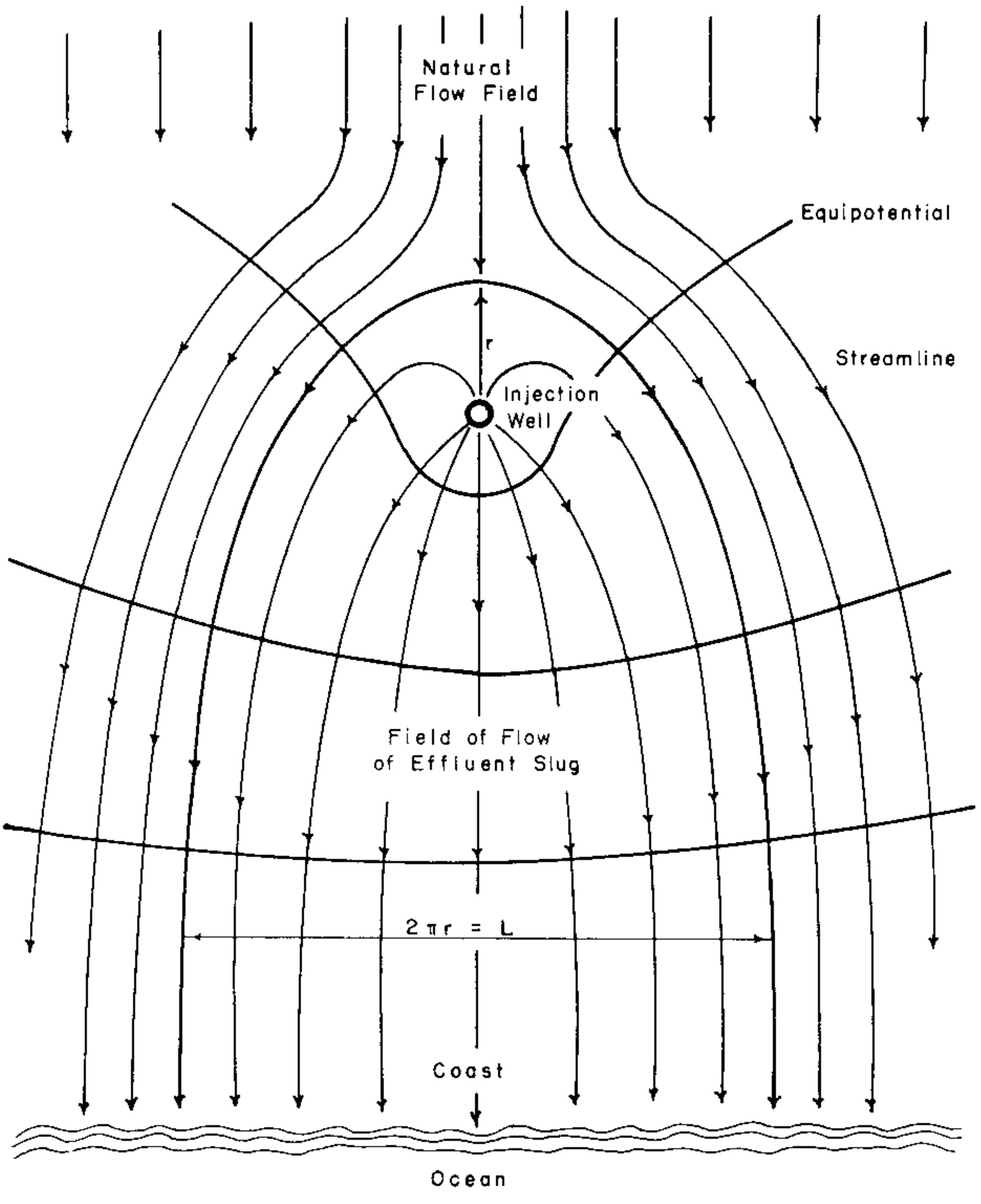


FIGURE 6-1

STEADY STATE FLOW FIELD OF AN EFFLUENT SLUG DERIVED FROM A FULLY PENETRATING INJECTION WELL RECEIVING A CONSTANT CONTINUOUS INPUT.

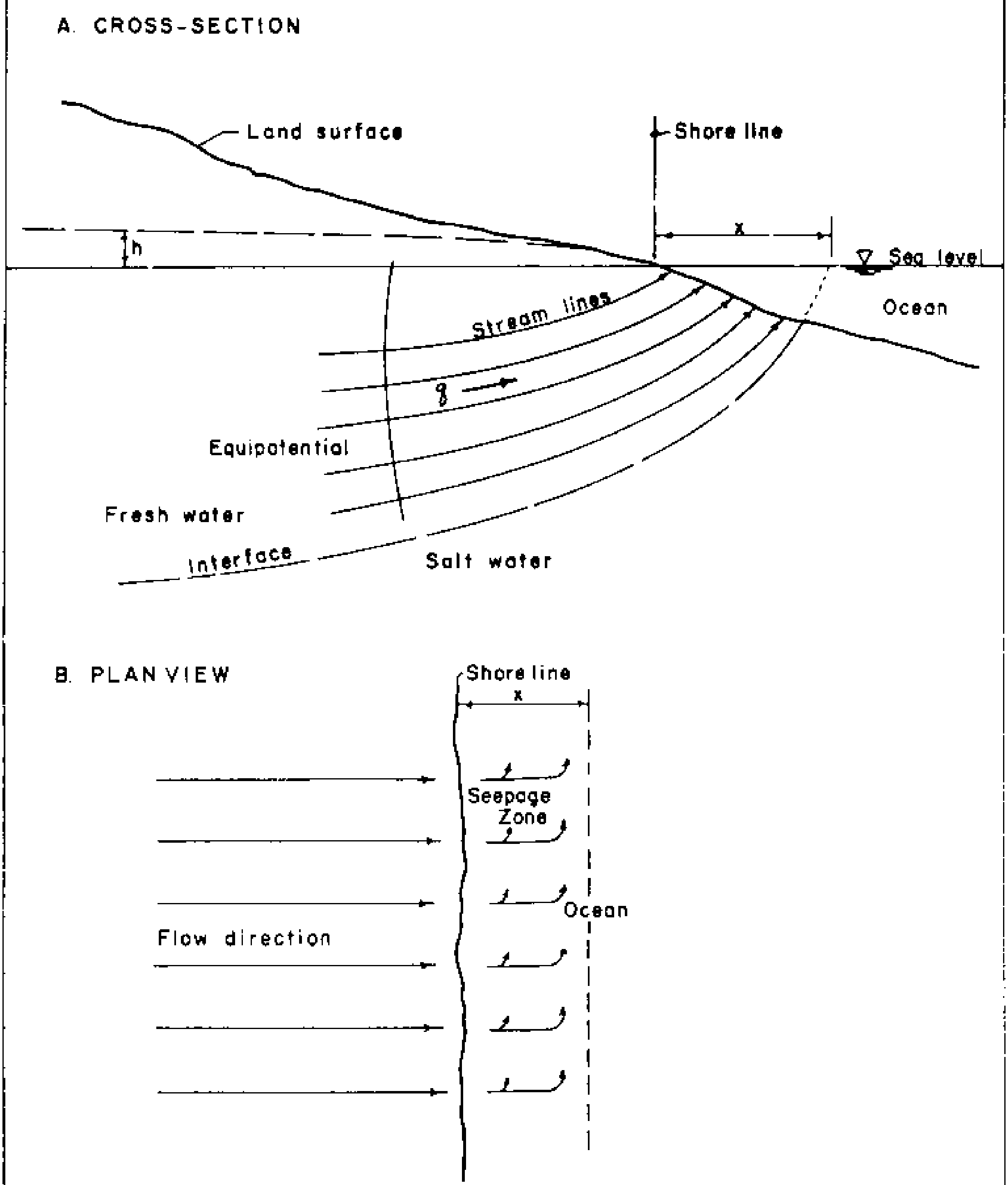


FIGURE 6-2

DISCHARGE FROM A BASAL LENS, IDEAL MODEL

No Scale

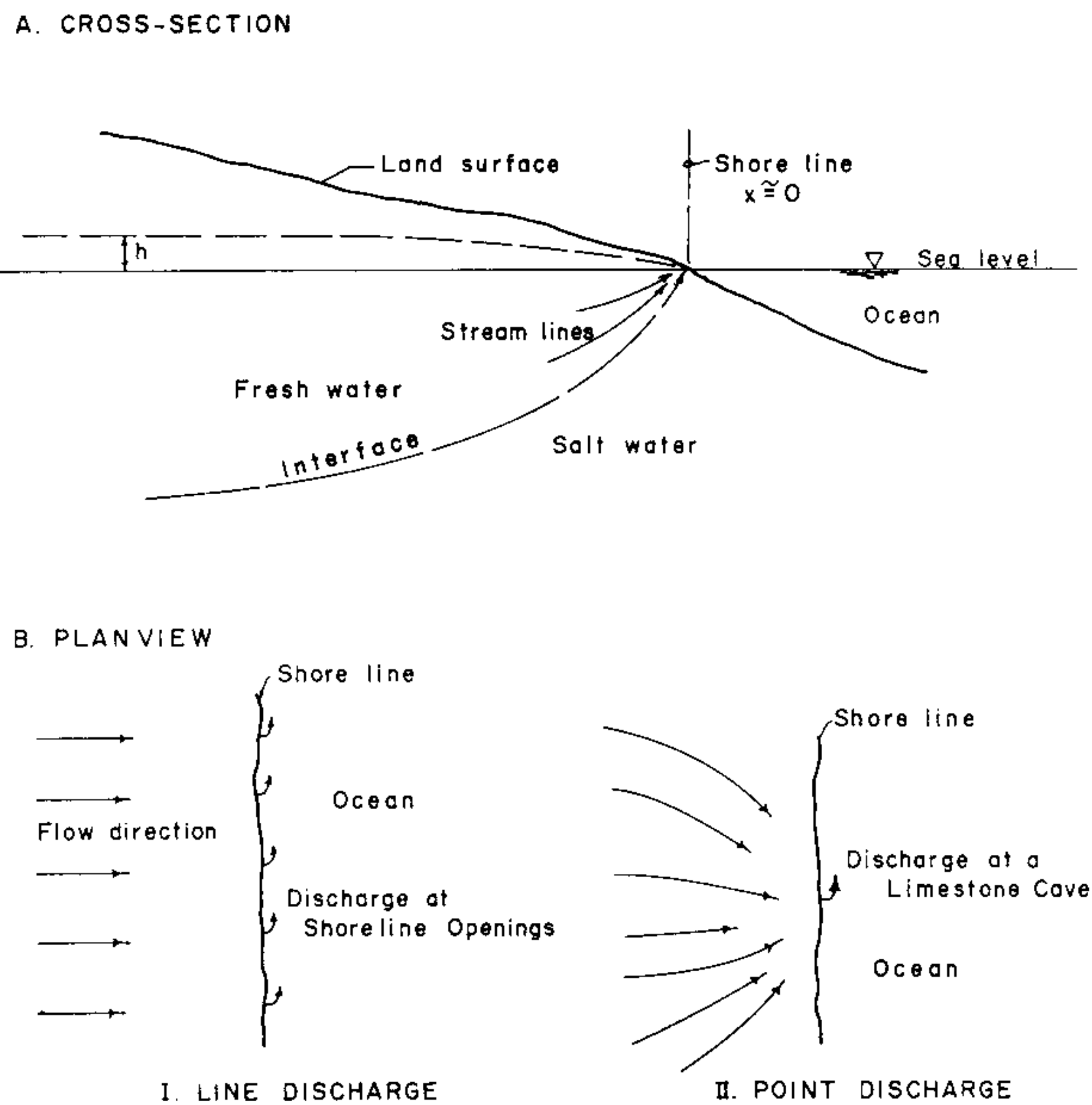


FIGURE 6-3

DISCHARGE FROM A BASAL LENS, HIGH LOCAL PERMEABILITY

No Scale

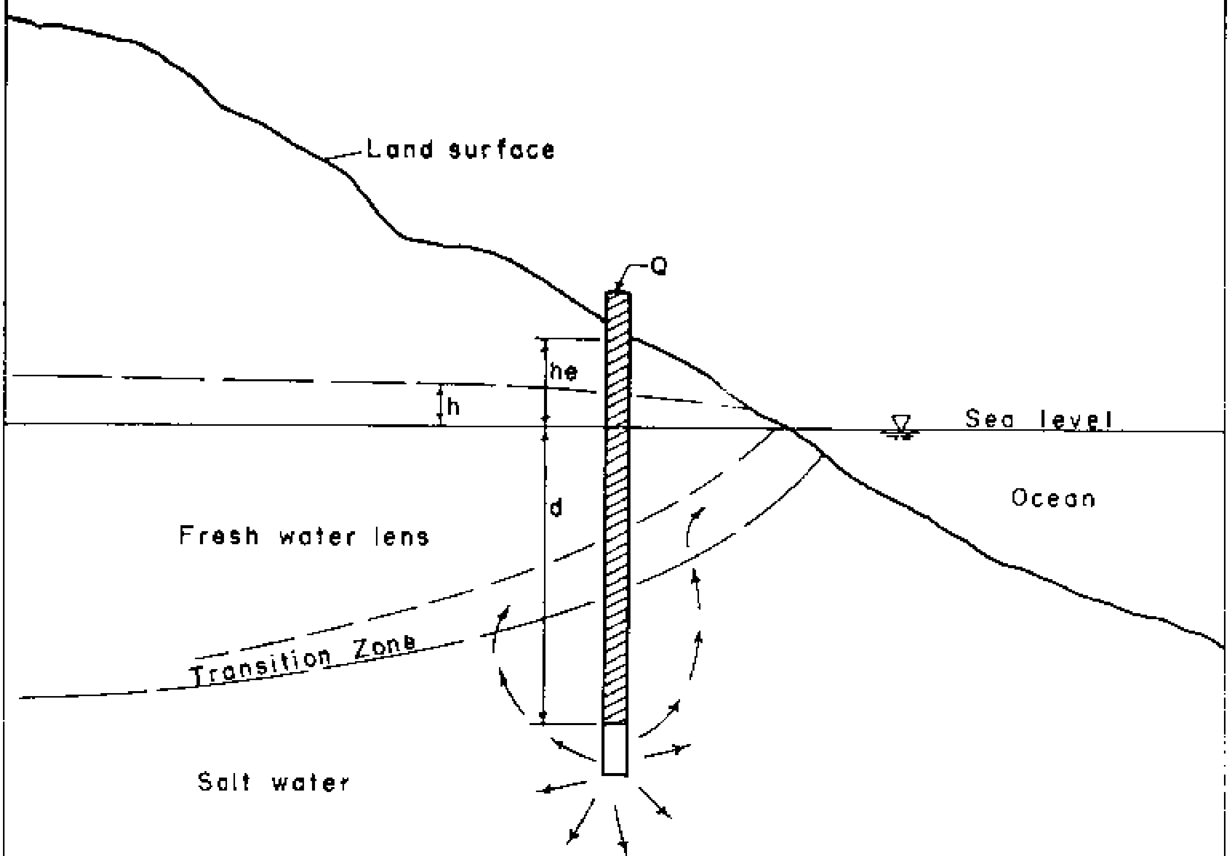


FIGURE 6-4

INJECTION WELL CASED THROUGH FRESH WATER LENS, OPEN TO SALT WATER

No Scale

APPENDIX A-7

Maximum rate of draft for wells in the basal lens as constrained by local conditions of head, aquifer penetration, and hydraulic conductivity

In the water budget study the volume of ground water moving in the hydrologic cycle was computed on a regional basis, which required a rather large value of hydraulic conductivity to acccount for the total flow in the lens. Ground water flow in an unconfined basal lens on a regional scale is described by:

$$(1) \quad q = k(B + 1)\, h \frac{dh}{dx}$$

in which q is specific flux, B is the Ghyben-Herzberg constant, k is hydraulic conductivity, h is head, x is distance along the flow path, and $\frac{dh}{dx}$ is the gradient of the flow path. In the water budget analysis, q was estimated, h and $\frac{dh}{dx}$ were measured, leaving k to be obtained by solving equation (1). The hydraulic conductivity determined in this fashion averaged about 2000 ft/d, a value applicable only on a regional scale in which local variations in the characteristics of the aquifer rock mass are subsumed in the average value.

Actually, the limestone aquifers of Guam are very heterogeneous and anisotropic, particularly where lagoonal deposition took place. As a result, on the scale of a single well the aquifer parameters, especially hydraulic conductivity, differ significantly from regional averages. Table B-10 (Appendix B), which summarizes information on wells constructed or reconstructed since 1964, lists transmissivities for wells on which analyzable pump tests were conducted, and also inferred hydraulic conductivities based on two assumptions, the first that the depth of penetration of the well is equivalent to depth of flow in the aquifer, and the second that depth of flow reaching the well extends 25% beyond the depth of penetration.

Unfortunately, in northern Guam time-drawdown data is available only for pumping wells, and thus the drawdown includes a component due to turbulence at the well face, which is very difficult to evaluate. N. Sheahan (1968) used step-drawdown analysis and J. Mink used drawdown and recovery techniques to obtain transmissivities and hydraulic conductivities in northern Guam. At Malolo, Talofofo, and Ylig, where wells penetrate small limestone aquifers in a predominately volcanic terrain, controlled tests with observation wells were conducted, giving fairly reliable values of hydraulic conductivity.

Hydraulic conductivities of limestone aquifers are determined by the variety and arrangement of the components laid down during sedimentation, structures subsequently formed, and chemical reactions, including solution, deposition and recrystallization. In particular, the quantity of clay mixed with lagoonal detritus profoundly diminishes local hydraulic conductivity while solution channels greatly increase it. In northern Guam the limestones range from highly argillaceous near the Adelup-Pago demarcation of the island to nearly pure in the Dededo and surrounding areas. For purposes of analysis it is convenient to arbitrarily classify the limestones as very argillaceous, argillaceus, and clean.

Table 7-1 below summarizes local transmissivities and hydraulic conductivities for limestones, assuming a flow depth equivalent to well depth plus 25%, and for volcanic rocks, in which flow depth is assumed equal to well depth.

Table 7-1

Well	Rock type	Transmissivity, T gpd/ft^2	Hydraulic Conductivity, k ft/d
A-12	Very arg. ls.	19000	10
A-1	Arg. ls.	90000-105000	56-66
D series	Clean ls.	24000-173000	64-441
Malolo	Arg. ls.	10400-21000	69-75
Talofofo	Arg. ls.	14000-21000	46-78
Ylig	Arg. ls.	14000-20000	12-18
Pulantat (RCA)	Volc		.013-.036
Malolo	Volc.		.034
Guam Oil Refinery	Volc.		2.61

From this data and field judgement of well behavior, mean local hydraulic conductivities assigned to limestone types are as follows:

Type	k(ft/d)
Clean limestone	190
Transitional limestone most probable case)	120
Argillaceous limestone	52
Very argillaceous limestone	26

These values are obviously approximations but are reasonable for analysis.

Drawdown which occurs during the pumping of a well consists of one component reflecting aquifer loss of head due to laminar flow, and another resulting from turbulent flow as water enters the well. In the limestone aquifers of northern Guam, for a pumping rate of 200 gpm the steady state aquifer loss, s_a, ranges from 1 ft. (clean ls.) to 8 ft. (very arg. ls.), and can be assumed to average 2 ft. in the probable case.

Well loss drawdown, s_w, is caused by the transiting from laminar flow in thee aquifer to turbulent flow near the well. In the early stages of pumping the specific capacity of a well chiefly reflects s_w. At a pumping rate of 200 gpm the median early time specific capacity of a clean limestone well is 40 gpm/ft ($s_w \cong 5$ ft) and for an argillaceous limestone well. it is 5 gpm/ft ($s_w \cong 40$ ft). The specific capacity is not constant for different flow rates, as it would be were flow strictly laminar. Well-loss drawdown varies as flow rate raised to an exponent between 1 and 2, conveniently estimated as:

(2) $s_w = a\ Q^{1.5}$

where a is a constant which may be calculated by assigning $s_w = 5$ ft at $Q = 200$ gpm, to give:

(3) $s_w = .0018\ Q^{1.5}$

so that, for instance at $Q = 400$ gpm, $s_w = 14.4$ ft rather than the 10 ft applicable for laminar flow, and at 500 gpm $s_w = 20$ ft rather than 12.5 ft.

Assigning average values for s_a and s_w, if limits are set on well design such that the pump lay 10 ft above the bottom of the well and would always be covered by at least 5 ft of water, the minimum permissible penetration depth, l, into the saturated zone would be:

(4) $l = a\,Q^{1.5} + s_a + 10 + 5 = .0018\,Q^{1.5} + 17$

Thus for a pumping ratio of 200 gpm the required minimum depth of penetration would be 22 ft to guarantee yield.

Equation (4) sets a lower limit on the depth of penetration for a well to satisfactorily produce a continuous rate of pumpage. However, in a basal lens the depth of the well is also constrained. by the thickness of the fresh water zone and the phenomenon of up-coming of the salt water below the lens under pumping stress. The threat of up-coming seriously limits the depth to which a well may be driven and the rate at which water may be pumped.

Schmorak and Mercado (1968) have provided an analysis of up-coming which is generally applicable to Guam. Figure 7-1 below illustrates the simple model for the analysis:

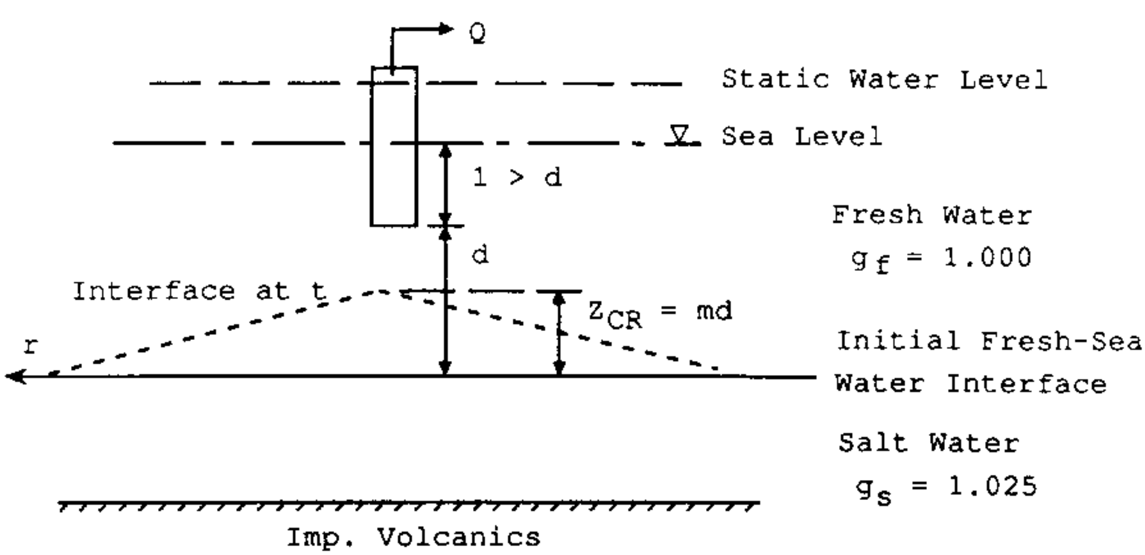


Fig. 7-1

The theory is based on an abrupt interface but is applicable to a lens with a narrow transition zone. In figure 7-1, Z_{CR} is the critical rise, the occurrence of which results in salt water being sucked into the well. The theoretical value for m is about 0.5, but tank model studies have shown that a value of 0.25 more nearly reflects actual conditions. The constants g_s and g_f are densities of salt and fresh waters, respectively, and their effect may be combined in another constant, $b = \frac{g_s - g_f}{g_f} = .025$, for the normal fresh water-sea water association.

At the steady state, the interface rise is expressed as:

$$(5) \quad Z(r) = \frac{Q}{2\pi \, bk_x d} \left\{ \frac{1}{\left[1 + \left(\frac{r}{d}\right)^2 \left(\frac{k_z}{k_x}\right) \right]^{1/2}} \right\}$$

in which k_x, k_z are horizontal and vertical hydraulic conductivities respectively, and Q is pumping rate. If only a vertical line directly below the well is considered, r = 0, and:

$$(6) \quad Z(0) = \frac{Q}{2\pi \, bkd}$$

where k is horizontal conductivity.

The critical rise is:

$$(7) \quad Z_{CR} = md$$

and therefore at steady state the theoretically allowable pumpage before salt water would be drawn into the well would be:

$$(8) \quad Q_{MAX} \leq 2\pi \, md^2bk$$

For a Ghyben-Herzberg lens with a transition zone, figure 7-1. may be modified as follows:

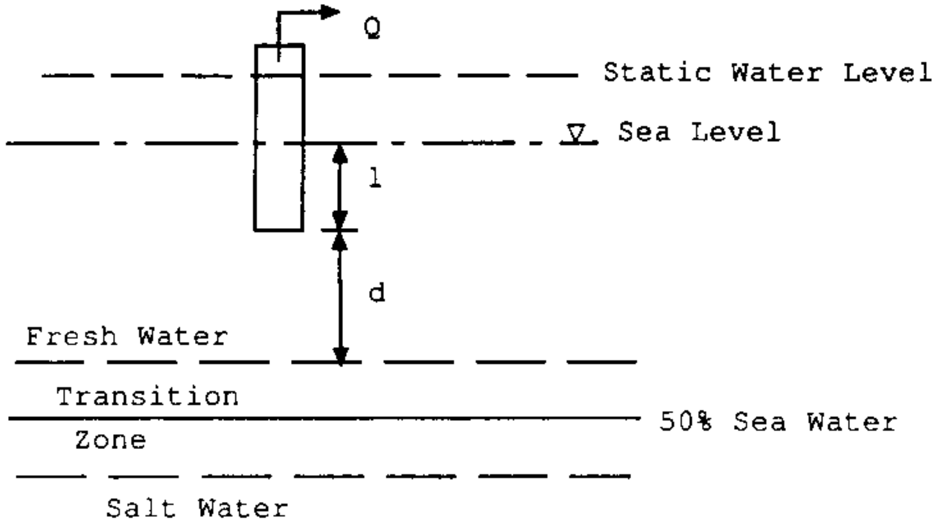


Fig. 7-2

The Ghyben-Herzberg constant applies to the depth below sea level to the middle of the transition zone. Let f be the half-width of the transition zone so that Z_{CR} is measured from the top margin of the upper half of the transition zone, then:

(9) $d = 40\ h - f - l$

If the transition zone is narrow, as it is toward the center of the island, a value of 16 ft for f is reasonable, so that:

(10) $d = 40\ h - 15 - l$

which in combination with equation (8) gives (Q)(l,h) as:

(11) $Q_{MAX} \leq 2\pi\ m\ (40\ h - 15 - l)^2\ bk$

Equation (11) yields unrealistically large values of Q for small l because it does not take into consideration s_a, s_w, and the prescribed pump setting constraints. Equation (4) gives the minimum l for a well at a selected pumping rate and is therefore a constraint on equation (11). If the minimum l as determined by equation (4) is denoted l_{min}, and l of equation (11) as l, then for, $l_{min} > l$, the

the computed Q cannot be produced. The constraint equation is not absolute, obviously, because it is based on assumed average aquifer characteristics.

Table 7-2 lists the theoretical maximum pump capacities computed from equation (11) for given l and h in clean to argillaceous limestones. Head is restricted to values of h = 2, 3, 4 ft because under optimal development maximum head in the lens will be 4 ft or less, and when h = 1 only a small quantity of fresh water could be pumped. In the table the pumpage rates considered unobtainable under the constraint equation (4) lie above the darkened lines. The rates shown are theoretical maximums which undoubtedly exaggerate the practicably obtainable rates. Nevertheless, the table serves as a general guide to allowable pumping rates, but each well must be individually evaluated before selecting a pump size.

The data of table 7-2 as well as the constraint equation are graphed in Figure 7-3. From table 7-2 and figure 7-3 the theoretical maximum pump rate, Q, at h = 4 ft., is seen to be 425 gpm for clean limestone, 325 gpm for the most probable limestone, and 140 gpm for argillaceous limestone. The theoretical maximum rates suggest that the present standard pump size of 200 gpm is a practical average. However, on re-evaluation some wells may be able to accommodate larger pumps, perhaps as high as 300 gpm, but no changes should be made except after the most careful evaluation.

TABLE 7-2

Matrix of Q_{MAX} (h,l) = 2π md^{2}bk over interval $2 \leq h \leq 4$ for k = 190, 120, and 52 ft/day. Values of Q_{MAX} lying above heavy line unfeasible under constraint l_{MIN} = .0018 $Q^{1.5}$ + 17. Q_{MAX} in gpm.

	Clean ls. k=190 ft/day			Probable ls. k=120 ft/d			Arg. ls. k=52 ft/d		
l \ h	2	3	4	2	3	4	2	3	4
10	115	350	708	75	225	450	30	95	190
20	78	280	605	50	175	380	20	75	165
30	48	218	512	30	135	325	10	60	140
40	30	160	425	20	100	270	5	45	115
50	9	115	350		75	220		30	95
60		78	275		50	175		20	75
70		48	218		30	135		10	60
80		30	170		15	105		5	45
90		10	125		10	75			30
100			78			50			20
110			50			30			10
120			25			15			5
130			10						
140									
150									
160									
170									
180									
190									
200									

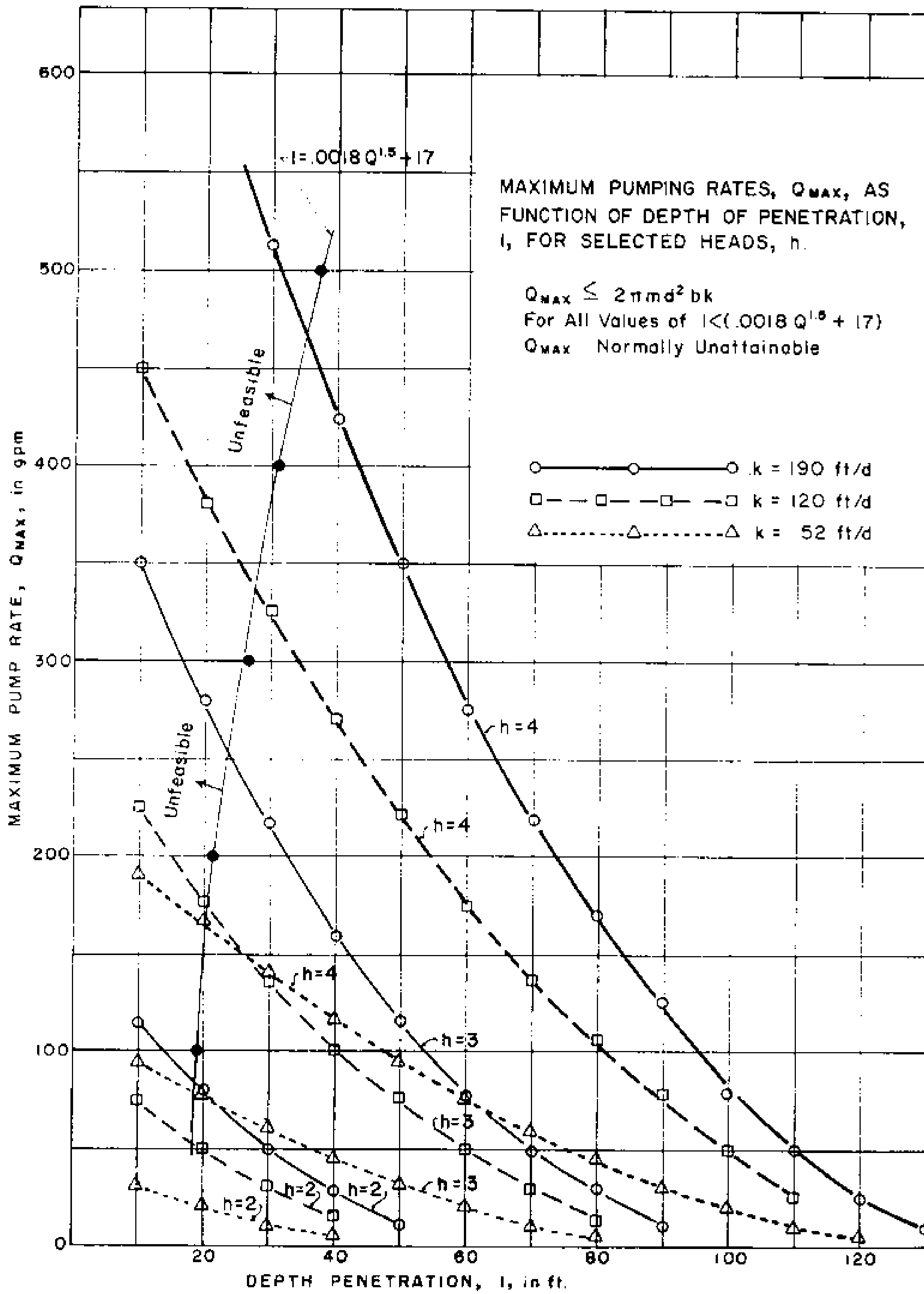

MAXIMUM PUMPING RATES, Q_{MAX}, AS FUNCTION OF DEPTH OF PENETRATION, l, FOR SELECTED HEADS, h.
$Q_{MAX} \leq 2\pi md^2 bk$
For All Values of $l < (.0018\,Q^{1.5} + 17)$
Q_{MAX} Normally Unattainable
k = 190 ft/d
k = 120 ft/d
k = 52 ft/d
$l = .0018\,Q^{1.5} + 17$
Unfeasible
Unfeasible
h=4
h=4
h=4
h=3
h=3
h=3
h=2
h=2
h=2
MAXIMUM PUMP RATE, Q_{MAX}, in gpm
DEPTH PENETRATION, l, in ft.
600
500
400
300
200
100
0
20
40
60
80
100
120

FIG. 7-3

APPENDIX A-8

Derivation of sustainable yields from a Ghyben-Herzberg lens for selected equilibrium heads

In a basal water aquifer a plot of head against draft usually appears to give a rough linear correlation, but actually in porous media the head-draft relationship must take into consideration leakage from the aquifer at any given head, and leakage is not a linear function of head. The relationship between head and draft, therefore, also is non-linear. In Appendix A-2 specific discharge (leakage) was shown to vary as the square of the head, and in the analysis which follows it will be shown that draft can also be related to the square of the head, thus permitting the determination of equilibrium heads for given steady drafts and known initial conditions.

The groundwater hydrologic balance for northern Guam may be expressed as:

(1) $I + \Delta S = D + L$

in which I is input (recharge) to the groundwater lens, ΔS is change in storage, D is draft, and L is leakage to the sea. For periods of equilibrium, $\Delta S = 0$, and the relationship becomes:

(2) $I = D + L$

Equations (7) and (8) of Appendix A-2 give leakage as a function of head for the cases of steady infiltration and no infiltration, respectively. For generality, equation (7) of Appendix A-2 (steady infiltration) may be used in deriving the relationship between head and draft. This equation is:

(3) $h^2 = \left[\frac{2x}{41\ k}\right]\left\{q_1 + wx_1 - \frac{wx}{2}\right\}$

If the entire lens from distance x_1 to the coast is treated as a unit, the leakage, L, under non-development conditions would be:

(4) $L = q_1 + wx_1$

also:

(5) $(q_1 + wx_1) = \frac{41\ k\ h^2}{2x} + \frac{wx}{2} = L$

or (6) $L = \frac{41\ k\ h^2}{2x} + \frac{wx}{2}$

By holding x constant so that $\frac{41k}{2x} = c_1$ and $\frac{wx}{2} = c_2$, from equation (2):

(7) $I = D + c_1h^2 + c_2$

When $D = 0$,

(8) $I = c_1h_o^2 + c_2$

and substituting (8) into (7),

(9) $c_1h^2 = I - D - c_2 = c_1h_o^2 + c_2 - D - c_2 = c_1h_o^2 - D$

which can be expressed as:

(10) $h^2 = h_o^2 - D/c_1$

This equation can be made linear by letting $h^2 = H$ and $h_o^2 = H_o$ so that:

(11) $H = H_o - D/c_1$

which gives a straight line on normal rectilinear graph paper with H_o as the intercept and $(-1/c_1)$ as the slope.

From equation (11), the sustainable yield (draft) of half of the total lens, assuming equal and symmetric drainage to the east and west margins of the island, can be computed for a selected equilibrium head if the initial head, h_o, which prevailed before the start of development, were known, as well as the constant, $c_1 = 41\ k/2x$. For northern Guam the initial free basal head could be considered to be 5.5 ft. at a distance 12000 ft. from the coast, and c_1 could be calculated by assigning a value to k.

For instance, if k = 2000 ft/d, and h_o = 5 5 ft. at x = 12000 ft, and these values held true for all of northern Guam north of Chaot-Ordot, the natural infiltration (recharge) could be computed as $D \cong I = 103.4\ ft^3/d$ per lineal foot of coast by letting H = 0. If the lens drained equally to the west and east, apportioning the northern coast equally to the east and west coasts, the shore line length multiplied by the specific recharge would yield the total recharge (approx. 210,000 ft x 100 ft^3/d = 21,000,000 ft^3/d = 157 mgd), a value which is of the same magnitude as those calculated by other means.

The linear form of equation (11) can be exploited to provide a simple and informative method of determining equilibrium heads for given steady drafts. When $H = H_o$, D = 0, and when D = I, H = 0, therefore by plotting H_o as the intercept on the H axis and I as the intercept on the D axis and joining the points by a straight line, equilibrium values for D and H can be read from the resulting graph. In this case the slope need not be known explicitly.

Figure 8-1 illustrates the use of the graphical method. Demand, D, is plotted as the abscissa, and H, the square of the head, as the ordinate. Values for D refer to the symmetrical half-lens and must be doubled to obtain values for the whole lens. In figure 8-1, straight lines connect various assumed values of recharge ($I \cong D$, H = 0 on the D axis with initial values of the square of the head on the H axis. Table 8-1 summarizes values of I as determined from hydrologic budget computations and which are used in the plot (see section on the Hydrologic Budget). These values range from 38 mgd to 101 mgd for the half-lens (76 mgd to 202 mgd for the whole lens).

Table 8-1

Location	Hydrologic Budget Areas	Minimum I (5% runoff)	Minimum I (no runoff)	Probable I (5% runoff)	Probable I (no runoff)
Highway 4 to Anderson Air Force Base	2,3,4	38 mgd	45 mgd	73 mgd	80 mgd
Highway 4 to the north coast	2,3,4,5	52 mgd	62 mgd	101 mgd	110 mgd

The hypothetical sustainable yields of the basal lens for different equilibrium conditions can be read directly from figure 8-1. First, an optimal equlibrium head, to which the original head at a given location will be allowed to decay, must be selected. The lower the selected equilibrium head relative to the initial head, the greater will be the sustainable yield because at low heads leakage is greatly decreased. However, too low an equilibrium head will endanger the production of fresh water because of induced sea water intrusion.

In figure 8-1 the sustainable yields may be determined for cases where an initial head of 5 ft, the position of which is reasonably well established for the lens of northern Guam, is allowed to decay to any lower equilibrium head. A first, probably conservative, choice of optimality would be to allow the 5 ft initial head contour to decay to 4 ft under pumping development. The most probable hydrologic budget (assuming rainfall runoff of 5%) assigns a half-lens recharge of 73 mgd to combined areas 2, 3, 4, providing the sustainable yield of the half-lens for this choice of optimality as 26 mgd (52 mgd for the whole lens), equivalent to 36% of the recharge. For all of northern Guam (areas 2, 3, 4. 5) the half-lens sustainable yield would be 36 mgd (72 mgd for the whole lens). For the minimum hydrologic budget (assuming rainfall runoff of 5%) the comparable half-lens yield for areas 2, 3, 4 would be 14 mgd (28 mgd for the whole lens) and for areas 2, 3, 3, 5 it would be 19 mgd (38 mgd for the whole lens).

Table 8-2 summarizes in matrix form relevant information deducible from figure 8-1. Matrix A gives sustainable yields under different recharge values for areas 2 through 4 and areas 2 through 5 when an initial head of 5 ft is permitted to decay to equilibrium heads, h_e, over a range of 4.5 ft to 2.5 ft. At the lowest equilibrium head shown, h_e = 2.5 ft, the sustainable yield is more than double that at the selected optimal head of 4 ft, but were the lens allowed to contract to h_e = 2.5 ft a more serious constraint on production would ensue, that of salt water intrusion. At the present state of production technology the choice of an optimal equilibrium head is in large part judgemental, based chiefly on experience in Guam and elsewhere. Guam's water needs could be met for many years to come by selecting as the optimality condition, $h_o = 5 \rightarrow h_e = 4$ ft. Evaluation of optimality should, of course, be constantly assessed as the development of ground water proceeds.

Matrix B shows the reductions in heads which will occur at given initial head contours ranging from the maximum initial head of 5.5 ft at the middle of the island to the down-gradient initial head of 2 ft when the initial head of 5 ft is allowed to decay to lower heads. For instance, if $h_o = 5$ decays to $h_e = 4$, then:

$$h_o = 5\ 5 \rightarrow h_e = 4.4 \text{ ft}$$

$$h_o = 4.0 \rightarrow h_e = 3.2 \text{ ft}$$

$$h_o = 3.0 \rightarrow h_e = 2.4 \text{ ft}$$

$$h_o = 2.0 \rightarrow h_e = 1.6 \text{ ft}$$

Matrix C indicates expected hypothetical reductions from original heads under current development (7.5 mgd for the half-lens; 15 mgd for the full lens) for different assumed recharge values. Considering areas 2 through 4, for the minimum budget case loss in head from the maximum head of 5.5 ft would be 0.6 ft, but only 0.3 ft for the probable budget case: if all of northern Guam (areas 2 through 5) were considered, the comparable losses in head would be 0.4 and 0.2 ft. These relatively slight losses fall within the normal error range of head-measurirg techniques used in Guam and explain why a significant change in water levels cannot be detected in the basal lens as a result of ground water development over the last decade or, for that matter, since the first well was drilled in 1937. It is not likely that significant regional head decays will be measurable until total draft is substantially increased.

All of the information contained in figure 8-1 and table 8-2 is derived from an idealization of the basal ground water lens of northern Guam. However, on a regional basis the information provides a practical framework for successfully exploiting ground water resources, but in detail each development point, such as a well, must be analyzed with respect to local conditions of heterogeneity and anisotropism in the aquifer before a production rate is specified.

Based on the most probable hydrologic budget, an average of about 50 mgd can be safely withdrawn from the basal lens in areas 2 through 4 if the head of the 5 ft isopiestic contour is allowed to decay to 4 ft.

TABLE 8-2

SUSTAINABLE YIELD, NORTHERN GUAM

Relationship among sustainable yield, head, and total recharge for the half basal lens of northern Guam. Volume rate values should be doubled to give values for the full lens.

A. Sustainable yield, D, in mgd for total recharge, I, in mgd when h_o = 5 ft. decays to a new equilibrium head, h_e. Values of I from the hydrologic budget.

		Sector (2+3+4)				Sector (2+3+4+5)				
h_o	h_e	I=38	I=45	I=73	I=80	I=52	I=62	I=101	I=110	D/I(%)
5.0	4.5	7.2	8.5	14	15	10	12	20	21	19
5 0	4.0	14	16	26	29	19	22	36	40	36
5.0	3.5	19	23	37	41	27	32	51	57	51
5.0	3.0	24	29	47	51	33	40	65	71	64
5.0	2.5	28	34	55	60	39	47	76	84	75

B. Decay of initial heads, h_o, to equilibrium heads, h_e, when h_o = 5 is allowed to go to h_e.

h_o	h_e	h_e	h_e	h_e	h_e
5.0	4.5	4.0	3.5	3.0	2.5
5.5	5.0	4.4	3.8	3.3	2.7
4.0	3.6	3.2	2.8	2.4	2.0
3.0	2.7	2.4	2.1	1.8	1.5
2.0	1.8	1.6	1.4	1.2	1.0

C. Expected decay from h_o to h_e under present pumping yield, D, of 7.5 mgd for half lens (15 mgd for whole lens) for different assumption of recharge, I.

	Sector (2+3+4)				Sector (2+3+4+5)			
h_o	I=38	I=45	I=73	I=80	I=52	I=62	I=101	I=1[illegible]
5.5	4.9	5.0	5.2	5.2	5.1	5 1	5.3	5.[illegible]
5.0	4.5	4.6	4.7	4.7	4.6	4.7	4.8	4.8
4.0	3.6	3.6	3.8	3.8	3.7	3.7	3.8	3.9

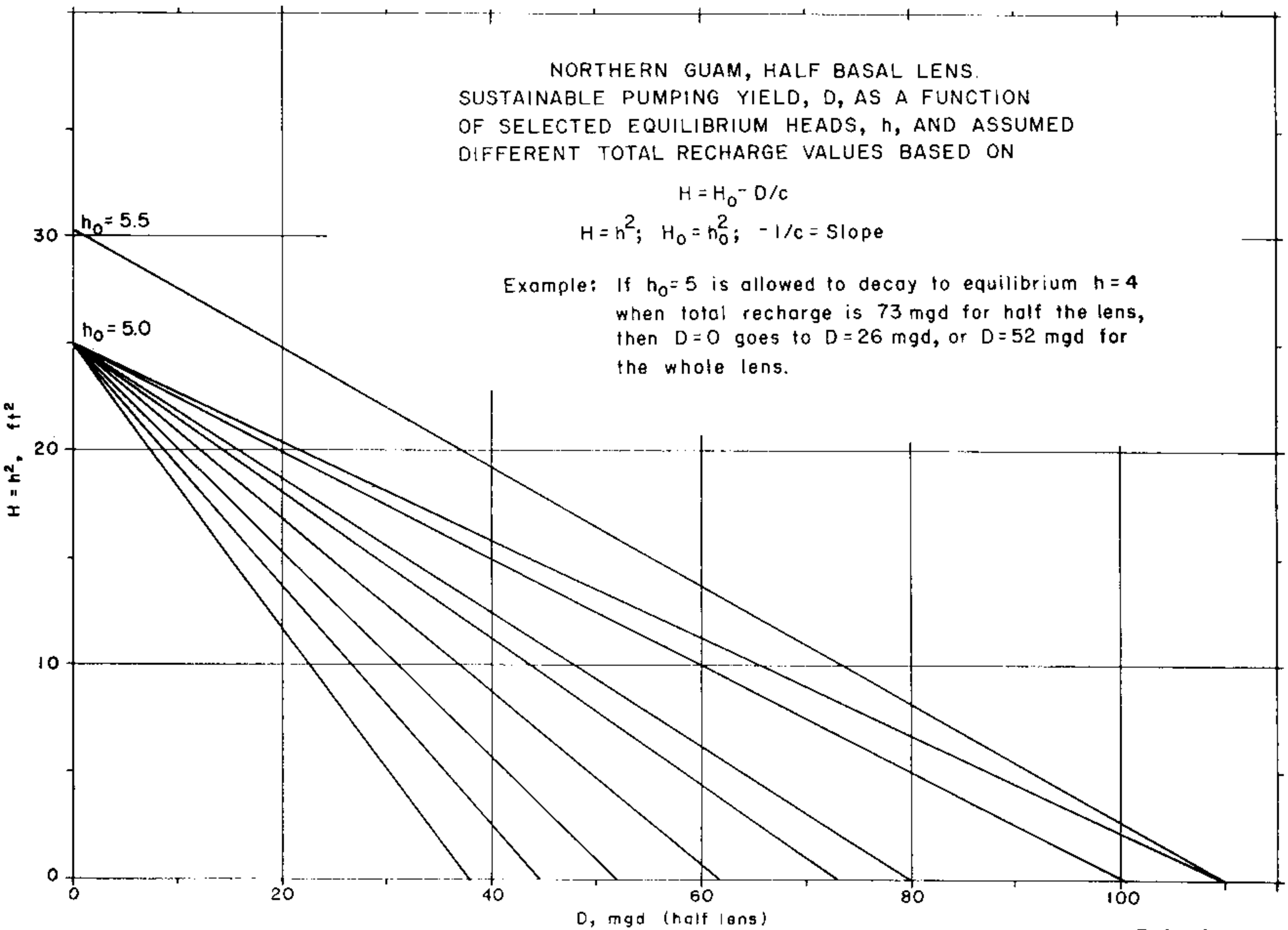

NORTHERN GUAM, HALF BASAL LENS.
SUSTAINABLE PUMPING YIELD, D, AS A FUNCTION OF SELECTED EQUILIBRIUM HEADS, h, AND ASSUMED DIFFERENT TOTAL RECHARGE VALUES BASED ON
$H = H_0 - D/c$
$H = h^2$; $H_0 = h_0^2$; $-1/c$ = Slope
Example: If $h_0 = 5$ is allowed to decay to equilibrium $h = 4$ when total recharge is 73 mgd for half the lens, then D = 0 goes to D = 26 mgd, or D = 52 mgd for the whole lens.
$h_0 = 5.5$
$h_0 = 5.0$
$H = h^2$, ft^2
30
20
10
0
0
20
40
60
80
100
D, mgd (half lens)

FIG. 8-1

APPENDIX A-9

Evaluation of flow from Asan Spring

Asan Spring is a typical example of high level perched water in a small limestone aquifer lying on an impermeable volcanic basement whose elevation is above sea level. Rainfall infiltrates into the limestone, accumulates in its lower section, and flows along the limestone-volcanics contact to discharge as a spring where the contact is exposed. Before emplacement of the limestone the volcanic surface had been eroded, and flow concentrated in pre-existing channels in the volcanic surface which lead to the spring. The ideal spring occurs where limestone was emplaced on an old stream valley to which all subsurface flow would drain. Asan Spring may represent such a situation with Alifan limestone as the principal aquifer rock lying on the Alutom surface as illustrated below.

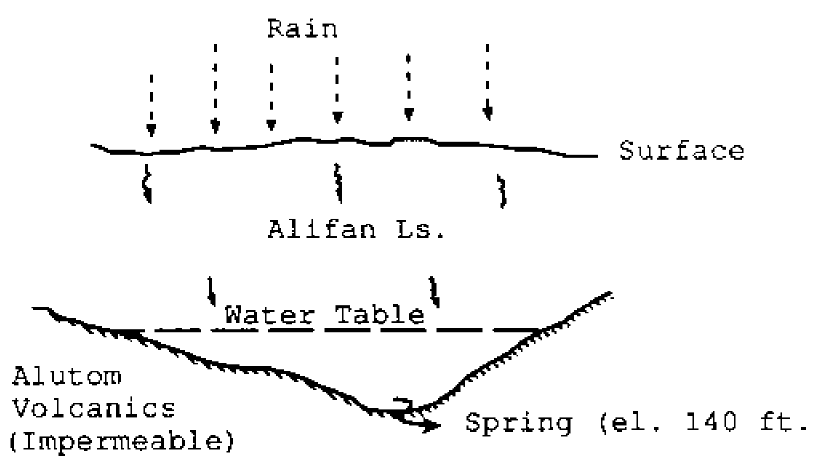


Fig. 9-1

In order for an exploitable perennial spring to exist, substantial storage in the limestone aquifer must be available. Storage will build up if the aquifer has a hydraulic conductivity sufficiently low to retard rapid subsurface flow during periods when infiltration is high. In addition to a relatively poor hydraulic conductivity, egress for the water must be restricted so that diffuse sheet flow does not take place at the exposed margins of the limestone-volcanics contact.

Most storage accumulation occurs during the wet months when infiltration is greater than discharge. During the dry season, discharge usually exceeds infiltration and decay of storage occurs. As a general rule, storage is at its maximum at the end of the wet season, from which it declines to a minimum at the end of the dry season. Unusual rainfall during the dry season will retard the decline and cause a temporary increase in storage, but ordinarily storage and flow decay monotonically towards the minimums.

Examination of flow records and climatologic data implies that maximum storage occurs in the early part of December and the minimum in June, giving a decay period of 6 months. These limits conform to stream flow characteristics in southern Guam (Appendix A-5) and to rainfall records.

Measurements of total daily flow at Asan Spring were taken between 2/9/65 and 6/11/65 in an attempt to evaluate the parameters of flow of the aquifer. The plot of these data illustrates how flow declines when it consists of drainage from storage alone (figure 9-2). For this period, total flow consisted of metered flow to the water main end metered overflow, as shown in figure 9-3.

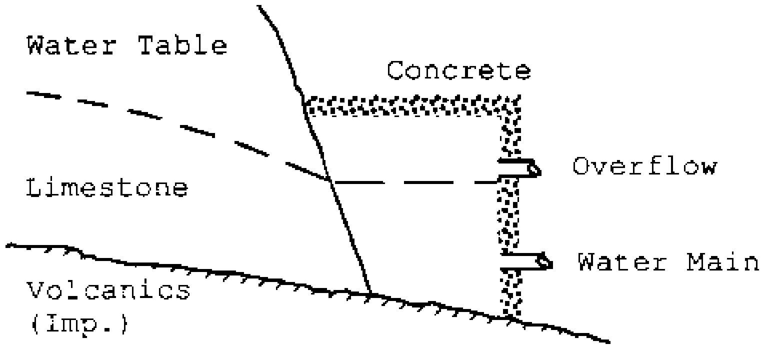


Fig. 9-3

Flow decay from porous media, in the absence of recharge, is expressed as:

(1) $Q = Q_0 e^{-at}$

In convenient units, Q = flow rate in mgd at any time, t, in days; Q_0 = initial flow rate in mgd; and a is the recession constant, 1/day. A small recession constant reflects slow drainage and inferentially low hydraulic conductivity and large storage. The recession constant is directly proportional to hydraulic conductivity and depth of flow and inversely proportional to length of flow path and porosity.

Figure 9-2 shows the flow decay for Asan Spring during the dry season of 1965, for which the equation is

(2) $Q = 0.62\ e^{-.005\ t}$

The theoretical flow at maximum storage (Dec. 1, 1964) was 0.62 mgd, and the minimum at the end of the dry season (June 1, 1965) was 0.25 mgd.

Stearns (1937) estimated the low flow of Asan as 0.2 mgd; Kennedy Engineers (1968) estimated the average flow as 0.5 mgd; and Austin, Smith Assoc. (1968) gave values of 1.0 mgd for maximum flow, 0.1 mgd for minimum flow, and 0.5 mgd as average flow.

From the parameters of equation (2), the total storage at the start of the decay is computed as:

(3) $V_O = Q_O/a = 124$ mg

However, not all storage was exhausted by June 1 since a substantial flow was still taking place at the onset of the wet season. The loss in volume of storage between December 1 and June 1 is calculated as:

(4) $v = \frac{Q_O - q}{a} = 74$ mg

from which average flow for the entire period of decay (180 days) may be computed as 0.41 mgd. Also, the remaining storage on June 1 amounted to 50 mg.

During the wet season storage increases even though discharge also increases because infiltration exceeds drainage. To return storage to 124 mg by December 1, assuming the average flow during storage buildup is equivalent to the average during decay, the average daily infiltration would have to be 2 x 0.41 mgd = 0.82 mgd during the wet season, equivalent on an annual basis to 0.41 mgd. The limestone area lying above the orifice of Asan Spring covers approximately 0.45 mi^2, of which, from surface geomorphology, perhaps 0.31 mi^2 drains to the spring. A rough calculation based on an infiltration rate of 2 mgd/mi^2 (see section on Hydrologic Budget) suggests that for 0.31 mi^2 an average daily infiltration (annual basis) of 0.63 mgd would be expected.

It is impossible to tell from the limited information available on the geology and sub-surface drainage pattern of the Asan area just how much of the limestone aquifer actually drains to the spring, but it is evident that the total infiltration is less than 1 mgd and that the average flow of 0.41 mgd derived from the flow equation is of the correct magnitude.

Recently the manner in which water is diverted from Asan Spring has been changed. The system now operates as follows:

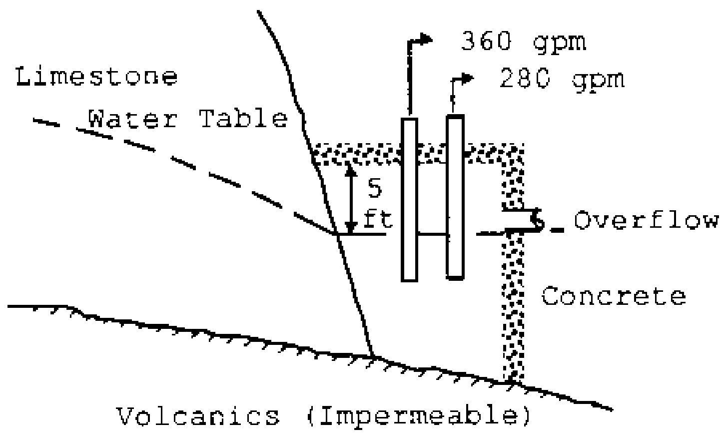


Fig. 9-4

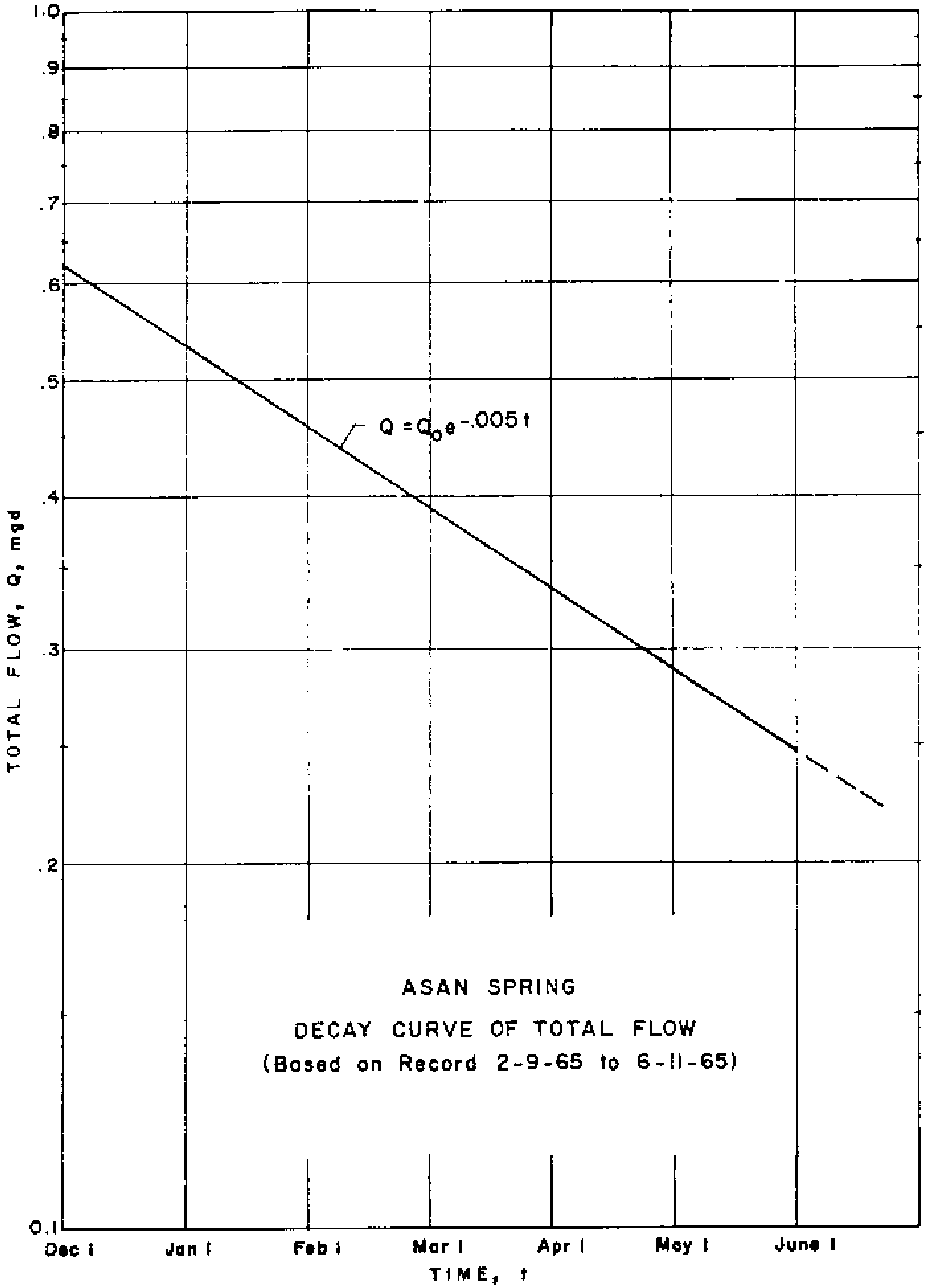
The pumps run as long as depth to water is less than 5 ft. Overflow no longer occurs: all water is used.

The same analytical approach used above can be applied to other high level springs if better data were collected. For the Almagosa complex (Dobo and Chepak Springs) the USN reports a maximum flow to their system of 3.5 mgd and the USGS reports a maximum overflow of 0.5 mgd, to give Q_0 = 4 mgd. The USN reports a minimum flow of 0.9 mgd, all of which is used. The approximate decay equation during the dry season is:

(5) $Q = 4\ e^{-.0083\ t}$

and $V_o = 482$ mg

For the dry season average flow of the complex would be 2.1 mgd.



1.0
.9
.8
.7
.6
.5
.4
.3
.2
0.1
TOTAL FLOW, Q, mgd
Q = Qoe-.005t
ASAN SPRING
DECAY CURVE OF TOTAL FLOW
(Based on Record 2-9-65 to 6-11-65)
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
June 1
TIME, t

FIG. 9-2

TABLE 1

RAINFALL RECORDS

(Source: R. C. Taylor, 1973, An Atlas of Pacific Islands

Rainfall: Hawaii Institute of Geophysics, Data Report No. 25)

Data in inches.

1. Andersen Air Force Base: 13°34′N 144°56′E. Period 1952 - 1972

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean	5.03	4.36	3.74	4.12	5.13	4.86	9.66	11.59	13.94	13.71	8.02	5.70	89.86
N	20	20	20	19	21	21	21	21	21	21	20	20	17
Std. Dev.	3.77	3.44	4.00	5.41	6.22	2.05	3.93	5.09	4.71	7.94	3.12	3.65	16.24
Median	3.95	3.81	2.29	2.83	2.73	4.99	9.15	10.77	13.03	11.53	7.37	4.97	86.85
Max.	17.28	12.37	14.66	24.00	25.45	8.15	15.78	26.28	23.27	37.09	13.85	16.90	149.66
Min.	1.64	0.66	0.30	0.38	1.10	1.40	3.00	3.99	6.69	4.05	3.11	2.10	62.42

2. Guam Naval Air Station: 13°29′N 144°48′E. Period 1956 - 1972

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean	4.81	2.96	2.77	4.05	5.51	5.36	10.04	11.84	14.08	11.22	8.26	4.96	85.86
N	16	16	16	17	17	17	17	17	17	17	17	17	16
Std. Dev.	3.04	2.05	2.09	3.79	4.91	2.61	3.95	4.17	3.65	4.13	3.08	2.47	11.92
Median	4.44	2.37	2.00	2.58	3.99	5.18	10.30	11.76	14.45	10.10	8.09	3.96	82.16
Max.	11.51	7.43	7.49	15.28	16.01	11.66	18.03	19.05	20.71	18.19	14.50	8.43	116.39
Min.	1.63	0.31	0.58	0.51	0.91	1.23	4.74	3.91	8.56	5.32	2.78	1.88	64.85

TABLE 1

3. U. S. Weather Bureau (Taguac): 13°33'N 144°50'E. Period 1956 - 1972

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean	5.54	4.19	4.44	4.65	6.26	6.19	11.25	13.41	15.78	13.19	9.48	6.48	100.84
N	16	16	16	16	16	16	16	16	17	17	17	17	16
Std. Dev.	3.08	2.91	4.63	4.81	6.62	2.47	4.27	4.74	4.50	5.25	3.65	3.86	15.14
Median	5.25	3.68	2.57	3.17	3.46	6.03	11.80	12.81	15.40	12.12	9.77	5.71	96.01
Max.	11.93	9.47	16.94	19.55	22.68	11.53	20.00	23.07	22.28	25.32	18.14	16.19	138.18
Min.	1.99	0.67	0.59	0.50	0.90	1.52	4.74	3.87	6.79	6.89	4.83	2.51	74.46

4. Sumay: 13°24'N 144°38'E. Period 1905 - 1940

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean	2.99	2.60	2.88	1.93	4.09	5.63	13.59	14.96	14.24	12.51	7.92	5.11	88.45
N	35	35	34	34	34	35	36	36	35	35	36	36	33
Std. Dev.	2.64	2.60	3.07	1.64	3.58	2.54	5.66	5.52	5.62	4.86	3.85	2.78	13.61
Median	2.50	1.85	1.91	1.28	3.25	5.23	13.92	14.73	13.09	12.59	6.85	4.54	89.36
Max.	16.04	11.30	14.97	8.69	18.85	13.35	27.83	26.30	26.96	30.62	21.25	11.50	118.08
Min.	0.40	0.08	0.58	0.12	0.44	2.31	5.88	5.97	5.45	3.27	3.63	1.65	59.68

TABLE 2

AVERAGE RAINFALL AND EVAPORATION

Rainfall (R) recorded at all stations. Pan evaporation (E) recorded at U. S. Weather Bureau, Taguac, period 1958 - 1973. Evaporation for Andersen Air Force and Naval Air Station computed from Taguac data by assuming rainfall and evaporation are inversely proportional:

$$(E)_i = \frac{[(R)(E)]_{USWB}}{(R)_i}$$

Data in inches.

1. U. S. Weather Bureau (Taguac). Rain record 1956 - 1972; evaporation record 1958- 1973

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Rain	5.54	4.19	4.44	4.65	6.26	6.19	11.25	13.41	15.78	13.19	9.48	6.48	100.84
Evaporation	5.49	5.93	7.23	7.64	7.68	6.52	5.84	5.15	4.85	5.12	5.22	5.74	72.41
Excess Rain	0.05	0	0	0	0	0	5.41	8.26	10.93	8.07	4.26	0.74	37.72

2. Andersen Air Force Base. Rain record 1952 - 1972

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Rain	5.03	4.36	3.74	4.12	5.13	4.86	9.66	11.59	13.94	13.71	8.02	5.70	89.86
Evaporation	6.05	5.70	8.58	8.62	9.37	8.30	6.80	5.96	5.49	4.93	6.05	6.53	81.23
Escess Rain	0	0	0	0	0	0	2.86	5.63	8.45	8.78	1.97	0	27.69

3. Guam Naval Air Station. Rain record 1956 - 1972

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Total
Rain	4.81	2.96	2.77	4.05	5.51	5.36	10.04	11.84	14.08	11.22	8.26	4.96	85.86
Evaporation	6.32	8.40	11.59	8.77	8.73	7.58	6.54	5.83	5.44	6.02	5.99	7.50	85.04
Excess Rain	0	0	0	0	0	0	3.50	6.01	8.64	5.20	2.27	0	25.62

TABLE 3

HYDROLOGIC BUDGET, NORTHERN GUAM

1. Minimum budget case, by sectors.

Based on average monthly rainfall (R) and evaporation (E):

$$I = \sum_{i} (r - E)_i \qquad I = \text{infiltration}$$

for all R > E; if R < E, then (R − E) ≡ 0

1 Sector	2 Ground Water Drainage	3 Area (mi^2)	4 I_1 (mgd)	5 I_2 (mgd)	6 Coast Length (ft)	7 q_1 (ft^3/d)	8 q_2 (ft^3/d)	9 $\overline{x}(h=5)$ (ft)	10 k_1 (ft/d)	11 k_2 (ft/d)	12 Remarks
1	W	2.58	3.2	2.6		(non	basal)				$I_1 = 1.22 mgd/mi^2$
1	E	2.58	3.2	2.6		(non	basal)				$I_2 = 1.02 mgd/mi^2$
Total		5.16	6.4	5.2							Based on NAS sta.
2	W	3.01	3.7	3.1							I per NAS sta.
2	E	3.01	3.7	3.1							
3	W	6.96	8.5	7.1							I per NAS sta.
3	E	13.38	16.3	13.6							Exclude Ypao Peninsula.
Total or	W	9.97	12.2	10.2	20000	81.6	68.2	7500	1194	998	
average	E	16.39	20.0	16.7	46000	58.1	48.5	9000	1020	852	
(2+3)		26.36	32.2	26.9	66000	65.2	54.5	8000	1017	851	
4	W	27.28	41.2	35.2	53000	104	88.8	11000	2232	1906	$I_1 = 1.51 mgd/mi^2$
4	E	10.98	16.6	14.2	16000	138	119	8000	2154	1858	$I_2 = 1.29 mgd/mi^2$
Total or average		38.26	57.8	49.4	69000	112	95.7	11000	2185	1867	Based on av. of NAS and USWB

TABLE 3

1	2	3	4	5	6	7	8	9	10	11	12
Total or av. (2+3+4)		64.62	90.0	76.3	135000	89.1	75.6	9000	1565	1328	Excludes Ypao Peninsula of 1.08 mi^2
5		24.82	32.8	27.6	73000	60.1	50.5	12500	1466	1232	I_1 = 1.32mgd/mi^2 I_2 = 1.11mgd/mi^2 Based on Andersen AF
Total or av. (2+3+4+5)		89.44	123	104	208000	79.1	66.9	10000	1543	1305	

Column explanation

1. See map for sector location.
2. Apparent general direction of groundwater drainage.
3. Area of sector
4. I_1 = computed average daily infiltration assuming no surface runoff.
5. I_2 = computed average daily infiltration assuming that 5% of rainfall is lost as direct surface runoff to the sea.
6. Approximate length of groundwater discharge front along coast.
7. q_1 = computed average daily groundwater flow per foot of coastline assuming no surface runoff
8. q_2 = computed average daily groundwater flow per foot of coastline assuming that 5% of the rainfall is lost as direct surface runoff to the sea.
9. $\bar{x}$ = average distance from the coast to the 5 ft. head contour.

TABLE 3

Column explanation (cont.):

10. k_1 = computed regional hydraulic conductivity assuming no surface runoff.
11. k_2 = computed hydraulic conductivity assuming that 5% of the rainfall is lost as direct surface runoff to the sea.

TABLE 4

HYDROLOGIC BUDGET, NORTHERN GUAM

2. Probable budget case.

Based on evaluation of rainfall and streamflow in southern Guam.

Conditions

1. Rainfall (Per USGS Guam Monthly Water Resources Memo. No. 8, Dec. 1972)

   a. Average rainfall at Ylig (1957 -1970) = 94.1 in/yr.

   b. Average rainfall at Umatac (1957 -1970) = 95.3 in/yr.

   c. Average of Ylig and Umatac = 94.7 in/yr = 4.51 mgd/mi^2.

   Assume this average occurs throughout southern Guam.

2. Streamflow of major streams (area greater than 2 mi^2). Flow includes both direct surface runoff and groundwater seepage. Total water yield of volcanics assumed to reach sea by way of streams,

	Streams (gaged portions)					
	Inarajan	Ugum	Umatac	Ylig	Pago	Total
Area (mi^2)	4.42	7.13	2.11	6.48	5.67	25.81
Av. Flow (mgd)	11.51	19.00	5.66	18.68	16.81	71.66
Av. Flow/mi^2	2.60	2.66	2.68	2.88	2.96	2.78

From above, the runoff:rainfall ratio is 2.78/4.51 = 0.616 and therefore the average annual runoff is 58.33 in.

TABLE 4

3. Evaporation (E) and evapotranspiration (ET). Potential evapotranspiration (PET) is assumed equal to E (see text). Given the average annual runoff as 58.33 in., the evapotranspiration in the south is therefore average rain less average runoff:

$$ET = 94.7 - 58.33 = 36.37 \text{ in/yr}$$

Assuming that evapotranspiration and rainfall are inversely proportional and by using the pan evaporation and rainfall data for the U. S. W. B. station at Taguac in northern Guam, the potential evapotranspiration for the south is ocmputed as 77.10 in/yr, yielding a potential evapotranspiration to actual evapotranspiration ratio of:

$$PET/ET = 77.10/36.37 = 2.12$$

This ratio can then be used ot compute ET for the rain gage stations in the north at Andersen Air Force Base, the Naval Air Station, and at Taguac for which evaporation computations have already been made. Thus,

$$ET(\text{Andersen Air Force}) = 81.23/2.12 - 38.3 \text{ in/yr}$$

$$ET(\text{Naval Air Station}) = 85.04/2/12 = 40.1 \text{ in/yr}$$

$$ET(\text{Taguac}) = 72.41/2.12 = 34.2 \text{ in/yr}$$

4, Infiltration: the difference between average rainfall and average evapotranspiration is equal to water yield. In the south water yield consists of direct surface runoff and groundwater seepage; in the north it consists of infiltration to the limestone aquifer.

TABLE 4

Direct surface runoff to the sea off the limestone of the north is negligible. Two values for infiltration, one assuming no direct runoff (I_1) and the other 5% direct runoff (I_2), enclose the range of probable infiltration and are computed as follows:

	Andersen Air Force	Naval Air Station	Taguac
Rainfall (in/yr)	89.86	85.86	100.84
Evapotranspiration (in/yr)	38.3	40.1	34.2
Infiltration, I_1 (mgd/mi^2)	2.46	2.18	3.17
Infiltration, I_2 (mgd/mi^2)	2.24	1.98	2.93

TABLE 4

HYDROLOGIC BUDGET, NORTHERN GUAM

2. Probable budget case, by sectors.

Based on evaluation of rainfall and streamflow in southern Guam

1 Sector	2 Ground Water Drainage	3 Area (mi^2)	4 I_1 (mgd)	5 I_2 (mgd)	6 Coast Length (ft)	7 q_1 (ft^3/d)	8 q_2 (ft^3/d)	9 $\overline{x}$(h=5) (ft)	10 k_1 (ft/d)	11 k_2 (ft/d)	12 Remarks
1	W	2.58	5.7	5.0		(n o n	b a s a l)				I_1 = 2.18mgd/mi^2
1	E	2.58	5.7	5.0		(n o n	b a s a l)				I_2 = 1.98mgd/mi^2
Total		5.16	11.4	10.0							Based on NAS
2	W	3.01	6.6	6.0							I per NAS
2	E	3.01	6.6	6.0							
3	W	6.96	15.2	13.8							I per NAS.
3	E	13.38	29.1	26.4							Exclude Ypao Peninsula.
Total or	W	9.97	21.8	19.8	20000	146	132	7500	2133	1937	
average	E	16.39	29.3	32.4	46000	104	94	9000	1823	1654	
(2+3)		26.36	57.5	52.2	66000	117	106	8000	1817	1652	
4	W	27.28	73.1	67.1	53000	185	169	11000	3961	3635	I_1 = 2.68mgd/mi^2
4	E	10.98	29.5	27.1	16000	245	227	8000	3822	3543	I_2 = 2.46mgd/mi^2
Total or average		38.26	102.6	94.2	69000	199	183	10000	3878	3560	Based on av. of NAS and USWB
Total or av. (2+3+4)		64.62	160.2	146.4	135000	159	145	9000	2792	2546	

TABLE 4

1	2	3	4	5	6	7	8	9	10	11	12
5		24.82	61.1	55.7	73000	112	102	12500	2732	2486	I_1 = 2.46mgd/mi^2 I_2 = 2.24mgd/mi^2 Based on Andersen AF
Total or av. (2+3+4+5)		89.44	221	202	208000	142	130	10000	2770	2537	

Column explanation

1. See map for sector location.
2. Apparent general direction of groundwater drainage.
3. Area of sector
4. I_1 = computed average daily infiltration assuming no surface runoff.
5. I_2 = computed average daily infiltration assuming that 5% of rainfall is lost as direct surface runoff to the sea.
6. Approximate length of groundwater discharge front along coast.
7. q_1 = computed average daily groundwater flow per foot of coastline assuming no surface runoff
8. q_2 = computed average daily groundwater flow per foot of coastline assuming that 5% of the rainfall is lost as direct surface runoff to the sea.
9. $\overline{x}$ = average distance from the coast to the 5 ft. head contour.
10. k_1 = computed regional hydraulic conductivity assuming no surface runoff.
11. k_2 = computed hydraulic conductivity assuming that 5% of the rainfall is lost as direct surface runoff to the sea.

TABLE 5

HYDROLOGIC BUDGET SUMMARY

Matrix of infiltration, I(mgd); groundwater discharge per foot of coastline, q(ft^3/d); and regional hydraulic conductivity, k(ft/d). Subscript 1 assumes no direct surface runoff; subscript 2 assumes 5% of rainfall lost as direct surface runoff. Values of k in matrix cells. Sector combinations in parentheses, e.g., q_1(2,3,4) means specific groundwater flow assuming no surface runoff for combined sectors 2,3,4.

	Minimum Budget				Probable Budget			
	q_1(2,3,4)	q_2(2,3,4)	q_1(2,3,4,5)	q_2(2,3,4,5)	q_1(2,3,4)	q_2(2,3,4)	q_1(2,3,4,5)	q_2(2,3,4,5)
	89.1	75.6	79.1	66.9	159	145	142	130
Minimum Budget								
I_1(2,3,4) 90.0	1565							
I_2(2,3,4) 76.3		1328						
I_1(2,3,4,5) 123			1543					
I_2(2,3,4,5) 104				1305				
Probable Budget								
I_1(2,3,4) 160					2792			
I_2(2,3,4) 146						2546		
I_1(2,3,4,5) 221							2770	
I_2(2,3,4,5) 202								2537

TABLE 6

FLOW CHARACTERISTICS OF STREAMS DRAINING VOLCANIC ROCK

FORMATIONS OF SOUTHERN GUAM. DATA FROM U. S. G. S. RECORDS

	16-8400 TINAGA Area=1.89 mi^2 El. 15ft Av. Flow 3.76 mgd Min. Flow 0.10 mgd		16-8350 INARAJAN Area=4.42mi^2 El. 15ft Av. Flow 11.51 mgd Min. Flow 0.64 mgd		16-8550 UGUM Area=7.13mi^2 El 3.23ft Av. Flow 19.00 mgd Min. Flow 0.71 mgd	
Year	Q_0(cfs)	Q_6(cfs)	Q_0(cfs)	Q_6(cfs)	Q_0(cfs)	Q_6(cfs)
1953	1.5	.20	5.5	1.9	14	4.5
1954	1.3	.22	5.5	1.3	14	3.5
1955	1.3	.19	4.7	1.2	17	2.7
1956	1.0	.16	3.4	.97	12	2.3
1957	1.4	.18	5.3	1.5	18	3.6
1958	1.2	.19	5.0	1.3	15	3.0
1959						
1960	1.7	.17	5.2	1.0	20	2.9
1961	3.0	.60	9.5	2.6	28	7.3
1962	2.4	.35	6.7	1.5	18	4.1
1963	3.2	.62	10.0	2.5	29	6.3
1964	3.0	.29	6.5	2.0	22	4.0
1965	1.8	.43	5.0	1.5	17	4.1
Av.(cfs)	1.9	.30	6.0	1.6	19	4.0
Av.(mgd)	1.2	.19	3.9	1.0	12	2.6

NOTE: Q_0 = initial flow from storage, December 1.
Q_6 = minimum flow from storage, June 1.

TABLE 6

FLOW CHARACTERISTICS OF STREAMS DRAINING VOLCANIC ROCK

FORMATIONS OF SOUTHERN GUAM. DATA FROM U. S. G. S. RECORDS

	16-8160 UMATAC Area=2.11 mi^2 El. 8ft Av. Flow 5.66 mgd Min. Flow 0.13 mgd		16-8580 YLIG Area=6.48mi^2 El. 20ft Av. Flow 18.68 mgd Min. Flow .10 mgd		16-8650 PAGO Area=5.67mi^2 El 25ft Av. Flow 16.81 mgd Min. Flow 0	
Year	Q_0(cfs)	Q_6(cfs)	Q_0(cfs)	Q_6(cfs)	Q_0(cfs)	Q_6(cfs)
1953	2.5	.53	9.8	.47	6.2	.28
1954	3.0	.38	7.9	.27	8.5	.21
1955	2.5	.40	7.2	.40	4.5	.28
1956	1.7	.25	5.8	.24	3.7	.18
1957	2.8	.64	7.6	.36	4.2	.12
1958	2.4	.49	6.2	.34	3.4	.16
1959						
1960	2.5	.50	12	.30	7.3	.14
1961	4.5	1.2	11	1.5	8.0	.40
1962	2.8	.65	9.5	.46	6.8	.17
1963	3.5	1.2	9.5	2.4	7.5	1.3
1964	3.0	.60	10	.70	7.0	.50
1965	2.5	.50	11	.55	5.5	.18
Av.(cfs)	2.8	.61	9.0	.66	5.8	.33
Av.(mgd)	1.8	.39	5.8	.43	3.8	.21

NOTE: Q_0 = initial flow from storage, December 1.
Q_6 = minimum flow from storage, June 1.

TABLE 7

SUMMARY OF FLOW CHARACTERISTICS OF STREAMS DRAINING

VOLCANIC ROCK FORMATIONS OF SOUTHERN GUAM

(Flow rates in mgd; volume in mg)

1	2	3	4	5	6	7	8	9	10	11	12	13
Stream	A (mi^2)	$\overline{Q}$	$\overline{Q}/A$	$\overline{R}/A$	$\overline{Q}/\overline{R}$	$\overline{Q}_0$	$\overline{Q}_6$	a	V_t	V_t/A	V_o	V_o/A
Bolanos member, Umatac fm.												
Tinaga	1.89	3.76	1.99	4.48	.444	1.2	.19	.0103	101	53.4	119	63.2
Inarajan	4.42	11.51	2.60	4.48	.581	3.9	1.0	.0073	390	88.3	532	120
Ugum	7.13	19.00	2.66	4.48	.595	12	2.6	.0085	1109	156	1414	198
Total or av.	13.44	34.27	2.55	4.48	.569	17	3.8	.0084	1588	118	2039	152
Facpi member, Umatac fm.												
Umatac	2.11	5.66	2.68	4.54	.590	1.8	.39	.0085	167	79.2	213	101
Alutom fm.												
Ylig	6.48	18.68	2.88	4.48	.643	5.8	.43	.0145	372	57.4	401	61.9
Pago	5.67	16.81	2.96	4.48	.662	3.8	.21	.0159	344	60.7	365	64.3

Column explanation:

1. Name of stream, U. S. G. S.
2. A = area of drainage, mi^2.
3. $\overline{Q}$ = average flow, mgd.

TABLE 8

GEOCHEMISTRY

MEDIAN[1] VALUES IN mg/l

(n) = number of samples

Source	Cl	Ca	Mg	Total Hardness	NO_3	SiO_2
A-1	18(20)	117(46)	3.9(26)	309(26)	7.8(9)	12(18)
A-2	16(13)	112(30)	2.9(17)	280(17)	9.2(9)	4.8(17)
A-3	16(17)	110(35)	4.2(18)	293(18)	6.8(9)	15(13)
A-4	17(12)	113(23)	2.2(11)	292(11)	8.9(9)	3.5(10)
A-5	16(6)	106(6)		284(15)	12(10)	9.7(3)
A-6	16(9)	107(9)		281(11)	12(9)	8.4(1)
A-7	17(6)	119(6)		308(17)	13(9)	6.0(4)
A-8	15(7)	119(7)		320(15)	8.5(9)	6.5(5)
A-11	15(6)	109(6)		288(11)	4.0(6)	17(1)
A-12	15(8)	121(8)		318(13)	3.5(9)	15(1)
Av. Med.	16(104)	113(176)	3.5(72)	293(154)	8.9(115)	8.4 (73)
D-1	60(18)	85(37)	10(26)	154(26)	11(9)	1.4(16)
D-2	50(12)	80(39)	10(27)	247(27)	11(9)	1.0(15)
D-3	35(13)	78(38)	7.5(25)	226(25)	10(9)	0.9(16)
D-4	35(12)	82(22)	7.3(20)	237(20)	11(8)	0.9(16)
D-5	60(9)	78(31)	4.8(22)	215(22)	11(9)	0.5(11)
D-6	45(13)	76(39)	7.3(26)	220(26)	7.9(9)	0.9(17)
D-7	50(9)	75(14)	5 4(5)	210(5)	8.0(9)	1.4(8)
D-8					9.5(9)	0.6(8)
D-9					8.0(9)	1.2(6)
D-10					9.4(9)	1.5(6)
D-11					8.0(9)	1.2(1)
Av. Med.	50(86)	78(220)	7.5(151)	226(151)	9.5(98)	0.9(120)
Y-1	17(10)	85(30)	7 2(20)	243(20)	9.1(9)	1.5(16)
Y-2	18(6)	86(10)	6.3(4)	241(4)	9.6(9)	1.5(8)
Av. Med.	17(16)	85(40)	7.1(24)	242(24)	9.3(18)	1.5(24)

TABLE 8

GEOCHEMISTRY

MEDIAN[1] VALUES, mg/l

(n) = number of samples

Source	Cl	Ca	Mg	Total Hardness	NO_3	SiO_2
M-1	160(7)	85(7)		255(10)	8.0(9)	2.2(1)
M-2	65(6)	70(6)		240(9)	8.4(9)	2.0(1)
M-3	21(6)	67(6)		226(10)	7.9(10)	2.0(2)
M-4	20(5)	70(5)		218(10)	8.5(10)	1.2(3)
M-8	20(6)	66(6)		209(2)	8.8(10)	1.2(1)
M-9	21(8)	71(8)		211(4)	9.3(10)	1.1(1)
Av. Med.	21(38)	70(38)		231(45)	8.5(58)	1.7(9)
M-5	32(5)	82(5)		232(5)	9.7(11)	1.2(1)
M-6	68(5)	82(5)		229(3)	10.8(10)	1.2(1)
M-7	30(6)	82(6)		233(7)	8.7(10)	1.1(1)
Av. Med.	32(16)	82(16)		232(15)	9.8(30)	1.2(3)
F-1	60(6)	76(6)		237(20)	7.4(9)	0.6(3)
AG-1	24(16)	87(42)	3.4(26)	232(26)	9.3(9)	1.0(15)
T-1	30(6)	110(26)	6.0(20)	300(20)	3.0(4)	14(10)
Ml-1	30(9)	98(36)	7.9(27)	279(27)	4.0(3)	17(14)
Asan Spr.	14(4)	80(4)		212(4)	7.0(4)	8.8(1)
Almagosa Spr.	11(4)	50(3)	5.0(2)	146(2)	1.0(3)	4.0(2)
Mataguac Spr.	19(1)	36(1)	5.0(1)	112(1)		71(1)
Janum Spr.	21(5)	60(4)	19(4)	229(4)	2.0(3)	6.2(4)

TABLE 8

GEOCHEMISTRY

MEDIAN(1) VALUES, mg/l

(n) = number of samples

Source	Cl	Ca	Mg	Total Hardness	NO_3	SiO_2
Streams						
(low flow)						
Umatac Fm.						
Ugum	13(4)	7.0(2)	7.0(2)	47(2)	0.4(2)	27(3)
Pauliluc	23(2)	18(1)	2.4(1)	56(1)	0.04(1)	47(2)
Inarajan	14(3)	17(1)	5.4(1)	65(1)	0.1(2)	22(2)
Fena Dam	11(4)	24(4)	5.5(1)	83(1)	0.6(1)	12(2)
Umatac	14(3)	48(2)	12(2)	170(2)	0.4(3)	29(2)
Alutom Fm.						
Pago	12(3)	38(2)	7.8(1)	128(1)	0.7(2)	32(2)
Ylig	16(3)	26(1)	6.8(1)	94(1)	0.2(1)	23(2)
Well						
Alutom Fm.						
Refinery	20(1)	50(1)	11(1)	171(1)		92(1)

Footnotes: (1) Average value for n = 2.

TABLE 9

GEOCHEMISTRY

TYPICAL ANALYSIS

MEDIAN VALUES, mg/l

Source	Number Anal.	PH	Ca	Mg	Na	K	Fe	Al	Cl	SO_4	NO_3	HCO_3	F	PO_4	SiO_2	Total Dissolved Solids	Con. Micro-MHOS
Wells[1]																	
A-1	3	7.0	120	2.9			.01		18	1.9		373	0		11.5	355	560
A-2	6	7.0	114	2.2			.01		15	2.1		329	0		4.5	323	535
A-3	5	7.0	103	4.1			.01		16	2.4		346	0		14.2	360	560
A-4	5	7.0	115	2.2			.02		17	2.2		327	0		2.9	335	535
A-5	1	7.0	106	4.9			.02		16	2.6	8.6	344	0		7.9	334	525
A-7	1	7.0	117	2.4			.01		16	0.3	4.2	360	0		4.6	342	535
A-8	1	6.9	132	2.4			.01		18	1.2	6.0	400	0		5.3	379	615
A-9	5	7.0	128	10.7			.01		138	14.2		346	0		5.2	606	930
D-1	6	7.3	86	8.8			.01		55	6.5	9.1	268	0		1.2	370	580
D-2	6	7.3	84	9.5			.01		55	5.4	9.0	268	0		0.9	353	575
D-3	6	7.3	78	6.3			.01		37	4.8	7.8	258	0		0.8	302	500
D-4	6	7.3	82	9.7			.01		42	5.2	7.9	271	0		0.9	330	515
D-5	5	7.3	80	6.8			.02		61	4.5	7.1	237	0		0.5	339	555
D-6	6	7.3	76	7.3			.02		47	6.0	5.1	224	0		0.6	300	490
D-7	5	7.4	76	5.4			.02		56	6.5	6.5	226	0		0.8	305	520
D-8	5	7.3	80	7.0			.04		132	8.5	3.2	217	0		0.6	450	740
D-9	3	7.4	81	11.7			.04		106	15	6.2	254	0		1.1	430	705
D-10	3	7.4	77	5.6			.03		42	3.9	4.0	239	0		1.4	280	485

TABLE 9

Source	Number Anal.	PH	Ca	Mg	Na	K	Fe	Al	Cl	SO_4	NO_3	HCO_3	F	PO_4	SiO_2	Total Dissolved Solids	Con. Micro-MHOS
Y-1	4	7.3	86	6.1			.01		18	3.0	6.4	266	0		1.4	271	450
Y-2	4	7.4	87	5.3			.01		18	3.2		278	0		1.2	275	455
H-1	6	7.3	90	10.2			.01		97	23	9	257	0		0.7	450	705
AG-1	5	7.3	87	3.2			.01		23	3.4	5.2	250	0		1.0	282	455
T-1	4	7.1	105	9.0			.08		27	4.6	3	339	0		14	358	580
ML-1	6	7.1	92	9.0			.04		31	4.4	0.3	300	0		15	345	560
GOR	1	7.4	50	11.2					20	1.5		234			92	330	430
Wells(2,3)																	
24(2)	1	7.3	90	6.4	45	2.8	.12	.1	76	13.4		281		0	6.8	476	
31(2)	1	7.9	76	12			.40	.1	26	3.8		298		.1	1.5	318	
33(2)	1	7.5	77	4.9	19	.6	.03		35	6.1		232		.1	0.6	267	
75(2)	1	7.6	83	16			.00	.04	143	19		298		.3	1.7	490	
79(2)	1	7.6	135	40	257	11	.01	.04	455	62		449			3.0	1343	
80(3)	1	8.0	89	7.3	3.3	1.5	.00		56	4.0	2.3	301	.2	.03	1.6	348	630
80(2)	1	7.7	80	27			.02	.05	118	7.2		373		.1	1.4	414	
83(3)	1	8.1	87	2.8	14	1.0	.07		20	5.0	8.7	268	.0	.0	2.0	277	489
83(2)	1	7.8	70	10			.01	.07	25	3.7		271		.2	1.5	204	
84(3)	1	7.7	86	9.6	26	1.9		.00	44	8.0	13	285	.0	.02	1.6	338	600
84(2)	1	8.0	77	13			.3	.1	43	6.1		298		.2	1.2	200	
90(2)	1	7.4	86	34	238	9.2	.04		431	60		240		.1	1.4	1040	
110(3)	1	7.8	89	6.5	38	2.5	.00		64	11	11	277	.1	.04	1.3	366	656
110(2)	1	7.7	74	14			.02	.1	90	8.6		278		.6	1.2	364	

TABLE 9

Source	Number Anal.	PH	Ca	Mg	Na	K	Fe	Al	Cl	SO_4	NO_3	HCO_3	F	PO_4	SiO_2	Total Dissolved Solids	Con. Micro-MHOS
113[2]	1	7.7	82	11			.03	.1	192	25		303		.1	1.6	602	
126[2]	1	7.8	80	36			.01	.1	360	52		300		.2	1.5	998	
157	1	7.9	73	12	24	1.6	.00		38	7	9.5	262	.1	.02	1.6	296	542
D-4	1	7.6	80	9.9	21	1.5	.00		34	6	9.9	275	.1	.02	1.9	308	549
112	1	7.9	97	13	49	2.8	.00		84	16	8	328	.1	.03	1.3	424	787
Springs[2,3]																	
Tarague[2]	1	7.5	92	48	380	13	.08		680	98		238		.1	1.5	1470	
Tarague[3]	1	8.2	74	14	92	3.7	.00		155	25	6.8	234	.1	.02	1.6	542	932
Janum[2]	1	7.3	63	17	12	.4	.05		20	4.8		272			6.2	244	
Janum(3)	1	8.0	42	8.7	7.5	1.3	.83		9.9	3.0	3.5	171	.1	.01	13.0	179	299
Agana[2]	1	7.4	101	6.6	26	2.4	.02		36	11		388			8.2	389	
Mataguac[2]	1	7.5	36	5			.05		19	3.4		171		.6	71	226	
Almagosa[2]	1	7.7	49	2.7	7.8	.8	.19		12	2.0		158			7.1	168	

Footnotes

(1) Anal. by Singer-Layne, 1967 - 1969.

(2) Anal. from Ward and Brookhart, 1962. Period of Anal., 1951 - 1957.

(3) Anal. from Feltz, Huxel, and Jordan, 1970. Anal. in 1969.

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
				Original	1972	1973			
				Pumping	Pumping	Pumping			
	Approx.	Bottom	h_o(ft)	Water Level	Water Level	Water Level	$(Cl)_0$	$(Cl)_{74}$	
Well	el. (ft)	el. (ft)	(yr)	(Q gpm)	(Q gpm)	(Q gpm)	mg/l	mg/l	Remarks
A-1	68	-152	19(65)	102(200)			20	18	volc. -252
A-2	118	- 54	12(65)	129(200)	136(179)	145	16	16	
A-3	127	-262	22(66)	204(273)	150(194)	172	16	16	volc. -256
A-4	140	-160	6.2(66)	145(300)	145(171)	148(171)	17	17	
A-5	146	-177	9.1(66)	142(214)	142(171)	144	16	16	volc. -186(?)
A-6	152	-154	10(67)	143(300)	148(211)	150	16	16	
A-7	136	- 50	10(67)	146(200)	150	155	16	18	
A-8	124	-177	15(67)	143(207)	157(200)	171	16	18	
A-9	187	- 50	6.6(67)	182(226)	187		95	152	
A-10	191	- 25	6.5(67)	185(218)			80	225	
A-11	178	-167	47(68)	320(179)	195(146)	280(133)	15	17	volc. -174
A-12	138	-190	31(68)	142(214)	155(145)	231(133)	15	15	
A-13	131	-199	7.0(68)	141(200)	148(197)	149	60	276	
A-14	200	- 60					110	218	Poor record
A-15	198	- 52	(73)	206(225)			105	141	Poor record
A-16	195	- 40	(73)	210(200)				527	Poor record

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_o(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/1	$(Cl)_{74}$ mg/1	Remarks
A-17	200	- 50	(73)	219(171)				151	Poor record
A-18	190	- 45		204					Poor record
A-19	163						32	131	Poor record
A-20	142	0	42(74)					21	volc. -47
A-21	180	- 53	(74)	194(200)			30		
A-22	240	- 40	(74)	240(200)			90		
D-1	381	- 36	3.4(64)	381(200)	381(155)		35	53	
D-2	381	- 36	5(65)	391(200)				54	
D-3	383	- 25		399(200)			35	35	
D-4	383	- 25	6.9(65)	385(200)	385(182)	385	35	37	
D-5	381	- 29	(65)	413(200)			28	60	
D-6	396	- 37	6(66)	400(200)	400(200)		48	46	
D-7	387	- 50	5(66)	395(200)	388(177)		61	50	
D-8	415	- 35	4.5(68)	433!200)	424(188)		15	204	
D-9	388	- 29	5(67)	389(200)	387(146)		122	124	
D-10	389	- 25	4.7(68)	389(200)	390(194)		35	37	

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_o(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/l	$(Cl)_{74}$ mg/l	Remarks
D-11	393	- 37	6(69)	398(200)	396(200)			81	
D-12	422	- 42	4.8(72)	432(200)			18	21	Poor record
D-13	404	- 53	5(70)	415(133)			13	415	Poor record
D-14	312	- 63	(73)	325(200)				33	Poor record
D-15	363		(74)						
Y-1	414	- 36		421(200)	413(182)		18	18	
Y-2	417	- 46					18	18	
YT-3	420	- 55	(73)				16	16	volc. +100
Y-3	420	- 51	(73)	421(200)				16	Poor record
J-1	583	- 12	(68)						volc. +293
H-1	290					294(221)		72	
M-1	394	- 56	4.7(65)	401(145)	401(106)		28	160	
M-2	401	- 50	5(68)	404(207)			20	89	
M-3	423	- 52	4.2(67)	423(200)	423(157)		20	33	
M-4	421	- 51	(67)	421(200)	423(183)		20	39	

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_o(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/l	$(Cl)_{74}$ mg/l	Remarks
M-5	273	- 52	4.3(69)	293(200)	295		35	41	volc. -220
M-6	326	- 80	5.3(69)	355(200)	361		20	70	
M-7	289	- 51	5.3(69)	295(200)	292(1SO)		30	32	
M-8	443	- 52	(69)				20	23	
MT-9	410	- 77	18(69)				20		volc. -28
M-9	440	- 40					20	174	Poor record
M-10	210	- 78	4.6(74)	211(200)			40		abandon oil
M-11	290	- 60	(74)				23	660	abandon
M-12	271		(74)				34		Poor record
M-13									Poor record
M-14	274	- 46	4.5(74)	281(200)			16		Poor record
Island Const.									No data
Foremost	142	- 22	4(65)				173		
112	205	- 8	4.5(68)				71		Now E.E. Black

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_o(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/l	$(Cl)_{74}$ mg/l	Remarks
San Migual	214	- 26	4.3(71)				74		
H. Rock #1									No data
H. Rock #2									No data
AG-1	468	- 27	5.6(69)				30	37	Old #83
AG-2	503	- 77	5.7(68)	503(200)			15		volc. -136
F-1	423	- 37	(69)		434(128)		56	76	
F-2	451	- 40	4(72)	463(200)			72		
F-3	455	- 55	(72)	457(200)			42		
USN Wells									
90					(220)				NCS 1B
81					(170)				NCS 2
91					429(210)				NCS 1A
133									NCS 3
Air Force Wells									
1	348	- 41		(275)					Old #84
2	351	- 28		(325)					Old #65
3	405	- 23		(310)					Old #31

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_o(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/l	$(Cl)_{74}$ mg/l	Remarks
4									Old #66. Not used.
5	417	- 58	4(72)	417(280)			36		
6	395	-102	3.6	(360)			89	60	
7	368	- 35	3.6	(360)			75		
8	358	- 32	3.3	(360)			78		
9	358	- 31	5.4	(370)					
Tumon									Old #80. Shaft
NW#4		- 31							Old #110. Not used.
Golf Course									Old #128
Southern Guam									
M1-1	257		(65)				35	25	Ls. lens in volc.
M1-2	257		(65)				35		Ls. lens in volc.
M1-3	315								Ls. lens in volc.
T-1	114	- 33	18(65)	124(120)			30	30	volc. -36
Y1-1	21	- 84	8.5	33(55)					volc. -71
Y1-2	32	-118	6.0	49(55)					volc. -118
Y1-3	24	-116	6.0	34(55)					volc. -117

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

(See column numbers at end of table for column explanations.)

1	2	3	4	5	6	7	8	9	10
				Original	1972	1973			
				Pumping	Pumping	Pumping			
	Approx.	Bottom	h_o(ft)	Water Level	Water Level	Water Level	$(Cl)_0$	$(Cl)_{74}$	
Well	el. (ft)	el. (ft)	(yr)	(Q gpm)	(Q gpm)	(Q gpm)	mg/l	mg/l	Remarks
Togcha									
Tg-1	79	- 32	1.5				31	53	
Tg-2	105	- 25	2.6				31	52	
Tg-3							29	34	
Tg-4							79	51	
Tg-5							77	66	
Tg-6							75	85	
Tg-7							76	92	
Tg-8							75	82	
Tg-9							75	123	
Tg-10							306		
Volcanic Wells									
RCA	362	+ 2	342	200(20)			20		Alutom fm.
(Pulantat)									
Guam Oil	134	- 66	135				20		Alutom fm.

TABLE 10

Column explanations:

1. Name of well as used by PUAG.
2. Elevations are not exact because of uncertainty of whether surveys were taken. Some elevations estimated from 1:24000 map.
3. Bottom elevations are also approximate.
4. Original head as reported by drillers, in records, or by previous investigators. For most cases accurate to no more than one foot.
5. Water levels recorded during pumping tests upon completion of well
6. Water levels recorded by C. Huxel, USGS.
7. Water levels recorded by C. Huxel, USGS.
8. Chloride content of water reported upon completion of well.
9. Chloride content or water as of May 1974.
10. For the last several years driller has been very careless in collecting and tabulating data.

TABLE 11

DRILLER LOGS

NORTH GUAM WELLS

Code to driller logs:

v	= very	w	= white
h	= hard, compact	b	= brown
m	= medium	y	= yellow
s	= soft	r	= red
cr	= coral	p	= pink
cl	= clay	gy	= gray
ls	= limestone	gn	= green
volc	= volcanic	bl	= blue
?	= possible	bk	= black

Logs

Well A-1 Approx. el. 67 ft.

Drilled Feb. 1965

Depth (ft)	Drillers log
0 - 55	h br ls
55 - 100	h br ls, cl
100 - 215	h br ls cl, h ledge
215 - 220	h ls

Well A-2 Approx. el. 118 ft.

Drilled Feb. 1965

Depth (ft)	Drillers log
0 - 4	s r cl
4 - 28	m s r w
28 - 75	m h w cr
75 - 84	s r cl
84 - 86	s r w cr, cl
86 - 90	s r cl
90 - 92	m s r w cr, cl
92 - 118	m h w cr
118 - 151	h w cr
151 - 152	m h w b
152 - 161	h w
161 - 170	m s w

Logs

Well A-3 Approx. el. 128 ft.

Drilled April 1966

Depth (ft)	Drillers log
0 - 18	s b
18 - 31	h w cr
31 - 39	s b cl
39 - 47	h w cr
47 - 51	s b cl
51 - 77	m h w cr
77 - 109	w b cr, cl
109 - 112	s b cl
112 - 125	m h w
125 - 200	cr, cl
200 - 245	m h, h w cr
245 - 250	m s w
250 - 320	h w
320 - 325	v h w
325 - 337	v h, h p w cr
337 - 338	m s gy cl
338 - 345	v h w cr
345 - 348	m s gy cl
346 - 383	v h, h w cr
383 - 410	m h gn w volc

Logs

Well A-4 Approx. el. 140 ft.

Drilled July 1966

Depth (ft)	Drillers log
0 - 50	m h w cr
50 - 52	m s w cr
52 - 155	m h, h cr
155 - 200	m h, m s
200 - 255	m h, h
255 - 270	h w cr
270 - 275	m s w cr
275 - 390	h w cr
390 - 395	m h cr
395 - 428	h cr
428 - 429	m s cl (?)
429 - 430	h

Backfill to 300 ft.

Well A-5 Approx. el. 147 ft.

Drilled Aug. 1966

Depth (ft)	Drillers log
0 - 5	s cl
5 - 85	m h, h w cr
85 - 130	m h, m s w cr
130 - 134	br m s cl
134 - 138	s w cr

Well A-5, (cont.)

Depth (ft)	Drillers log
138 - 170	m h, s
170 - 178	m s, s cl (?)
178 - 243	m h, h
243 - 244	m s, s
244 - 247	v h
247 - 251	m s
251 - 308	h, v h
308 - 311	m s, s
311 - 332	m h, h
332 - 340	void

Well A-6 Approx. el. 152 ft.

Drilled Aug. 1967

Depth (ft)	Drillers log
0 - 4	s r cl
4 - 163	m h w cr
163 - 167	open
167 - 279	s, m s, m h
279 - 301	h, v h

Logs

Well A-7 Approx. el. 136 ft.

Drilled April 1967

Depth (ft)	Drillers log
0 - 12	r, w m s
12 - 26	bk, gn m s cl
26 - 97	w m s, m h cr
97 - 100	gy s cl
100 - 110	w m s cr
110 - 115	gy, br s cl
115 - 190	w m s, m h cr

Well A-8 Approx. el. 124 ft.

Drilled June 1967

Depth (ft)	Drillers log
0 - 10	w s
10 - 121	w m h, m s cr
121 - 155	w m h, h cr
155 - 163	w v h cr
163 - 165	w m h cr
165 - 172	w v h cr
172 - 174	w m h cr
174 - 175	w v h cr
175 - 201	m h, h
201 - 203	m s
203 - 210	v h

Well A-8 (cont.)

Depth (ft)	Drillers log
210 - 212	m h
212 - 220	v h
220 - 225	m h
225 - 238	v h
238 - 245	m h, h
245 - 290	s, m h, h
290 - 305	s, m s

Well A-9 Approx. el. 187 ft.

Drilled March 1967

Depth (ft)	Drillers log
0 - 25	r m s cl
25 - 38	w m h cr
38 - 49	w m s cl
49 - 83	w m s, m h cr, cl
83 - 109	w cr, cl
109 - 125	m h, m s
125 - 155	m h
155 - 165	v h
165 - 183	m h, m s
183 - 209	h
209 - 211	m s
211 - 215	h
215 - 217	m s
217 - 240	m h, h

Logs

Well A-10 Approx. el. 191 ft.

Drilled May 1967

Depth (ft)	Drillers log
0 - 25	r w m s, s cr, cl
25 - 100	w m s, m h cr
100 - 170	w h cr
170 - 215	w m s, m h cr

Well A-11 Approx. el. 178 ft.

Drilled June 1968

Depth (ft)	Drillers log
0 - 12	y cr, cl
12 - 17	y m s cl
17 - 28	b, w m h cr
18 - 33	b m s cl
33 - 45	w m h cr
45 - 47	bk s, wood
47 - 60	m s cl
60 - 82	y m s cl
82 - 84	y, w m h cr
84 - 121	y, b m s cl, cr
121 - 124	w m h cr
124 - 138	bl m s cl
138 - 141	w m h cr
141 - 159	b m s cl
159 - 175	w m h cr, cl

Well A-11 (cont.)

Depth (ft)	Drillers log
175 - 273	w m h, h cr
273 - 276	w s cl
276 - 320	w m h, h cr
320 - 321	bk s cl, wood
321 - 323	w m h cr
323 - 324	bk s cl, wood
324 - 339	w m s, m h, h cr
339 - 343	b s cl
343 - 352	w m s cr
352 - 375	bl m s cl (volc)

Well A-12 Approx. el. 138 ft.

Drilled July 1968

Depth (ft)	Drillers log
0 - 5	y m h cr, cl
5 - 35	w m h, h cr
35 - 38	b s cl
38 - 51	w m h, h
51 - 58	w, b m h cr, cl
58 - 60	b s cl
60 - 65	w m h cr
65 - 203	m s, m h, h
203 - 204	open
203 - 216	h

Well A-12 (cont.)

Depth (ft)	Drillers log
216 - 249	m s, m h
249 - 251	s cl
251 - 263	m h, s cl
263 - 275	h
275 - 285	s cl (?)
285 - 305	m h, h
305 - 310	m s cl (?)
310 - 333	m h, h
333 - 335	m s cl (?)
335 - 338	h
338 - 343	m s cl (?)
343 - 349	m h
349 - 354	m s cl (?)
354 - 365	h
365 - 376	m s cl, cr
376 - 390	m s cl

Well A-13 Approx. el. 131 ft.

Drilled Nov. 1968

Depth (ft)	Drillers log
0 - 35	b m s cl
35 - 46	gy m s cl
46 - 165	b h cl, cr
165 - 185	m
185 - 194	y s cl

Well A-13 (cont.)

Depth (ft)	Drillers log
194 - 208	b w m h, h cr
208 - 227	v s, m s cr
227 - 240	h, v h cr
240 - 249	s cr
249 - 256	h, v h cr
256 - 262	m s
262 - 276	h, v h cr
276 - 280	s cr
280 - 283	s cr
283 - 286	h, m h cr
286 - 296	v h cr
296 - 321	s, m s cr
321 - 324	m h cr
324 - 325	s cr
325 - 329	h, v h cr
329 - 331	s cr
331 - 339	m h, v h cr
339 - 362	m h, m s cr
362 - 364	v h gy cr
364 - 365	m s gy cr
365 - 372	v h gy cr
372 - 418	h, m h, m s gy cr

Logs

Well D-5 Approx. el. 381 ft.

Drilled Nov. 1965

Depth (ft)	Drillers log
0 - 175	w m h, m s
175 - 203	w h
203 - 397	w m h, m s
397 - 410	w m s, s

Well D-9 Approx. el. 388 ft.

Drilled Dec. 1967

Depth (ft)	Drillers log
0 - 167	s, m s, m h cr
167 - 222	h, m h
222 - 235	m s
235 - 278	h, m h
278 - 330	m s, m h
330 - 378	m h, h
378 - 381	v h
381 - 383	m s
383 - 397	h
397 - 420	m h, m s
420 - 435	m h
435 - 440	v h

Logs

Well D-10 Approx. el. 389 ft.

Drilled Feb. 1968

Depth (ft)	Drillers log
0 - 81	w m h, h
81 - 84	w s
84 - 140	w m h, m s
140 - 143	w h
143 - 277	m h, m s
277 - 281	h
281 - 282	s
282 - 376	m h, h
376 - 383	m s
383 - 385	h
385 - 391	s
391 - 410	m s, m h
410 - 415	h

Well D-11 Approx. el. 393 ft.

Drilled March 1969

Depth (ft)	Drillers log
1 - 20	b w m s
20 - 80	w m h cr
80 - 96	w h, v h cr
96 - 108	w m h cr
108 - 115	w v h cr
115 - 120	w m h cr

Well D-11 (cont.)

Depth (ft)	Drillers log
120 - 139	w v h cr
139 - 145	w m h cr
145 - 162	w v h cr
162 - 184	w m h, m s cr
184 - 215	w v h cr
215 - 219	w m h cr
219 - 235	w v h cr
235 - 240	w m h cr
240 - 260	w v h cr
260 - 266	w m h cr
266 - 283	w v h cr
283 - 361	w m h, m s cr
361 - 384	w s cr
384 - 392	w v h cr
392 - 410	w m h cr
410 - 413	w s cr

Well D-13 Approx. el. 404 ft.

Drilled Nov. 1970

Depth (ft)	Drillers log
0 - 110	w m h, h cr
110 - 357	w v h cr
357 - 395	m h
395 - 415	s
415 - 450	m h

Logs

Well M-1 Approx. el. 394 ft.

Drilled March 1965

Depth (ft)	Drillers log
0 - 97	w m s ls
97 - 107	w h ls (lost circ.)
107 - 148	v h (no returns)
148 - 175	m h, h (no returns)
175 - 183	v h (no returns)
189 - 190	m h (no returns)
190 - 227	v h (no returns)
227 - 240	w v h (some returns)
240 - 281	w m h, h (some returns)
281 - 283	w s
283 - 290	w h
290 - 311	h (lost circ.)
311 - 397	m s, h, v h (no returns)
397 - 401	v s (no returns)
401 - 425	m h, h (no returns)
425 - 430	v h (no returns)
430 - 435	bk m s cl
435 - 450	w m h cr

Logs

Well M-2 Approx. el. 401 ft.

Drilled March 1968

Depth (ft)	Drillers log
0 - 123	w m h, m s
123 - 155	w h
155 - 156	open
156 - 159	h
159 - 160	opem
160 - 261	h, m h
261 - 268	m s, m h
268 - 271	h
271 - 273	open
276 - 281	m s
281 - 319	h, m h
319 - 324	s
324 - 333	h
333 - 430	m h, m s
430 - 433	h
433 - 452	m s, s
452 - 455	h
455 - 460	gy m s (volc?)

Logs

Well M-3 Approx. el. 423 ft.

Drilled Nov. 1967

Depth (ft)	Drillers log
0 - 80	w m s, m h cr
80 - 85	s
85 - 237	m h, h
237 - 252	m s, m h
252 - 256	s
256 - 289	h, m h
289 - 293	open (lost all mud)
293 - 327	m h, h
327 - 329	open
329 - 383	h, m h
383 - 387	open
387 - 392	m s
392 - 418	h, v h, m h
418 - 449	m s, m h
449 - 451	open
451 - 453	h
453 - 459	m s
459 - 475	s, m s

Logs

Well M-4 Approx. el. 421 ft.

Drilled Oct. 1967

Depth (ft)	Drillers log
0 - 125	w m h, m s cr
125 - 175	w m h, h cr
175 - 200	h, v h
200 - 253	h, m h
253 - 268	h, v h
268 - 320	h, m h
320 - 420	m s, m h (caving)

Well M-5 Approx. el. 273 ft.

Drilled Dec. 1968

Depth (ft)	Drillers log
1 - 45	w v h cr
45 - 65	w m h cr
65 - 168	w h, v h cr
168 - 315	w v h, h, m h cr
315 - 320	w m s, m h cr
320 - 323	w s cr
323 - 324	open (lost circ.)
324 - 328	w m h cr
328 - 334	w s cr
334 - 345	w m s, m h cr
345 - 355	w h cr
355 - 490	w m s cr
490 - 500	bl gy volc

(backfill to 330)

Logs

Well M-6 Approx. el. 326 ft.

Drilled May 1969

Depth (ft)	Drillers log
1 - 4	b s cr
4 - 55	m s, m h, h cr
55 - 84	h, v h cr
84 - 88	s cr
88 - 93	h cr
93 - 108	s cr
108 - 180	v h, h cr
180 - 192	m s cr
192 - 360	m h, h, v h cr
380 - 384	m s cr
384 - 405	h, v h cr

Well M-7 Approx. el. 289 ft.

Drilled June 1969

Depth (ft)	Drillers log
1 - 13	w h cr
13 - 20	w m s cr
20 - 84	w h, v h cr
84 - 86	open
86 - 286	w h, m h, v h cr
286 - 314	w m h, open
314 - 315	w s cr
315 - 338	w h cr

Logs

Well M-8 Approx. el. 443 ft.

Drilled 1969

Depth (ft)	Drillers log
0 - 10	r w m h cl
10 - 52	m h cr
52 - 68	m h cr, cl
68 - 155	m h, m s cr
155 - 320	m h, h, v h cr
320 - 344	m s cr
344 - 355	h cr
355 - 361	m s cr
361 - 363	v h cr
363 - 419	m h, m s cr
419 - 457	h, v h cr

Test Well MX-9 (original M-9) Approx. el. 410 ft.

Drilled Aug. 1969

Depth (ft)	Drillers log
30 - 263	w m h, h cr
263 - 275	w s cr
275 - 309	w v h cr
309 - 389	w m h, h, v h cr
389 - 398	w s cr
398 - 416	w m h cr
416	volc

Logs

Well J-1 Approx. el. 583 ft.

Drilled Sept. 1968

Depth (ft)	Drillers log
0 - 15	cr, cl
15 - 167	w m h, h cr
167 - 200	w h, v h cr
200 - 208	s
208 - 215	v h
215 - 270	m s, m h h
275 - 290	v h
290 - 300	bl gy m h (volc?)
300 - 310	h cl
310 - 325	m h cr
325 - 345	h cl
345 - 385	bl gy h cl
385 - 415	gy v h cl
415 - 445	h cl
445 - 450	h rock
450 - 528	gy v h
528 - 545	m h
545 - 595	gy h, v h

Logs

Well AG-2 Approx. el. 503 ft.

Drilled April 1968

Depth (ft)	Drillers log
0 - 132	w m s, m h, h
132 - 442	m h, m s
442 - 446	s
446 - 470	m h, s
470 - 473	h
473 - 476	s
476 - 495	h
495 - 505	m s, m h
505 - 513	m s, h
513 - 517	m s, s
517 - 526	h, v h
526 - 532	m s
532 - 536	h
536 - 576	m s, m h
576 - 582	gy m s cl
582 - 590	w m h cr
590 - 597	y m s cl
597 - 636	w m h cr
636 - 639	h
639 - 668	gy m s cl (volc?)
668 - 680	bl gy m h cl

Logs

Well F-1 Approx. el. 423 ft.

Drilled Feb. 1969

Depth (ft)	Drillers log
0 - 155	w m s, m h, h cr
155 - 173	w v h cr
173 - 250	w m h, h, v h cr
250 - 418	w m s, m h, h cr
418 - 425	w s cr
425 - 455	w m h, m s cr

TABLE 12

EFFECTS OF ACIDIZING ON PUMP TESTS

	Before Acidizing			After Acidizing			
Well	Pump Rate Q(gpm)	Drawdown s(ft)	Sp. Cap. Q/s	Pump Rate Q(gpm)	Drawdown s(ft)	Sp. Cap. Q/s	Change Q/s
A-1	200	47	4.3	202	52	3.9	- 0.4
A-12	230	111	2.1	214	36	5.9	+ 3.8
D-9	200	25	8	218	0.4	545	+537
D-11	200	4.8	42	200	2.7	74	+ 32
M-1	250	21	12	145	7	21	+ 9
M-2	207	6.8	30	207	3.1	68	+ 38
M-5	185	38	4.9	200	20	10	+ 5.1

TABLE 13

SUMMARY OF PUMPING TESTS AT TIME OF WELL COMPLETION

NORTH GUAM

	Pumping			Recovery	
Well	Rate gpm	Time From Start (min)	Drawdown (ft)	Residual Drawdown (ft)	Time From Stop (min)
A-1	202	90	51	5.5	2
	202	1500	51	1.0	30
				.83	60
A-2	210	30	24	0.5	0.5
	210	840	24	0	1
A-3	273	15	102	43	1
	273	1440	98	3.3	10
				0.1	35
A-4	300	30	9		
	300	450	12.9		
A-5	207	15	4.0	.03	1
	207	240	4.2	0	3
	207	585	4.2		
A-6	321	30	.7		
	321	450	.7		
A-7	207	30	19.9		
	207	450	20.3		
A-8	273	30	48.3		
	273	210	52		
	273	450	52.7		
A-9	226	30	0.7		
	226	450	0.7		

TABLE 13

Well	Pumping Rate gpm	Pumping Time From Start (min)	Drawdown (ft)	Recovery Residual Drawdown (ft)	Recovery Time From Stop (min)
A-10	207	30	0.5		
	207	450	0.5		
A-11	177	30	187		
	177	450	188		
A-12	214	30	31.2		
	214	120	33.7		
	214	180	36.0		
	214	210	36.0		
A-13	253	30	4.3		
	253	180	28.5		
	253	420	28.3		
D-5	150	15	23.3	9.2	15
	150	180	23.6	0	30
	150	240	24.5		
D-7	218	30	8.3		
	218	450	8.5		
D-9	218	30	.35		
	218	450	.35		
D-10	218	30	.50		
	218	450	.30		
D-11	200	30	2.5		
	200	150	2.7		
D-12	200	240	8.8		
	200	360	8.8		

TABLE 13

	Pumping			Recovery	
Well	Rate gpm	Time From Start (min)	Drawdown (ft)	Residual Drawdown (ft)	Time From Stop (min)
D-13	133	10	9		
	133	30	9		
	133	120	11.5		
	133	480	11.1		
112	143	1	0		
	143	28	0		
	200	30	0.1		
	200	40	0.1		
	300	60	0.2		
	300	1440	0.2		
M-1	240	60	14.3		
	240	300	13.8		
M-2	214	30	3.3		
	214	150	3.4		
M-3	207	30	.35		
	207	450	.20		
M-4	214	30	.1		
	214	450	.2		
M-5	200	30	19.3		
	200	450	19.3		
M-6	240	30	27.5		
	240	330	27.7		

TABLE 13

	Pumping			Recovery	
Well	Rate gpm	Time From Start (min)	Drawdown (ft)	Residual Drawdown (ft)	Time From Stop (min)
M-7	48	30	1.5		
	100	90	4.3		
	154	60	7.1		
	200	120	10.6		
	267	150	17.5		
AG-2	222	1	.2		
	222	810	.1		
128	86	20	2.2		
	111	40	4.0		
	150	240	8.5		

TABLE 14

1	2	3	4	5	6	7
Well	l. (ft)	T(gpd/ft)	k(l) ft/d	k(1.25 l) ft/d	Type Analysis	Investigator
Southern limestone (cont.)						
Ml-3	38	10400	37		Obs. Well Drawdown (Jacob)	J. F. Mink
T-1	33	14000-24000	57-97		Obs. Well Drawdown (Jacob)	J. F. Mink
Yl-1	90	15000	23	18	Obs. Well Drawdown (Jacob)	J. F. Mink
Yl-3	122	14000	15	12	Obs. Well Drawdown (Jacob)	J. F. Mink
		24000	22	18	Drawdown (Jacob)	J. F. Mink
Volcanic						
RCA	340		.013-.036		Pump Well Drawdown (Hantush)	J. F. Mink
Guam Oil	200	3900	2.61	2.09	Pump Well Drawdown (Jacob)	J. F. Mink
Ml X-2	195	50	.034		Slug test	J. F. Mink

Column explanations:

1. Well number used by PUAG.

2. l = depth of penetration into saturated aquifer.

3. T = transmissivity.

4. k(l) = hydraulic conductivity based on depth of flow equivalent to depth of penetration.

TABLE 14

Column explanations (cont.):

5. k(1.25 l) = hydraulic conductivity based on depth of flow equivalent to 125% of depth of penetration.

6. In general, data obtained from testing justified approximate (Jacob, Hantush) non-steady analysis rather than the more sophisticated type-curve matching.

7. Investigator who analyzed data.

TABLE 14

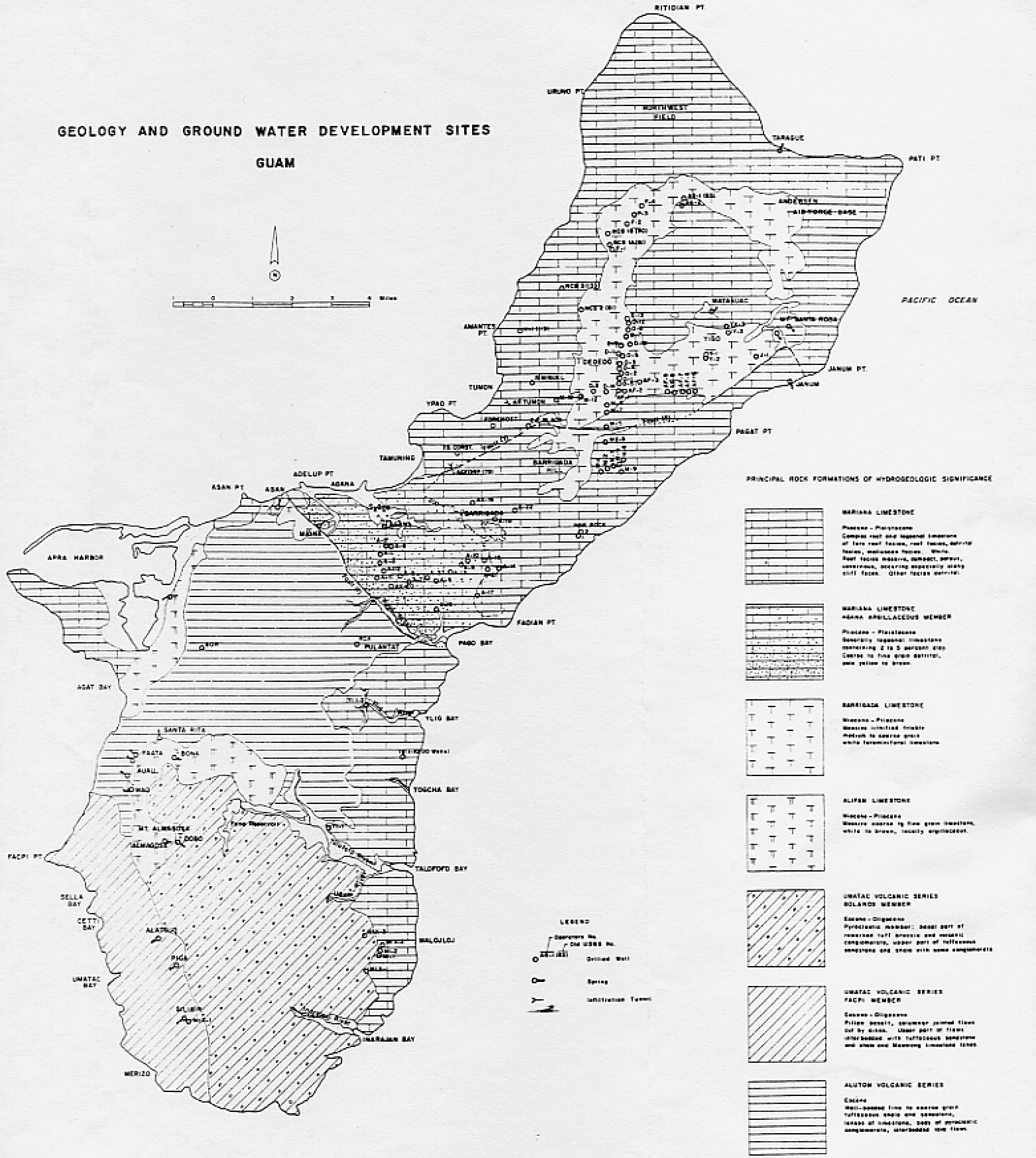
SUMMARY OF PUMPING TEST ANALYSIS

(See column numbers at end of table for column explanations)

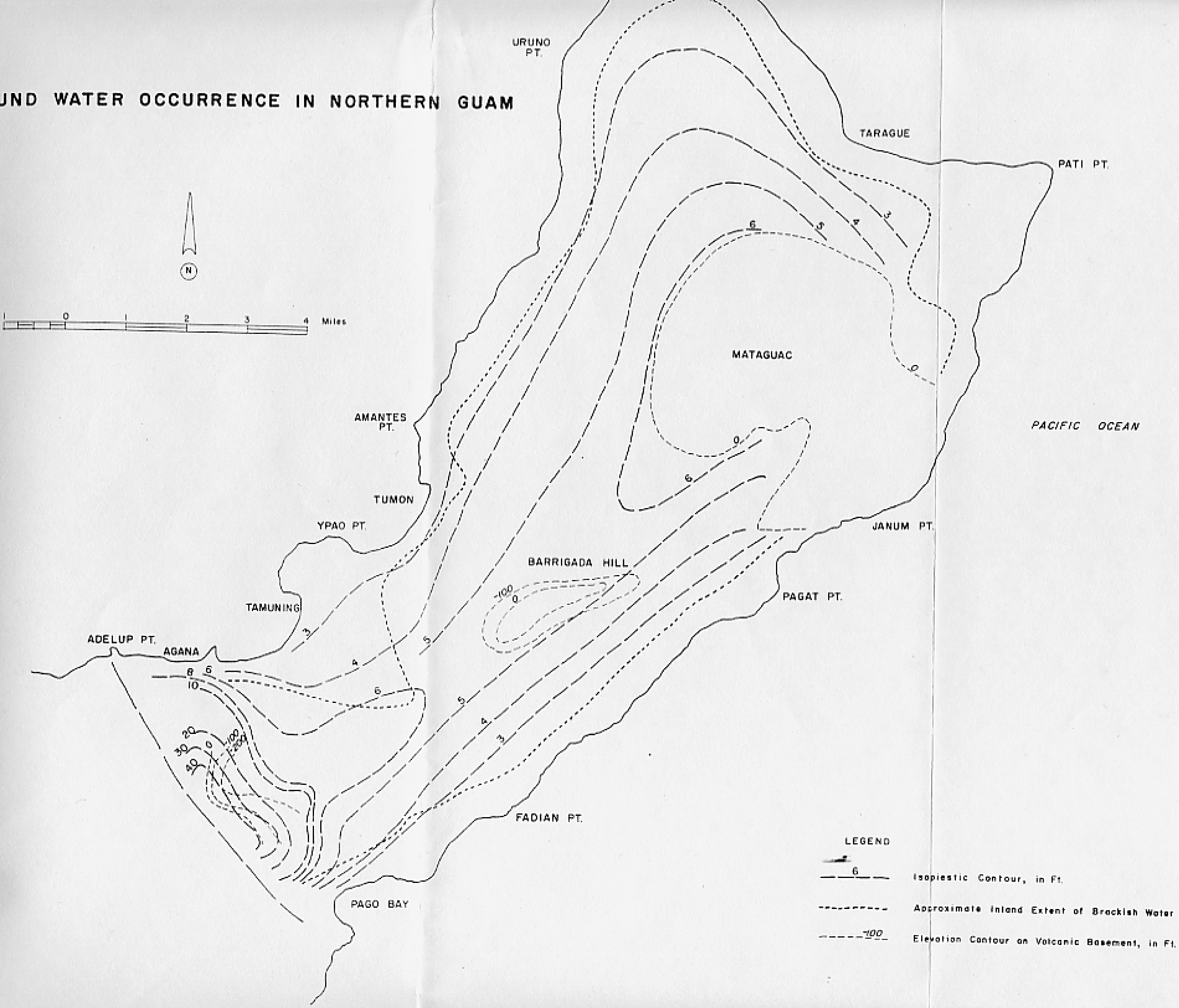
1	2	3	4	5	6	7
Well	l (ft)	T(gpd/ft)	k(l) ft/d	k(1.25 l) ft/d	Type Analysis	Investigator
Northern limestone						
A-1	171	106000	82	66	Pump Well Recovery (Jacob)	J. F. Mink
		90000	70	56	Pump Well Drawdown (Jacob)	J. F. Mink
		90000	70	56	Step Drawdown	N. T. Sheahan
A-12	221	19000	12	9.6	Step Drawdown	N. T. Sheahan
D-2	41	67000	219	175	Step Drawdown	N. T. Sheahan
D-3	30	51000	227	182	Step Drawdown	N. T. Sheahan
D-6	42	173000	551	441	Step Drawdown	N. T. Sheahan
D-7	55	117000	284	226	Step Drawdown	N. T. Sheahan
D-8	40	24000	80	64	Step Drawdown	N. T. Sheahan
D-11	42	25000	80	64	Step Drawdown	N. T. Sheahan
Southern limestone						
M1-1	30	18000	81		Obs. Well Drawdown (Jacob)	J. F. Mink
		13000	58		Obs. Well Recovery (Jacob)	J. F. Mink
M1-2	30	21000	94		Obs. Well Drawdown (Jacob)	J. F. Mink
		16000	71		Obs. Well Recovery (Jacob)	J. F. Mink

MAP 1

GEOLOGY AND GROUND WATER DEVELOPMENT SITES
GUAM

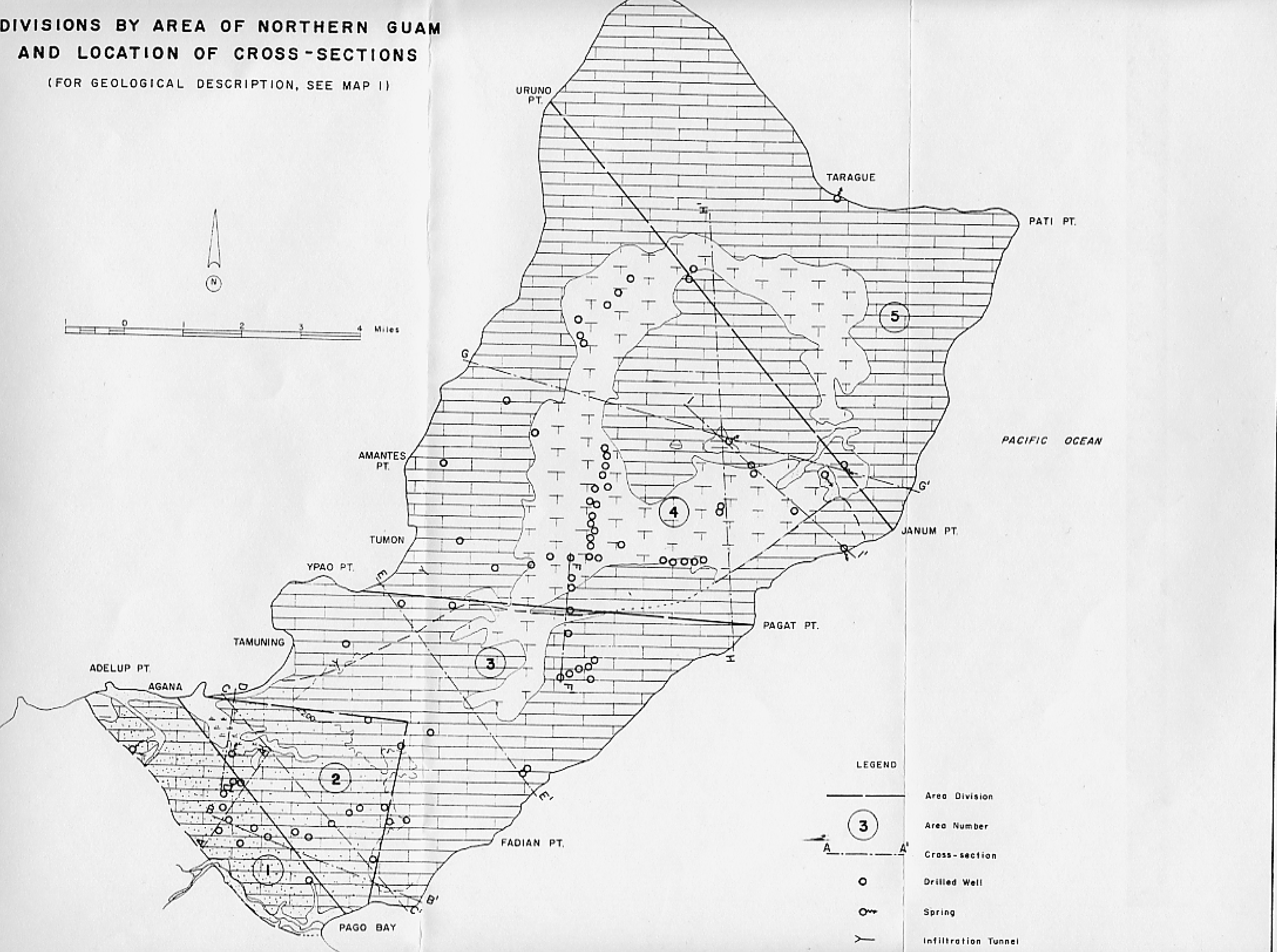


(Geology from Tracey, et al. 1964) J.F. Mink, S.T. Sun


UND WATER OCCURRENCE IN NORTHERN GUAM
N
0
1
2
3
4
Miles
URUNO PT.
TARAGUE
PATI PT.
MATAGUAC
AMANTES PT.
TUMON
YPAO PT.
TAMUNING
ADELUP PT.
AGANA
BARRIGADA HILL
JANUM PT.
PAGAT PT.
FADIAN PT.
PAGO BAY
PACIFIC OCEAN
3
4
5
6
0
8
10
20
30
40
-100
-200
LEGEND
Isopiestic Contour, in Ft.
Approximate Inland Extent of Brackish Water
Elevation Contour on Volcanic Basement, in Ft.

DIVISIONS BY AREA OF NORTHERN GUAM AND LOCATION OF CROSS-SECTIONS

(FOR GEOLOGICAL DESCRIPTION, SEE MAP I)



HYDROGEOLOGY OF THE AGANA-BARRIGADA REGION