Northern Guam Lens Study

AQUIFER YIELD REPORT

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GUAM ENVIRONMENTAL PROTECTION AGENCY · 1973 ·

NORTHERN GUAM LENS STUDY

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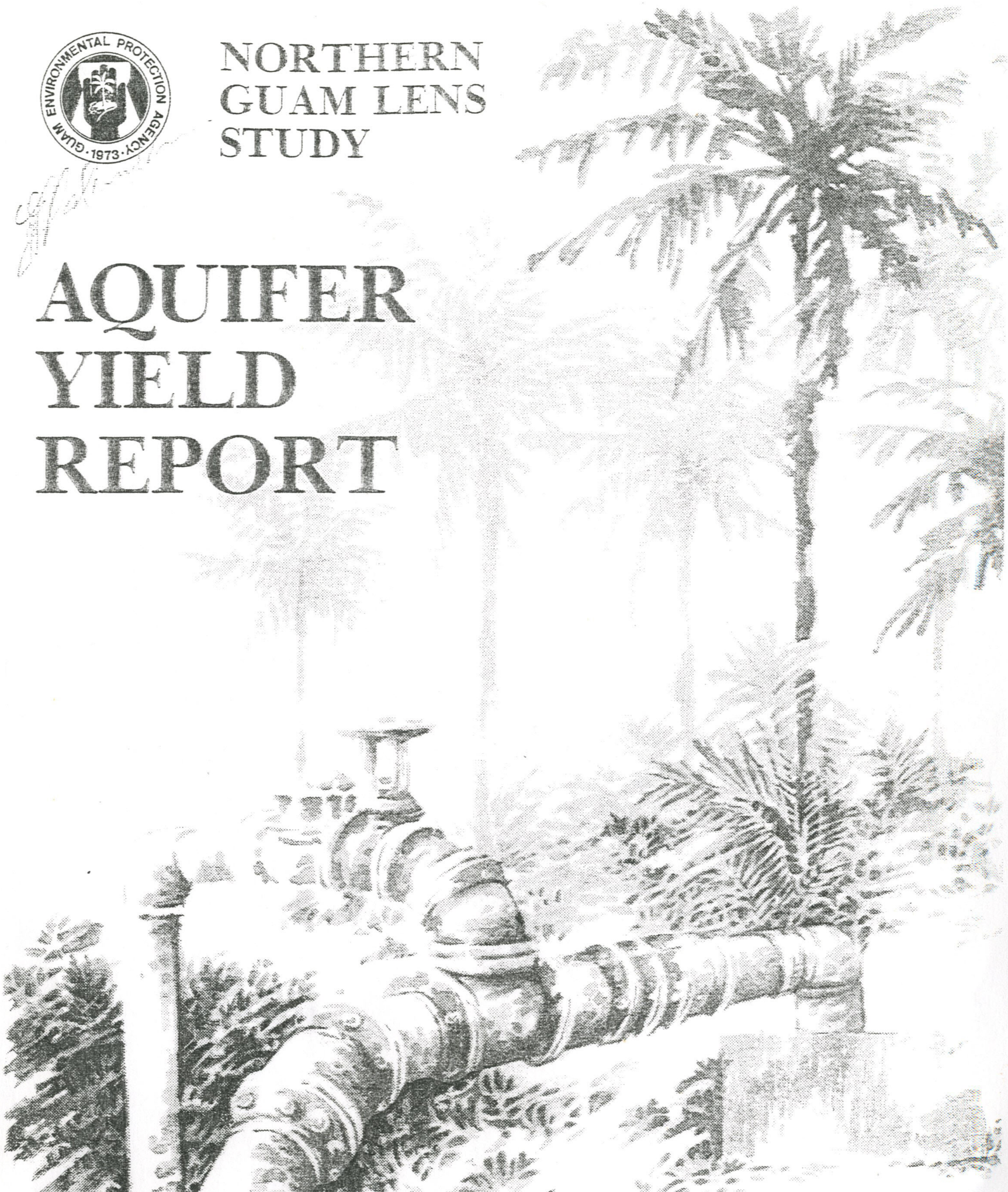

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FINAL REPORT

NORTHERN GUAM LENS STUDY
GROUNDWATER MANAGEMENT PROGRAM
AQUIFER YIELD REPORT

Prepared for the

GOVERNMENT OF GUAM
GUAM ENVIRONMENTAL PROTECTION AGENCY

December 1982

Prepared by

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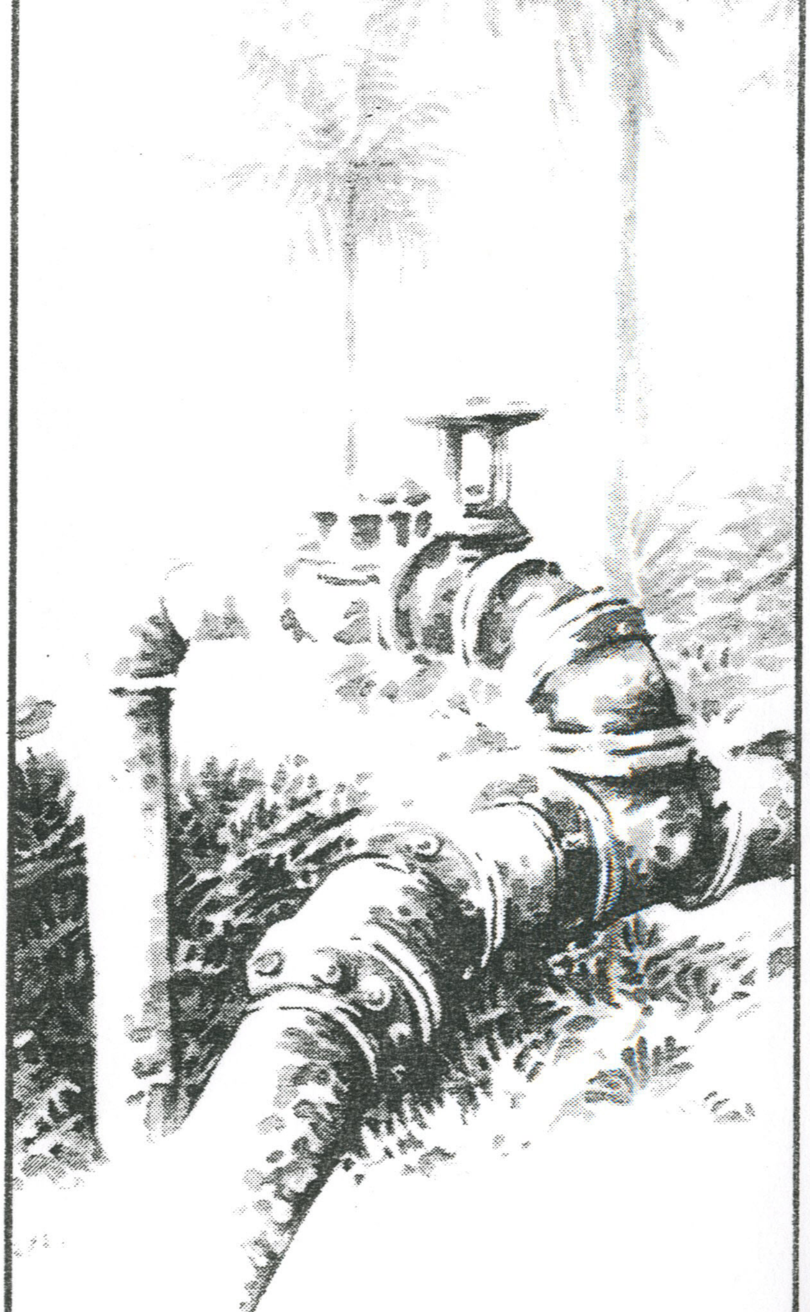


I. SUMMARY OF FINDINGS AND RECOMMENDATIONS

BACKGROUND

In 1964, the Government of Guam established a policy that the majority of its water supply would be taken from the limestone aquifers in the northern portion of the island. The fresh groundwater contained in these aquifers is collectively referred to as the Northern Lens. Because this valuable resource was insufficiently understood to insure safe, large-scale groundwater development, in 1974 the Government of Guam selected John Mink to conduct an in-depth evaluation of the long-term reliability of the Northern Lens water supply. Based on limited data, Mink (1976) estimated the sustainable yield of the Northern Lens to be at least 50 million gallons per day. Consequently, he recommended that a detailed hydrogeologic study be completed prior to extensive development of this groundwater supply. Mink's recommendation was realized in 1980 when the Guam Environmental Protection Agency (GEPA) initiated a water resource study that involved the participation of the United States Geologic Survey (USGS); the University of Guam's Water and Energy Research Institute of the Western Pacific (WERI); Barrett, Harris & Associates, Inc. (BHA); and Camp Dresser & McKee Inc. (CDM). The USGS was primarily responsible for hydrogeologic data collection. WERI was responsible for hydrogeologic data interpretation and mathematical modeling of the Northern Lens. BHA and CDM were charged with conducting an in-depth evaluation of water resources management practices in northern Guam and reevaluating the sustained yield of the Northern Lens based on new hydrogeologic data collected during the study. John Mink was given the responsibility of project director. He acted as liaison between GEPA and the study team and coordinated the technical and management studies.

SUMMARY OF FINDINGS

The aquifers of northern Guam consist of thick sequences of porous limestones that were deposited on the submarine slopes of a volcanic island.

Mount Santa Rosa and Mataguac Hill are exposed remnants of this volcanic mass. The two primary geologic formations are the Barrigada and Mariana limestones. These formations are thick and massive, and are interlaced with pores and channels that easily transmit water from the ground surface into and through the aquifers. Permeability of the aquifers varies both horizontally and vertically. Over the Northern Lens, the permeability increases from the southern part of the aquifer to the northern part, and ranges in value from under 500 feet per day in the Agana area in the south to over 12,000 feet per day in the Yigo and Finegayan areas in the north.

The Northern Lens has two primary types of groundwater conditions: basal and parabasal. In the basal portions of the lens, the fresh water floats on saline water which has intruded into the limestone formations. In the parabasal portions of the lens, the fresh water overlies the volcanic formations, but is hydraulically connected to the adjacent basal lens. Figure 1-1 illustrates the geographic distribution of the basal and parabasal lenses in northern Guam.

The average rainfall in northern Guam is 94 inches per year and ranges between 86 and 100 inches per year at the various raingaging stations over the lens. Of this rainfall, an average of approximately 35 inches per year recharges the groundwater aquifers. Sustainable yield is estimated to be approximately 40 percent of the recharge in the basal areas and about 60 percent in the parabasal areas. The difference in yield is due to the susceptibility of wells in basal aquifers to salt water intrusion (upconing).

In this study, the Northern Lens was divided into six hydrologic subbasins, which, in turn, were subdivided into 47 management zones, as shown on Figure 1-2. For each management zone, rainfall and recharge values were calculated and a sustainable yield was determined.

Table 1-1 summarizes the recharge, production, and sustainable yield of the Northern Lens as well as for each of the six hydrologic subbasins. The results are further subdivided into the basal and parabasal lenses for each subbasin. The table shows that the total recharge to the Northern Lens is

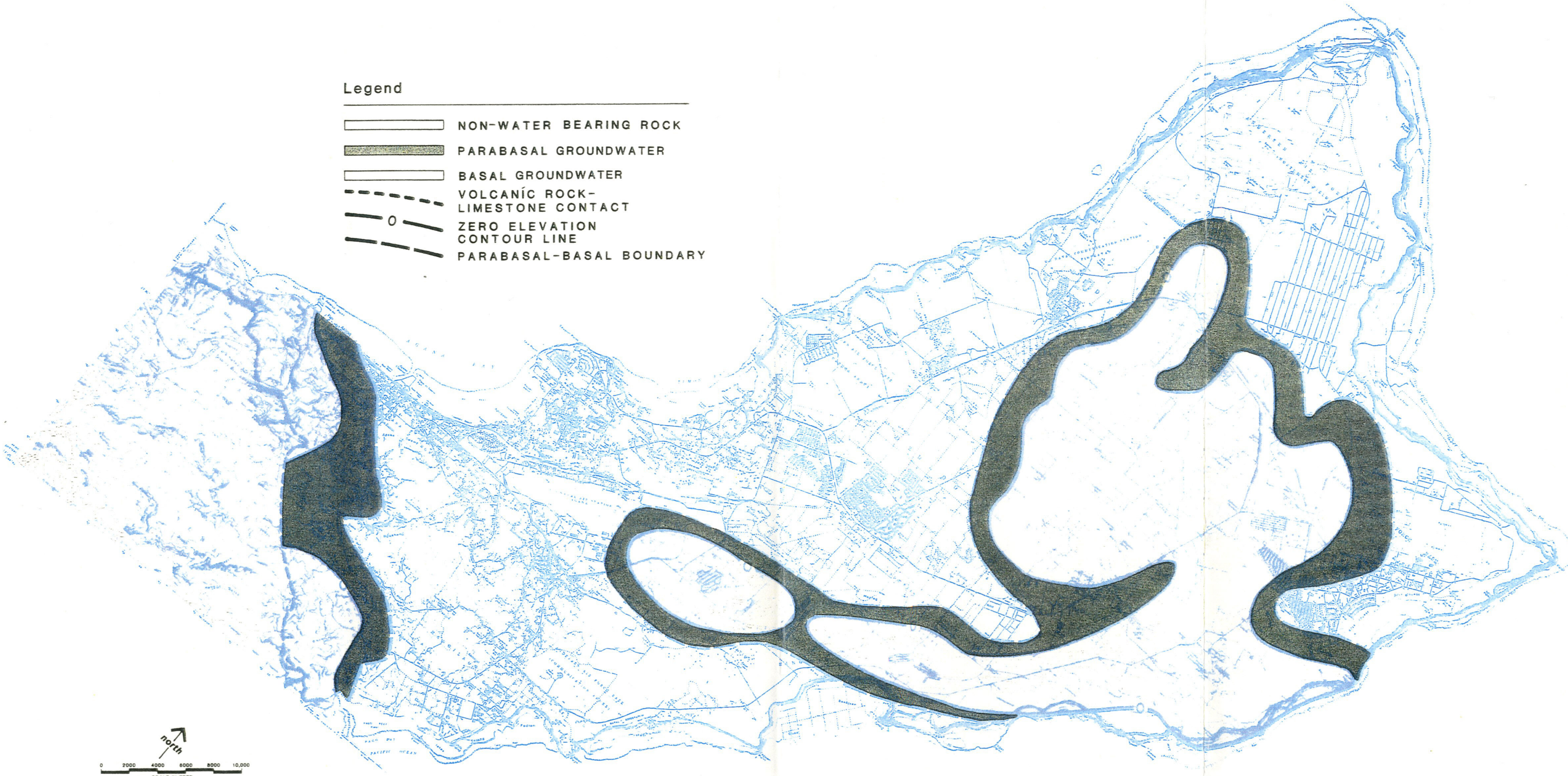


FIGURE 1-1

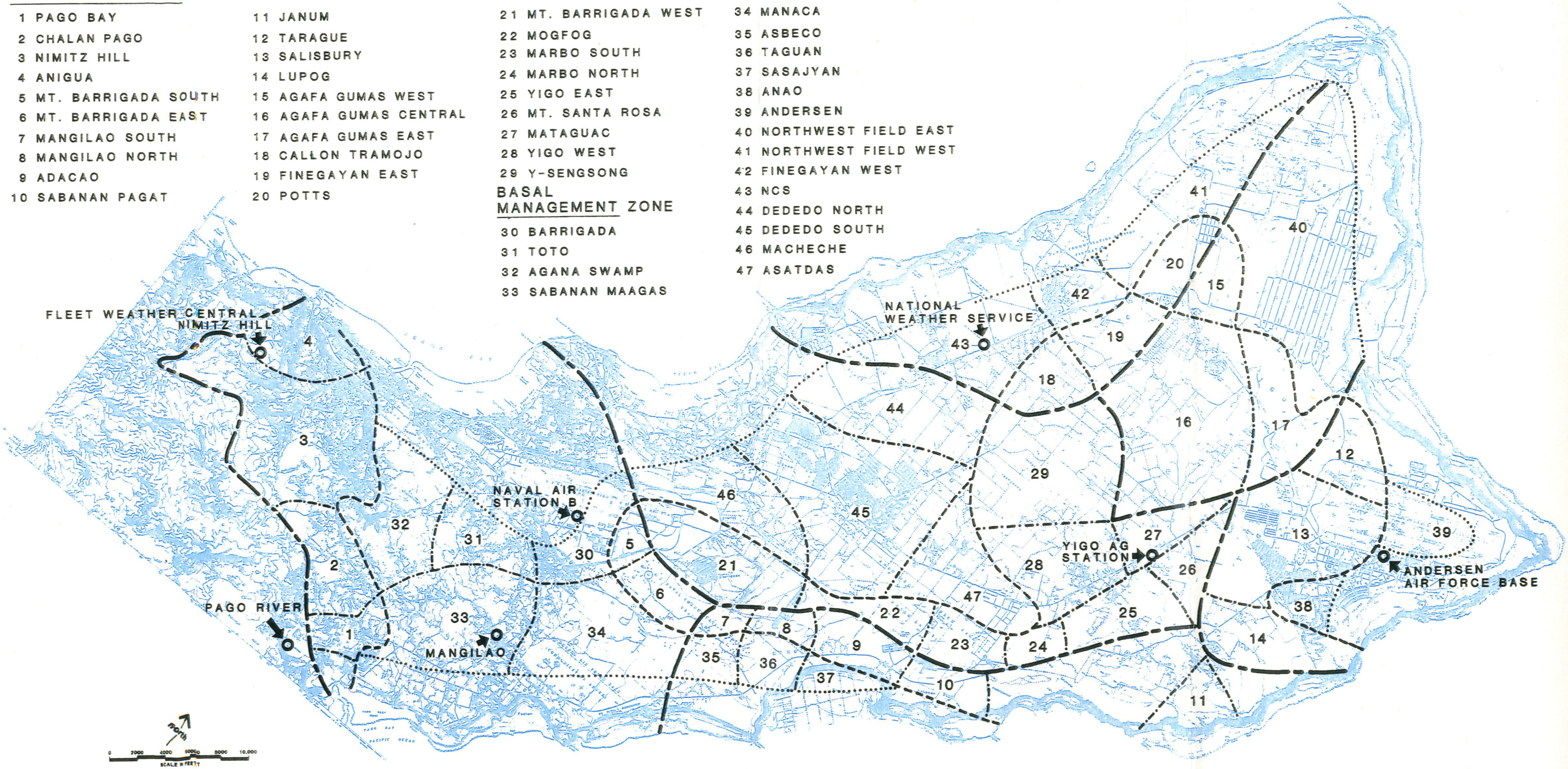
DISTRIBUTION OF
GROUNDWATER TYPES

PARABASAL
MANAGEMENT ZONE

1 PAGO BAY
2 CHALAN PAGO
3 NIMITZ HILL
4 ANIGUA
5 MT. BARRIGADA SOUTH
6 MT. BARRIGADA EAST
7 MANGILAO SOUTH
8 MANGILAO NORTH
9 ADACAO
10 SABANAN PAGAT
11 JANUM
12 TARAGUE
13 SALISBURY
14 LUPOG
15 AGAFA GUMAS WEST
16 AGAFA GUMAS CENTRAL
17 AGAFA GUMAS EAST
18 CALLON TRAMOJO
19 FINEGAYAN EAST
20 POTTS
21 MT. BARRIGADA WEST
22 MOGFOG
23 MARBO SOUTH
24 MARBO NORTH
25 YIGO EAST
26 MT. SANTA ROSA
27 MATAGUAC
28 YIGO WEST
29 Y-SENGSONG

BASAL
MANAGEMENT ZONE

30 BARRIGADA
31 TOTO
32 AGANA SWAMP
33 SABANAN MAAGAS
34 MANACA
35 ASBECO
36 TAGUAN
37 SASAJYAN
38 ANAO
39 ANDERSEN
40 NORTHWEST FIELD EAST
41 NORTHWEST FIELD WEST
42 FINEGAYAN WEST
43 NCS
44 DEDEDO NORTH
45 DEDEDO SOUTH
46 MACHECHE
47 ASATDAS



Legend

GROUNDWATER SUBBASIN BOUNDARY
PARABASAL - BASAL BOUNDARY
MANAGEMENT ZONE BOUNDARY
BOUNDARY FOR SAFE PUMPING
RAINGAGE STATION

FIGURE 1-2
GROUNDWATER MANAGEMENT ZONES
NORTHERN LENS

TABLE 1-1

ESTIMATES OF RECHARGE, PRODUCTION, AND SUSTAINABLE YIELD FOR SIX HYDROLOGIC SUBBASINS
(Million Gallons Per Day)

Subbasin	Recharge	Sustainable Yield	Subbasin Production	Unused Yield
AGANA				
Parabasal	12.51	7.50	2.80	3.26
Basal	12.94	5.63	2.87	2.76
River Outflow			1.44	
Subtotals	25.45	13.13	7.11	6.02
MANGILAO				
Parabasal	5.53	3.14	0.95	2.19
Basal	1.94	0.76	0.46	0.30
Subtotals	7.47	3.90	1.41	2.49
ANDERSEN				
Parabasal	8.90	5.33	-0-	5.33
Basal	2.25	0.91	-0-	0.91
Subtotals	11.15	6.24	-0-	6.24
AGAFA GUMAS				
Parabasal	11.14	6.69	0.42	6.28
Basal	8.51	3.40	-0-	3.40
Subtotals	19.65	10.09	0.42	9.68
FINEGAYAN				
Parabasal	4.84	2.91	0.37	2.53
Basal	8.08	3.48	2.28	1.21
Subtotals	12.92	6.39	2.65	3.74
YIGO				
Parabasal	18.19	10.53	2.20	8.32
Basal	17.08	8.55	8.11	0.45
Subtotals	35.27	19.08	10.31	8.77
TOTALS	111.91	58.84	21.90*	36.94

* 20.46 MGD maximum well capacity and 21.90 MGD with additional 1.44 MGD Fonte River outflow to the ocean.

about 112 million gallons per day (MGD), of which about 59 MGD are available as sustainable yield. The combination of surface runoff to the ocean and the production capacity of existing wells is estimated to be 22 MGD, which leaves an additional 37 MGD to be developed.

RECOMMENDATIONS

The results of the hydrologic investigation of northern Guam led to the following recommendations specifically regarding the estimated sustainable yield of the Northern Lens.

1. Until the findings of the Northern Guam Lens Study (NGLS) are substantiated during expansion of groundwater production facilities, groundwater production should be limited to the sustainable yield estimated in the Aquifer Yield Report for each management zone and hydrologic subbasin.

2. For the development of basal groundwater, the following well design constraints should be imposed:

   a. In management zones where fresh water heads are less than 4 feet, wells should be limited to 200 gallons per minute (gpm) capacity and the well bottom elevation should not exceed 40 feet below mean sea level (MSL), and preferably not more than 25 feet below MSL.

   b. In management zones with fresh water heads greater than 4 feet, wells should be limited to 350 gpm capacity and the well bottom elevation should not exceed 50 feet below MSL, and preferably not more than 35 feet below MSL.

3. For the development of parabasal groundwater, wells should be designed for the maximum that the aquifer can deliver without exceeding the sustainable yield of the management zone and without exceeding 750 gpm. However, because of low permeabilities in many

parts of the Northern Lens, the following well designs are provided as guidelines for groundwater development.

a. In the southern part of the Agana Subbasin, low permeabilities will probably limit well capacities to 200 gpm, and perhaps 350 gpm under special conditions. Wells in this area should probably be drilled no deeper than 50 feet below MSL.

b. In the upper part of the Yigo Subbasin, wells will probably yield 750 gpm. Wells in this area should probably not be drilled any deeper than 50 to 60 feet below MSL.

c. Wells in all other parabasal zones should have a capacity of about 500 gpm with well bottom elevations not exceeding 50 feet below MSL.

d. Wells should not be placed any closer than 500 feet from the estimated salt water toe position in clean limestone, and 1,000 feet from the estimated salt water toe position in argillaceous limestone.

4. Wells should be placed at least 300 feet apart in both the basal and parabasal zones.

To refine the estimates of sustainable yield and to provide a method of monitoring the changes in the fresh water lens as production capacity approaches sustainable yield, the following steps are recommended in order of greatest importance.

1. Three new permanent raingaging stations should be established in northern Guam to refine the estimates of areal distribution of precipitation. These stations should be located in Ordot, Latte Heights, and Agafa Gumas.

2. To monitor the impacts of future groundwater production, water level measurements should be conducted semi-annually in all production and monitoring wells during the months of April (the end of the dry season) and October (the end of the wet season).

3. Each hydrologic subbasin should have at least one continuous water level recorder located in the basal lens to determine the impact of well production and tides on water levels and fresh water lens configuration.

4. All new data should be compiled bi-annually and the estimates of recharge, production, and sustainable yield for each subbasin should be reevaluated, refined and updated. This bi-annual reevaluation will insure that the groundwater resource remains protected from over-development. The reevaluation should be done on an annual basis as the sustainable yield is approached or if salt water contamination of wells becomes frequent.

5. A monitoring well network should be established and expanded to complement the existing exploratory wells and the USGS observation wells. At least one monitoring well which fully penetrates the fresh water lens should be established in each major well field within the basal areas of the lens for the purpose of monitoring long-term changes in the position of the fresh water-salt water interface as groundwater production increases and approaches the sustainable yield. A major well field is an area where several wells are closely spaced such as exists in Dededo. Though existing monitoring wells may be adequate for most well fields in operation today, new monitoring wells should be drilled as new well fields are constructed.

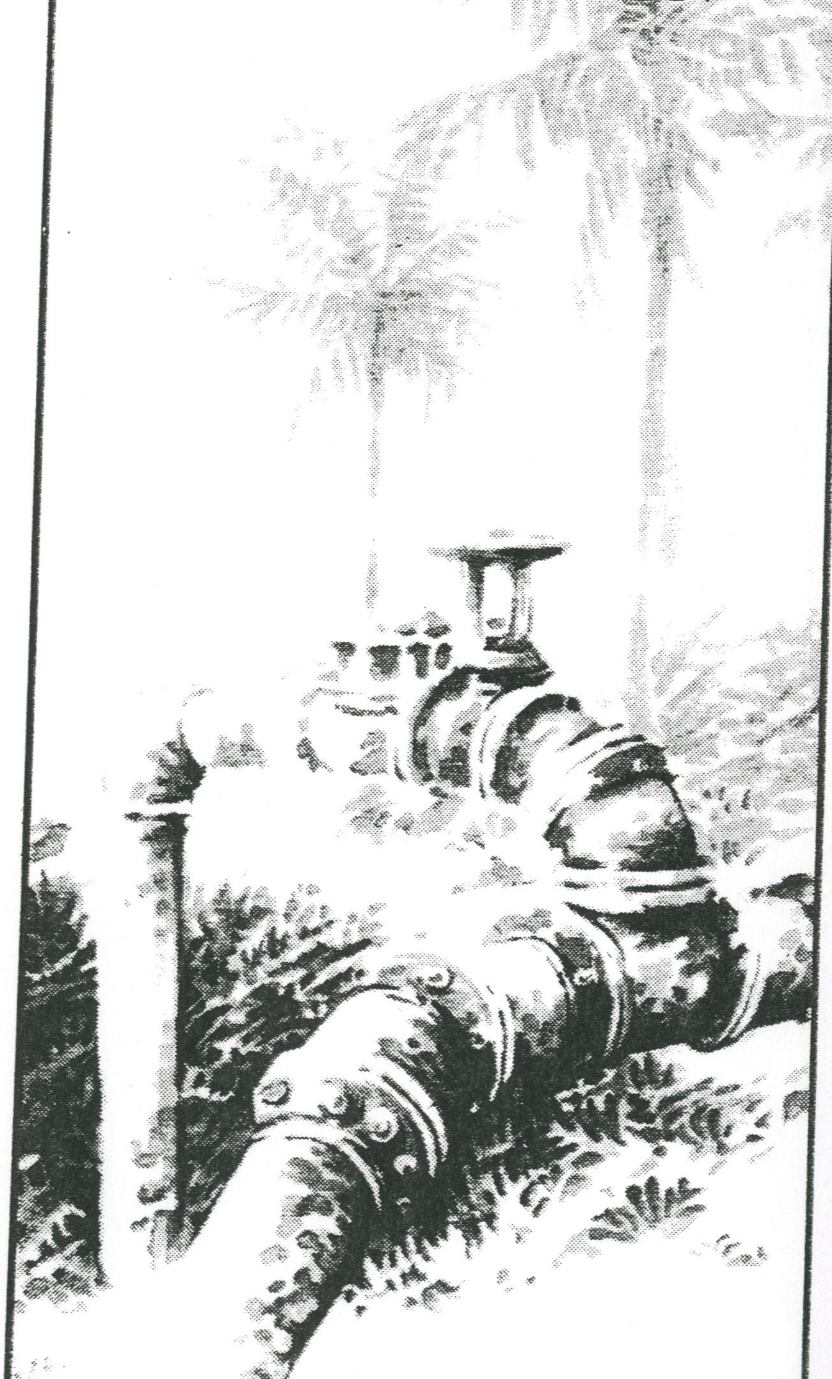
6. Lysimeters or other similar devices should be established at locations in northern Guam so that accurate evapotranspiration data can be obtained. Though these types of devices are relatively expensive to construct and maintain, the data will provide

more accurate information on the amount of rainfall that infiltrates to the groundwater system, and thus, the amount of recharge that enters the Northern Lens. This, in turn, will lead to a better assessment of sustainable yield.

7. In areas where little or conflicting data exist on where the limestone aquifer makes contact with the top of the volcanic formation, further exploratory drilling and/or seismic surveys should be conducted. Of particular concern are the northern Dededo Well Field area and the Andersen-Northwest Field areas.

II

INTRODUCTION



II. INTRODUCTION

GENERAL

The island of Guam is located in the western Pacific region, approximately half way between Japan and New Guinea (Figure 2-1), and is the largest island in the Mariana Island group. Guam has an area of about 212 square miles, is approximately 30 miles long, and ranges between 4 and 11.5 miles wide (Figure 2-2). The island has two very distinct physiographic divisions; the southern half is composed of rugged volcanic upland and the northern half is characterized by a limestone plateau. The fresh groundwater resource of northern Guam (commonly known as the Northern Lens) is the subject of this report and the Northern Guam Lens Study (NGLS).

In 1964 the Government of Guam established a policy to rely on the groundwater resources of the Northern Lens for its long-term water supply needs. The policy was adopted because of the increasing expense associated with constructing surface reservoirs and because surface reservoirs are not a long-term, reliable water supply source. Large-scale groundwater development began in Guam in 1937 and peaked during the troop build-up in World War II. Many of the wells used for the military occupation are noted on Plate I; however, and most of these are not now in use. Shortly after the war, the U.S. Geological Survey (USGS) conducted several hydrologic studies and established an ongoing surface water and groundwater data collection program. Their efforts were followed by a thorough evaluation of the long-term reliability of Guam's groundwater resources published by John Mink in 1976. In that report, Mink estimated the sustainable yield of the Northern Lens to be on the order of 50 million gallons per day (MGD). However, Mink was quick to point out that his estimates, though conservative, were rough because of the lack of detailed hydrogeologic and hydrologic data available for northern Guam. Furthermore, he recommended that prior to any extensive groundwater development of the lens, the hydrologic features of the aquifers needed to be determined. This recommendation was acted on in 1980, when the Government of Guam, with the administrative guidance of the Guam Environmental Protection Agency (GEPA), contracted the water resources consulting firms of Barrett, Harris, and Associates, Inc. (BHA) and Camp Dresser and McKee Inc. (CDM) (hereafter jointly referred to as "the Consultant") to conduct a thorough evaluation of water resources management practices as well as a detailed reevaluation of the sustainable yield based on new hydrogeolgic data being generated for GEPA during 1980, 1981, and 1982. Concurrently, the University of Guam's Water and Energy Research Institute of the Western Pacific (WERI) and the USGS were contracted to expand the hydrogeologic understanding of the groundwater resources of the Northern Lens.

To address the need for subsurface hydrogeologic data, GEPA contracted to have seismic and gravity surveys conducted throughout Northern Guam. These surveys did more to advance the understanding of the boundary conditions of the groundwater system than any previous investigation. GEPA also contracted to have 11 exploratory wells drilled and a topographic survey conducted of all water wells in Northern Guam. The data collected from the surveys and drilling were evaluated and used by the USGS, WERI, and the Consultant to complete their assigned tasks in the NGLS.

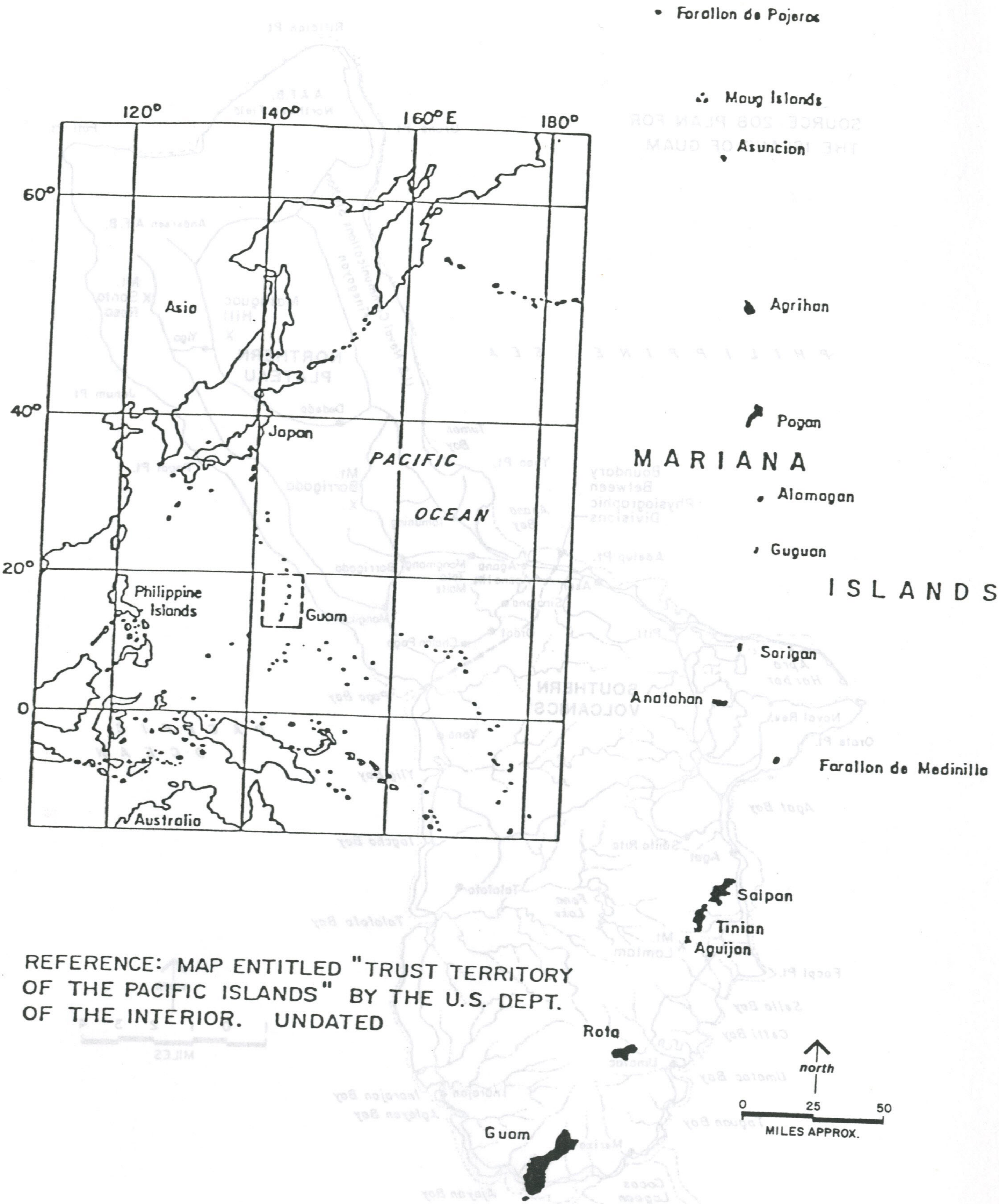
SCOPE OF WORK

The underlying major objectives of the hydrogeologic study, as presented in this report, were to: 1) more accurately delimit the limestone aquifer of the Northern Lens, and 2) reevaluate the sustainable yield based on the newly generated hydrogeologic data.

After work started on the NGLS, the Scope of Work was modified slightly with regard to numerical modeling. That portion of the work dealing with numerical modeling (Task V-1(b)) was turned over to WERI to complete. The emphasis of the Contractor was placed on analytical analyses of the groundwater system.

ACKNOWLEDGEMENTS

The NGLS was successfully completed because of the cooperative effort of many diverse organizations now involved with the water resources of Guam.



REFERENCE: MAP ENTITLED "TRUST TERRITORY OF THE PACIFIC ISLANDS" BY THE U.S. DEPT. OF THE INTERIOR. UNDATED

FIGURE 2-1

LOCATION MAP

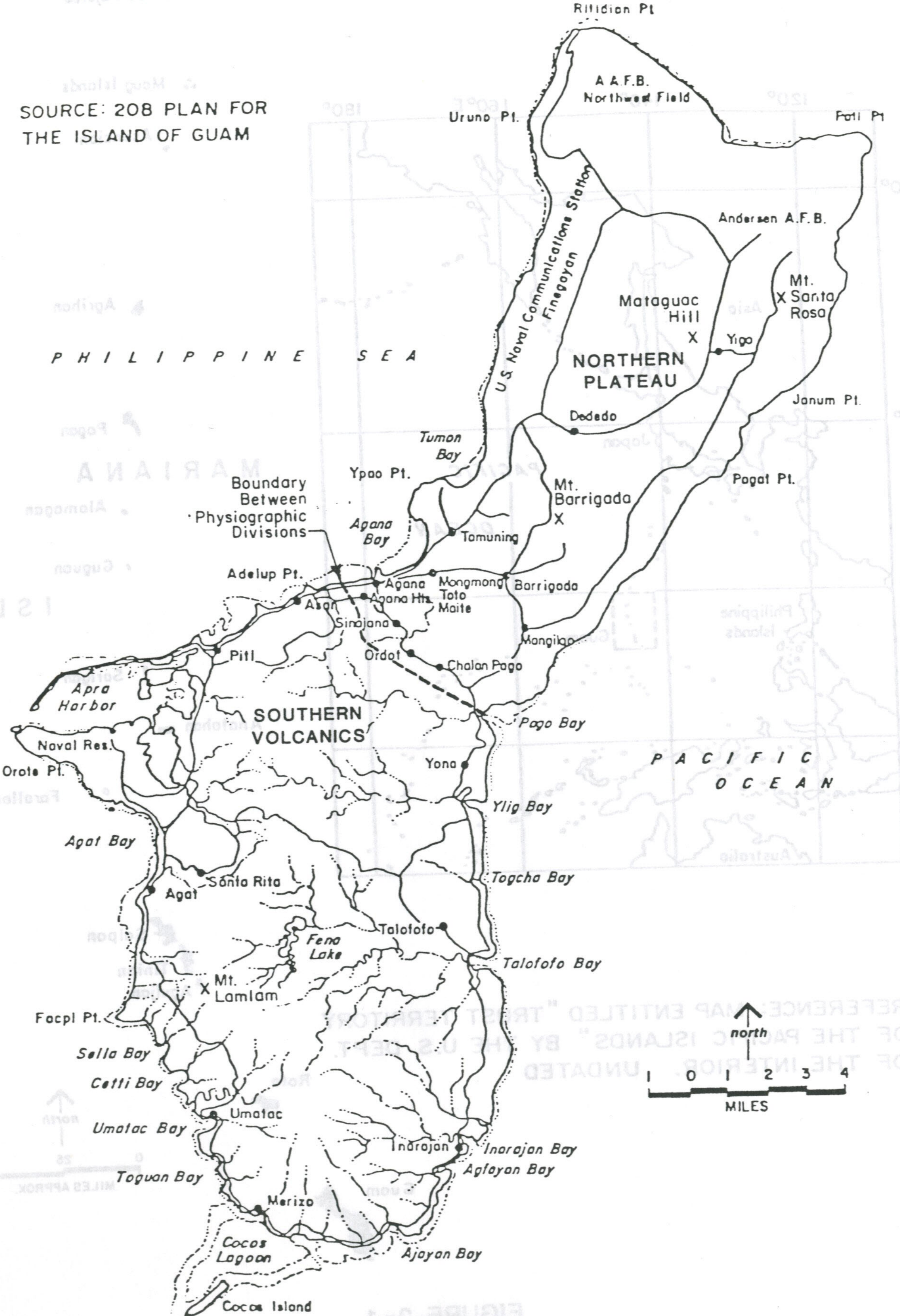


FIGURE 2-2

MAJOR PHYSIOGRAPHIC DIVISIONS OF GUAM

We are especially appreciative of Ricardo Duenas, Administrator of GEPA; James Branch, Deputy Administrator of GEPA and Project Manager of NGLS; John Mink, Project Director of the NGLS; and John Worlund, Chief Engineer of GEPA and Assistant Project Director of the NGLS. The staff of GEPA is to be commended for its efforts in providing water quality analyses and other data, office and conference room space, and assisting in the day-to-day logistics of the project. WERI provided considerable input for both hydrogeologic data interpretation and computer modeling of the Northern Lens groundwater system. Valuable data were provided by other Government of Guam agencies, in particular, the Public Utility Agency of Guam (PUAG) and the Division of Land Management. The United States Navy and United States Air Force also greatly assisted the project by supplying data as well as access to their bases. Finally, the USGS, in particular Chuck Huxel and Gregg Ikehara, are to be commended for their efforts to complete the data collection portions of the project.

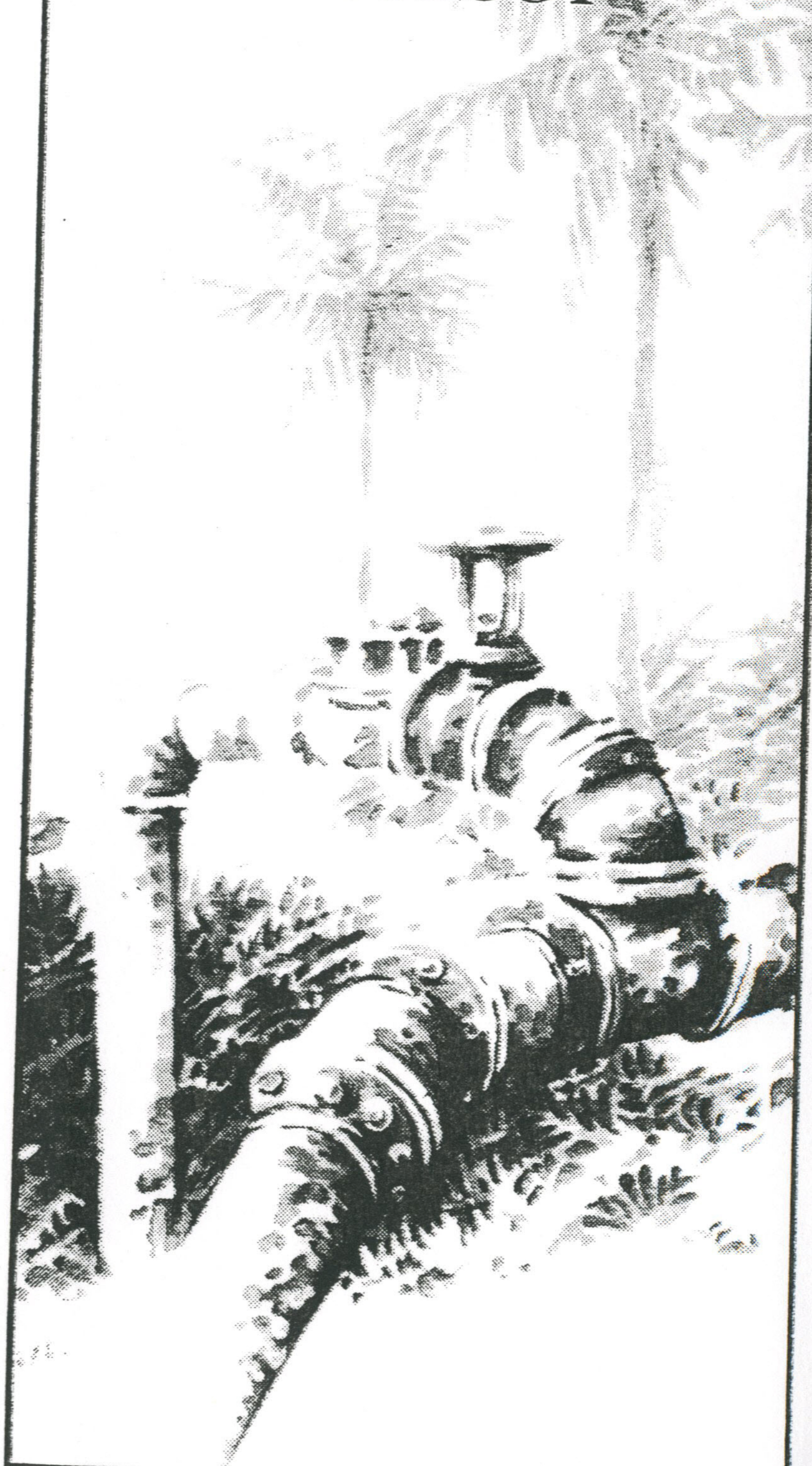
REPORT FORMAT

The report is divided into two major portions, the main text and technical appendices. The main text presents a summary of those topics that led to conclusions regarding sustainable yield of the Northern Lens, including geology, hydrogeology, hydrology, and groundwater quality. Information presented in this portion of the report includes reviews of work previously done which is pertinent to the study. Discussions, such as those of detailed geology, hydrogeology, and basic hydrodynamics of the fresh water-salt water system, are intentionally brief because they have been well covered in previous reports (for example, Mink, 1976 and WERI, 1982). The main text also focuses on updating and refining the results of previous studies based on new understanding of the aquifer and fresh water lens geometries.

The second part of the report consists of technical appendices which contain a summary of all data and analytical methods used to obtain aquifer and fresh water lens geometries and sustainable yield, as well as a more in-depth discussion of aquifer permeability and recharge, an analysis of transition zone geometry, and a review of analytical and numerical modeling efforts undertaken during the investigation by various participants in the NGLS. Appendix A contains those tables from the Data Report that are referenced in the Aquifer Yield Report. The Data Report is published under separate cover and includes a compilation and summary of all data used in the preparation of this report. Appendix B summarizes the results of the geophysical surveys conducted early in the project, as well as a description of the preparation of the Volcanic Basement Contour Map (Plate 1). Appendices C, D, E, and F provide the calculations used in evaluating permeability, response of the lens to pumping, evaporation and evapotranspiration, and recharge, respectively. Appendix G summarizes the numerical modeling efforts by WERI. Appendix H provides the definitions of some of the technical terms used in this report.

III

GEOLOGY



III. GEOLOGY

PREVIOUS WORK

The following discussion of Guam's geology is a summary of the work performed by Tracey, et al, and published as USGS Professional Paper 403-A in 1964. Their work is the most complete of any geologic study done of Guam. For a more detailed consideration of Guam's geology, the reader is directed to that publication.

The first geologic observations of Guam were conducted by Agassiz in 1903. H.T. Stearns of the USGS completed a detailed geologic investigation on Guam in 1937 for the U.S. Navy. Between 1937 and 1964, a number of studies, especially by the USGS, contributed more detail to Stearns' original work. Then, in 1964, the comprehensive investigation of Guam's geology by Tracey, et al, was published by the USGS. After 1964, only a few geologic investigations, performed in localized areas of Guam, were done until the recent seismic surveys and exploratory drilling in the Northern Lens were completed for GEPA in 1981 and 1982.

GEOLOGIC SETTING

Guam is the largest and southern-most island in the Mariana Island Chain (see Figure 3-1). The island chain is located atop a large submarine ridge known as the Mariana Island Arc System, which is the boundary between subducting tectonic plates. The Mariana Trench is located east and south of the arc. Within the trench is the lowest point on the surface of the earth, the Challanger Deep, which lies about 35,760 feet below sea level.

Guam has two major physiographic divisions (see Figure 3-2). The southern half of the island is the oldest and is characterized primarily by a dissected and relatively rugged volcanic upland, on which limestones were sometimes deposited. The upland areas of the eastern part of the island are fringed by discontinuous fossil limestone reef deposits. The western volcanic upland lies along a north-south ridge on which is the highest point of the island, Mount Lamlam, at an elevation of 1,334 feet.

The northern half of the island is characterized by a broad and gently undulating limestone plateau which slopes from Mount Santa Rosa (elevation 858 feet) on the northeast toward the Agana Swamp area (near sea level) on the southwest. The limestone plateau ends abruptly in near vertical cliffs along most of the coastline of northern Guam. Volcanic rocks are exposed at the ground surface near the tops of Mount Santa Rosa and Mataguac Hill and form the surface expressions of the volcanic backbone on which the thick sequences of limestone were deposited. Figure 3-3 illustrates the volcanic foundation below the limestone sequence. The volcanic basement is roughly circular in form in the northern part of the province and has a ridge that extends from Mount Santa Rosa on the north to Mount Barrigada on the south. The volcanic rocks of northern Guam probably formed during events that are both separate and younger than those in the south. Limestone sequences grew on the submerged volcanic surfaces as they were uplifted, and eventually connected with the southern half of the island.

MAJOR GEOLOGIC FORMATIONS

For the purposes of this report, only the major formations which occur within the northern physiographic division will be briefly discussed. For more detail regarding the lithology of any of the formations in Guam, the reader is again directed to Tracey, et al, (1964).

Alutom Formation

The Alutom Formation contains the oldest rocks exposed on Guam and is of probable Eocene to Oligocene age (approximately 40 to 60 million years old). This formation is volcanic (andesitic) and consists primarily of pyroclastics ranging in size from tuffaceous shale to coarse conglomerate and breccia, as well as flow rocks, usually in the form of pillow basalts. These deposits erupted on to the submarine floor as both flow and pyroclastic deposits and form the core or basement complex of Guam. The formation is highly folded and faulted as a result of its association with long

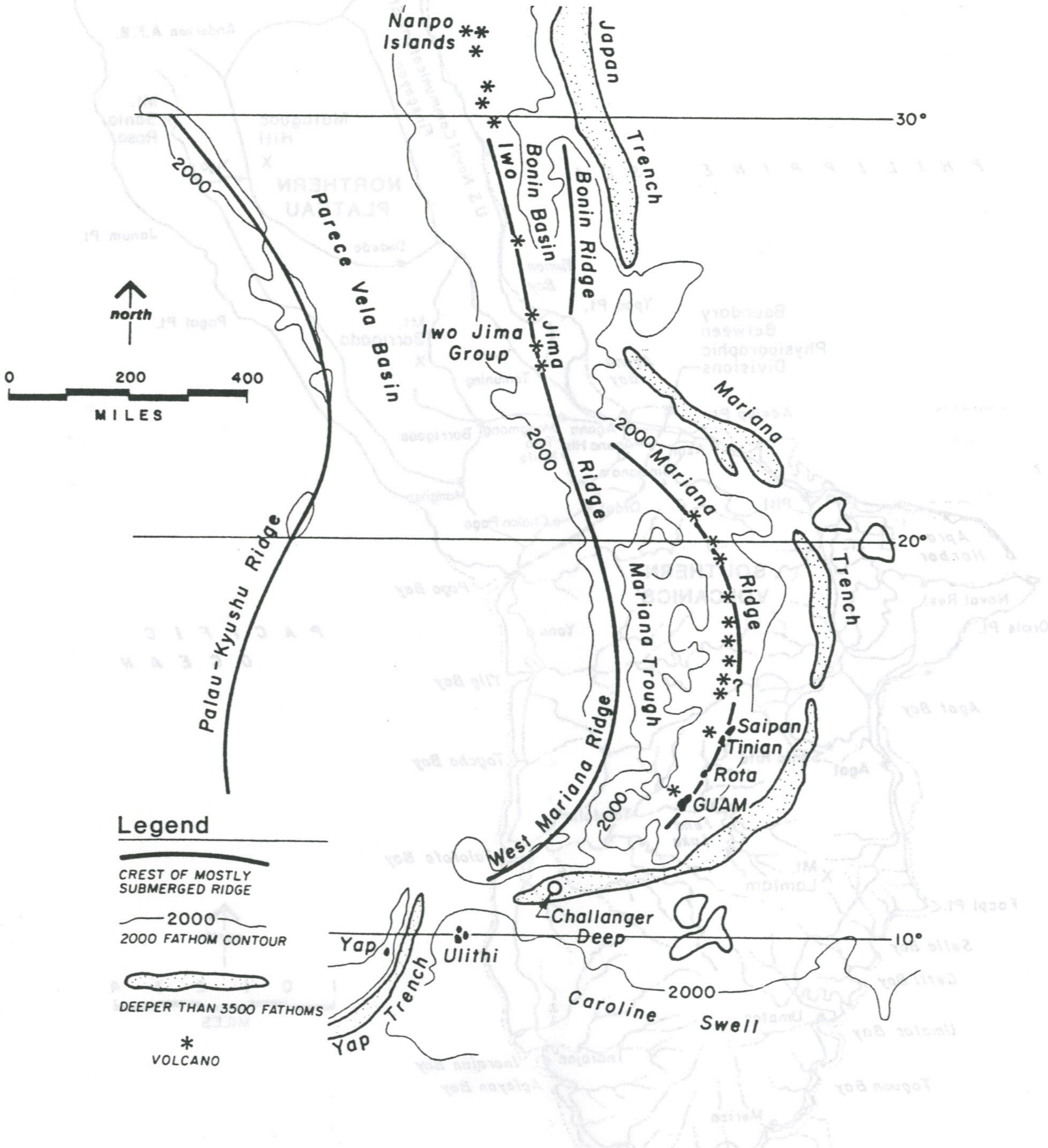


FIGURE 3-1

REGIONAL RELATIONS IN THE WESTERN NORTH PACIFIC

SOURCE: 208 PLAN FOR
THE ISLAND OF GUAM

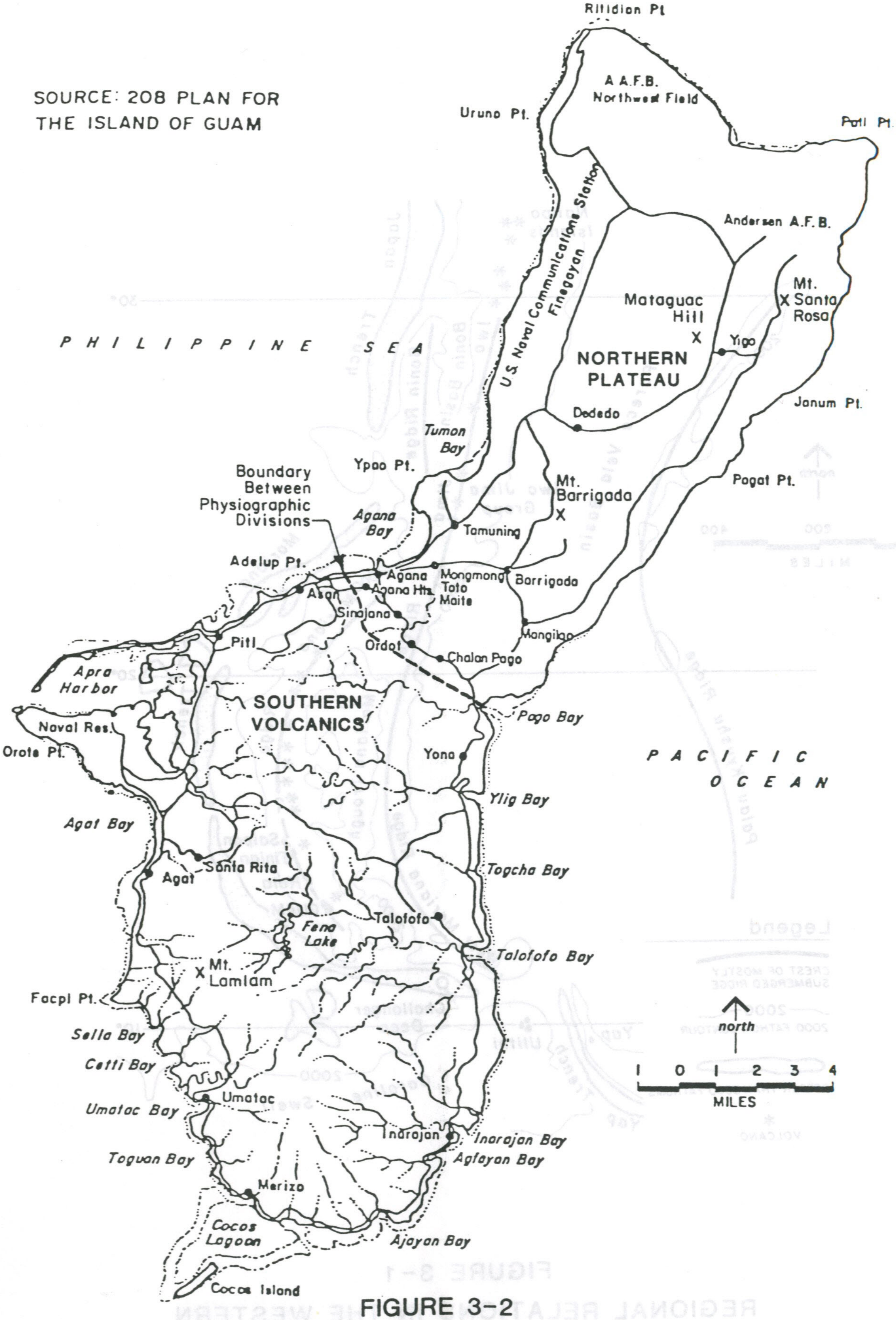


FIGURE 3-2
MAJOR PHYSIOGRAPHIC DIVISIONS OF GUAM

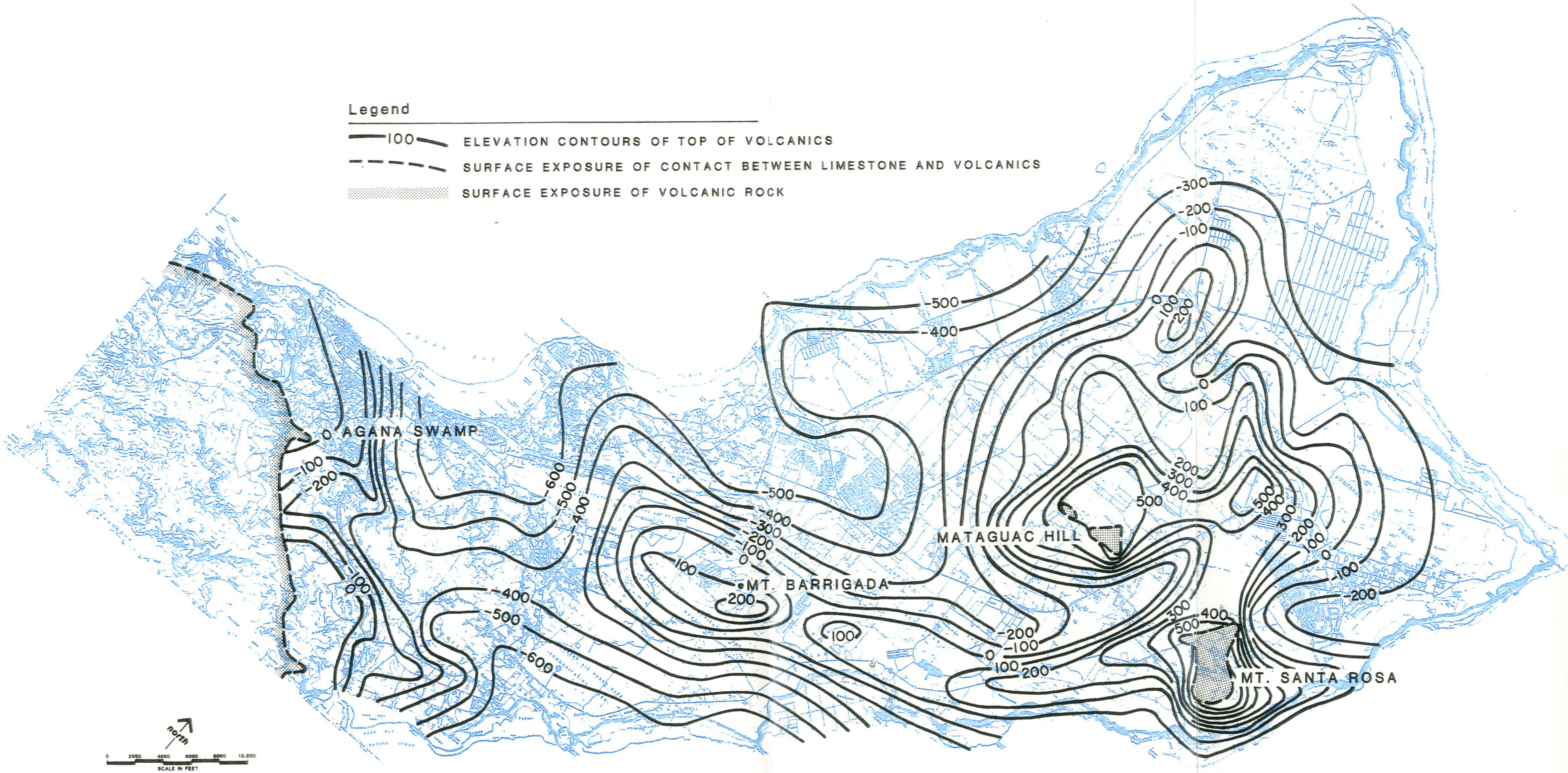


FIGURE 3-3

CONTOUR MAP
OF THE VOLCANIC BASEMENT

and very active tectonism common to those areas along tectonic plate boundaries. The Alutom Formation forms the volcanic formations exposed at Mataguac Hill and Mount Santa Rosa in central part of northern Guam (see Figure 3-4). Here the formation consists of interbedded tuffaceous shale and sandstone, lapillic tuff and conglomerate, flow breccas, and pillow basalts. These beds are cut by numerous minor joints and faults and are moderately folded. Relative to the overlying limestones, the volcanics are virtually impermeable.

The distribution of the volcanic formation beneath northern Guam was determined during the course of the NGLS by both exploratory drilling and geophysical surveys. An explanation of the drilling and geophysical surveys is described in detail in Appendix B-1. A contour map of the subsurface expression of the top of the volcanics was the final product of the exploratory work and is presented on Plate 1. The method by which Plate 1 was developed is described in Appendix B-2.

Barrigada Limestone

The Miocene (20 million years old) Barrigada limestone was deposited on the volcanic Alutom Formation in northern Guam and is exposed in the form of a ring that surrounds Mataguac Hill and Mount Santa Rosa and extends south, around, and over Mount Barrigada (see Figure 3-4). This massive detrital limestone is bright white, pure, and medium- to coarse-grained in an unweathered condition (Tracey, et al, 1964). Fossils range from abundant foraminifera near the bottom to poorly preserved mollusk and coral molds near the top. The maximum thickness of the Barrigada limestone is probably greater than 600 feet (as seen in exploratory wells EX-5 and EX-5a).

The lithology of the Barrigada limestone is somewhat different than the overlying Mariana limestone. Differentiation between the formations is generally based on fossil content, with the Barrigada containing mostly foraminifera and few mollusks and the Mariana containing mostly mollusks and corals and few foraminifera. The vertical variation in fossil content in the Barrigada limestone suggests that the lower part was deposited in water up to 600 feet deep and the top of the formation was probably deposited in less than 200 feet of water.

Mariana Limestone

The Mariana limestone is of Plio-Pleistocene age (about 2 to 5 million years old) and constitutes about 80 percent of the exposed limestones of Guam. It onlaps the Barrigada limestone as a vertical and transgressional facies change from a deep to a shallow water depositional environment. The lithology of the Mariana limestone, though generally massive, varies significantly laterally and vertically and is associated with deposition within different reef and lagoon environments. The reef facies consists of well-cemented, crystalline coral limestone. The detrital or lagoonal facies ranges in composition from coarse, granular limestone with scattered coral heads near the reef facies to fine-grained limestone with scattered to abundant mollusk molds and shells near the paleo-shoreline. The Mariana limestone contains a facies known as the Agana Argillaceous member, which is hydrologically significant because of its relatively low permeability. This member is located below an elevation of 200 feet between Mount Barrigada and the volcanic formation to the south. It is generally yellow to tan in color and is characterized by a high content of calcareous mud associated with the near-shore environment and fine-grained detrital material contributed from the adjacent volcanic rocks.

GEOLOGIC HISTORY

The volcanic formations in the southern half of Guam probably emerged in Early Miocene time as evidenced by the older limestones that were deposited on the volcanic upland. Approximately 10 to 15 million years ago, in late Miocene time, the volcanic islands of northern Guam (Mount Santa Rosa, Mataguac Hill and Mount Barrigada were submerged but came close enough to the ocean surface to support deep limestone formation. These volcanic islands could have been formed as a result of several small independent eruptions, or are the parts of a single larger volcano that subsequently collapsed, leaving remnant ridges and hills. While these volcanos were still at 600 feet below sea level, the Barrigada limestone was forming. As

Legend

- MARIANA LIMESTONE
- AGANA ARGILLACEOUS MEMBER OF THE MARIANA LIMESTONE
- BARRIGADA LIMESTONE
- OTHER LIMESTONE
- ALUTOM FORMATION

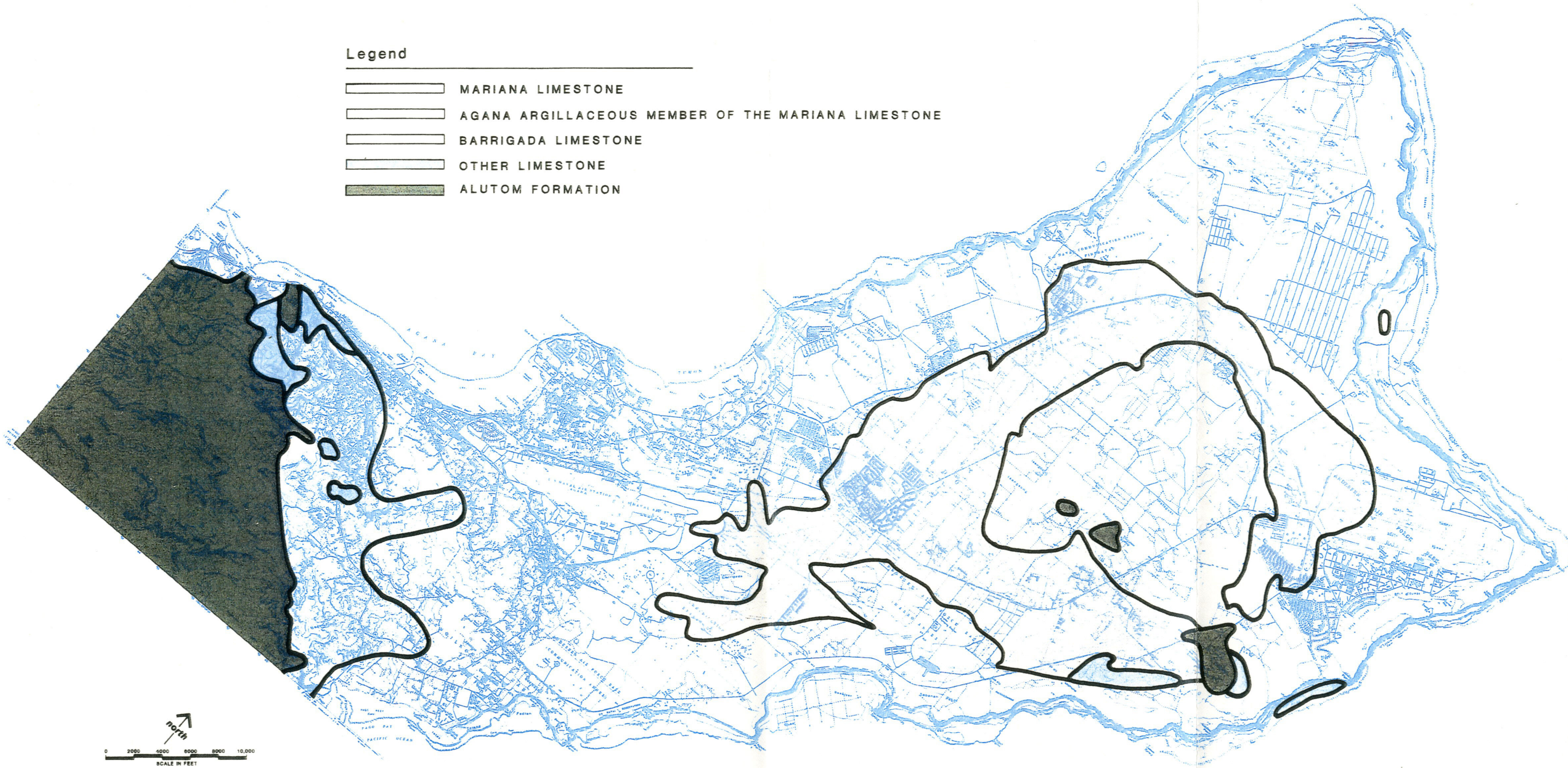
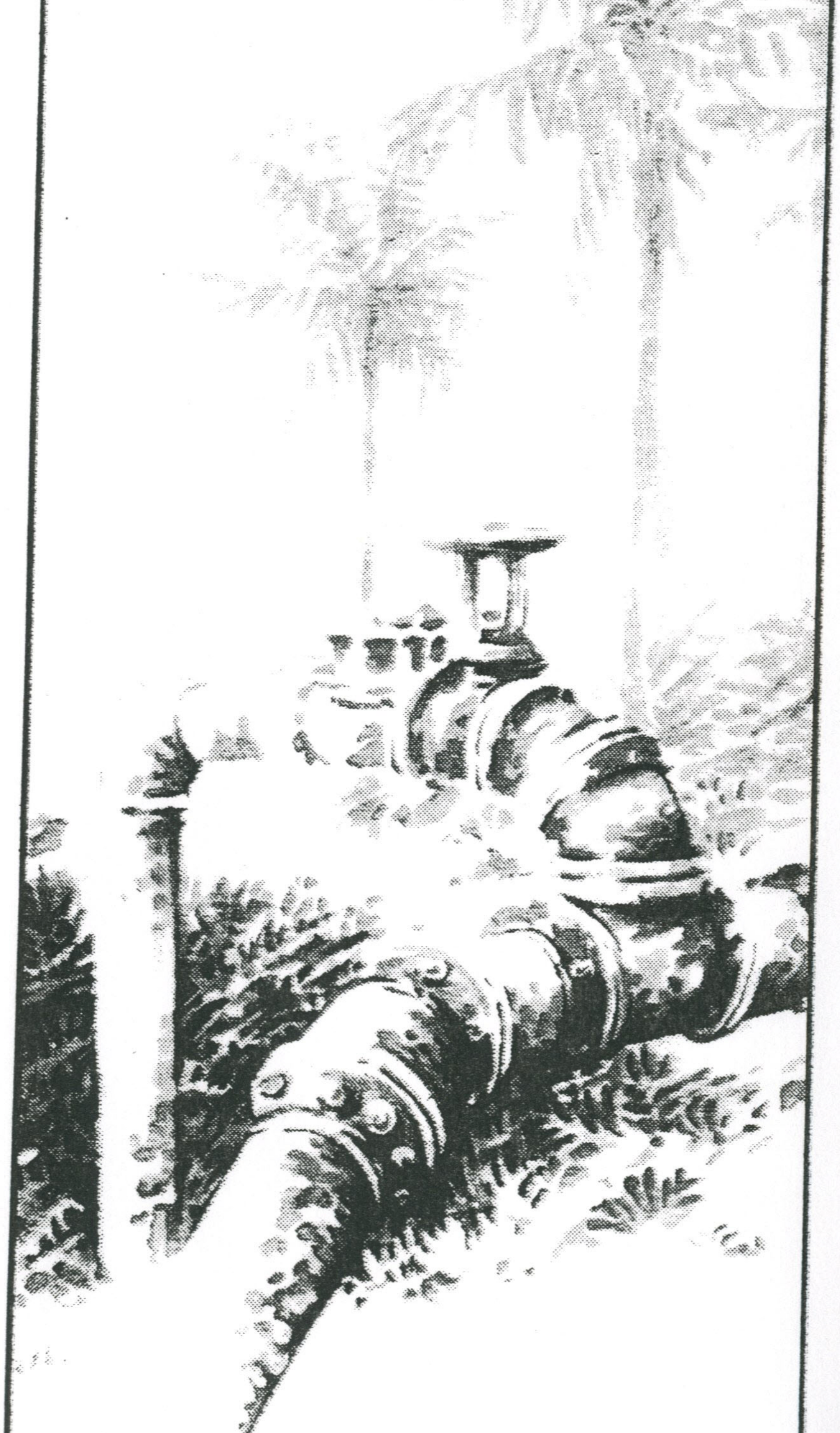


FIGURE 3-4
GENERALIZED GEOLOGY MAP

the volcanic formation rose toward the ocean surface, the change in environment allowed gradual changes in limestone formation (going from foraminiferal Barrigada limestone to coral Mariana limestone associated with abundant mollusk growth). The transition from deep water limestone (Barrigada) to shallow water limestone (Mariana) was completed in Pliestocene time. The island has continued to rise sporadically to its present-day position. Long periods of quiesence were probably punctuated by periods of rapid emergence in the northern half of the island, as evidenced by the terrace formations that occur along the present coastline and along a line extending from Agana past the west side of Mount Barrigada to Yigo. Because this inland cliff slopes from Yigo (on the north) down to Agana (on the south), the northern part of the plateau appears to be rising faster than the southern part. The inland cliff feature has been interpreted by Tracey, et al, (1964) and others to be the result of normal fault activity. At this time, the island appears to be in a period of relative quiesence, with active fringing reefs being formed around the coast of northern Guam. However, because tectonic activity is still on-going in the region of the Mariana Trench, uplift of the island arc and Guam is expected to continue into the geologic future.

IV

HYDROGEOLOGY



IV. HYDROGEOLOGY

GENERAL

This chapter of the report presents a brief discussion of the hydrogeology of the Northern Lens. For the purposes of the report, hydrogeology is defined as the interrelationship between the geology of the aquifer and the fluids (both fresh water and salt water) which are stored in and move through the aquifer. The information presented includes summaries of the work done by the USGS, Mink (1976), and WERI (1982), especially that pertaining to the description of the aquifer and the hydraulic parameters associated with the aquifer. Also discussed are the water level fluctuations in the fresh water lens and an evaluation of the dynamics of the fresh water-salt water interface. Finally, additional investigations are recommended to further advance the understanding of the aquifer geometry, its hydraulic properties, and the dynamics and interrelationship of the fresh water-salt water system.

AQUIFER DESCRIPTION

The aquifer containing the Northern Lens is composed primarily of the Barrigada and Mariana limestones. As discussed in the previous chapter, the Barrigada limestone is primarily a deep water formation containing abundant foraminifera near its stratigraphic base and scattered coral and mollusk shell molds near its upper contact with the Mariana limestone. The Mariana limestone, on the other hand, was deposited in relatively shallow waters of the reef, fore reef, and lagoonal environments.

Porosity

In the aquifer section associated with the fresh water lens, porosity occurs as a result of elliptical voids in the limestone as well as continuous and discontinuous passages through the limestones. These pores range in size from microscopic openings to large, well developed cavern systems;

however, passages are generally about 1/8 to 1/4 inches in diameter. Many of the isolated openings are usually the result of the voids left by mollusk shells. Porosity in passages are formed by dissolution of the limestone by chemically aggressive fresh water which percolates through the aquifer. This latter type of opening is usually associated with fractures or small-scale lithologic differences (such as around and through coral heads) that provide the microscopic passages through which the fresh water can travel.

The Mariana limestone overlies the Barrigada limestone and is composed of a several facies that ranges from clean, fore reef limestone to clastic and calcareous detrital material deposited in a near-shore environment. The porosity of the Mariana limestone varies considerably through the different facies. Research done in Puerto Rico (FUGRO, 1974) suggested that the clean, crystalline limestones deposited in the reef and fore reef environments have higher porosities because their potential for dissolution by fresh groundwater was much higher than for argillaceous limestones. The limestones deposited in a near-shore environment contain more carbonate mud, which effectively reduces dissolution potential, thus exhibiting lower porosity. Finally, the limestones deposited immediately adjacent to subaerially exposed volcanics contain very fine-grained volcanic detrital material that washed into the limestone, significantly reducing its effective porosity (the amount of interconnected pore space available for fluid flow).

Cores from exploratory wells EX-1 and EX-5 were analyzed by WERI (1982) during the NGLS. Exploratory well EX-1 was drilled into the argillaceous limestones located in the southern part of the study area (see Figure 4-1). As was expected, porosities were low, generally less than four percent. Exploratory well EX-5 is located in the clean limestones near Dededo (see Figure 4-1). The porosities in this well ranged from three percent to 26 percent and averaged 13 percent above the water table and 21 percent below the water table.

Core analysis depict very local conditions. To gain insight into regional porosity variations, the gravity data were evaluated (see Appendix B1).

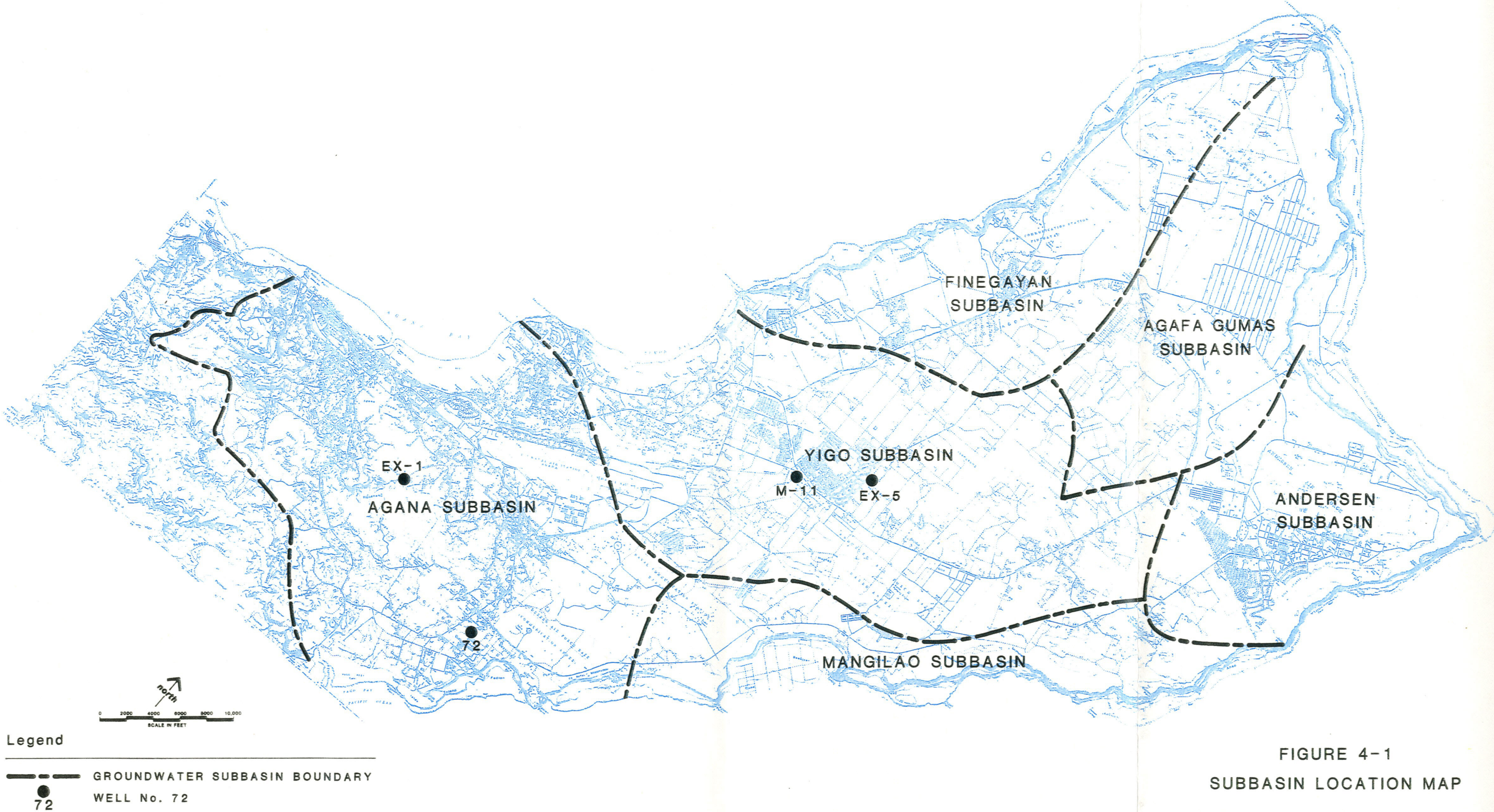


FIGURE 4-1
SUBBASIN LOCATION MAP

That analysis indicated a range in porosity from 13 percent to 20 percent, depending on the mineral composition of the limestone (i.e., aragonite or calcite). These regional porosity estimates compare very favorably to the results of the core analyses done for exploratory well EX-5 by WERI.

The areal variation in limestone porosities varies considerably in northern Guam. But as an overall observation, the porosity, as interpreted by water level heads, core analyses, and computer modeling efforts, increases from south to north.

Permeability

Several methods were used to estimate permeabilities in the limestones of northern Guam. These methods are discussed in detail in Appendix C and are summarized below (and in Table 4-1). The magnitude of limestone permeability is directly related to that of porosity and also increases from south to north through the Northern Lens.

Fresh water heads measured in April 1982, when related to the distances from a well to the coast and from the well to the top of the drainage divide, indicate that permeabilities increase from south to north, through the Northern Lens. In the Agana Subbasin, permeabilities deduced from head and gradiant data range from 1,500 to 3,000 ft/d. Permeabilities in the Mangilao Subbasin are about 1,500 ft/d. In the central part of the lens, permeabilities generally range from about 2,000 ft/d to about 12,000 ft/d, and in the case of Y-4, to as high as 17,590 ft/d.

Using tidal-signal attenuation data, WERI (1982) suggested that the permeability (hydraulic conductivity) ranged from 2,380 feet per day (ft/d) at the USGS monitoring well No. 72, located above Pago Bay (see Figure 4-1), to 12,400 ft/d at M-11, located near Dededo. WERI noted that these permeabilities were quite sensitive to porosity, which they assumed to be 15 percent for the permeabilities quoted on Table 4-1.

TABLE 4-1

COMPARISON OF PERMEABILITIES
(Feet Per Day)

	Method			
Well No.	Fresh Water Head and Gradient*	Tidal Attentuation (porosity=0.15)	Drawdown Recovery Test	Salt-Water Intrusion Analyses
72	2,355	2,380	-	-
H-107	3,745	5,610	-	-
M-10a	4,940	6,790	-	-
A-16	3,035	8,155	-	-
A-10	1,575	-	1,030	-
A-13	2,285	-	780	-
D-4	11,475	-	1,300	-
D-15	12,760	-	-	-
F-2	3,410		2,080	3,300
M-6	7,530	-	450	-
M-7	5,470	-	1,850	-
M-11	9,950	12,400	-	-
M-9	1,680	-	-	525
M-4	-	-	1,300	-
Y-4	17,590	-	-	-

*Permeabilities for other wells are provided on Table C-1 in Appendix C.

During the course of the NGLS, permeabilities were evaluated on the basis of drawdown-recovery tests conducted for several wells throughout the lens. The permeabilities range from about 780 to about 1,000 ft/d in the argillaceous limestone in the Agana Subbasin (Figure 4-1). In the clean limestones of the Mangilao and Finegayan Subbasins, permeabilities generally ranged between 1,000 and 2,000 ft/d.

Analyses of salt water intrusion using a numerical model were conducted for the Finegayan and Mangilao Subbasins. In the Mangilao Subbasin, permeability is estimated to be about 525 ft/d. In the Finegeyan and western Yigo Subbasins, the permeabilities ranged between 2,500 and 4,000 ft/d, and averaged 3,300 ft/d.

Basal and Parabasal Lenses

Figure 4-2 shows the relative distribution of the basal and parabasal lenses. A basal lens is defined as the area in which fresh groundwater is immediately underlain by salt water. A parabasal lens is in hydraulic continuity with the basal lens except that the fresh water is underlain by impermeable volcanic formations. The salt water toe is located along the line of intersection between the fresh water-salt water interface and the contact between the limestone and volcanic basement rocks. The delineation of these two lens types is important because salt water can rise vertically into a pumping well located in the basal lens (upconing), but cannot rise into a well in a parabasal lens because it is not underlain by salt water. However, if a parabasal lens is heavily pumped, salt water will intrude inland, thus causing the salt water toe (the boundary between the basal and parabasal lens) to move inland. If the toe migrates beneath a parabasal well, that well will be susceptible to upconing.

FRESH WATER-SALT WATER LENS CHARACTERISTICS

This section discusses the characteristics of the fresh water and salt water aquifers in northern Guam. Particular emphasis is given to the short-term and seasonal fluctuations in the fresh water levels, as well as the conditions that affect the transition zone between the fresh water lens and underlying salt water.

Water Level Fluctuations in the Fresh Water Lens

Until late in the NGLS, reliable long-term and seasonal fresh water head measurements were restricted to seven USGS monitoring stations and about seven wells periodically measured by the USGS. Extensive groundwater measurement programs were undertaken in 1972 and 1973, but accurate head values were unreliable because the topographic control at the measuring points was not accurate to the degree required for the lens analysis. At the beginning of the NGLS, a detailed elevation survey was completed for all the wells in the Northern Lens for GEPA (see Appendix A). In September 1981, water levels in a few key wells were measured by the Consultant and the USGS. Then, in April 1982, the Consultant and the USGS measured water levels in nearly every municipal well in the Northern Lens (over 70). This information provided a reliable indication of the areal distribution of water levels in northern Guam. These efforts were important for three reasons:

1. They provided information on seasonal variations in water levels at various locations throughout the lens. This information augmented the data collected at the seven continuous water level recording wells established by the USGS.

2. They permitted limestone permeabilities to be estimated using the water levels in conjunction with measured distances between the observation well and the coast.

3. They allowed better estimates of the location of the salt water toe to be calculated over a wider area. These estimates are shown on Figure 4-2.

Figure 4-3 shows the April 1982 (middle of the dry season) fresh water elevation contours for the Northern Lens. As is shown on this figure, basal heads are quite high in the Agana Subbasin, ranging over 7 feet above MSL.

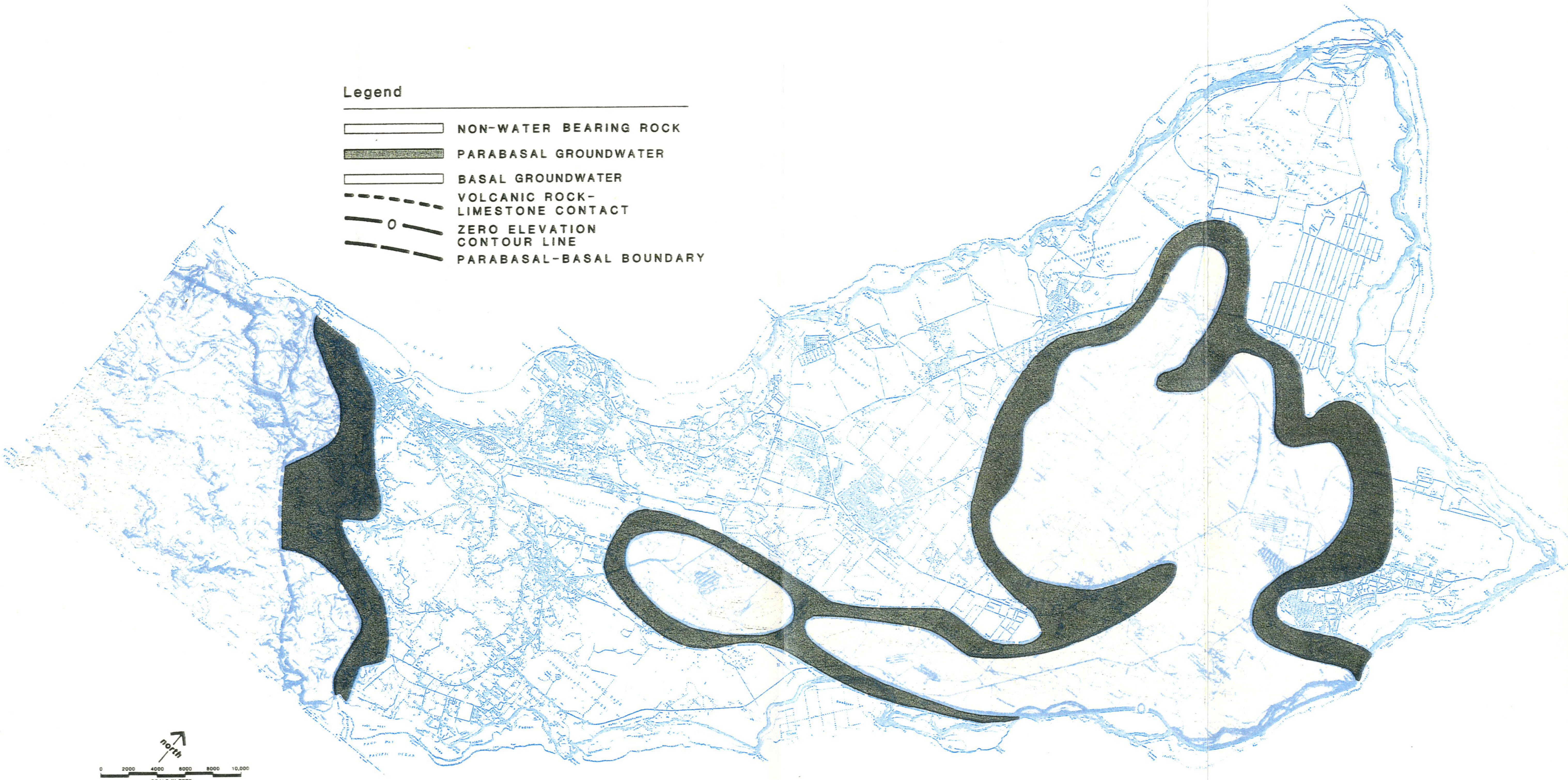


FIGURE 4-2

DISTRIBUTION OF
GROUNDWATER TYPES

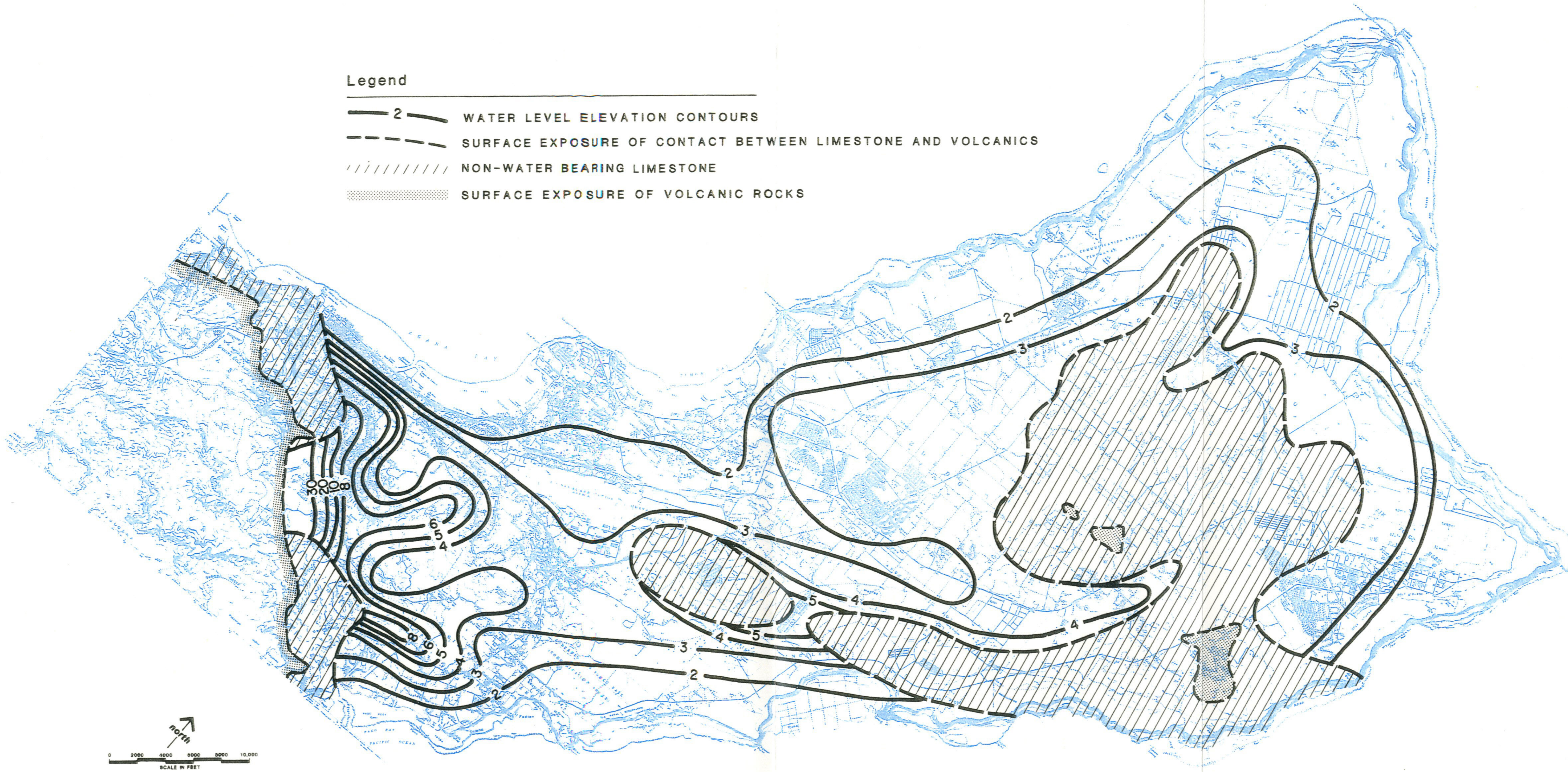


FIGURE 4-3

WATER LEVEL CONTOUR MAP
APRIL 1982

These high head values are the result of the low permeability of the limestone aquifer in this area (assuming that recharge is relatively constant over the region). In the northern and central parts of the lens, the heads generally range between 2.5 and 4 feet above sea level, indicating relatively high permeability for the aquifer.

Because limited water level data are available for other seasons of the year, regional water level variations can only be estimated. At Well No. A-16 (Plate 1) in the Agana Subbasin, the USGS water level recorder shows seasonal fluctuations of about 1.75 feet for water year 1977-1978, and a historic extreme fluctuation of about 3.6 feet. Water levels in September 1981 (wet season) and April 1982 (dry season) taken by the USGS and the Consultant during the NGLS at Well No. A-9 show a variation of about two feet seasonally for the 1981-82 water year (Appendix A, Table A-8). In the northern and central subbasins, where permeabilities are higher, fluctuations are lower. For example, water levels in Exploratory Well EX-7 (west of Dededo) varied about 0.35 feet between September 1981 and April 1982; EX-10 (south of Finegayan) varied about 0.20 feet between those dates (see Plate 1 for well locations).

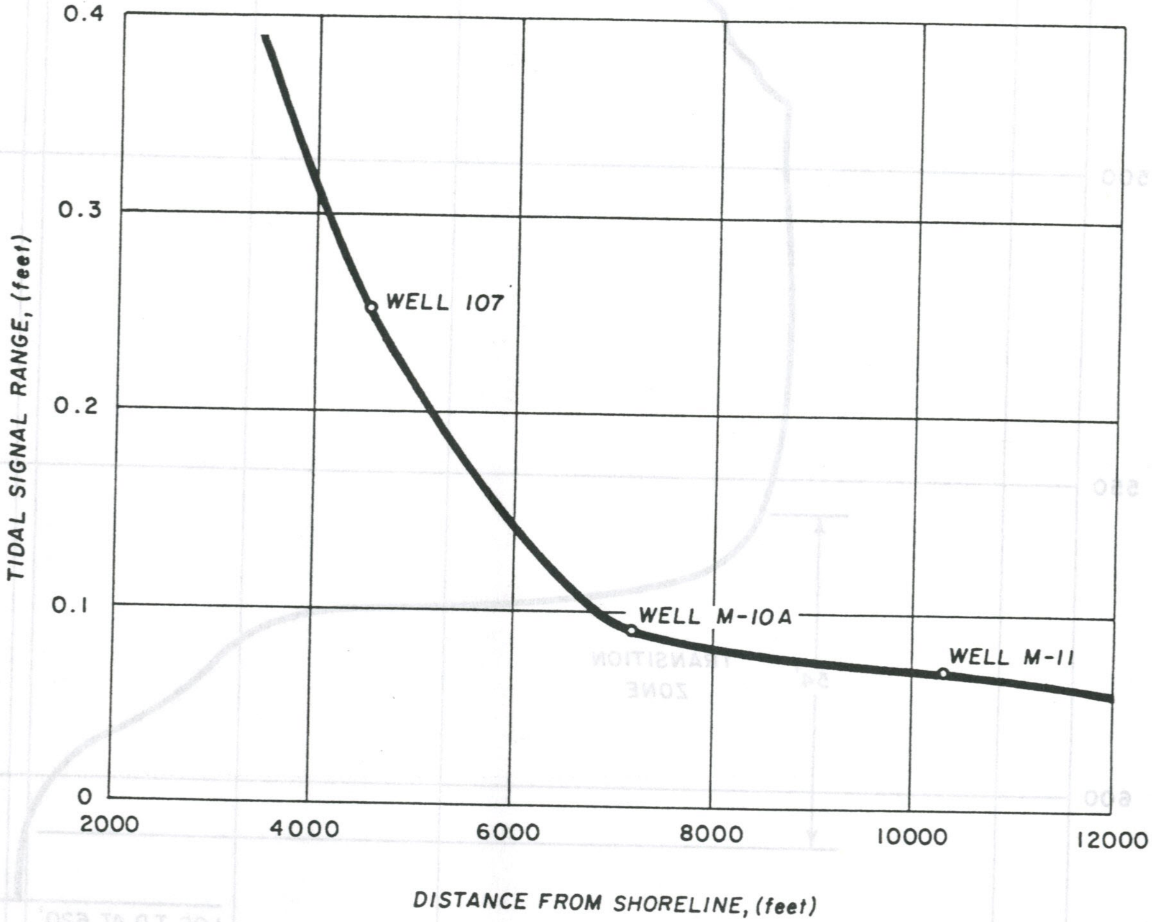
As pointed out in WERI's hydrogeologic report (1982), water level fluctuations also vary as a result of regional sea level changes and tidal influence from the nearby coast. Figure 4-4 shows that tidal effects decrease with distance from the coastline because of the dampening effect of the aquifer formation. At Well No. 107 (see Plate 1) near the coast in the Yigo Subbasin, the tidal signal range is on the order of 0.4 feet. Inland, this effect decreases to less than 0.1 feet at Wells M-10a and M-11. Regional sea level changes may account for ranges in groundwater level fluctuations on the order of one foot relative to mean sea level. Because these changes have a relatively long period (on the order of yearly), the response of the water levels is much smoother compared to the sharp diurnal and semi-diurnal changes found for tidal effects.

Transition Zone

The thickness of the fresh water lens over a salt water body is governed by the amount of head above sea level that exists at a particular location. At equilibrium, for every foot of head above sea level, 40 feet of fresh water theoretically occurs below sea level (this relationship, known as the Ghyben-Herzberg principal, is based on the density difference between fresh water and salt water). For this relationship to be entirely accurate, the boundary between the two types of water must be sharp. Actually, this boundary is gradational, resulting in a zone of varying salinity between the sea water and fresh water lens known as the transition zone. To analytically evaluate the interrelationship between the salt water and fresh water lens, the assumed boundary between the two lenses is taken to be the point where salinity is 50 percent of the salinity of sea water. A detailed description of the transition zone is provided in Appendix D; the pertinent points are discussed below.

The transition zone occurs as a result of stresses on the aquifer, such as tidal fluctuations, seasonal variations in recharge, and pumping. The thickness of the transition zone varies over the Northern Lens. The configuration of the transition zone is measured by passing a conductivity probe through the fresh water into the underlying salt water. An example of this type of survey is illustrated on Figure 4-5 for Exploratory Well No. EX-8. The relative salinity in transition from fresh water to salt water roughly follows the error function curve of normal distribution. As shown on Table 4-2, lower permeability aquifers generally have thicker transition zones than those areas of higher permeability. For example, EX-4, which is located in the argillaceous limestone, has a permeability of about 1,300 ft/d (Table C-1, Appendix C) and a transition zone thickness of 80 feet (Figure A-3, Appendix A). On the other hand, EX-10, drilled into clean limestones in the central part of the Northern Lens, has a permeability of about 6,600 ft/d (Table C-1, Appendix C) and a transition zone thickness of about 32 feet (Figure A-7, Appendix A).

The relative impact of the stimuli affecting the aquifer varies regionally. For example, in the Yigo Subbasin, fresh water head fluctuations due to



NOTE: FROM HYDROGEOLOGIC REPORT FOR THE NORTHERN GUAM LENS STUDY BY THE UNIVERSITY OF GUAM, WATER AND ENERGY RESEARCH INSTITUTE (1982).

FIGURE 4-4

TIDAL SIGNAL ATTENUATION RATE FOR INLAND WELLS

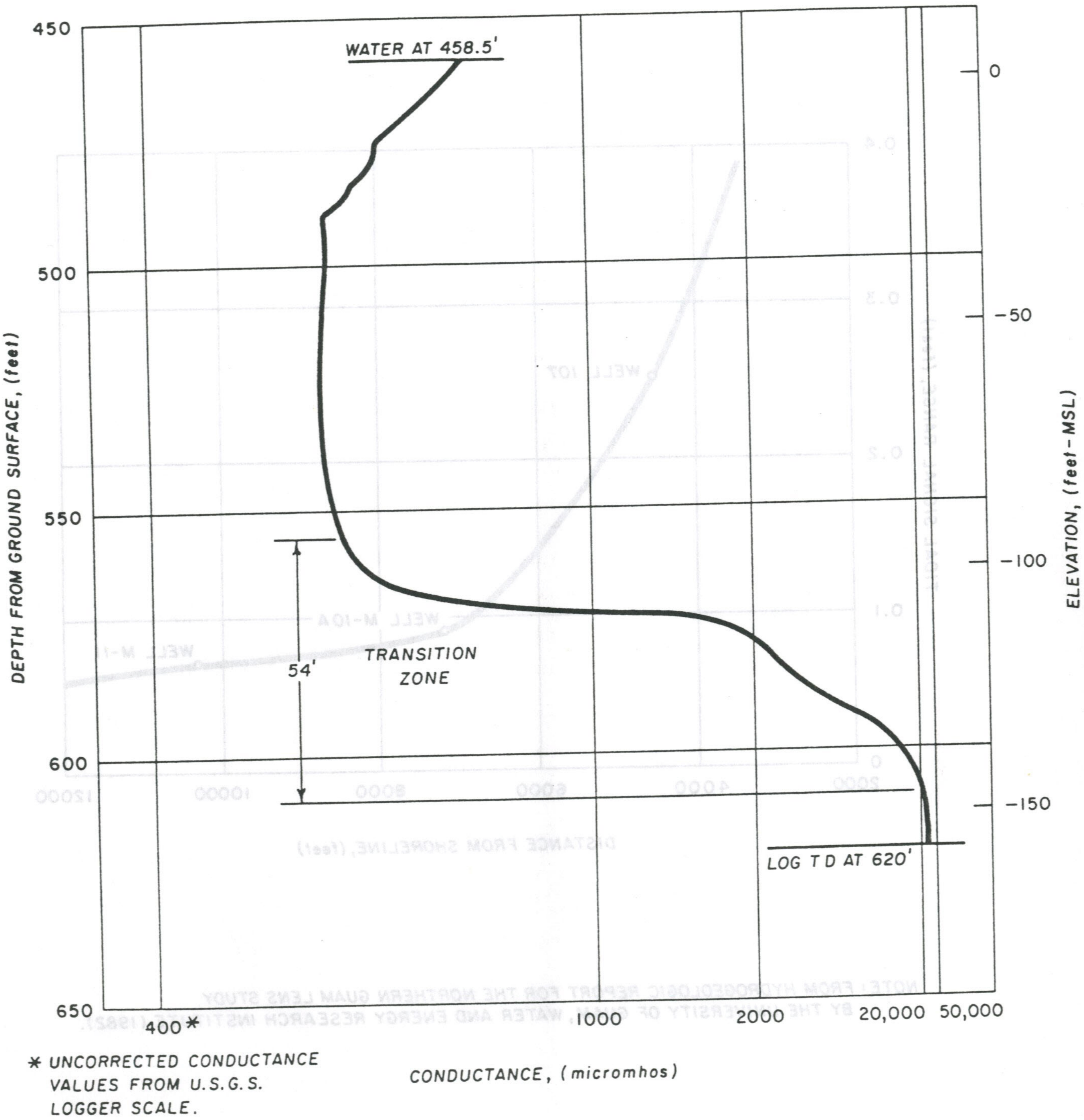


FIGURE 4-5
CONDUCTIVITY LOG - WELL EX-8
FEBRUARY 12, 1982

TABLE 4-2

COMPARISON OF PERMEABILITY AND TRANSITION ZONE THICKNESS IN NORTHERN GUAM

Exploratory Well Number	Transition Zone * Thickness (feet)	Permeability ** (feet/day)
EX-1	104	830
EX-4	80	1,300
EX-7	27	5,700
EX-8	54	8,500
EX-9	45	4,500
EX-10	32	6,600

* From Figures A-2 though A-8, Appendix A.
** From Table C-1, Appendix C.

tidal effects vary from 0.4 feet near the coast to less than 0.1 feet inland (see Figure 4-4). At the equilibrium condition, these fluctuations would translate into a 4- to 16-foot variation in transition zone thickness for instantaneous adjustment according to the Ghyben-Herzberg relationship. However, equilibrium conditions of the lens are never achieved instantaneously due to hydrostatic influences, so that actual movement of the interface cannot be determined directly from changes in water level elevations. In this same area, recharge causes a seasonal fluctuation of about 0.5 feet, which translates (again, at equilibrium) into a transition zone variation of 20 feet. Pumping can cause a local variation in groundwater level of about 0.3 feet, with a corresponding fluctuation in the transition zone of about 12 feet. Taken together, these stimuli theoretically create a transition zone that is on the order of 35 to 50 feet thick. In the Dededo area, measured transition zone thicknesses vary from about 27 feet at Exploratory Well No. EX-7 (see Appendix A, Figure A-4) to 47 feet at the Guam Housing and Urban Renewal Authority Monitoring Well, referred to locally as the GHURA-Dededo well (see Appendix A, Figure A-8). Therefore, the theoretical and actual transition thicknesses are comparable.

SUMMARY OF SUBBASIN HYDROGEOLOGY

The hydrogeologic characteristics of the six subbasins of northern Guam (see Figure 4-1) vary considerably. The following paragraphs summarize the hydrogeology of each subbasin.

Agana Subbasin

The aquifer in the Agana Subbasin is the Argillaceous member of the Mariana limestone. As indicated by the investigation of drilling cores by WERI (1982), porosities within the fresh water aquifer of this area are generally less than four percent. Permeabilities range from less than 500 ft/d in the southern part of the subbasin to over 3,000 ft/d near Mount Barrigada in the northern part of the subbasin (Table C-1, Appendix C); regional permeabilities probably average between 500 ft/d and 1,500 ft/d in the subbasin. The very high parabasal lens heads (20 to 30 feet) measured in the extreme southern portion of the Northern Lens suggests that permeabilities in this area are much lower than the subbasin average and are probably on the order of 10 to 100 ft/d.

Because permeabilities are low in the subbasin, water recharging the aquifer does not flow quickly toward the ocean upon reaching the water table. Because of this, the recharge waters accumulate, resulting in higher water levels relative to other areas of the Northern Lens. Basal lens water levels in the central part of the subbasin generally range between 4 and 7 feet above sea level and fluctuate 2 to 3 feet seasonally. Parabasal water levels range to over 30 feet along the southern boundary of the subbasin.

Mangilao Subbasin

The Mangilao Subbasin is located on the east side of the ridge connecting Mount Barrigada and Mount Santa Rosa. Aquifers in this subbasin are in both the Barrigada and Mariana limestones. Based on analysis of similar limestones and the estimated aquifer permeability, porosities within the fresh water aquifer of this area are probably in the range of 10 to 20 percent. Permeabilities range from about 500 to 2,000 ft/day (Table 4-1). Water levels in the basal portion of the aquifer are around 3 feet above mean sea level. Parabasal heads measured at Well No. M-11 (near Mount Barrigada) range up to about 5 feet above mean sea level. In the northern part of the subbasin, near Janum Point, limestones are relatively thin over the volcanic formation, and as a result, water recharging this area tends to migrate as sheet flow on the volcanics that make up the east flank of Mount Santa Rosa. Flow continues to nearly the coastline, where it discharges from springs (the largest is Janum Spring). Basal groundwater does not appear to occur in this area.

Andersen Subbasin

The Andersen Subbasin is located on the northeast corner of northern Guam, beneath Andersen Air Force Base. The Mariana and Barrigada limestones form the aquifer of this subbasin. Porosities within the fresh water aquifer are estimated to be in the range of 10 to 20 percent, based on the estimated permeability of about 2,000 ft/d. Maximum basal water levels are about 3 feet. Wells are not known to penetrate the parabasal portion of the lens in this subbasin, so water levels here are unavailable. Tarague Spring, located west of the main runway at Andersen Air Force Base occurs in cavernous Mariana limestone. The spring produced water for many years until intrusion of saline water contaminated the supply.

Agafa Gumas Subbasin

The Agafa Gumas Subbasin is located on the northwest corner of the island. The aquifer is contained within the Barrigada and Mariana limestones. Permeabilities are relatively high and probably range to over 8,000 ft/d (Table C-1, Appendix C). Judging from the magnitude of the permeabilities, porosities in the fresh water aquifer are probably also high, on the order of 15 to 25 percent. Basal water levels are highest near Agafa Gumas, with a value of 4 to 5 feet above sea level. In the larger portion of the subbasin north of Agafa Gumas, water levels are between 2.5 and 3 feet. Parabasal water levels are greater than 5 feet above sea level.

Finegayan Subbasin

The Finegayan Subbasin is located along the western flank of Mataguac Hill. The aquifer consists of the Mariana and Barrigada limestones. Permeabilities range from about 3,000 to over 4,000 ft/d in the subbasin. Porosities within the fresh water aquifer are probably correspondingly high, in the range of 15 to 20 percent. Maximum basal water levels are between 2.5 and 3.5 feet above mean sea level. Parabasal water levels have never been measured, but are probably on the order of 4 to 5 feet above sea level.

Yigo Subbasin

The Yigo Subbasin is the largest subbasin in northern Guam and is located on the western flank of the ridge that connects Mount Santa Rosa and Mount Barrigada. Unique among the Northern Lens subbasins, the aquifer is contained in a long, relatively narrow trough between Mataguac Hill and the Mount Barrigada-Mount Santa Rosa Ridge. The head of the trough begins between Mount Santa Rosa and Mataguac Hill and extends southwestward into Tumon Bay. The aquifer formations within the trough are the Barrigada and Mariana limestones. Permeabilities here are the highest of northern Guam's aquifers range between about 4,000 and 15,000 ft/d. The corresponding porosities are probably as much as 15 to 30 percent. Basal water levels within the subbasin range from about 3 feet near Dededo to over 4 feet near Yigo. Parabasal water levels have not been measured.

RECOMMENDED STUDIES

To refine the estimates of the limestone aquifer hydrodynamics, particular emphasis should be placed on determining the areal distribution of aquifer permeability and porosity, as well as further investigation of those areas where the geometry of the aquifer is not well known (such as at Northwest Field and Andersen Air Force Base). Much of this knowledge will automatically become available as the groundwater production facilities are expanded. Therefore, the information presented in this report should be reevaluated as new wells are drilled and tested.

V. HYDROLOGY

GENERAL

This chapter of the report discusses the hydrologic aspects of the NGLS which are directly pertinent to determining the sustainable yield of the Northern Lens. Topics addressed are the determination of the amounts and areal distributions of precipitation, pan evaporation, potential evapotranspiration, recharge and leakage. Because hydrologic data are limited for the purposes of accurately determining sustainable yield, the chapter concludes with recommendations for future hydrologic data collection programs that could be used to verify these estimates.

MANAGEMENT ZONES

To make it easier to determine the hydrologic parameters and to provide maximum flexibility in implementating and managing future water supply development programs, northern Guam has been divided into six major hydrologic subbasins, which, in turn, have been subdivided into 47 management zones (see Figure 5-1). The boundaries between hydrologic subbasins have been drawn along sub-topographic divides on the top of the volcanic basement (see Plate 1). By subdividing the basins into management zones, areal variations in meteorological data can be more accurately represented. In addition, management alternatives can be easily evaluated and implemented because the magnitude of resource development is dependent upon the sustainable yield in the specific area of demand. The management zones in each subbasin are separated into areas underlain by basal and parabasal groundwater. The management zones underlain by basal groundwater do not extend any closer to the coastline than 4,000 feet to provide a fresh water barrier or buffer between the ocean and the inland areas being heavily produced. The management zones underlain by parabasal groundwater extends from the salt water toe inland to the drainage divide. However, significant amounts of groundwater cannot be produced much further inland than the zero elevation volcanic basement contour because groundwater occurs here only as a relatively thin sheet which flows on top of the volcanics. For further ease, the existing well fields have been isolated in their own management zones as much as possible from those areas that are relatively undeveloped.

PRECIPITATION

The first rainfall measurements were made in Guam in 1906 at the Naval Station. Three raingages operated in Guam up until 1941 and the Japanese occupation of the island. Bewteen 1947 and 1951, Pacific Island Engineers established 13 raingages throughout the island, and in 1952, the USGS, U.S. Navy, and U.S. Air Force established about 20 stations. Most of these stations were operated for only a few years and abandoned. The long-term and most reliable raingage stations in northern Guam were installed in 1950, and from this date, the best record of rainfall for northern Guam was established. The USGS started compiling all records starting in 1951 for their own stations, as well as those stations operated by the Government of Guam, the U.S. Navy, and the U.S. Air Force. Their efforts continued through 1979. The National Oceanographic and Atmospheric Administration (NOAA) has compiled and published meteorological data for a few raingage stations in Guam since 1954. In 1980, seven raingage stations were in operation today, as shown on Figure 5-2. Appendix A (Tables A-1 through A-2h) contains a summary of northern Guam precipitation data which were used in this report for determining recharge, leakage, and sustainable yield.

The base period of record for the rainfall analyses performed during the NGLS was selected for the 31-year period from 1950 through 1980. Over that period, the Northern Lens had an average annual rainfall of about 94 inches. Average annual rainfall values ranged from 86 inches at the Naval Air Station in Tamuning to nearly 100 inches at the Yigo Agricultural Station. The areal variation in annual average rainfall is shown on the isohyetal map for northern Guam (see Figure 5-2).

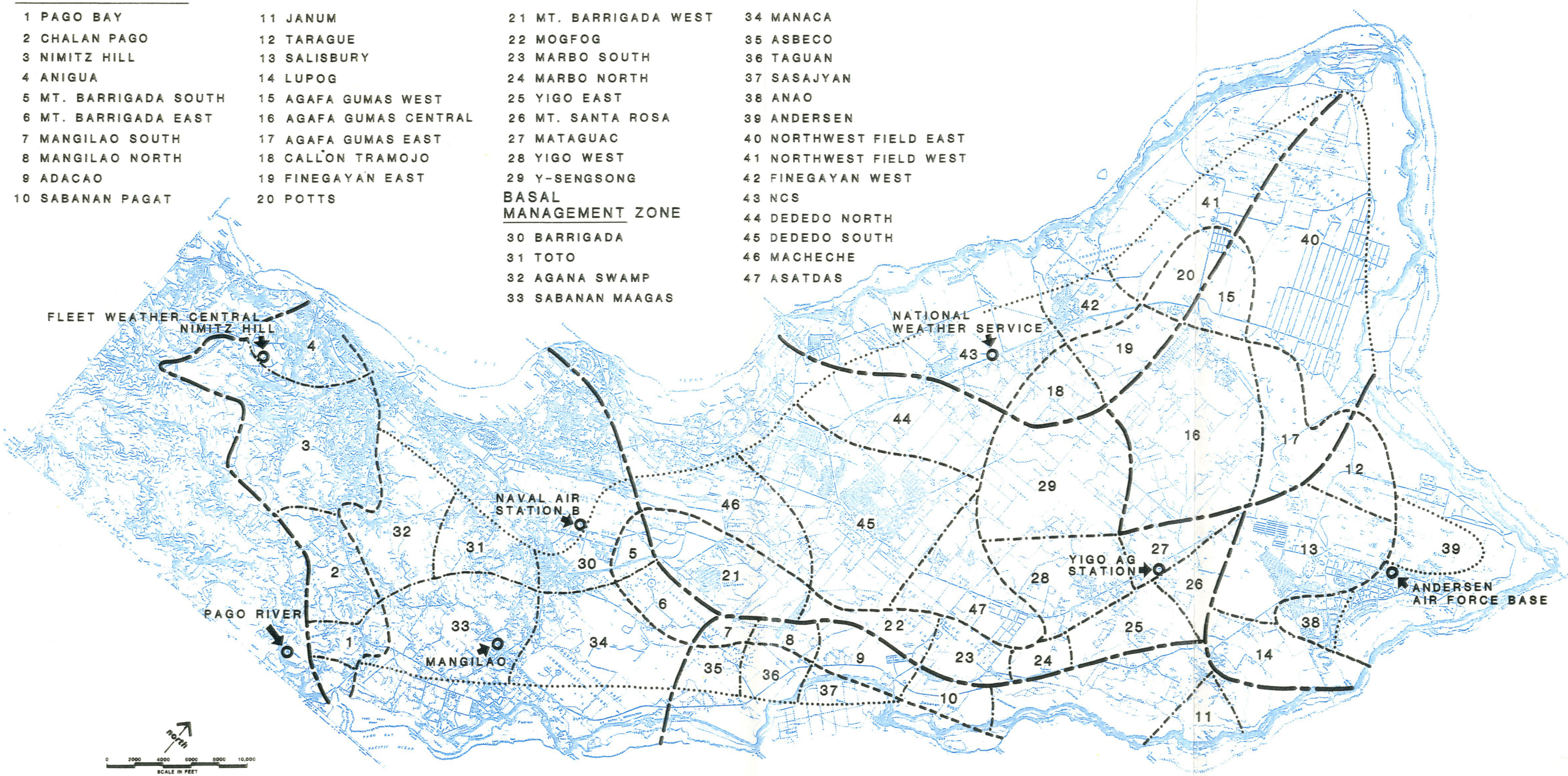
Table 5-1 shows the monthly and annual average precipitation for the eight stations (as shown on Figure 5-2) used to evaluate the areal distribution

PARABASAL MANAGEMENT ZONE

1 PAGO BAY
2 CHALAN PAGO
3 NIMITZ HILL
4 ANIGUA
5 MT. BARRIGADA SOUTH
6 MT. BARRIGADA EAST
7 MANGILAO SOUTH
8 MANGILAO NORTH
9 ADACAO
10 SABANAN PAGAT
11 JANUM
12 TARAGUE
13 SALISBURY
14 LUPOG
15 AGAFA GUMAS WEST
16 AGAFA GUMAS CENTRAL
17 AGAFA GUMAS EAST
18 CALLON TRAMOJO
19 FINEGAYAN EAST
20 POTTS
21 MT. BARRIGADA WEST
22 MOGFOG
23 MARBO SOUTH
24 MARBO NORTH
25 YIGO EAST
26 MT. SANTA ROSA
27 MATAGUAC
28 YIGO WEST
29 Y-SENGSONG

BASAL MANAGEMENT ZONE

30 BARRIGADA
31 TOTO
32 AGANA SWAMP
33 SABANAN MAAGAS
34 MANACA
35 ASBECO
36 TAGUAN
37 SASAJYAN
38 ANAO
39 ANDERSEN
40 NORTHWEST FIELD EAST
41 NORTHWEST FIELD WEST
42 FINEGAYAN WEST
43 NCS
44 DEDEDO NORTH
45 DEDEDO SOUTH
46 MACHECHE
47 ASATDAS

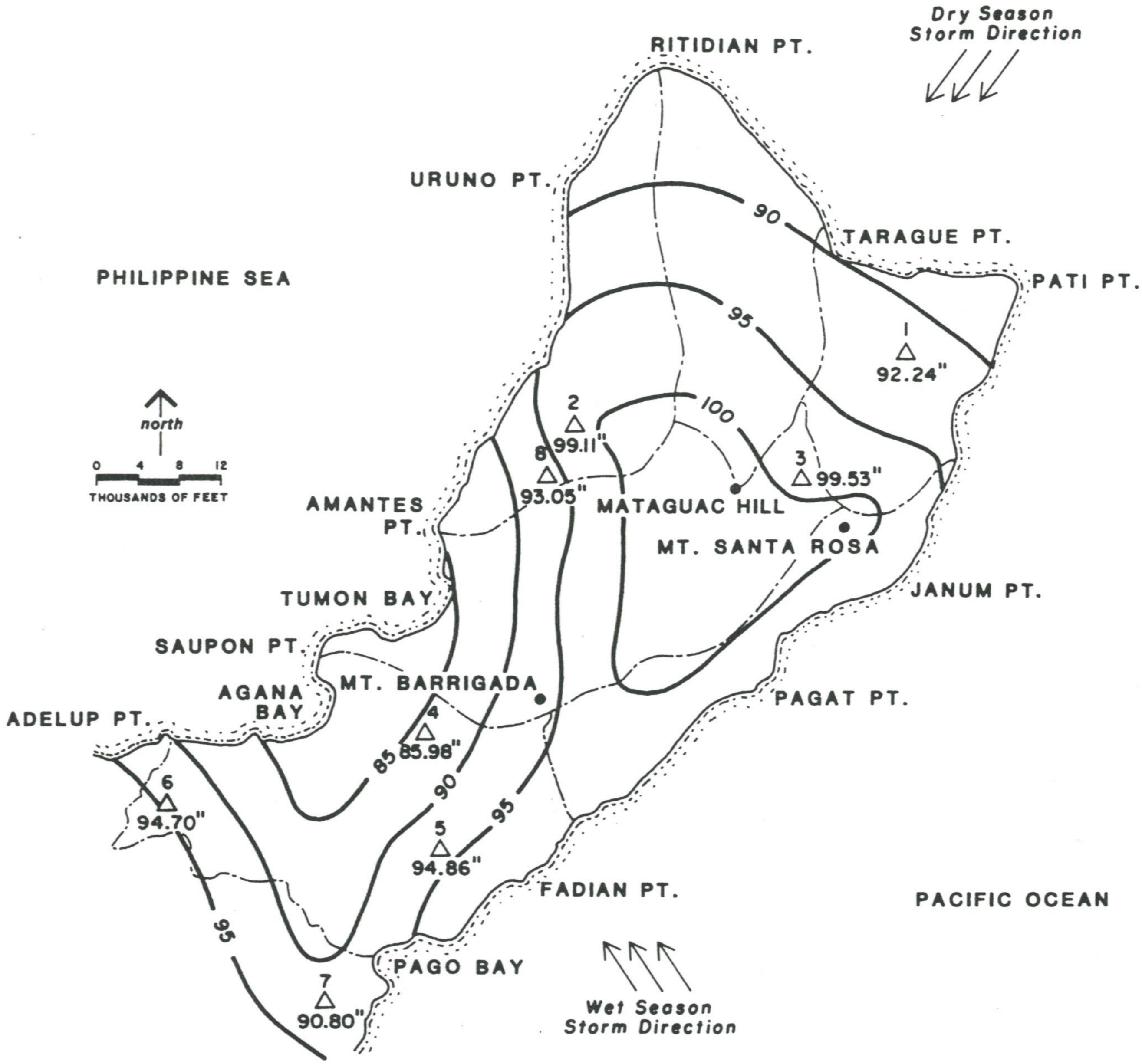


Legend

GROUNDWATER SUBBASIN BOUNDARY
PARABASAL - BASAL BOUNDARY
MANAGEMENT ZONE BOUNDARY
BOUNDARY FOR SAFE PUMPING
RAINGAGE STATION

FIGURE 5-1

GROUNDWATER MANAGEMENT ZONES
NORTHERN LENS



Raingage Stations

1. ANDERSEN AIR FORCE BASE
2. NATIONAL WEATHER SERVICE
3. YIGO-FINEGAYAN AG. STATION
4. NAVAL AIR STATION
5. MANGILAO
6. FLEET WEATHER CENTRAL - NIMITZ HILL
7. PAGO RIVER
8. NAVAL COMMUNICATIONS STATION

Legend

△ 93.05"	RAINGAGE STATION LOCATION & AVG. ANN. RAINFALL IN INCHES
(dash-dot line)	HYDROLOGIC SUBBASIN BOUNDARY
90 (heavy line)	AVERAGE ANNUAL RAINFALL CONTOUR (INCHES)

FIGURE 5-2

AVERAGE ANNUAL RAINFALL
NORTHERN GUAM

TABLE 5-1

SUMMARY OF MONTHLY AND ANNUAL AVERAGE
PRECIPITATION AT SELECTED SITES IN NORTHERN GUAM*

Station Location	Average Monthly Precipitation (inches)												Average Annual Precipitation (inches)
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Naval Air Station	4.53	3.40	2.91	3.52	5.41	5.36	9.84	12.57	13.55	11.94	8.90	4.99	85.98
Andersen Air Force Base	5.04	4.64	3.85	3.86	6.11	5.12	9.72	13.00	12.66	13.52	8.55	5.87	92.24
Yigo Agricultural Station	3.85	5.50	4.04	4.41	6.91	5.38	10.26	13.64	13.27	14.81	9.04	7.68	99.53
National Weather Service Finegayan	5.56	4.70	4.03	4.07	6.71	5.61	10.70	13.97	14.66	13.93	8.93	6.24	99.11
Mangilao	5.64	4.14	3.15	4.10	5.80	6.38	9.40	13.14	15.42	11.92	9.15	5.61	94.86
Fleet Weather Central Nimitz Hill	5.23	3.93	3.63	5.89	5.09	5.95	10.58	13.43	13.35	13.35	9.41	5.62	94.70
Naval Communications Station	5.93	3.38	3.72	3.13	6.40	6.31	9.31	14.59	12.72	13.17	8.58	5.82	93.05
Pago River	4.61	3.89	3.06	3.53	5.48	6.37	9.92	13.46	13.04	12.47	8.92	5.89	90.80
Average of Stations	5.05	4.20	3.55	3.81	5.99	5.81	9.97	13.48	13.58	13.14	8.93	5.96	93.78

* Incomplete rainfall records correlated to the Naval Air Station record which covers a 31-year base period from 1950-1980.

of rainfall in northern Guam. The longest and most complete record of these eight stations was from the Naval Air Station (NAS). The other seven stations had records that varied in length from seven years at the Mangilao station to 31 years at Andersen Air Force Base. So that rainfall estimates would be based on the entire 31 years for all stations, the record at the Naval Air Station was used to fill in the missing monthly data for the other seven stations. Date fill-in was done by performing a regression analysis for the corresponding years and months for NAS and the station in question. These expanded records are provided on Tables A-2a through A-2h in Appendix A.

The filled in rainfall record indicates distinct dry and wet seasons in Guam. The dry season runs from January through June. During this season rainfall comes from local showers. The seasonal average rainfall during the dry season is approximately 5 inches per month.

The typhoon season marks the beginning of the wet season, which runs from July through December. Rainfall during the wet season is produced from major regional storm systems. During this season, the average rainfall is about 12 inches per month. The maximum monthly rainfall generally occurs in August and September and has historically ranged to over 30 inches per month, but averages about 14 inches per month. During typhoons, rainfall intensities are extreme and can be as much as eight inches in two hours, 18 inches in 12 hours, and 24 inches in 24 hours (Tracey, et al; 1964). However, the long-term records show that monthly and annual rainfall are rather consistent on Guam, with the exception of high intensity rain generated during the occassional strong typhoons.

Northern Guam does not have a well established, incised drainage system because the limestones are so permeable that rainfall infiltrates almost immediately upon reaching the ground. An exception to this is the Fonte River which flows from the volcanic upland area of sourthern Guam toward the north and west around Nimitz Hill. The average annual flow for the Fonte River is estimated to be about 1,000 gpm (see Appendix F). In developed areas of the interior, runoff over streets is usually diverted to open trenches, such as in Liguan, or to dry wells, such as those used at

Andersen Air Force Base. Upon reaching storm water retention areas, the runoff infiltrates. Some areas near the coast have storm drains that lead to the ocean. Although this water may be relatively significant locally, the areas drained in this way generally are within the 4,000 foot buffer zone established for determining sustainable yield values, and therefore, should not significantly impact the recharge values developed.

EVAPORATION AND EVAPOTRANSPIRATION

Pan evaporation is measured in only one location in northern Guam, and that is at the National Weather Service (NWS) Station of the U.S. Weather Bureau located in Finegayan. It is measured using a standard Weather Bureau Class A evaporation pan. The average monthly pan evaporation is tabulated in Appendix A for the period from 1974 through 1981. Evaporation, like precipitation, varies seasonally, though not as drastically. During the dry season, average pan evaporation is about 7 inches per month. In the wet season, it averages about 6 inches per month. The average monthly pan evaporation is 6.85 inches and the annual average is about 82 inches.

To properly calculate recharge for the Northern Lens, potential evapotranspiration values should be used. Potential evapotranspiration (hereafter referred to as just evapotranspiration) is the combined total of evaporation and biological (plant) transpiration of water that occurs if the plant has a continuous supply of water.

Evapotranspiration rates for various types of vegetation have not been measured in Guam. However, research conducted by Chang, et al (1963) suggested that pan evaporation and evapotranspiration are roughly equivalent for tropical vegetation. Mink (1976) based his estimates of recharge in northern Guam on Chang's research results. However, because the use of evapotranspiration is more accurate in determining recharge, it is used in this report. Through the use of calculated evapotranspiration rates, this report establishes the method used to estimate recharge. When actual evapotranspiration rates have been determined for northern Guam, the actual values can replace the calculated values. Then, using the procedures discussed in this chapter and in the Appendices, recharge can be more accurately evaluated.

To establish the procedure for calculating recharge, areal variation in evapotranspriation rates had to be estimated. Three established methods were used to estimate evapotranspiration: the Hargreaves (1956), the Thornthwaite (1944), and the Blaney-Criddle (1950) methods. These methods of determining evapotranspiration are discussed in detail in Appendix E. The calculated mean monthly evapotranspiration rate ranged from 3.40 inches (Hargreaves method) to 6.65 inches (Blaney-Criddle method). The selection of the method used for estimating recharge was based on two factors: 1) obtaining a conservative estimate of recharge and sustainable yield (until which time recharge could be reevaluated using actual evapotranspiration rate data), and 2) obtaining results that most closely correspond to Chang's and Mink's assumptions in which evapotranspriation and pan evaporation are roughly equivalent. Table 5-2 summarizes the evapotranspiration values calculated in Appendix E, as well as the measured evaporation from the NWS station in Finegayan. The Blaney-Criddle method yielded an average monthly evapotranspiration rate of about 6.65 inches, which is the most conservative for calculating recharge and which is quite close to the average monthly evaporation of 6.85 inches. For this reason, evapotranspiration rates determined by the Blaney-Criddle method were used to estimate recharge to the Northern Lens and to establish the procedure for updating the estimated recharge using actual evapotranspiration data when they become available.

RECHARGE

Recharge to the Northern Lens was evaluated by computing the rainfall-evapotranspiration relationship for northern Guam and by evaluating the rainfall-runoff characteristics of the Pago River Basin of southern Guam. These methods of estimating recharge are summarized in the following paragraphs and discussed in detail in Appendix F.

TABLE 5-2

COMPARISON OF CALCULATED EVAPOTRANSPIRATION RATES
AT THE NATIONAL WEATHER SERVICE STATION, FINEGAYAN
(inches)

	Evapotranspiration Rates			
Month	Hargreaves Method	Thornthwaite Method	Blandy-Criddle Method	Pan Evaporation Rate
JAN	3.55	4.42	6.19	6.65
FEB	3.39	4.42	5.72	6.49
MAR	3.93	4.55	6.56	8.05
APR	4.00	5.01	6.65	8.32
MAY	4.04	5.14	7.08	8.43
JUN	3.75	5.35	6.98	7.46
JULY	3.28	5.14	7.13	6.47
AUG	2.90	5.07	6.96	5.91
SEPT	2.91	5.07	6.55	5.70
OCT	2.96	5.01	6.54	6.17
NOV	2.76	5.07	6.18	6.24
DEC	3.27	4.81	6.23	6.34
Total	40.74	59.08	78.78	82.23

Very little rainfall leaves northern Guam (excluding that portion within the 4,000-foot buffer zone) except for surface runoff from the Nimitz Hill management zone via the Fonte River. Using the Pago River surface water runoff analyses (see Appendix F), average Fonte River runoff to the ocean is estimated to be about 1,000 gpm (or about 1.44 MGD). Except for this runoff, all other rainfall that remains after evapotranspiration is assumed to recharge the groundwater system. Water that infiltrates past the root zone is assumed to move vertically downward until it reaches the fresh water lens or until it reaches the volcanic basement rocks above sea level, at which time it moves laterally until it reaches the fresh water lens. Annual recharge is calculated by subtracting the evapotranspiration rate from mean monthly precipitation and then summing these monthly recharge rates for the twelve months of the year.

During the dry season, when rainfall is low, evapotranspiration continues because the plants can extract the needed water from storage in the soil. This eventually results in a soil moisture deficiency. During these periods of little or no rainfall, the plant will also go into drought stress and will consume less water than it would if unlimited water were available. Thus, actual transpiration is generally less than potential evapotranspiration. During the next rainfall event, the soil moisture deficiency is replaced prior to any recharge to the groundwater system. Soil moisture deficiency is very difficult to estimate, so in order to estimate recharge, when evapotranspiration exceeds rainfall in any particular month, recharge is assumed to be zero.

Recharge was calculated at the eight raingage locations shown on Figure 5-2. As indicated on Table 5-3, recharge at these locations varied from 28.75 inches per year at the Naval Air Station to 37.97 inches per year at the NWS Station in Finegayan. The average recharge rate for these stations is about 32.97 inches per year for the 31-year base period.

An evaluation of recharge was also done by comparing rainfall to runoff characteristics of the Pago River Basin, located just south of the northern plateau limestone province, along its southeastern boundary (see Appendix F). A water balance was determined by correlating the stream flow data for the Pago River Basin (where groundwater base flow is minimal) for the period 1976 to 1979 to rainfall data measured in the Pago River Basin for the period 1952 to 1966 (but adjusted to the 1976 to 1979 time period using 1976 to 1979 rainfall data at the nearby Mangilao raingage station). Using this method, recharge was estimated to be between 40 and 50 percent of rainfall, or about 35 to 40 inches per year. Though these results are similar to those shown in Table 5-3, problems encountered with this method for determining recharge led to its not being used to evaluate sustainable

TABLE 5-3

AVERAGE MONTHLY RECHARGE ESTIMATES AT VARIOUS RAINGAGE STATIONS IN NORTHERN GUAM

Station Location	Months												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	(Inches)
Naval Air Station	0.82	0.58	0.14	0.48	1.65	0.50	2.96	5.63	6.94	5.76	2.92	0.37	28.75
Yigo Agricultural Station	0.19	1.08	0.55	1.10	2.52	0.49	3.20	6.61	6.83	8.19	2.90	1.88	35.54
Mangilao	1.11	0.76	0.18	0.54	1.58	0.76	2.20	6.09	8.90	5.32	3.02	0.68	31.14
Andersen Air Force Base	1.04	1.22	0.76	0.93	2.41	0.28	2.91	6.24	6.34	7.04	2.61	0.95	32.73
Naval Communications Station	1.46	0.22	0.40	0.14	2.29	1.00	2.56	7.80	6.19	6.92	2.46	0.50	31.94
Pago River	0.60	0.79	0.11	0.56	1.34	1.06	3.36	6.33	6.37	5.79	2.93	1.02	30.26
Fleet Weather Central - Nimitz Hill	1.00	0.67	0.64	0.87	0.94	0.92	5.21	6.33	7.91	6.76	3.47	0.74	35.46
National Weather Service - Finegayan	1.21	1.12	0.75	0.88	2.54	0.44	3.62	7.14	8.40	7.39	3.41	1.07	37.97
Northern Guam Average													32.97

yield. One problem is that the runoff characteristics between the southern volcanics and the northern limestones are quite different because of terrain, lithology, and vegetation (type and density) differences. Another problem is the major differences in soil type and thicknesses.

Average annual recharge rates on northern Guam have been estimated in several ways by researchers in the past. Mink (1976) estimated annual recharge rates of 25.62 inches at the Naval Air Station, 27.69 inches at Andersen Air Force Base, and 37.72 inches at the NWS Station in Taguac (Finegayan). These values are in the same range as developed in the NGLS. Ayers (1981) used a much different approach to calculate recharge by relating the average chloride-ion concentration of rainfall in Guam to the chloride-ion concentration observed in the parabasal groundwater areas. By this method, he estimated recharge to be about 32.68 inches per year. He reports that previous estimates by other researchers ranged from about 31 inches per year to about 53 inches per year, with most of the estimates falling between 31 and 38 inches per year. These recharge rates, determined by independent methods, suggest that the rates used in this report are realistic.

As discussed earlier, northern Guam has been subdivided into 47 management zones (shown in Figure 5-1). Each zone was assigned a recharge value based on the recharge rates calculated for nearby precipitation stations using the rainfall-evapotranspiration method developed in Appendix F. These assigned unit recharge rates are shown on Table 5-4 for the parabasal management zones and Table 5-5 for the basal management zones. To determine the recharge over the management zones, the area of each zone is multiplied by the unit recharge. As an example, the recharge in the Chalan Pago management zone is calculated as follows:

Zone area (A) = 35,748,000 sq.ft.

assigned unit recharge Ru = 34 in/yr or 0.00776 ft/day

TABLE 5-4

RECHARGE RATES FOR PARABASAL MANAGEMENT ZONES
OF THE NORTHERN LENS

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	AREAL RECHARGE (MGD)
AGANA						
Pago Bay	14,035,000	31	0.00708	99,400	520	0.74
Chalan Pago	35,748,000	34	0.00776	277,400	1,440	2.07
Nimitz Hill	97,993,000	36	0.00822	805,500	4,180	6.03
Anigua	31,700,000	36	0.00822	260,600	1,350	1.95
Mt. Barrigada South	9,798,000	30	0.00685	67,100	350	0.50
Mt. Barrigada East	22,280,000	32	0.00731	162,900	850	1.22
MANGILAO						
Mangilao South	9,222,000	34	0.00776	71,600	370	0.54
Mangilao North	11,527,000	35	0.00799	92,100	480	0.69
Adacao	25,648,000	36	0.00822	210,800	1,100	1.58
Sabanan Pagat	17,061,000	37	0.00845	144,200	750	1.08
Janum	27,608,000	35	0.00799	220,600	1,150	1.65
ANDERSEN						
Tarague	29,517,000	34	0.00776	229,100	1,190	1.71
Salisbury	79,490,000	35	0.00799	635,100	3,300	4.75
Lupog	41,960,000	34	0.00776	325,600	1,690	2.44
AGAFA GUMAS						
Agafa Gumas West	23,977,000	35	0.00799	191,600	1,000	1.43
Agafa Gumas Central	113,832,000	36	0.00822	935,700	4,860	7.00
Agafa Gumas East	45,378,000	35	0.00799	362,600	1,880	2.71

TABLE 5-4

(Continued)

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	AREAL RECHARGE (MGD)
FINEGAYAN						
Callon Tramojo	25,937,000	36	0.00822	213,200	1,110	1.60
Finegayan East	29,452,000	36	0.00822	242,100	1,260	1.81
Potts	23,977,000	35	0.00799	191,600	1,000	1.43
YIGO						
Mt. Barragada West	48,713,000	31	0.00708	344,900	1,790	2.58
Mogfog	23,631,000	32	0.00731	172,800	900	1.29
Marbo South	19,020,000	33	0.00753	143,200	740	1.07
Marbo North	9,798,000	34	0.00776	76,000	400	0.57
Yigo East	30,259,000	35	0.00799	241,800	1,260	1.81
Mt. Santa Rosa	20,634,000	36	0.00822	169,600	880	1.27
Mataguac	23,285,000	37	0.00845	196,800	1,020	1.47
Yigo West	50,287,000	37	0.00845	424,900	2,210	3.18
Y-Sengsong	80,434,000	36	0.00822	661,200	3,430	4.95
TOTALS					42,460	61.1

TABLE 5-5

RECHARGE RATES FOR BASAL MANAGEMENT ZONES OF THE NORTHERN LENS

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	AREAL RECHARGE (MGD)
AGANA						
Barrigada	25,245,000	29	0.00662	167,100	870	1.25
Toto	32,219,000	32	0.00731	235,500	1,220	1.76
Agana Swamp	47,769,000	34	0.00776	370,700	1,930	2.77
Sabanan Maagas	65,517,000	31	0.00708	463,900	2,410	3.47
Manaca	67,343,000	32	0.00731	492,300	2,560	3.68
MANGILAO						
Asbeco	14,294,000	34	0.00776	110,900	580	0.83
Taguan	12,587,000	35	0.00799	100,600	520	0.75
Sasajyan	5,764,000	36	0.00822	47,400	250	0.35
ANDERSEN						
Anao	14,727,000	34	0.00776	114,300	590	0.85
Andersen	24,734,000	33	0.00753	186,200	970	1.39
AGAFA GUMAS						
Northwest Field East	142,301,000	35	0.00799	1,137,000	5,910	8.50
FINEGAYAN						
Northwest Field West	52,334,000	35	0.00799	418,100	2,170	3.13
Finegayan West	22,939,000	36	0.00822	188,600	980	1.41
NCS	57,637,000	36	0.00822	473,800	2,460	3.54
YIGO						
Dededo North	64,762,000	35	0.00799	517,400	2,690	3.87
Dededo South	112,406,000	36	0.00822	924,000	4,800	6.91
Macheche	55,385,000	33	0.00753	417,000	2,170	3.12
Asatdas	53,245,000	35	0.00799	425,400	2,210	3.18
TOTAL					35,290(gpm)	50.8(MGD)

Therefore, recharge = (RT) = A x Ru

$$= 35{,}748{,}000 \times 0.00776$$

$$= 277{,}400 \ ft^3/day$$

$$= 1{,}440 \ gpm$$

$$= 2.07 \ MGD$$

The average subbasin unit recharge, as shown on Tables 5-4 and 5-5, is fairly consistent over the Northern Lens and ranges from about 33 inches per year (in/yr) in the Agana Subbasin to about 36 in/yr in the Finegayan Subbasin. As shown on Table 5-6, the 68 square miles of the Northern Lens being considered for potential production (excluding the 4,000-foot coastal buffer zone) has a total recharge of about 112 mgd, which yields an overall average recharge rate over that area of about 34.6 inches per year.

GROUNDWATER PRODUCTION

Except for a few privately owned wells on northern Guam, the production from the groundwater system is done by PUAG, the U. S. Air Force, and the U. S. Navy. There are presently over 70 municipal wells in operation in northern Guam (excluding those wells in the 4,000-foot buffer zone) which have a maximum capacity to yield about 20.46 MGD. The maximum production capacity is slightly higher than the actual amount of water extracted from wells because the wells are periodically shut down for maintenance and wells may be cycled on and off in response to reservoir level fluctuations and local demands. For example, in 1980, actual production was about 18 MGD. In addition, about 1.5 MGD leaves the Agana Subbasin as outflow to the ocean via the Fonte River.

Table 5-7 summarizes the maximum production capacity from the basal and parabasal groundwater systems in each subbasin. The Yigo Subbasin has the highest groundwater production capacity of any subbasin in northern Guam, with about 10.31 MGD. The Agana Subbasin can produce about 5.67 MGD from wells, the Finegayan Subbasin about 2.65 MGD, and the Agafa Gumas Subbasin about 1.41 MGD. The Andersen Subbasin produces only occassionally from the

TABLE 5-6

SUMMARY OF RECHARGE TO SUBBASINS OF THE NORTHERN LENS

Subbasin	Area (ft^2)	Recharge (ft^3/day)	(gpm)	(mgd)
AGANA				
Parabasal	211,554,000	1,673,200	8,690	12.51
Basal	238,093,000	1,729,500	8,990	12.94
Subtotals	449,647,000	3,402,700	17,680	25.45
MANGILAO				
Parabasal	91,066,000	739,300	3,850	5.53
Basal	32,645,000	258,900	1,350	1.94
Subtotals	123,711,000	998,200	5,200	7.47
ANDERSEN				
Parabasal	150,967,000	1,189,800	6,180	8.90
Basal	39,461,000	300,500	1,560	2.25
Subtotals	190,428,000	1,490,300	7,740	11.15
AGAFA GUMAS				
Parabasal	183,187,000	1,489,900	7,740	11.14
Basal	142,301,000	1,137,000	5,910	8.51
Subtotals	325,488,000	2,626,900	13,650	19.65
FINEGAYAN				
Parabasal	79,366,000	646,900	3,370	4.84
Basal	132,910,000	1,080,500	5,610	8.08
Subtotals	212,276,000	1,727,400	8,980	12.92
YIGO				
Parabasal	306,061,000	2,431,200	12,630	18.19
Basal	285,798,000	2,283,800	11,870	17.08
Subtotals	591,859,000	4,715,000	24,500	35.27
TOTALS	1,893,409,000 or 67.92 sq. mi.	14,960,500	77,750	111.9

TABLE 5-7

SUMMARY GROUNDWATER PRODUCTION CAPACITY
FOR THE NORTHERN LENS

Subbasin	Subbasin (gpm)	Production (mgd)
AGANA		
Parabasal	1,945	2.80
Basal	1,995	2.87
Subtotals	3,940	5.67
MANGILAO		
Parabasal	660	0.95
Basal	320	0.46
Subtotals	980	1.41
ANDERSEN		
Parabasal	-0-	-0-
Basal	-0-	-0-
Subtotals	-0-	-0-
AGAFA GUMAS		
Parabasal	290	0.42
Basal	-0-	-0-
Subtotals	290	0.42
FINEGAYAN		
Parabasal	260	0.37
Basal	1,580	2.28
Subtotals	1,840	2.65
YIGO		
Parabasal	1,530	2.20
Basal	5,630	8.11
Subtotals	7,160	10.31
TOTALS	14,210	20.46

well located on the Andersen Air Force Base golf course. Production from the Yigo, Agana, and Finegayan Subbasins account for over 90 percent of total pumping capacity from the Northern Lens.

LEAKAGE

Leakage from the Northern Lens aquifer is the amount of fresh water loss to the ocean that occurs around the periphery of northern Guam. In the dry season, when little or no recharge reaches the water table, leakage is derived from groundwater that is in storage in the fresh water lens. The water depleted from storage during the dry season due to loss by leakage is usually replaced during the wet season period of high recharge. Therefore, over the long-term average (steady-state) conditions, leakage can be estimated by subtracting annual groundwater production from the average annual recharge rate.

Average annual recharge to the Northern Lens is about 112 MGD in the area of potential production (68 square miles) plus about 53 MGD contributed by rainfall infiltration to the area within the 4,000-foot coastal buffer zone (33 square miles with about 34 inches per year recharge), for a total recharge of about 165 MGD. Present maximum production capacity (20.46 MGD) plus surface runoff to the ocean (1.44 MGD) in the Northern Lens is about 21.90 MGD (see Table 5-7). Therefore, average annual leakage from the Northern Lens is about 143 MGD.

RECOMMENDATIONS FOR FURTHER STUDY

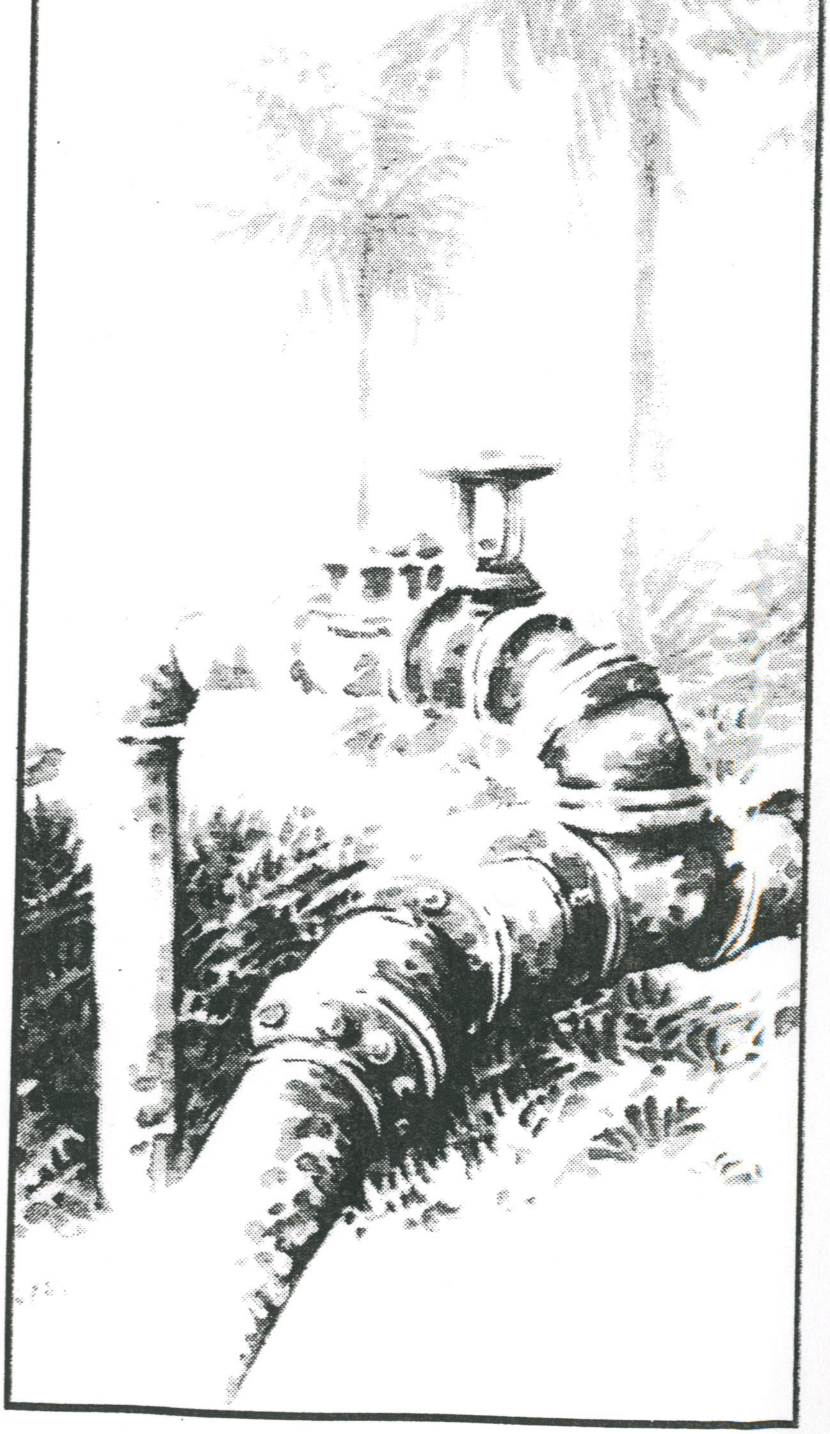
To refine the estimated recharge rates calculated in this report, two items are recommended for future consideration:

1. Raingage stations should be established in the Latte Heights area (near well M-9), in Agafa Gumas (near well AG-1), and in the Ordot area (as shown on Figure A-1 in Appendix A).

2. An investigation should be conducted in order to determine the actual evapotranspiration of vegetation in northern Guam.

VI

GROUNDWATER QUALITY



VI. GROUNDWATER QUALITY

GENERAL

This section summarizes the overall water quality of the Northern Lens. Special consideration is given to chloride and nitrate concentrations, as well as specific conductance. Table 6-1 summarizes the general water quality trends for well fields within each subbasin. The Data Report (Appendix A) summarizes the water quality trends on a well-by-well basis, usually from the time each was drilled through 1982. A more detailed discussion of groundwater quality is presented in the NGLS Groundwater Management Alternatives report and the Groundwater Management Program report.

Water quality analyses of varying detail are available for wells in northern Guam. In the past (through the early 1970's), the USGS made numerous thorough analyses. PUAG, on the other hand, has done monthly analyses on each of its wells, but has limited the analyses to chlorides, alkalinity, pH, hardness and conductivity. However, enough information is available to indicate that the main constituents of water in northern Guam are calcium and bicarbonate, which is typical of limestone aquifers.

Scattered samplings were gathered during the NGLS and were analyzed for priority pollutants designated by the U.S. EPA. These analyses indicate that northern Guam's groundwater resources are extremely clean, with only isolated minor contamination. High selenium concentrations (.013 mg/l) were noted in Well No. A-17. The U.S. EPA recommended drinking water standard is 0.010 mg/l. The source of this contaminant was not readily apparent during field investigations. In addition, Well No. M-1 showed a concentration of 0.30 mg/l of methylene chloride, which is used as a cleaning solvent for metal and electronic parts. No apparent source was evident, but it may be related to historic land use after the war.

TABLE 6-1

NORTHERN LENS SUBBASIN GROUNDWATER QUALITY SUMMARY

SUBBASIN	GENERAL CHARACTER	WATER QUALITY TRENDS: CHLORIDES	WATER QUALITY TRENDS: NITRATES (as NO_3)	CONDUCTIVITY (micromhos)
AGANA	Calcium Bicarbonate	-Initially at 15 mg/l. -Early wells increased slightly to and steady at 20 - 40 mg/l. -Later wells from 75 to 250-300 mg/l.	-Though low have generally doubled from less then 3-5 to 6-10 mg/l.	-Steady at about 500 for earlier wells. -900 to 1300 for some later wells.
YIGO	Calcium Bicarbonate	-Initially 15-20 mg/l. -Most steady at about 50 mg/l. -D-8, 9, 13, rose to 200-400 mg/l. -Y-series wells rose from 20 to 40 mg/l and steady.	-Nitrates steady between 3 to 10 mg/l.	-Steady at 400 to 600.
FINEGAYAN	Calcium Bicarbonate	-Initially at 20 mg/l -Steady between 50 and 150 mg/l.	-Steady at 5-6 mg/l.	-Steady at 500 to 800.
AGAFO GUMAS	Calcium Bicarbonate	-Initially at 13 mg/l. -Steady between 15 and 40 mg/l.	-Steady 8 mg/l.	Steady at 450.
ANDERSEN	Calcium Bicarbonate	-Generally elevated to 400 mg/l. -BPM 35-50 mg/l.	-Less than 3 mg/l.	-BPM steady at 600. -Older wells 1000 to 2000.
MANGILAO	Calcium Bicarbonate	-Initially at 20-30 mg/l. -Generally steady at 30-50 mg/l. -M-1 150 - 250 mg/l.	-Steady at 7-9 mg/l.	-Most steady at 400 to 500. -M-1 and M-9 800 to 1000.

The results of this water quality survey are published in the Investigation of the Priority Pollutants chapter of the NGLS Groundwater Management Program report. Past significant contamination of the groundwater with such constituents as trichlorolethylene (TCE) and fuel have been mitigated naturally because of the very rapid flushing action of the highly permeable limestone aquifers.

CHLORIDES

Chloride concentrations generally indicate the success of a well in a fresh water lens which is underlain or immediately adjacent to salt water. Elevated chlorides indicate upconing or intrusion of the salt water into the fresh water lens. Based on a comparison of historic water quality (particularly chloride concentration) in Northern Lens wells and the corresponding well's location relative to estimated basal and parabasal lens areas, chloride concentrations of less than 30 mg/l probably indicate parabasal conditions in the underlying aquifer. Concentrations between 70 mg/l and 150 mg/l in wells indicate basal conditions in the underlying aquifer. Concentrations between 30 and 70 mg/l probably reflect the area overlying the salt water toe. Concentrations over 150 mg/l may indicate a critical upconing condition in the basal aquifer.

As indicated in Table 6-1, wells in most areas of the Northern Lens have operated successfully and are not experiencing severe degradation of water quality as a result of upconing. In the Andersen Subbasin and the northwest part of the Agana Subbasin, chloride concentrations are generally elevated. In the Andersen Subbasin, all wells, except for the well located at the golf course, were abandoned because they exhibited high chloride concentrations, which made them useless as a drinking water supply. This problem may have arisen because the wells were drilled too deep into the fresh water lens, which increases upconing potential. The Tumaning area between the town of Agana and the Naval Air Station has historically exhibited elevated chlorides. This may be because rainfall runoff from the airport is diverted by storm drains to Agana Bay. Diverting the water in this fashion significantly reduces recharge to the groundwater system, thus allowing encroachment of salt water from Agana Bay toward Mount Barrigada. This area of encroachment is illustrated on Figure 5-1 (see Chapter V) by the inland positioning of the "boundary for safe pumping" beyond the established 4000-foot coastal buffer zone.

NITRATES

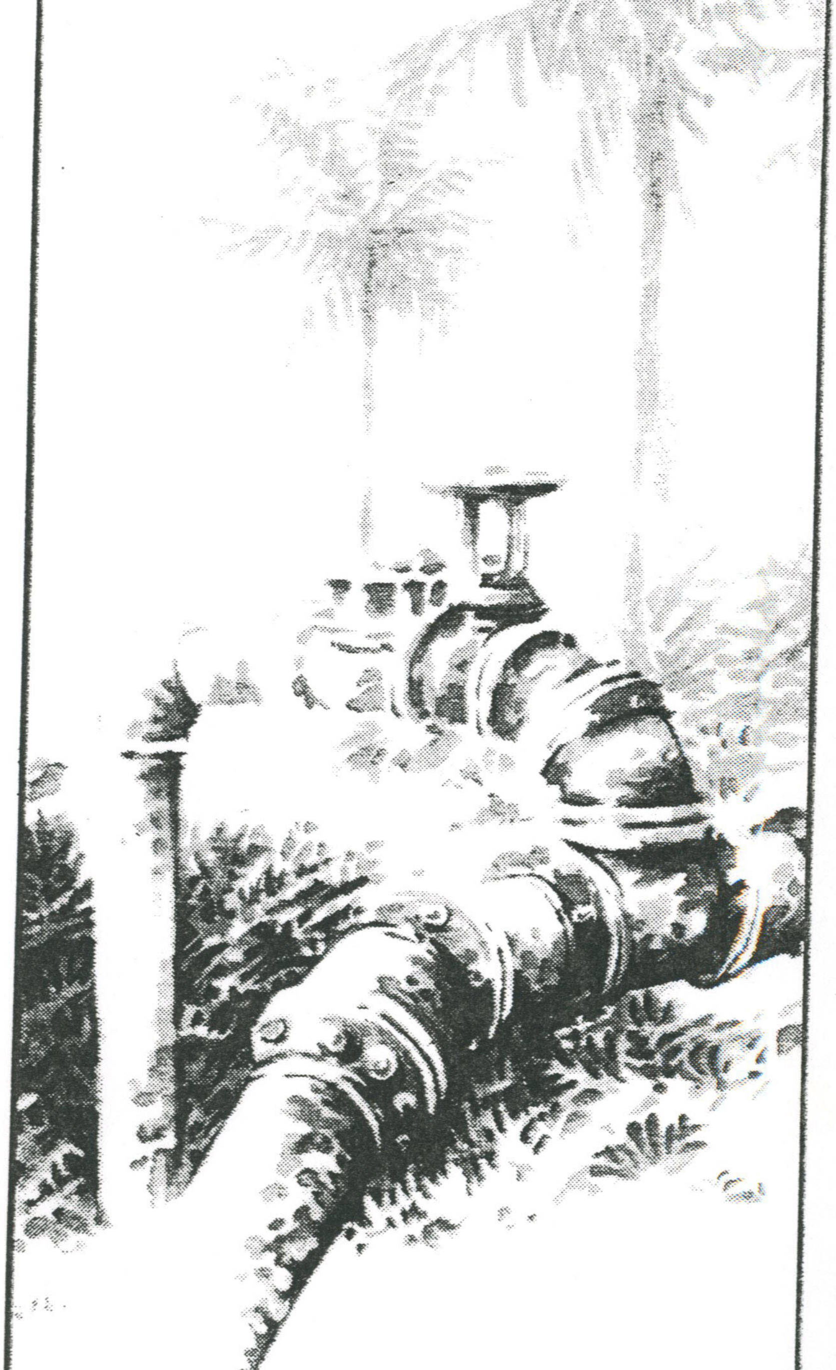
Nitrate concentrations are generally indicative of waste contamination. Because people live over the groundwater lens, minor contamination is expected. For the most part, nitrate levels have remained reasonably low, in the range of 2 to 10 mg/l (as NO_3). However, Mink (1976) noted that the nitrate load from on-site sewage disposal systems is not sufficient to account for the nitrate levels observed in the lens. He felt that nitrates contributed from on-site disposal systems should not be any higher than 2 mg/l in the Northern Lens. He suggested that the nitrate-fixing, tree-like shrub called tangan-tangan (Leucaena glauca), which is very common throughout northern Guam, could generate enough nitrate to account for at least 10 mg/l concentrations in the groundwater system. However, more research is needed to substantiate the magnitude of the impact that tangan-tangan has as a major nitrate source to the groundwater system.

SPECIFIC CONDUCTANCE

Specific conductance, which correlates closely with total dissolved solids (TDS), is an indicator of overall water quality. Water produced from the Northern Lens exhibits specific conductance in the range between 300 and 1,300 micromhos and averages from 550 to 600 micromhos. This is equivalent to about 400 mg/l TDS. These values for specific conductance are somewhat high by drinking water standards, but, at these levels, do not constitute a health hazard. These levels are indicative of the often high chlorides associated with nearby salt water. Historically, specific conductance has usually remained steady from well to well. Those wells displaying above average specific conductance are usually the same ones that also exhibit high chloride concentrations caused by unusual hydraulic properties of the aquifer or by improper well design. If the general well design criteria that are outlined in the "Well Construction Manual" are followed, then future wells should not exhibit unusually high specific conductance or chloride concentrations. Occassionally, wells such as Nos. D-13, A-16, and M-11 will be drilled properly yet have poor quality water probably due to extreme anisotropic aquifer conditions in which vertical permeability far exceeds horizontal permeability. This condition cannot be predicted. However, proper well design can help insure that water quality remains high.

VII

SUSTAINABLE YIELD



VII. SUSTAINABLE YIELD

GENERAL

This section presents the estimates of the sustainable yield for the Northern Lens of Guam. The information presented represents the culmination of the work presented in previous sections and the appendices of this report.

Sustainable yield is defined as the maximum amount of water that can be continuously withdrawn from the fresh water lens without impairing the integrity of the lens and the water quality. Sustainable yield is not equal to recharge, for if all water contributed by recharge were extracted, the lens would slowly dissipate because of continued leakage along the coastline.

To protect the integrity of the lens, conservative assumptions were made to determine the sustainable yield. These assumptions are:

1. The sustainable yield is calculated for each basal and parabasal management zone independent of recharge and/or production from other management zones.

2. Additional yield will not be produced in a 4,000-foot coastal buffer zone.

3. The yield available to each management zone is derived only from the infiltration of recharge to that zone from above and not from lateral inflow from an adjoining management zone.

4. Yield is a percentage of recharge based on historic head variations within a particular management zone.

MANAGEMENT ZONES

Figure 5-1 in Chapter V shows the 18 basal and 29 parabasal management zones that subdivide the six hydrologic subbasins of northern Guam. Basal management zones are differentiated from parabasal zones because wells in parabasal zones can generally yield more water than wells in basal zones without the adverse water quality effects caused by upconing (Appendix D). Under basal conditions where fresh water heads are less than four feet, present well design practices have demonstrated that wells operated at about 200 gpm have few failures due to upconing. Where fresh water heads exceed four feet in elevation, wells operated at 350 gpm in most cases should not be adversely affected by upconing. On the other hand, parabasal area wells do not have this problem, and if placed at least 500 feet away from the basal zone to avoid problems with local salt water intrusion, they should yield 500 to 750 gpm in clean limestone without causing adverse water quality changes. However, in the argillaceous limestone in the southern part of the lens, parabasal wells may only yield 350 gpm or less because of the relatively low regional aquifer permeabilities, and should not be placed any closer than 1,000 feet to the basal zone.

By subdividing the hydrologic subbasins into management zones, the groundwater resources can be easily managed because the available yield in the areas of demand is easier to identify. Also, by utilizing smaller subdivisions, areal variations in recharge can be evaluated in more detail, and areas of existing highly concentrated production, such as the Dededo and Mangilao well fields, can be isolated and excluded from consideration for future development.

A 4,000-foot wide coastal buffer zone without any new production is recommended around much of the coastline of northern Guam. Mink (1976) used a 2,000-foot wide zone that was based on low heads near the coast. The basis for expanding the zone from 2,000 feet to 4,000 feet zone is:

1. Heads are generally less than two feet above sea level in this area, and any significant production from this buffer zone will

cause more upconing than from the same amount of production further inland.

2. Tidal effects are greatest near the coast and will cause a corresponding increase in thickness within the transition zone. A thicker transition zone and lower heads near the coast significantly decreases the thickness of the fresh water lens and increases the potential for salt water upconing to wells.

3. A higher percentage of wells has been abandoned due to salt water contamination along the coast than inland. Evidence clearly shows more risk of upconing is likely along the coast.

4. Given the lower heads and thinner fresh water lens near the coast, wells placed here will probably yield less than 100 gpm safely. With higher capacity well development areas available inland, the cost per gallon of water produced would be higher along the coast.

5. Most of the commercial enterprises in northern Guam are located along the west coast, and groundwater production areas are located upstream of the commercial areas. Potential contamination of the drinking water supply can be avoided if future wells are not placed near commercial areas.

RECHARGE CONSIDERATIONS

The yield available from each management zone is assumed to occur as a result of direct infiltration of recharge within that zone with no contribution from lateral inflow from adjacent management zones. This assumption allows each management zone to be independently considered and unaffected by development in an adjacent or upstream management zone. By making this assumption, a conservative sustainable yield value can be derived, and subsequent development and management programs can be easily implemented.

The percentage of yield derived from recharge in parabasal management zones is greater than that in basal zones. Mink (1976) calculated a range of ratios for yield-to-recharge for basal aquifer areas and recommended that production of sustainable yield should not lower the head of the fresh water lens by more than one to two feet in clean limestone in order to protect the quality of water pumped from the wells. By relating production (P) from the lens to the recharge (R) and leakage (L), the percentage recharge available for sustainable yield can be developed on a regional basis.

$$L = \frac{41\ K}{2X} h_e^2 \qquad (7\text{-}1)$$

Recharge, on the other hand, is calculated at steady-state without any production from the aquifer;

where: K = permeability (ft/d)

X = distance from the coast to an inland observation point (feet)

h_e = the stable fresh water head at the observation point at full production, with $h_e < h$ (feet)

$$\text{Recharge (R)} = \frac{41\ K}{2x} h_o^2 \qquad (7\text{-}2)$$

where: h_o = initial fresh water head at the observation point prior to any pumping from the aquifer (feet)

Under steady-state conditions, the amount of water that can be developed (P) from the aquifer for a given equilibrium head, h_e, is obtained by subtracting equation (7-2) from (7-1):

$$P = R\text{-}L = \frac{41K}{2x}\left(h_o^2 - h_e^2\right) \qquad (7\text{-}3)$$

Under steady-state conditions, the fraction of recharge available for sustainable yield resulting from a drop in fresh water head from h_o to h_e is given by:

$$\frac{P}{R} = \frac{h_o^2 - h_e^2}{h_o^2} \qquad (7\text{-}4)$$

The fraction of original head that yields the equilibrium head as a result of aquifer production is:

$$\frac{h_e}{h_o} = \left(1 - \frac{P}{R}\right)^{1/2} \qquad (7\text{-}5)$$

Equation 7-5 is a powerful concept regarding the integrity of the fresh water lens under pumping conditions. For example, if production reduces recharge by 50 percent, the corresponding equilibrium head is only 70 percent of the original head.

Using the relationship described by equation (7-4) as the fraction of recharge available for sustained yield, Mink (1976) estimated that yield from basal aquifers was between 35 and 40 percent assuming a change in head between the dry season and wet season. To determine the areal distribution of percentage yield, the basal areas of each subbasin were evaluated using water level data measured in April of 1982 (Appendix A, Table A-8) and the estimated water levels during the wet season. As shown on Table 7-1, the ratio of yield to recharge ranges from 40 percent in the Dededo area to 55 percent in the eastern part of the Agana Subbasin.

In parabasal zones, establishing a percentage of recharge available for sustainable yield is somewhat arbitrary. Two items must be considered in establishing this value:

1. Production must be limited to the extent that the salt water toe does not advance inland more than about 1,000 feet due to seasonal fluctuations in recharge. As a design consideration, parabasal

TABLE 7-1

SUSTAINABLE YIELD AND EQUILIBRIUM HEADS

Subbasin Area	Initial* Head (ft)	Equilibrium** Head (ft)	$\frac{P}{R}$*** (%)	$\frac{h_e}{h_o}$**** (%)
West Agana	10.0	7.0	51.0	70
East Agana	6.0	4.0	55.6	67
Mangilao	4.0	3.0	43.8	75
Andersen	4.0	3.0	43.8	75
Northwest Field	3.0	2.25	43.8	75
Finegayan	3.5	2.5	49.9	71
Dededo	4.5	3.5	39.5	78
Yigo	5.0	3.5	51.0	70

* Estimate of wet season water levels.
** Measured in April 1982.
*** Draft (or production) divided by recharge.
**** The percentage decrease in head for a given equilibrium production.

wells should be located as far from the toe as possible, without going inland of the zero contour line of the basement complex.

2. Maximum production should be limited by how much water can be feasibly intercepted by a well field, allowing minimum flow to pass. Many small-capacity wells closely spaced, could capture most of the recharge. However, drilling, as well as operation and maintenance costs would be high when compared to similar costs of far fewer high-capacity wells spaced further apart.

Taking these items into consideration and considering that parabasal areas are not susceptible to upconing, 60 percent of the recharge was estimated to be available for sustainable yield from the parabasal lens.

DETERMINATION OF SUSTAINABLE YIELD

Recharge values were assigned to each management zone based on the estimates developed in the Hydrology Chapter and Appendix F. The values for recharge and the resulting yield from basal management zones of each subbasin are shown on Table 7-2. Similarly, the recharge values for the parabasal zones are shown on Table 7-3. On these tables, the percentage of recharge used to obtain sustainable yield are shown in parenthesis in the "Subbasin Yield" column. Table 7-4 summarizes these values for each subbasin. The following paragraphs review the subbasin yields, current production capacity, the unused yield for each subbasin, and the approximate number and capacity of wells required to produce the unused yield; these values are summarized on Tables 7-2, 7-3, and 7-4.

Agana Subbasin

The Agana Subbasin is subdivided into five basal management zones and six parabasal zones as shown on Figure 7-1. Recharge to the basal zones ranges between 29 and 34 inches per year. Recharge to the parabasal zones ranges between 30 and 36 inches per year. The amount of sustained yield is 60 percent of available recharge in the parabasal management zones and range between 30 and 50 percent in the basal zones. Maximum existing basal zone well production occurs in the Sabana management zone with about 1,560 gpm capacity. The Chalan Pago parabasal zone has an existing production capacity of 1,110 gpm.

Highest unused yield in the parabasal areas occurs in the Nimitz Hill zone (820 gpm), followed closely by Anigua (810 gpm), and Mt. Barrigada East (510 gpm). Mt. Barrigada South and Pago Bay have little unused yield remaining for future development. In the Chalan Pago management zone, production exceeds sustainable yield which means that the yield is being produced from adjacent zones and from a greater percentage of incoming recharge.

In the basal management zones, the highest unused yield occurs in the Manaca zone (1,150 gpm), followed by Agana Swamp (625 gpm) and Toto (430

TABLE 7-2

RECHARGE, PRODUCTION AND YIELD
PARABASAL AQUIFER ZONES

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	SUBBASIN YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	UNUSED YIELD (gpm)
AGANA								
Pago Bay	14,035,000	31	0.00708	99,400	520	310 (60)*	145	165
Chalan Pago	35,748,000	34	0.00776	277,400	1,440	860 (60)	1,110	(250)**
Nimitz Hill	97,993,000	36	0.00822	805,500	4,180	2,510 (60)	1,690†	820
Anigua	31,700,000	36	0.00822	260,600	1,350	810 (60)	-0-	810
Mt. Barrigada So.	9,798,000	30	0.00685	67,100	350	210 (60)	-0-	210
Mt. Barrigada East	22,280,000	32	0.00731	162,900	850	510 (60)	-0-	510
MANGILAO								
Mangilao So.	9,222,000	34	0.00776	71,600	370	220 (60)	-0-	220
Mangilao No.	11,527,000	35	0.00799	92,100	480	290 (60)	660	(370)**
Adacao	25,648,000	36	0.00822	210,800	1,100	660 (60)	-0-	660
Sabanan Pagat	17,061,000	37	0.00845	144,200	750	550 (60)	-0-	550
Janum	27,608,000	35	0.00799	220,600	1,150	460 (40)	-0-	460
ANDERSEN								
Tarague	29,517,000	34	0.00776	229,100	1,190	710 (60)	-0-	710
Salisbury	79,490,000	35	0.00799	635,100	3,300	1,980 (60)	-0-	1,980
Lupog	41,960,000	34	0.00776	325,600	1,690	1,015 (60)	-0-	1,015

TABLE 7-2

(Continued)

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	SUBBASIN YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	UNUSED YIELD (gpm)
AGAFA GUMAS								
Agafa Gumas West	23,977,000	35	0.00799	191,600	1,000	600 (60)*	-0-	600
Agafa Gumas Central	113,832,000	36	0.00822	935,700	4,860	2,920 (60)	290	2,630
Agafa Gumas East	45,378,000	35	0.00799	362,600	1,880	1,130 (60)	-0-	1,130
FINEGAYAN								
Callon Tramolo	25,937,000	36	0.00822	213,200	1,110	660 (60)	-0-	660
Finegayan East	29,452,000	36	0.00822	242,100	1,260	760 (60)	260	500
Potts	23,977,000	35	0.00799	191,600	1,000	600 (60)	-0-	600
YIGO								
Mt. Barragada West	48,713,000	31	0.00708	344,900	1,790	900 (50)	-0-	900
Mogfog	23,631,000	32	0.00731	172,800	900	450 (50)	-0-	450
Marbo South	19,020,000	33	0.00753	143,200	740	450 (60)	-0-	450
Marbo North	9,798,000	34	0.00776	76,000	400	240 (60)	-0-	240
Yigo East	30,259,000	35	0.00799	241,800	1,260	750 (60)	170	580

TABLE 7-2

(Continued)

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	SUBBASIN YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	UNUSED YIELD (gpm)
YIGO (continued)								
Mt. Santa Rosa	20,634,000	36	0.00822	169,600	880	530 (60)	-0-	530
Mataguac	23,285,000	37	0.00845	196,800	1,020	610 (60)	-0-	610
Yigo West	50,287,000	37	0.00845	424,900	2,210	1,320 (60)	675	645
Y-Sengsong	80,434,000	36	0.00822	661,200	3,430	2,060 (60)	685	1,375
TOTALS					42,460 gpm	25,075 gpm	5,685 gpm	19,390 gpm
					61.1 MGD	36.1 MGD	8.2 MGD	27.9 MGD

* Indicates the percentage of recharge available for sustainable yield.

** Numbers in parenthesis indicate that production exceeds sustainable yield and that the deficit is being drawn from surrounding cells.

† For the Nimitz Hill Management Zone, 690 gpm is from well production and about 1000 gpm is from Fonte River outflow (average annual) to the ocean.

TABLE 7-3

RECHARGE, PRODUCTION AND YIELD
BASAL AQUIFER ZONES

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	SUBBASIN YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	USED YIELD (gpm)
AGANA								
Barrigada	25,245,000	29	0.00662	167,100	870	260 (30)*	190	70
Toto	32,219,000	32	0.00731	235,500	1,220	430 (35)	-0-	430
Agana Swamp	47,769,000	34	0.00776	370,700	1,930	870 (45)	245	625
Sabanas Maagas	65,517,000	31	0.00708	463,900	2,410	1,200 (50)	1,560	(360)**
Manaca	67,343,000	32	0.00731	492,300	2,560	1,150 (45)	-0-	1,150
MANGILAO								
Asbeco	14,294,000	34	0.00776	110,900	580	230 (40)	-0-	230
Taguan	12,587,000	35	0.00799	100,600	520	210 (40)	320	(110)**
Sasajyan	5,764,000	36	0.00822	47,400	250	90 (35)	-0-	90
ANDERSEN								
Anao	14,727,000	34	0.00776	114,300	590	240 (40)	-0-	240
Andersen	24,734,000	33	0.00753	186,200	970	390 (40)	-0-	390
AGAFA GUMAS								
Northwest Field East	142,301,000	35	0.00799	1,137,000	5,910	2,360 (40)	-0-	2,360

TABLE 7-3

(Continued)

SUBBASIN NAME	AREA (ft^2)	UNIT RECHARGE (in/yr)	UNIT RECHARGE (ft/day)	AREAL RECHARGE (ft^3/day)	AREAL RECHARGE (gpm)	SUBBASIN YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	USED YIELD (gpm)
FINEGAYAN								
Northwest Field West	52,334,000	35	0.00799	418,100	2,170	870 (40)*	-0-	870
Finegayan West	22,939,000	36	0.00822	188,600	980	440 (45)	1,240	(800)**
NCS	57,637,000	36	0.00822	473,800	2,460	1,110 (45)	340	770
YIGO								
Dededo No.	64,762,000	35	0.00799	517,400	2,690	1,340 (50)	600	740
Dededo So.	112,406,000	36	0.00822	924,000	4,800	2,400 (50)	3,800	(1,400)**
Macheche	55,385,000	33	0.00753	417,000	2,170	870 (40)	-0-	870
Asatdas	53,245,000	35	0.00799	425,400	2,210	1,330 (60)	1,230	100
TOTAL					35,290 gpm	15,790 gpm	9,525 gpm	6,265 gpm
					50.8 MGD	22.7 MGD	13.7 MGD	9.0 MGD

* Indicates the percentage of recharge available for sustainable yield.

** Numbers in parenthesis indicate that production exceeds sustainable yield and that the deficit is being drawn from surrounding cells.

TABLE 7-4

RECHARGE, PRODUCTION, AND YIELD SUMMARY FOR NORTHERN LENS

SUBBASIN	AREA (ft^2)	RECHARGE (ft^3/day)	RECHARGE (gpm)	SUSTAINABLE YIELD (gpm)	SUBBASIN PRODUCTION (gpm)	UNUSED YIELD (gpm)
AGANA						
Parabasal	211,554,000	1,673,200	8,690	5,210	2,945	2,265
Basal	238,093,000	1,729,500	8,990	3,910	1,995	1,915
Subtotals	449,647,000	3,402,700	17,680	9,120	4,940	4,180
MANGILAO						
Parabasal	91,066,000	739,300	3,850	2,180	660	1,520
Basal	32,645,000	258,900	1,350	530	320	210
Subtotals	123,711,000	998,200	5,200	2,710	980	1,730
ANDERSEN						
Parabasal	150,967,000	1,189,800	6,180	3,705	-0-	3,705
Basal	39,461,000	300,500	1,560	630	-0-	630
Subtotals	190,428,000	1,490,300	7,740	4,335	-0-	4,335
AGAFA GUMAS						
Parabasal	183,187,000	1,489,900	7,740	4,650	290	4,360
Basal	142,301,000	1,137,000	5,910	2,360	-0-	2,360
Subtotals	325,488,000	2,626,900	13,650	7,010	290	6,720
FINEGAYAN						
Parabasal	79,366,000	646,900	3,370	2,020	260	1,760
Basal	132,910,000	1,080,500	5,610	2,420	1,580	840
Subtotals	212,276,000	1,727,400	8,980	4,440	1,840	2,600
YIGO						
Parabasal	306,061,000	2,431,200	12,630	7,310	1,530	5,780
Basal	285,798,000	2,283,800	11,870	5,940	5,630	310
Subtotals	591,859,000	4,715,000	24,500	13,250	7,160	6,090
TOTALS	1,893,409,000	14,960,500	77,750	40,865	15,210	25,655
	67.92 sq. mi.		111.9 MGD	58.8 MGD	21.9 MGD	36.9 MGD

gpm). The Barrigada management zone has little unused yield remaining. Within the Sabana zone, production exceeds yield by 360 gpm and is probably utilizing yield from adjacent management zones, which should be taken into consideration in exploiting the sustainable yield in those adjacent zones.

The parabasal management zones which are most promising for future development are the Nimitz Hill, Anigua, and Mt. Barrigada East Zones. However, because the aquifers are contained in the low peremeability argillaceous limestone, new wells will probably be limited to a productivity of 200 gpm with an occassional 350 to 500 gpm well. The basal zones that are most promising for future development are the Manaca, Agana Swamp, and Toto. Wells in these management zones should be limited in capacity to 200 gpm. As shown on Table 7-4, the Agana Subbasin is presently producing about 55 percent of its available yield.

Mangilao Subbasin

The Mangilao Subbasin is subdivided into five parabasal and three basal management zones, as shown on Figure 7-2. Recharge to these zones ranges between 34 and 37 inches per year. Maximum recharge occurs in the Janum (1,150 gpm) and Adacao (1,100 gpm) parabasal zones. The amount of sustained yield is 60 percent of available recharge in the parabasal zones and ranges between 35 and 40 percent in the basal zones. The sustained yield is limited to 2,710 gpm in the Mangilao Subbasin because of the relatively small recharge area and its proximity to the coastline.

Presently, the only production in the subbasin occurs in the Mangilao North (660 gpm) and Taguan (320 gpm) management zones. In both of these zones, production exceeds yield. The parabasal zones in which development can most favorably occur are the Janum, Adacao, and Sabanan Pagat zones. The Adacao and Sabanan Pagat zones can accommodate one 500 gpm well each. Because the limestone is fairly thin in the Janum zone, the sustainable yield would probably best be produced using infiltration galleries. Among the basal management zones, the Asbeco is the only one capable of any further production and it should be limited to one 200 gpm well.

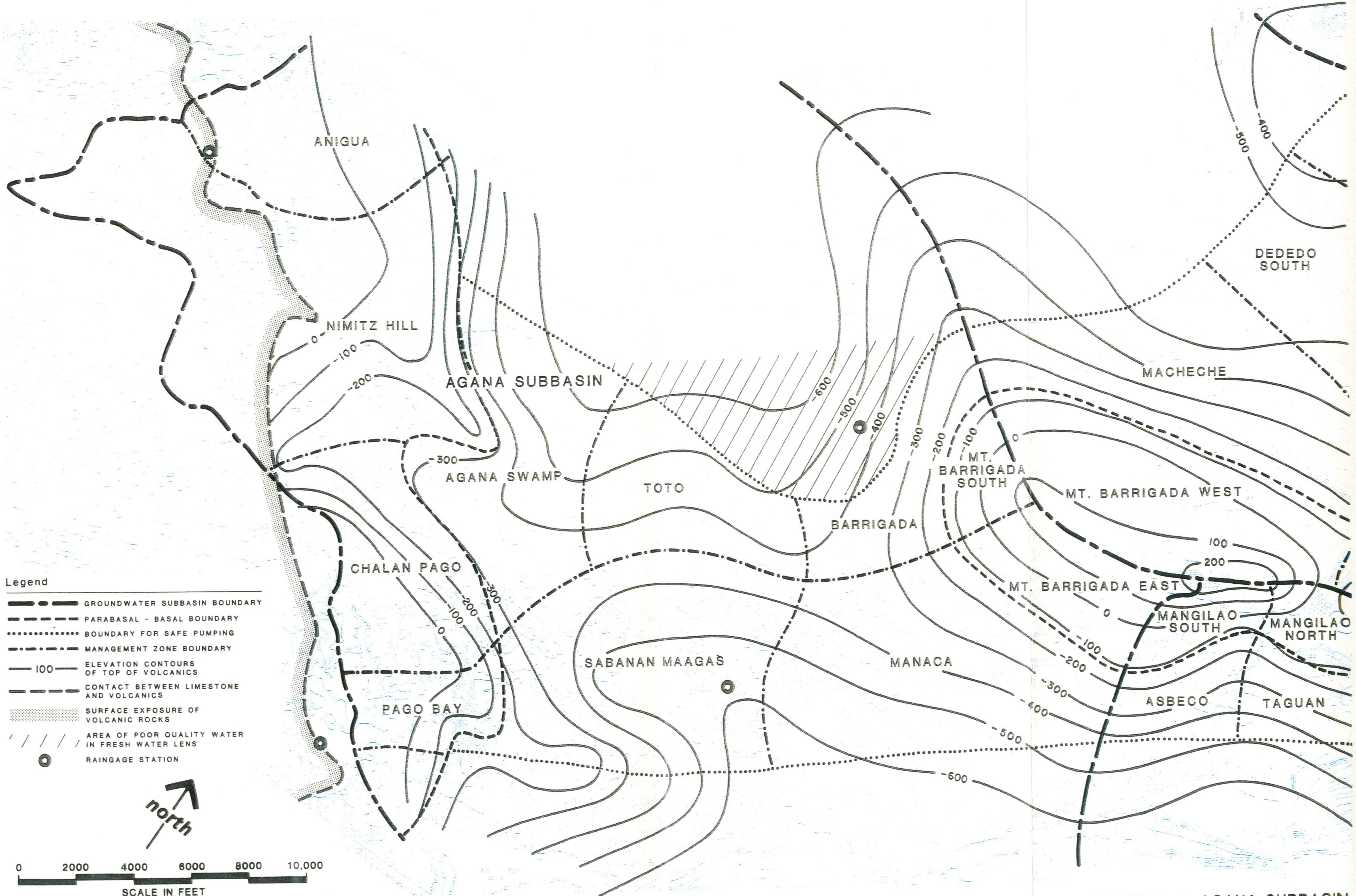


FIGURE 7-1 AGANA SUBBASIN

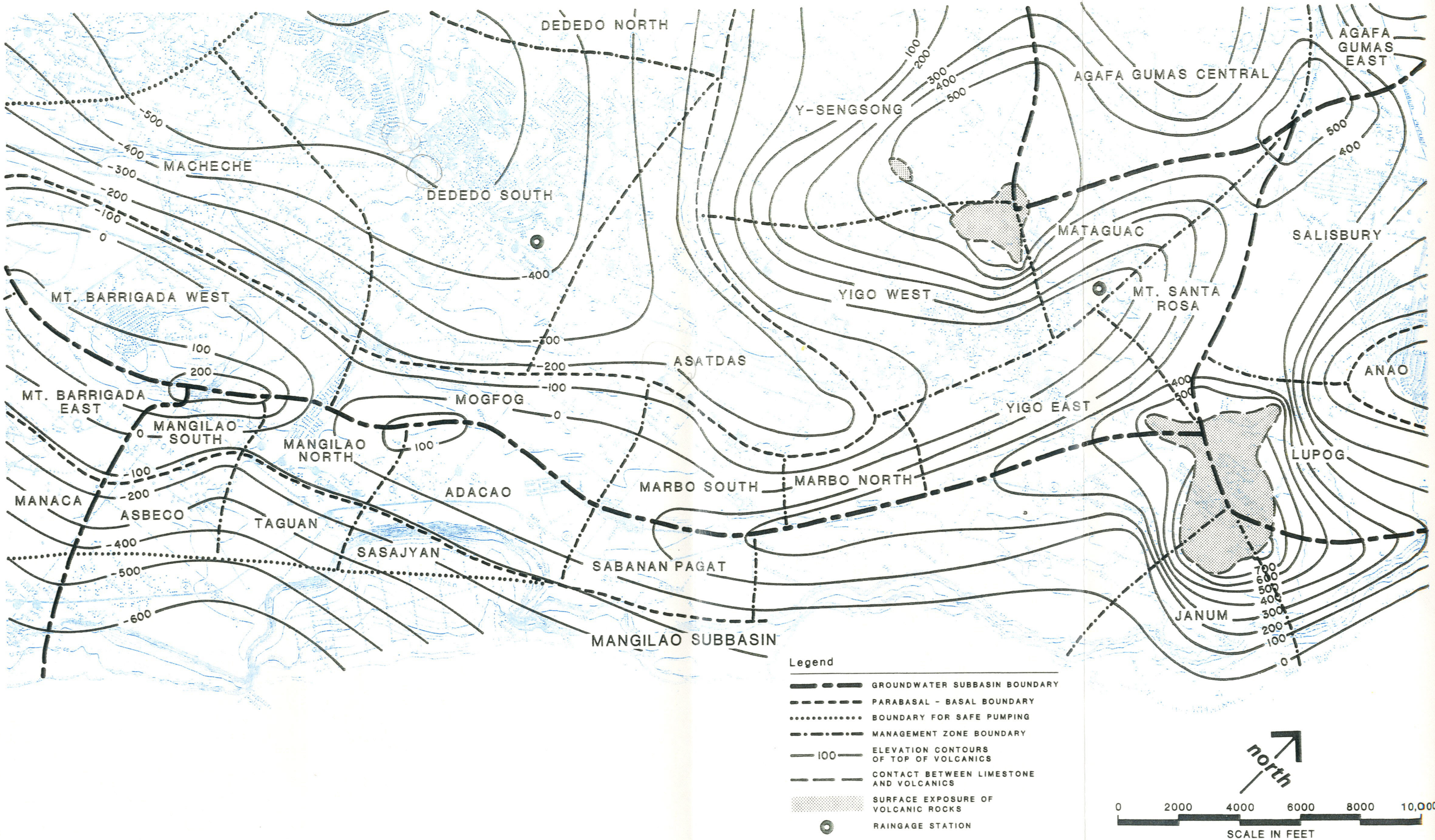


FIGURE 7-2 MANGILAO SUBBASIN

Andersen Subbasin

The Andersen Subbasin is subdivided into three parabasal and two basal management zones, as shown on Figure 7-3. Recharge to the subbasin ranges from 33 to 35 inches per year. The highest recharge occurs in the parabasal management zones and ranges from 1,190 gpm in the Tarague zone to 3,300 gpm in the Salisbury zone. The amount of sustainable yield is 60 percent of available recharge in the parabasal zones and 40 percent in the basal zones.

At present, no water is produced from the subbasin on a continuous basis. However, the BPM well located on the Andersen Air Force Base golf course is operational. Unused yield in the parabasal zones is substantial, with 1,980 gpm available in the Salisbury management zone, 710 gpm available in the Tarague zone, and 1,015 gpm available in the Lupog zone. The parabasal zones can accommodate a total of up to 7 additional 500 gpm wells. The basal zones have some water available for production, but many of the now abandoned wells in these areas have historically had salt water upconing problems. The yield is available for one well in each management zone, but development should be done carefully.

Agafa Gumas Subbasin

The Agafa Gumas Subbasin is subdivided into three parabasal management zones and one basal zone, as shown on Figure 7-4. Recharge to the subbasin ranges between 35 and 36 inches per year. The highest recharge occurs in the Agafa Gumas Central (4,860 gpm), and Agafo Gumas East (1,880) parabasal zones, and in the Northwest Field-East (5,910 gpm) basal zone. The amount of sustainable yield is 60 percent of available recharge in the parabasal management zones and 40 percent in the basal zone.

The only production in the subbasin occurs at Well Nos. AG-1 and AG-2, which have a combined pumping capacity of about 300 gpm. Because of the very large drainage basin located upgradient from these two production zones, the subbasin can yield substantial amounts of water. Unused yield in the subbasin ranges from 2,630 gpm in the Agafa Gumas Central zone to

600 gpm in the Agafa Gumas West zone. Total unused yield in the subbasin is nearly 7,000 gpm. Because most of the recharge that enters the parabasal management zones is funnelled through a fairly narrow section of aquifer at Agafa Gumas, use of larger capacity wells may be feasible. Approximately 7 wells with capacities of 500 gpm would probably be sufficient to exploit the sustainable yield in the parabasal zone. The basal Northwest Field-East zone has an unused yield of 2,360 gpm which can be extracted by about eleven to twelve 200 gpm wells.

Finegayan Subbasin

The Finegayan Subbasin is subdivided into three basal and three parabasal management zones, as shown on Figure 7-5. Recharge to the subbasin ranges between 35 and 36 inches per year. Areal recharge to the basal zones varies between 980 gpm in the Finegayan West zone and 2,460 gpm in the NCS zone. Recharge to the parabasal zones varies between 1,000 gpm in the Potts zone and 1,260 gpm in the Finegayan East zone. The amount of sustainable yield is 60 percent of the available recharge in the parabasal management zones and 40 to 45 percent in the basal zones.

Production in the parabasal management zones is currently limited to the Finegayan East zone, which has a well capacity of about 260 gpm. Production in the basal zones occurs in the Finegayan West (1,240 gpm) and the NCS (340 gpm) zones. In the Finegayan West zone, production exceeds yield by about 800 gpm. The Northwest Field-West zone has unused yield of about 870 gpm, and the NCS zone has unused yield of 770 gpm. In the parabasal management zones, unused yield ranges between 500 gpm in the Finegayan East zone to 660 gpm in the Callon Tramolo zone. Each of the parabasal zones can accommodate about one additional 500 gpm well. However, because existing production is so high in the Finegayan West basal zone, further production in the Finegayan East zone should be done carefully. In the basal zones, the Northwest Field-West zone can accommodate about four additional 200 gpm wells, and the NCS zone can accommodate about three additional 200 gpm wells.

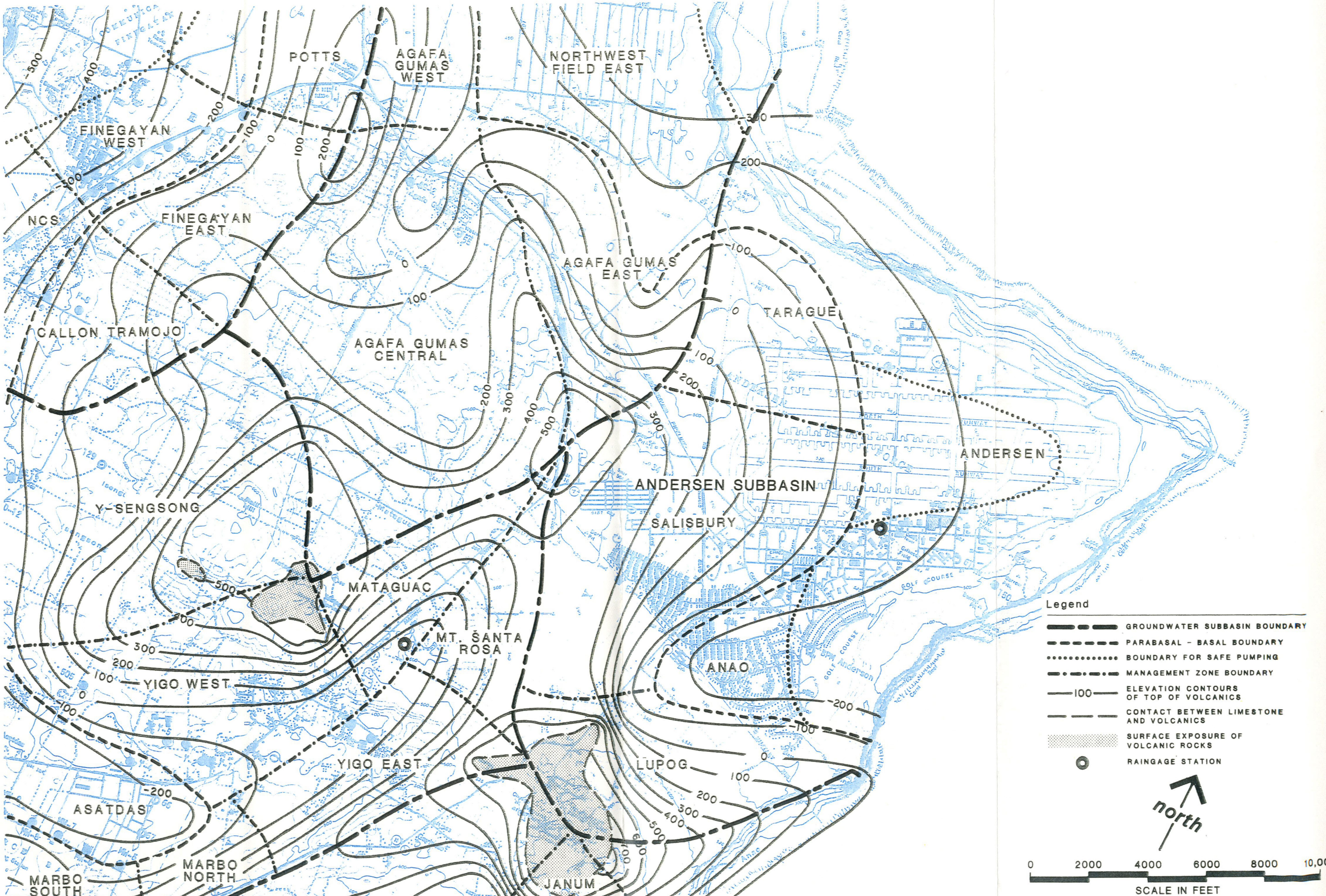


FIGURE 7-3 ANDERSEN SUBBASIN

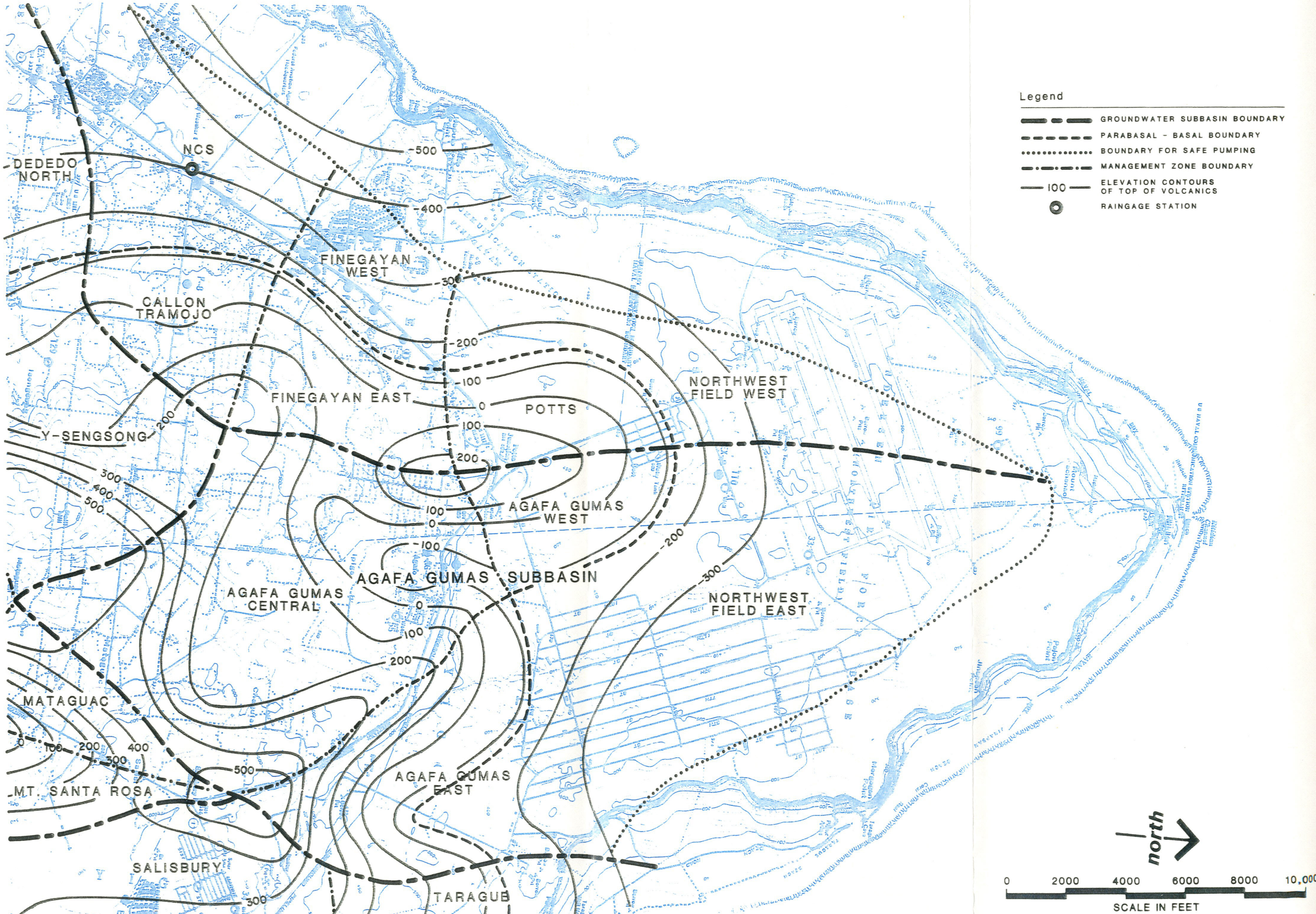


FIGURE 7-4 AGAFA GUMAS SUBBASIN

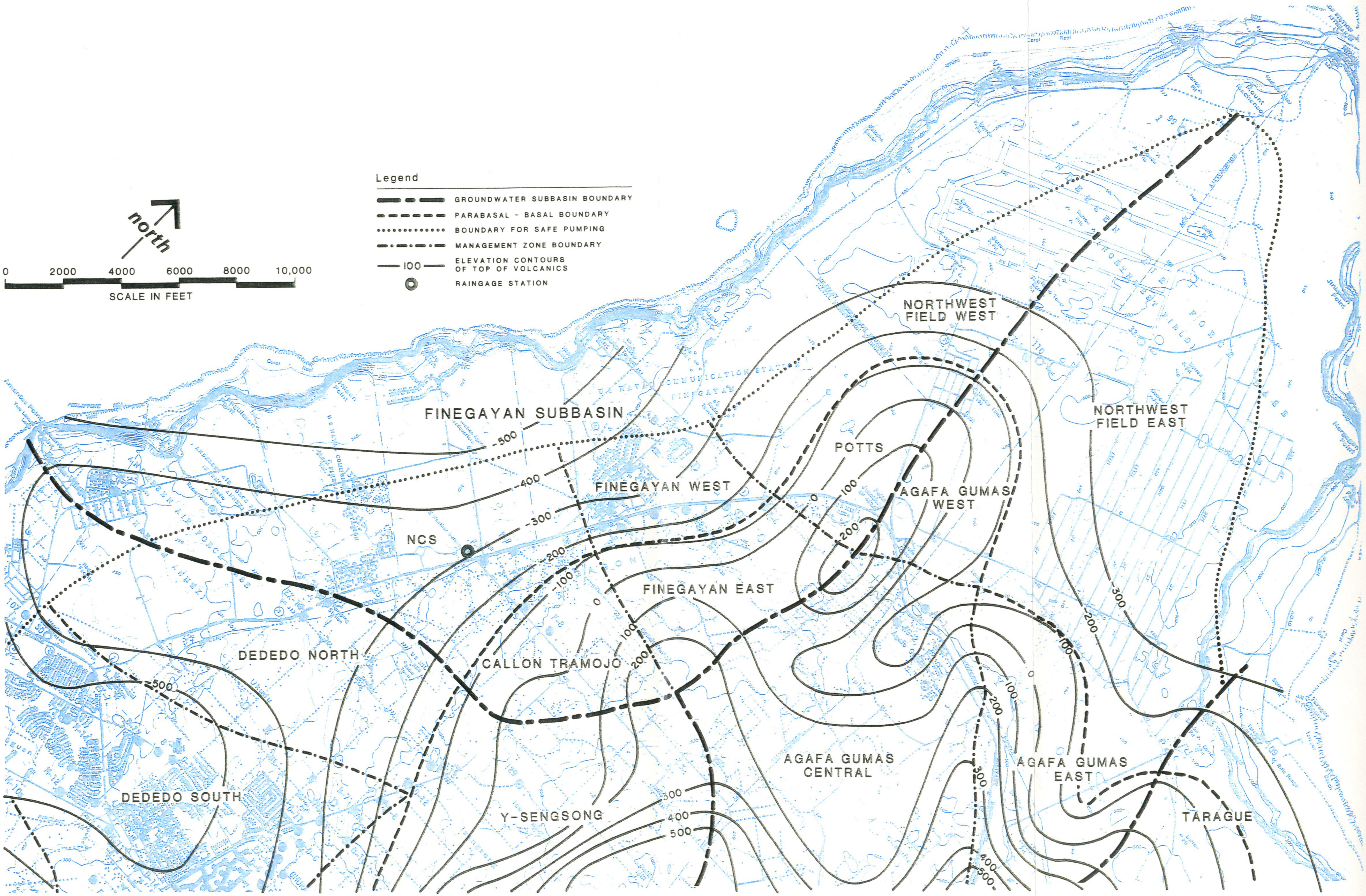


FIGURE 7-5 FINEGAYAN SUBBASIN

Yigo Subbasin

The Yigo subbasin is subdivided into nine parabasal management zones and four basal zones as shown on Figure 7-6. Recharge to the subbasin ranges between 31 and 37 inches per year, with the maximum recharge occurring in the Y-Sengsong parabasal zone (3,430 gpm) and in the Dededo South basal zone (4,800 gpm). The amount of sustainable yield varies between 50 and 60 percent of available yield in the parabasal management zones and 40 to 60 percent in the basal zones. The lower percentage recharge values in the parabasal zones have been assigned because of the rugged terrain in those areas, which would limit the ability of wells to intercept recharge. The higher values in the basal zones are assigned because of the fairly high fresh water heads that result from the long distance to the coastline.

Production capacity is quite high in the Yigo Subbasin, totalling over 7,000 gpm, with most of this production coming from the basal zones. The Dededo South zone produces up to 3,800 gpm, and the Asatdas management zone produces about 1,230 gpm. Current production in the parabasal zones is relatively limited, with most of the extractions coming from the Yigo West (675 gpm) and Y-Sengsong (685 gpm) zones. The majority of the unused yield occurs in the parabasal zones with each zone having between 240 and 1,375 gpm additional yield. Because of the high permeability of the limestone aquifer, parabasal wells should yield between 500 and 750 gpm without detriment to the fresh water lens. However, several parabasal zones may be limited to 200 and 350 gpm wells because sustainable yield is being approached.

The existing production capacity in the basal management zones is high, so additional yield is limited. The Dededo North zone has 680 gpm of unused yield, while the Macheche zone has about 920 gpm. These zones can accommodate up to three and four 200 gpm wells each, respectively. But further development in the basal zones should be done carefully because production in the Dededo South management zones greatly exceeds available yield which may impact the amount of water available for yield from adjacent zones.

SUMMARY

As shown on Table 7-4, the total recharge to the Northern Lens is about 112 MGD over about a 68 square-mile area of the Northern Lens (excluding the 4,000-foot wide coastal buffer zone). Total sustainable yield for the parabasal and basal management zones is about 59 MGD, or about 53 percent of recharge. Total subbasin runoff and production capacity is about 22 MGD, and the total unused yield is about 37 MGD.

WELL DESIGN CONSIDERATIONS

In designing the capacity of any new well or well field, the following factors should be considered:

1. The optimum well capacity is directly related to permeability; that is, the lower the permeability, the lower the well capacity that can be expected.

2. Production from a management zone should not exceed the sustainable yield of the zone. If sustainable yield is presently being exceeded in a mangement zone, then the yield from upstream zones should be correspondingly reduced.

3. If water quality in a particular management zone is being degraded to the point of becoming unuseable, any future well facility development should be halted, and sustainable yield reevaluated, even if the reported sustainable yield has not been exceeded.

4. In clean limestones with relatively high permeability, wells should be placed no closer than 300 feet from one another. In the lower permeability argillaceous limestones of the Agana Subbasin area, wells should be placed at least 500 feet apart, and preferably, 1,000 feet apart.

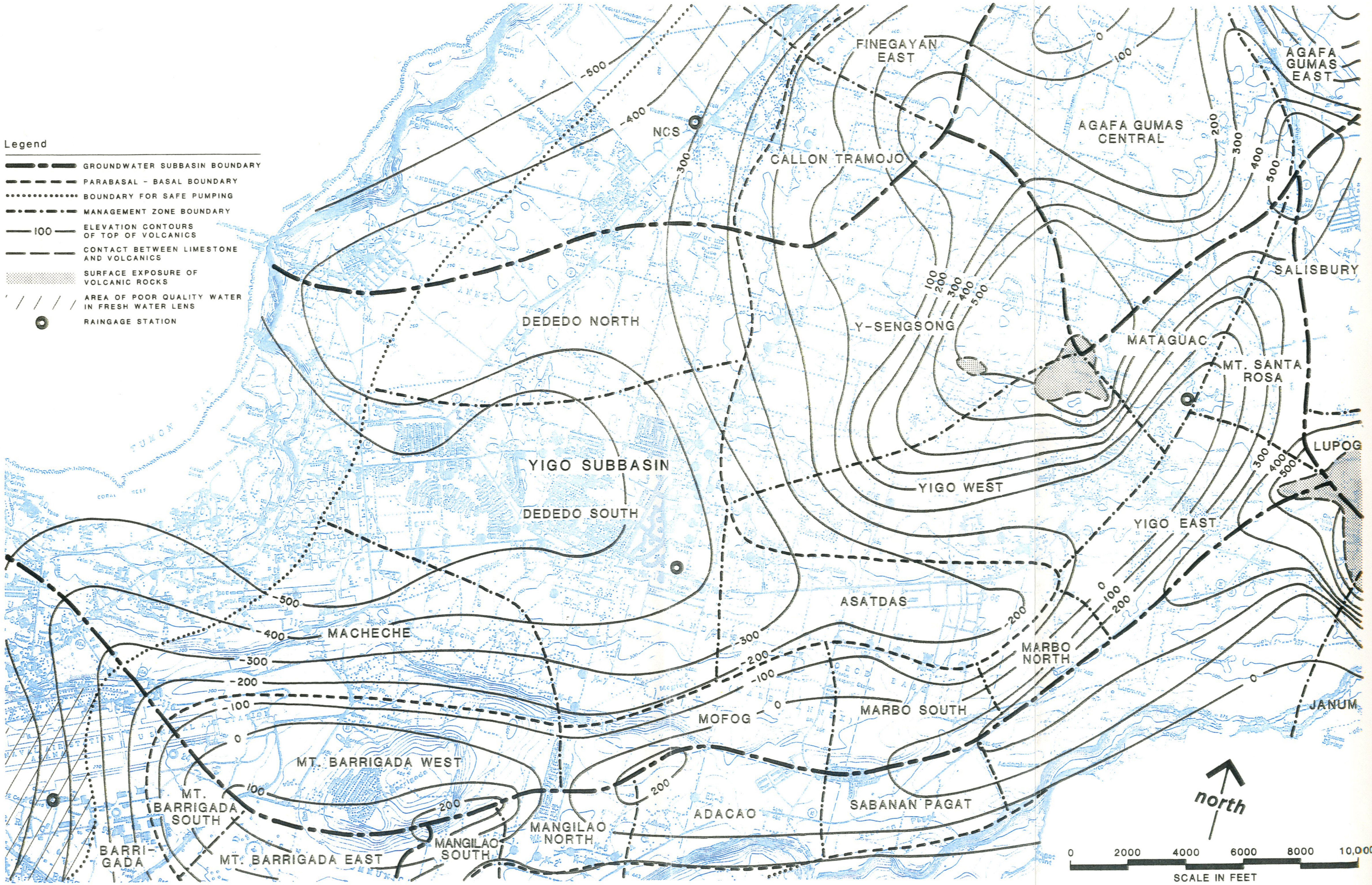


FIGURE 7-6 YIGO SUBBASIN

VIII

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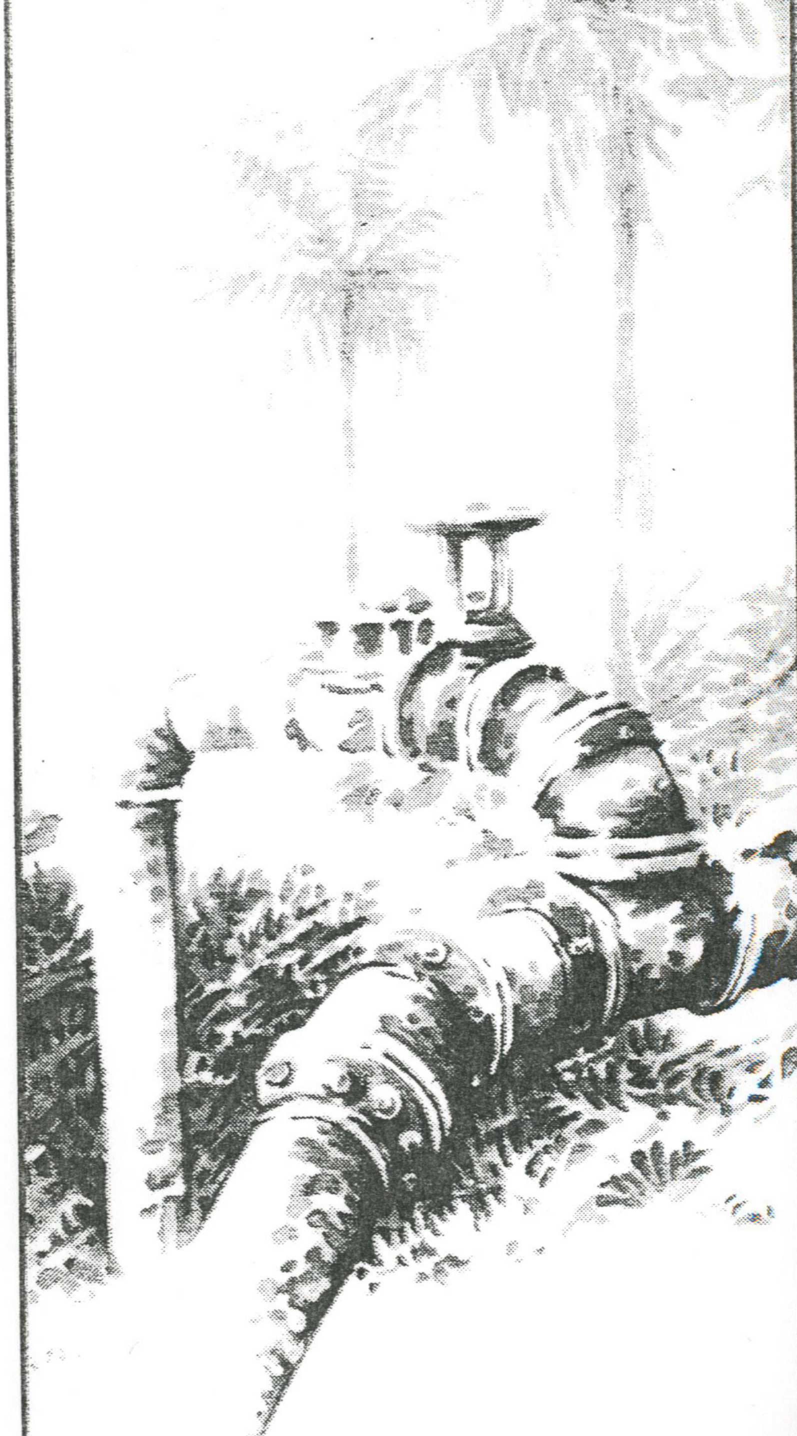

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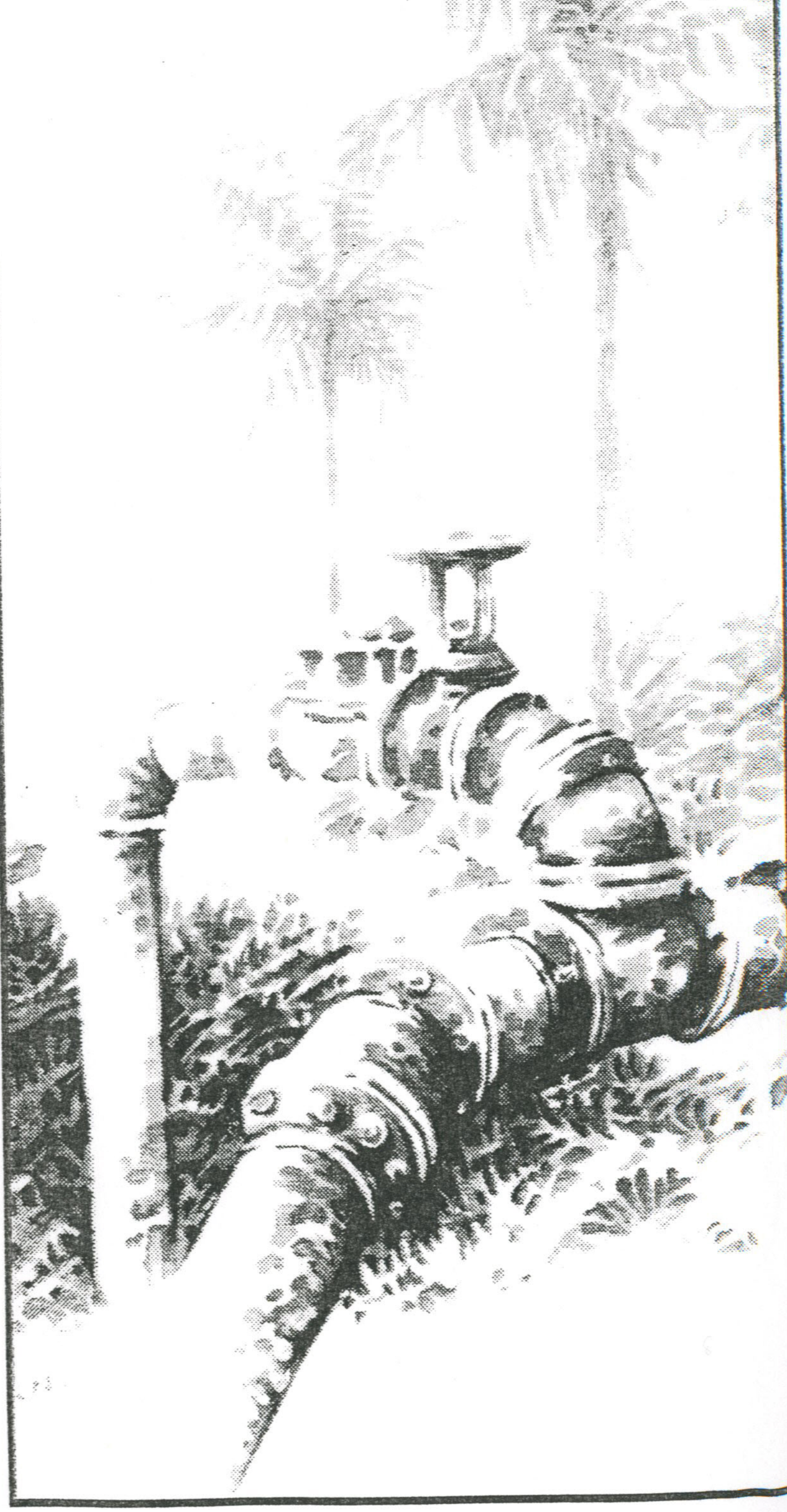
APPENDICES



APPENDIX A

TABLES AND FIGURES FROM DATA REPORT REFERENCED IN AQUIFER YIELD REPORT

TABLE A-1

MEAN MONTHLY PRECIPITATION

NOAA-USGS

STATION NAME	SITE NO.	OBSERVER	NO. OF YEARS OF RECORD	MEAN MONTHLY PRECIPITATION JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVERAGE ANNUAL
Pago River (upstream)	2645100	USGS	16	4.69	3.26	2.17	3.93	4.88	5.84	8.98	13.04	13.68	12.44	9.49	6.77	89.17
Mangilao	2647550	DOA	7	6.69	5.16	4.42	4.47	5.06	7.40	9.13	13.09	13.88	12.04	10.29	4.97	96.60
Nimitz Hill (USGS) Fleet Weather Central (Nimitz Hill)	2743440 2743430	USN USN	22 7	5.41	3.54	3.44	3.76	4.38	5.59	10.36	13.51	13.83	13.33	9.39	5.54	92.08
Agana Springs	2745430	USN	6	3.86	4.52	2.22	2.29	3.74	3.55	7.95	13.38	13.83	14.26	10.92	5.92	86.44
Adelup Reservoir	2843150	USN	6	2.90	2.97	1.43	1.49	2.84	3.19	7.39	13.02	15.27	14.95	9.53	4.78	79.76
Barrigada Booster School	2846201	USN	3	3.00	3.27	1.79	0.69	2.81	2.90	5.93	18.98	14.28	20.86	12.23	5.99	92.73
Tamuning (ACEORP)	2846542	USN	1	3.37	1.80	2.54	0.99	7.57	9.52	12.04	7.54	12.96	13.60	7.41	3.81	83.15
Fleet Weather Central NAS-A NAS-B	2847501 2847340	USN USN	8 23	4.53	3.40	2.91	3.52	5.55	5.30	9.84	12.72	12.61	11.94	8.74	4.99	86.05
Tamuning (USGS)	2946051	USGS	15	4.63	2.65	1.91	3.11	4.39	5.22	8.88	13.89	15.19	13.47	9.36	5.86	88.56
Dededo	3150044	PUAG	3	5.16	9.38	5.13	4.80	7.09	7.67	13.30	17.56	18.09	22.75	8.78	9.69	129.40
Naval Communications Station	3245450	USN	10	5.27	3.01	2.64	2.23	3.70	5.14	8.46	13.87	13.47	15.13	9.37	6.01	88.30
National Weather Service	3350210	NWS	22	5.84	4.65	4.33	4.65	7.83	5.76	10.80	14.08	14.60	13.57	8.91	6.15	101.17
Yigo Agricultural Stn Yigo (Animal Quar. Stn)	3245450 3253420	USGS Gov Guam	6 4	3.57	6.56	3.57	7.32	8.85	6.23	10.06	14.32	14.31	15.90	8.94	9.45	109.08
Andersen AFB-A Andersen AFB-B	3355500 3455230	USAF USAF	21 11	5.12	4.28	3.86	4.10	5.93	5.11	9.62	13.04	12.34	13.51	8.56	5.87	91.34

TABLE A-2a
ADJUSTED MONTHLY PRECIPITATION
NATIONAL WEATHER SERVICE, FINEGAYAN

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*3.06*	*2.81*	*2.61*	*1.12*	*11.59*	*7.21*	*12.18*	*9.12*	*23.61*	*15.75*	*8.23*	*6.47*	103.76
1951	*6.27*	*7.61*	*5.89*	*7.70*	*-0-*	*3.35*	*7.86*	*17.63*	*4.47*	*17.99*	*9.52*	*8.74*	97.03
1952	*3.61*	*1.55*	*2.44*	*1.48*	*5.74*	*4.34*	*10.75*	*12.96*	*16.78*	*14.73*	*12.22*	*8.81*	95.41
1953	*2.45*	*11.75*	*1.91*	*0.54*	*1.80*	*3.48*	*9.10*	*25.03*	*10.86*	*27.53*	*11.50*	*7.03*	112.98
1954	*6.92*	*2.80*	*1.57*	*1.93*	*1.91*	*5.27*	*8.46*	*14.14*	*20.70*	*14.50*	*13.12*	*4.65*	95.97
1955	*9.06*	*4.34*	*3.27*	*3.76*	*2.77*	*6.19*	*14.46*	*8.81*	*19.70*	*11.13*	*8.01*	*5.36*	96.86
1956	*3.39*	*4.69*	*2.95*	*2.66*	*6.55*	*4.29*	*10.16*	*8.75*	*18.09*	*10.74*	*13.15*	*9.82*	95.24
1957	*4.62*	*3.20*	*2.96*	*2.70*	*1.06*	*4.77*	*7.29*	*10.54*	*12.88*	*13.91*	*13.74*	*3.09*	80.76
1958	7.91	2.23	1.70	2.44	3.87	11.53	12.89	11.22	14.43	12.12	5.80	4.62	90.76
1959	3.48	2.30	1.93	3.22	0.90	2.27	6.15	11.56	18.39	10.76	11.71	6.31	78.98
1960	2.71	0.67	1.73	1.44	5.69	7.54	7.93	14.83	9.35	11.78	11.30	6.23	81.20
1961	7.66	2.74	4.85	4.28	5.37	5.90	8.10	16.61	15.40	19.17	5.31	4.35	99.74
1962	2.24	9.17	1.66	8.66	6.68	7.79	14.98	14.12	21.86	14.95	13.09	12.16	127.36
1963	9.33	9.47	2.40	19.55	12.56	7.11	11.25	11.85	13.47	18.06	6.88	16.19	138.12
1964	1.99	4.11	4.44	7.48	20.69	7.49	7.67	8.92	19.30	14.62	6.05	6.92	109.68
1965	10.29	1.02	0.48	0.50	1.69	5.35	15.67	3.87	22.27	6.89	6.95	3.13	78.11
1966	2.13	1.69	1.71	1.31	2.51	5.72	6.74	11.39	22.28	6.96	7.26	4.76	74.46
1967	5.26	4.45	11.28	8.97	3.76	8.37	12.62	23.07	20.28	14.20	11.75	2.51	126.52
1968	5.75	8.48	3.71	1.69	3.16	6.17	12.36	14.61	11.82	13.31	11.92	3.36	96.34
1969	2.79	1.12	0.97	1.36	2.72	1.52	13.83	9.30	6.79	25.32	10.10	10.11	85.93
1970	11.93	3.60	2.68	1.22	2.96	5.60	8.99	10.39	13.70	11.65	9.77	5.71	88.20
1971	5.25	5.78	16.94	5.74	22.68	5.06	16.06	20.92	12.21	8.63	6.75	3.14	129.16
1972	*5.10*	*4.57*	*6.12*	*1.93*	*2.29*	*5.29*	*13.92*	*16.16*	*12.97*	*6.98*	*4.55*	*4.18*	84.09
1973	2.10	2.94	1.57	1.90	3.01	4.85	9.55	6.65	9.05	17.82	2.08	5.35	66.87
1974	4.27	3.13	12.25	14.83	12.00	10.46	9.32	25.66	9.96	10.00	8.03	6.20	126.11
1975	9.68	1.15	2.25	3.67	1.33	2.46	11.13	22.57	8.86	10.68	12.33	6.42	92.53
1976	20.39	13.56	9.04	4.37	40.13	6.40	13.38	24.40	10.79	6.63	7.91	8.91	165.91
1977	3.12	3.01	4.98	2.29	6.88	5.10	7.25	6.09	17.32	16.67	12.38	2.22	87.31
1978	2.44	4.99	0.85	2.65	3.48	7.89	8.91	19.63	10.01	10.49	14.10	4.80	90.24
1979	5.60	1.85	4.20	1.89	1.48	4.28	11.83	12.75	8.34	25.79	6.78	5.67	90.46
1980	2.07	14.79	3.42	2.92	8.60	7.96	10.93	9.42	25.34	12.02	7.76	6.14	111.37
AVG.	5.56	4.70	4.03	4.07	6.71	5.61	10.70	13.97	14.88	13.93	9.36	6.24	99.76

Italicized numbers are estimated from NAS data using simple regression technique.

TABLE A-2b

ADJUSTED MONTHLY PRECIPITATION
ANDERSEN AIR FORCE BASE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*2.82*	*2.51*	*2.24*	*0.67*	*10.79*	*6.60*	9.27	13.21	15.64	17.51	18.32	7.17	106.75
1951	7.96	6.40	4.81	3.58	0.77	1.21	8.97	15.35	5.64	10.00	6.93	8.09	79.71
1952	1.51	*1.09*	1.89	1.27	4.11	2.58	7.05	8.34	12.30	12.43	12.98	5.55	71.10
1953	1.84	12.37	2.31	1.17	2.46	1.42	5.92	26.28	8.55	37.09	8.83	8.22	116.46
1954	4.11	3.12	2.54	2.37	1.59	3.43	3.46	10.42	23.27	11.53	7.51	2.77	76.62
1955	6.40	3.31	3.12	3.71	1.63	4.94	10.07	6.37	16.55	8.95	4.38	4.28	73.71
1956	2.70	3.92	1.62	1.13	3.09	2.56	9.15	5.48	13.03	6.11	7.24	6.39	62.42
1957	3.69	2.17	1.84	2.50	1.67	3.12	3.00	10.47	6.69	17.71	7.86	2.10	62.82
1958	5.36	0.68	0.69	1.11	2.31	7.70	11.80	5.59	14.61	7.34	*8.14*	6.12	71.45
1959	2.15	1.30	1.62	1.92	1.41	1.40	6.13	9.12	*15.89*	8.54	6.80	6.94	63.22
1960	3.39	0.66	1.59	0.38	5.93	5.92	8.59	16.71	9.02	16.88	11.91	5.99	86.97
1961	4.79	3.73	5.04	3.20	4.37	4.09	6.45	14.95	14.51	17.88	5.97	4.43	89.41
1962	1.64	8.78	1.42	8.43	5.32	6.85	*15.28*	*17.71*	13.76	*11.92*	6.95	13.26	111.25
1963	10.92	11.06	3.35	24.00	13.97	6.93	13.25	10.77	11.56	20.24	6.71	16.90	149.66
1964	2.47	3.89	3.37	6.56	25.45	5.90	6.29	13.03	10.49	11.20	4.30	4.97	97.92
1965	9.46	0.98	0.30	*0.10*	1.10	6.49	15.78	3.99	18.41	5.36	8.68	3.37	74.02
1966	2.22	1.34	1.59	0.78	2.73	5.52	7.95	13.58	19.87	9.54	6.12	3.68	74.92
1967	5.45	4.16	10.33	8.70	3.34	7.26	15.23	16.83	22.31	13.48	*8.68*	2.15	117.92
1968	5.16	8.37	3.15	2.83	2.49	4.99	13.37	12.95	1.58	13.23	10.39	3.07	91.58
1969	2.35	1.39	1.34	0.93	2.01	2.58	9.69	8.09	8.09	27.75	6.52	6.78	77.52
1970	17.28	4.16	2.27	1.32	1.29	4.57	7.25	8.25	10.54	9.98	7.74	4.98	79.63
1971	5.47	5.50	14.66	3.95	17.56	5.63	15.39	15.31	12.95	8.17	10.28	2.99	117.80
1972	3.79	6.37	12.59	3.20	3.36	8.15	13.99	15.30	14.09	4.05	4.26	6.00	95.15
1973	1.51	2.67	2.18	1.71	3.10	4.04	8.99	13.84	10.90	20.88	2.61	6.95	79.38
1974	5.66	2.98	11.78	14.55	9.99	6.94	9.29	22.24	3.95	12.49	6.88	4.95	111.70
1975	7.83	0.71	2.30	2.92	2.07	2.92	10.67	23.88	10.03	11.70	16.75	3.93	95.71
1976	16.09	12.47	7.36	4.68	35.28	5.20	10.83	19.60	12.36	8.03	9.30	11.39	152.59
1977	3.62	3.21	4.77	2.26	3.30	7.83	6.44	5.00	15.66	14.25	10.80	1.13	78.27
1978	1.94	5.32	0.90	3.69	2.63	9.72	9.50	17.78	10.57	8.19	15.76	5.29	91.29
1979	5.34	1.19	4.40	1.35	2.48	1.77	10.36	13.25	7.52	24.59	7.42	5.59	85.26
1980	1.46	*18.09*	2.03	4.26	11.96	10.50	11.81	*9.16*	*22.10*	*11.97*	8.00	6.55	117.51
AVG.	5.04	4.64	3.85	3.86	6.11	5.12	9.72	13.00	12.66	13.52	8.55	5.87	92.24

Italicized numbers are estimated from NAS data using simple regression technique.
1950-1970 are from USGS records of Andersen AFB-A precipitation station.
1971-1981 are from USGS and NOAA records of Andersen AFB-B precipitation station.

TABLE A-2c
ADJUSTED MONTHLY PRECIPITATION
YIGO

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*2.69*	*3.15*	*2.76*	*1.47*	*11.14*	*7.31*	*11.99*	*9.83*	*22.43*	*16.50*	*8.94*	*8.04*	106.25
1951	*4.17*	*9.12*	*5.74*	*8.02*	*1.24*	*1.87*	*7.01*	*16.17*	*1.73*	*17.93*	*9.86*	*11.48*	94.34
1952	*2.94*	*1.59*	*2.61*	*1.83*	*6.24*	*3.26*	*10.35*	*12.69*	*15.04*	*15.76*	*11.78*	*11.58*	95.67
1953	*2.40*	*14.28*	*2.13*	*0.89*	*2.93*	*2.06*	*8.44*	*21.68*	*8.64*	*24.27*	*11.27*	*8.87*	107.86
1954	*4.48*	*3.13*	*1.82*	*2.28*	*3.02*	*4.58*	*7.70*	*13.56*	*19.28*	*15.61*	*12.42*	*5.27*	93.15
1955	*5.47*	*5.05*	*3.36*	*4.10*	*3.74*	*5.88*	*14.62*	*9.60*	*18.20*	*13.37*	*8.79*	*6.35*	98.53
1956	*2.84*	*5.48*	*3.07*	*3.00*	*6.91*	*3.19*	*9.67*	*9.55*	*16.46*	*13.11*	*12.44*	*13.11*	98.83
1957	*3.41*	*3.63*	*3.08*	*3.04*	*2.31*	*3.87*	*6.35*	*10.89*	*10.82*	*15.21*	*12.85*	*2.91*	78.37
1958	*4.49*	*2.83*	*0.92*	*3.18*	*3.39*	*7.77*	*11.13*	*12.45*	*14.00*	*14.16*	*9.26*	*5.68*	89.26
1959	2.91	2.67	2.53	2.28	0.98	2.00	6.03	10.29	18.84	10.06	9.30	7.12	75.01
1960	3.14	1.88	1.81	1.65	4.24	4.49	4.06	12.06	8.90	11.40	11.10	15.63	80.90
1961	3.79	3.46	4.60	4.81	9.13	4.78	6.71	15.97	12.26	21.20	3.92	7.59	98.22
1962	1.43	8.69	1.78	7.32	5.88	7.57	16.60	13.04	14.04	13.57	12.67	10.60	113.19
1963	7.17	8.97	1.74	20.29	8.71	7.00	10.30	9.45	13.46	18.90	4.90	12.98	123.87
1964	2.44	3.24	2.37	10.66	22.78	4.88	8.16	9.32	13.44	*12.50*	*7.48*	*9.09*	106.36
1965	*7.04*	*2.60*	*1.24*	*0.84*	*2.54*	*4.22*	*14.44*	*6.90*	*17.69*	*11.88*	*7.87*	*8.57*	85.83
1966	*2.66*	*2.23*	*1.75*	*0.71*	*1.91*	*5.21*	*6.69*	*14.25*	*21.36*	*11.26*	*9.53*	*5.48*	83.04
1967	*4.00*	*4.60*	*10.19*	*8.35*	*5.02*	*11.20*	*11.94*	*18.33*	*20.99*	*15.90*	*9.89*	*2.79*	123.20
1968	*4.05*	*11.27*	*4.76*	*3.02*	*3.09*	*6.62*	*11.14*	*14.83*	*14.05*	*18.55*	*11.06*	*2.48*	104.92
1969	*2.79*	*3.28*	*3.76*	*3.80*	*5.23*	*1.63*	*11.89*	*11.66*	*7.28*	*18.86*	*9.94*	*13.40*	93.52
1970	*4.96*	*4.18*	*2.76*	*1.52*	*1.68*	*5.42*	*8.25*	*10.04*	*10.39*	*12.29*	*8.18*	*5.95*	75.62
1971	*3.99*	*7.86*	*9.91*	*4.86*	*19.22*	*5.32*	*14.04*	*15.48*	*7.17*	*11.74*	*8.58*	*2.93*	111.10
1972	*3.64*	*5.34*	*5.94*	*2.28*	*3.34*	*4.60*	*13.07*	*15.07*	*10.93*	*10.61*	*6.33*	*4.56*	85.71
1973	*2.31*	*3.08*	*1.51*	*1.43*	*2.27*	*3.63*	*7.35*	*11.13*	*6.61*	*17.14*	*6.30*	*11.33*	74.09
1974	*3.04*	*3.22*	*13.05*	*12.86*	*15.94*	*7.85*	*12.56*	*20.03*	*6.80*	*14.19*	*8.36*	*8.46*	126.36
1975	*5.01*	*1.56*	*2.45*	*3.26*	*1.81*	*2.34*	*10.03*	*14.89*	*6.43*	*14.86*	*10.76*	*3.81*	77.21
1976	*10.31*	*13.88*	*10.52*	*4.98*	*28.75*	*6.32*	*14.20*	*23.17*	*9.24*	*10.30*	*10.55*	*7.34*	149.56
1977	*2.62*	*3.42*	*5.25*	*1.62*	*4.92*	*4.45*	*7.20*	*7.05*	*13.32*	*17.09*	*10.02*	*2.99*	79.95
1978	*2.22*	*3.71*	*0.68*	*2.73*	*4.87*	*10.76*	9.49	22.86	17.20	*13.62*	13.79	5.95	107.88
1979	3.99	1.98	4.97	2.24	1.21	4.15	13.83	13.47	9.51	21.22	8.02	6.32	90.91
1980	3.02	21.00	6.29	7.34	19.80	12.49	12.77	16.34	24.92	18.65	7.80	9.37	156.79
AVG	3.85	5.50	4.04	4.41	6.91	5.38	10.26	13.64	13.27	14.81	9.04	7.68	99.53

Italicized numbers are estimated from NAS data using simple regression technique.

1959-1964 are from USGS records of Yigo Agricultural Station precipitation station.

1978-1981 are from NOAA records of Yigo precipitation station.

TABLE A-2d

ADJUSTED MONTHLY PRECIPITATION

FLEET WEATHER CENTRAL (NAS)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	1.97	1.76	1.95	1.13	9.17	7.45	12.11	7.79	21.62	14.57	7.46	5.21	92.19
1951	5.23	5.93	4.17	6.47	0.79	1.56	5.60	16.19	3.91	16.75	9.11	7.27	82.98
1952	2.53	0.67	1.84	1.42	5.02	3.07	9.96	11.58	15.30	13.43	12.56	7.33	84.71
1953	1.34	9.53	1.48	0.66	2.22	1.76	7.47	23.49	9.82	26.48	11.64	5.71	101.60
1954	5.90	1.75	1.25	1.79	2.30	4.49	6.50	12.74	18.93	13.19	13.71	3.55	86.10
1955	8.07	3.09	2.40	3.27	2.91	5.90	15.55	7.48	18.00	9.76	7.18	4.20	87.81
1956	2.30	3.39	2.18	2.38	5.59	2.99	9.07	7.42	16.51	9.36	13.75	8.25	83.19
1957	3.55	2.10	2.19	2.41	1.70	3.73	4.74	9.19	11.69	12.59	14.50	2.14	70.53
1958	5.92	1.54	0.58	2.52	2.61	7.95	10.98	11.26	14.41	10.97	8.03	3.80	80.57
1959	2.47	1.43	1.78	2.90	0.66	1.20	5.02	12.60	16.79	9.39	6.78	3.74	64.76
1960	2.51	0.38	1.59	1.11	5.39	4.74	6.69	11.01	10.05	10.10	9.17	7.97	70.71
1961	6.18	2.27	4.08	5.75	6.07	7.03	6.08	15.73	15.14	17.03	7.42	5.14	97.92
1962	1.63	3.93	1.59	7.35	6.11	9.38	18.03	18.06	15.09	11.27	*13.71*	7.53	113.68
1963	11.14	7.26	2.06	15.28	15.02	*7.24*	8.74	7.20	12.85	16.82	5.77	8.43	117.81
1964	1.95	2.65	1.31	8.91	14.31	4.86	10.30	8.65	12.77	9.05	4.83	5.84	85.43
1965	11.52	1.38	0.82	0.62	1.89	4.10	15.31	3.91	17.57	7.48	5.53	5.53	70.13
1966	1.92	1.12	1.20	0.51	1.36	5.18	5.18	13.65	20.71	6.53	8.52	3.68	69.56
1967	4.85	2.77	7.49	6.74	3.99	11.66	12.04	19.05	20.39	13.64	9.17	2.07	113.86
1968	4.96	7.43	3.44	2.39	2.36	6.70	11.00	14.42	14.45	17.71	11.26	1.88	98.00
1969	2.20	1.85	2.70	3.03	4.17	1.30	11.98	10.22	8.66	18.19	9.25	8.42	81.97
1970	6.96	2.48	1.95	1.17	*1.16*	5.40	7.22	8.07	11.32	8.11	6.09	3.96	63.89
1971	4.83	5.05	7.28	3.89	16.01	5.29	14.79	15.28	8.56	7.27	6.81	2.15	97.21
1972	4.05	3.29	4.32	1.79	2.57	4.52	13.52	14.74	11.78	5.53	2.75	3.13	71.99
1973	1.15	1.71	1.02	1.10	1.66	3.46	6.04	9.51	8.08	15.55	2.70	7.18	59.16
1974	2.75	1.81	9.62	10.41	13.24	8.04	12.85	21.67	8.25	11.02	6.41	5.46	111.53
1975	7.07	0.65	1.72	2.59	1.27	2.07	9.55	14.49	7.93	12.04	10.73	2.68	72.79
1976	18.69	9.25	7.73	3.99	24.08	6.38	15.00	25.47	10.33	5.06	10.35	4.79	141.12
1977	1.82	1.95	3.81	1.25	3.91	4.35	5.84	4.11	13.83	15.47	9.39	2.19	67.92
1978	0.95	2.15	0.40	2.16	3.86	11.19	10.94	16.29	9.85	10.14	16.15	3.88	87.96
1979	2.71	1.06	3.45	1.50	1.60	3.21	7.38	10.37	11.56	25.25	9.29	5.07	82.45
1980	1.21	13.74	2.74	2.77	10.34	9.90	9.69	8.11	23.90	11.31	5.85	6.66	106.22
AVG.	4.53	3.40	2.91	3.52	5.41	5.36	9.84	12.57	13.55	12.61	8.90	4.99	87.59

Italicized numbers are filled in using USWB, Finegayan data.

1950-1957 are from USGS records of Fleet Weather Central NAS-A precipitation station.

1958-1980 are from USGS and NOAA records of Fleet Weather Central NAS-B precipitation station.

TABLE A-2e

ADJUSTED MONTHLY PRECIPITATION
MANGILAO
NOAA

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*3.04*	*2.43*	*2.22*	*1.75*	*9.21*	*8.33*	*10.69*	*9.25*	*24.96*	*12.76*	*7.98*	*5.84*	98.46
1951	*6.35*	*6.79*	*4.38*	*6.99*	*1.22*	*2.83*	*6.98*	*16.09*	*3.71*	*13.69*	*9.32*	*8.05*	86.40
1952	*3.61*	*1.29*	*2.12*	*2.03*	*5.25*	*4.24*	*9.46*	*12.34*	*17.50*	*12.27*	*12.14*	*8.11*	90.36
1953	*2.40*	*10.55*	*1.77*	*1.29*	*2.58*	*3.02*	*8.05*	*22.03*	*11.03*	*17.86*	*11.39*	*6.38*	98.34
1954	*7.03*	*2.42*	*1.54*	*2.40*	*2.66*	*5.57*	*7.49*	*13.28*	*21.78*	*12.16*	*13.08*	*4.07*	93.49
1955	*9.24*	*3.82*	*2.66*	*3.85*	*3.24*	*6.89*	*12.54*	*9.00*	*20.69*	*10.70*	*7.75*	*4.76*	95.23
1956	*3.38*	*4.13*	*2.45*	*2.98*	*5.80*	*4.17*	*8.96*	*8.95*	*18.93*	*10.52*	*13.11*	*9.10*	92.46
1957	*4.65*	*2.78*	*2.46*	*3.01*	*2.09*	*4.86*	*6.49*	*10.39*	*13.24*	*11.91*	*13.72*	*2.56*	78.15
1958	*7.05*	*2.20*	*0.89*	*3.11*	*2.95*	*8.80*	*10.04*	*12.07*	*16.45*	*11.21*	*8.44*	*4.34*	87.57
1959	*3.55*	*2.08*	*2.06*	*3.49*	*1.09*	*2.49*	*6.65*	*13.17*	*19.26*	*10.54*	*7.42*	*4.27*	106.99
1960	*3.59*	*0.99*	*1.87*	*1.73*	*5.60*	*5.80*	*7.60*	*11.87*	*11.31*	*10.84*	*9.37*	*8.80*	79.38
1961	*7.32*	*2.96*	*4.29*	*6.28*	*6.25*	*7.94*	*7.25*	*15.72*	*17.31*	*13.81*	*7.94*	*5.77*	102.85
1962	*2.70*	*4.70*	*1.87*	*7.85*	*6.29*	*10.14*	*14.06*	*17.61*	*17.25*	*11.34*	*13.08*	*8.33*	115.23
1963	*12.36*	*8.17*	*2.33*	*15.64*	*14.79*	*8.14*	*8.77*	*8.77*	*14.61*	*13.72*	*6.60*	*9.29*	123.17
1964	*3.02*	*3.36*	*1.60*	*9.39*	*14.11*	*5.91*	*9.66*	*9.95*	*14.51*	*10.39*	*5.83*	*6.52*	94.25
1965	*12.74*	*2.03*	*1.13*	*1.25*	*2.27*	*5.20*	*12.51*	*6.09*	*20.18*	*9.72*	*6.40*	*6.19*	85.70
1966	*2.99*	*1.76*	*1.50*	*1.14*	*1.76*	*6.21*	*6.74*	*14.02*	*23.88*	*9.31*	*8.84*	*4.21*	82.37
1967	*5.97*	*3.48*	*7.60*	*7.26*	*4.27*	*12.27*	*10.65*	*18.42*	*23.51*	*12.36*	*9.37*	*2.48*	117.63
1968	*6.08*	*8.35*	*3.67*	*2.99*	*2.72*	*7.63*	*10.05*	*14.65*	*16.50*	*14.10*	*11.08*	*2.28*	100.10
1969	*3.28*	*2.52*	*2.95*	*3.61*	*4.44*	*2.59*	*10.61*	*11.23*	*9.66*	*14.31*	*9.44*	*9.28*	83.92
1970	*8.11*	*3.18*	*2.22*	*1.79*	*1.57*	*6.42*	*7.90*	*9.48*	*12.80*	*9.99*	*6.86*	*4.51*	74.83
1971	5.95	*5.87*	*7.40*	*4.46*	*15.73*	*6.32*	*12.21*	*15.35*	9.55	9.63	*7.45*	*2.57*	102.48
1972	5.15	*4.03*	*4.52*	*2.40*	*2.92*	*5.60*	*11.49*	*14.91*	*13.35*	*8.88*	*4.13*	*3.62*	80.99
1973	*2.21*	*2.38*	*1.32*	*1.72*	*2.05*	*4.60*	*7.23*	*10.65*	*8.98*	*13.18*	*4.09*	*7.95*	66.37
1974	4.51	3.29	9.44	10.36	14.14	10.06	13.37	18.04	11.46	13.63	*7.12*	6.03	121.45
1975	7.57	0.64	2.41	2.74	0.43	2.52	9.22	17.06	8.37	11.89	17.24	4.68	84.76
1976	20.20	10.04	8.09	6.59	*23.42*	6.94	*12.33*	*23.65*	20.98	3.97	8.78	6.20	151.19
1977	*2.89*	2.25	3.74	*1.87*	5.34	7.51	8.59	5.51	12.00	16.41	10.84	2.77	79.72
1978	2.31	3.42	0.38	2.38	5.36	10.32	6.59	17.83	10.37	10.52	13.24	3.27	85.99
1979	3.64	1.48	4.01	1.32	1.89	3.16	6.78	12.46	4.35	14.25	6.31	2.52	62.17
1980	1.92	14.99	2.85	3.44	8.26	11.28	10.23	7.64	29.66	13.61	5.33	9.30	118.51
AVG	5.64	4.14	3.15	4.10	5.80	6.38	9.40	13.14	15.42	11.92	9.15	5.61	94.86

Italicized numbers are estimated from NAS data using simple regression technique.

TABLE A-2f

ADJUSTED MONTHLY PRECIPITATION

NIMITZ HILL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*3.01*	*2.33*	*2.24*	*1.24*	*7.59*	*8.17*	*12.93*	*10.38*	*21.39*	*14.93*	*7.92*	*5.88*	98.51
1951	4.95	*6.40*	3.85	*7.16*	*1.73*	*1.93*	*7.01*	15.87	7.63	13.13	9.36	5.99	85.01
1952	3.51	1.36	1.18	1.94	4.70	2.75	5.12	11.76	20.74	16.18	12.24	7.23	88.71
1953	6.25	10.47	2.28	1.79	0.72	3.58	9.19	16.74	11.27	19.67	14.21	6.74	102.91
1954	5.98	0.93	1.97	1.22	3.39	5.67	3.92	12.84	*19.46*	6.04	*14.37*	4.37	80.16
1955	5.78	2.36	1.78	2.52	4.43	3.36	12.57	6.02	15.74	11.81	6.37	5.09	77.83
1956	1.68	2.78	2.08	2.32	4.72	3.19	10.77	7.73	12.06	8.23	11.82	7.62	75.00
1957	3.00	2.17	2.58	0.89	2.68	2.86	4.21	10.24	11.68	19.71	13.18	3.10	76.30
1958	5.35	2.05	0.74	1.81	3.86	9.65	11.00	13.30	10.78	9.45	8.67	2.81	79.47
1959	3.14	1.47	0.93	2.91	1.55	2.25	5.80	14.88	22.81	10.02	5.80	2.88	74.44
1960	2.86	0.84	1.80	1.19	4.69	4.10	10.08	12.48	9.93	12.06	8.95	8.85	77.83
1961	8.06	2.13	4.88	2.58	*5.42*	7.69	11.23	13.27	13.02	20.43	4.81	3.23	96.75
1962	2.17	6.21	1.15	8.50	*5.45*	11.74	13.52	23.76	19.78	12.26	13.95	10.28	128.77
1963	6.80	8.62	2.37	16.44	7.59	7.05	5.53	7.92	11.91	19.33	5.71	9.90	109.17
1964	2.68	3.82	2.35	9.99	16.38	5.08	7.72	11.71	11.99	7.36	4.55	5.24	88.87
1965	12.40	2.96	1.90	0.58	1.42	5.78	16.73	7.88	16.25	6.52	4.92	2.90	80.24
1966	1.36	0.89	1.34	0.60	1.14	6.50	4.84	15.43	18.66	14.96	6.58	6.06	78.36
1967	8.08	4.50	9.68	9.28	2.84	13.40	18.58	15.88	27.20	14.30	11.75	2.32	137.81
1968	5.70	6.86	3.28	2.22	3.58	5.54	17.64	12.78	14.10	14.50	11.44	2.65	100.29
1969	1.91	1.59	1.21	0.95	3.68	1.86	9.06	11.70	7.44	17.16	10.69	14.30	81.55
1970	10.16	6.40	1.66	1.10	1.98	4.15	6.76	8.53	9.90	10.27	8.77	6.20	75.88
1971	11.26	4.64	10.15	11.70	11.45	6.03	21.23	13.83	9.59	14.56	5.46	4.25	124.15
1972	5.42	5.06	8.06	2.02	3.55	3.82	13.18	16.57	12.40	4.76	4.55	*3.91*	83.30
1973	1.45	0.90	0.72	1.33	2.81	4.14	8.97	*11.47*	13.89	11.00	3.01	7.21	66.90
1974	3.11	3.40	*13.32*	*11.53*	*10.43*	*8.79*	*13.61*	*19.20*	10.55	10.70	8.61	4.04	117.29
1975	6.04	1.37	2.43	2.56	1.81	1.95	7.21	19.14	9.41	10.82	13.26	3.85	79.85
1976	18.80	8.64	11.44	5.79	*18.00*	10.91	18.88	18.41	12.23	6.43	14.05	7.20	150.78
1977	3.86	2.03	7.73	2.08	6.58	7.90	8.77	10.27	23.42	23.30	14.01	2.75	112.70
1978	1.62	3.67	0.51	2.15	3.43	10.96	11.66	22.02	13.84	11.98	18.72	4.55	105.11
1979	3.45	0.96	3.45	1.19	1.71	2.96	9.46	13.81	8.93	29.64	7.58	5.53	88.67
1980	*2.35*	*14.03*	*3.39*	*3.05*	*8.41*	*10.76*	*10.73*	*10.58*	*23.95*	*12.30*	*6.26*	*7.26*	113.07
AVG.	5.23	3.93	3.63	3.89	5.09	5.95	10.58	13.43	13.35	13.35	9.41	5.62	94.70

Italicized numbers are estimated from NAS data using simple regression technique.

1951-1972 are from USGS records of Nimitz Hill (USGS) precipitation station.

1973-1979 are from USGS records of Fleet Weather Central (Nimitz Hill) precipitation station.

TABLE A-2g

ADJUSTED MONTHLY PRECIPITATION

NAVAL COMMUNICATION STATION

USGS

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	2.39	1.02	3.04	0.97	12.08	9.82	14.04	9.91	14.64	13.32	8.00	5.42	94.65
1951	11.08	*4.93*	5.46	*4.93*	2.13	*2.18*	12.17	16.97	6.24	11.65	11.01	9.26	98.01
1952	2.30	1.40	1.82	2.72	5.56	4.26	7.68	13.37	13.86	18.25	14.32	5.86	91.40
1953	3.78	7.05	3.10	1.63	2.69	2.38	5.13	30.98	6.46	33.17	12.31	9.73	118.41
1954	5.69	2.61	1.87	2.76	2.60	5.12	5.78	13.82	25.94	12.97	10.19	3.79	93.14
1955	9.44	3.28	3.73	4.53	3.58	4.81	14.77	9.99	15.34	12.50	7.56	6.15	95.68
1956	2.62	3.88	2.56	2.20	3.76	4.82	5.86	9.92	14.36	5.06	8.76	6.04	69.84
1957	6.40	2.00	2.48	0.66	0.49	3.93	3.40	13.73	12.18	18.25	7.76	2.85	74.13
1958	6.26	2.72	1.35	2.87	3.51	9.38	8.27	11.45	12.17	11.04	4.43	5.00	78.45
1959	2.75	3.15	1.03	1.69	0.59	1.73	7.51	8.56	*15.35*	*8.97*	*7.72*	*4.95*	64.00
1960	*3.70*	*1.52*	*2.19*	*1.65*	*6.16*	*5.64*	*6.97*	*12.72*	*9.90*	*9.89*	*8.68*	*7.87*	76.89
1961	*7.76*	*2.68*	*5.09*	*4.49*	*6.97*	*8.13*	*6.52*	*18.36*	*14.01*	*18.92*	*7.98*	*5.92*	106.83
1962	*2.73*	*3.70*	*2.19*	*5.47*	*7.01*	*10.69*	*15.37*	*21.15*	*13.97*	*11.42*	*10.51*	*7.57*	111.78
1963	*13.26*	*5.74*	*2.73*	*10.32*	*17.51*	*8.36*	*8.49*	*8.16*	*12.16*	*18.65*	*7.32*	*8.19*	120.89
1964	*3.08*	*2.92*	*1.86*	*6.42*	*16.67*	*5.77*	*9.65*	*9.89*	*12.09*	*8.52*	*6.94*	*6.40*	90.21
1965	*13.68*	*2.14*	*1.29*	*1.35*	*2.04*	*4.94*	*13.35*	*4.22*	*15.98*	*6.48*	*7.22*	*6.19*	78.88
1966	*3.05*	*1.98*	*1.73*	*1.28*	*1.42*	*6.12*	*5.86*	*15.87*	*18.51*	*5.24*	*8.42*	*4.91*	74.39
1967	*6.29*	*2.99*	*9.05*	*5.09*	*4.52*	*13.17*	*10.93*	*22.33*	*18.26*	*14.51*	*8.68*	*3.80*	119.62
1968	*6.41*	*5.85*	*4.34*	*2.43*	*2.60*	*7.77*	*10.16*	*16.80*	*13.45*	*19.81*	*9.52*	*3.67*	102.81
1969	*3.36*	*2.43*	*3.48*	*2.82*	*4.73*	*1.89*	*10.89*	*11.77*	*8.77*	*20.44*	*8.72*	*8.18*	87.48
1970	*8.63*	*2.81*	*2.61*	*1.68*	*1.18*	*6.36*	*7.37*	*9.20*	*10.92*	*7.30*	*7.45*	*5.11*	70.62
1971	*6.27*	*4.39*	*8.81*	*3.35*	*18.67*	*6.24*	*12.97*	*17.82*	*8.69*	*6.21*	*7.74*	*3.86*	105.02
1972	*5.41*	*3.31*	*5.36*	*2.06*	*2.84*	*5.40*	*12.03*	*17.18*	*11.29*	*3.94*	*6.11*	*4.53*	79.46
1973	*2.19*	*2.34*	*1.52*	*1.64*	*1.77*	*4.24*	*6.49*	*10.92*	*8.30*	*16.99*	*6.09*	*7.32*	69.81
1974	*3.97*	*2.40*	*11.53*	*7.34*	*15.41*	*9.23*	*11.53*	*25.47*	*8.44*	*11.09*	*7.58*	*6.14*	120.13
1975	*8.75*	*1.69*	*2.34*	*2.55*	*1.31*	*2.73*	*9.09*	*16.88*	*8.18*	*12.42*	*9.31*	*4.22*	79.47
1976	*21.62*	*6.96*	*9.33*	*3.41*	*28.18*	*7.42*	*13.12*	*30.01*	*10.12*	*3.33*	*9.16*	*5.68*	148.34
1977	*2.94*	*2.49*	*4.77*	*1.73*	*4.42*	*5.21*	*6.34*	*4.46*	*12.95*	*16.89*	*8.77*	*3.89*	74.86
1978	*1.97*	*2.61*	*0.80*	*2.29*	*4.36*	*12.66*	*10.12*	*19.03*	*9.73*	*9.95*	*11.49*	*5.05*	90.06
1979	*3.92*	*1.94*	*4.35*	*1.89*	*1.70*	*3.97*	*7.48*	*11.95*	*11.12*	*29.63*	*8.73*	*5.87*	92.55
1980	*2.26*	*9.72*	*3.53*	*2.66*	*11.99*	*11.25*	*9.19*	*9.25*	*21.09*	*11.47*	*7.35*	*6.97*	106.73
AVG	5.93	3.38	3.72	3.13	6.40	6.31	9.31	14.59	12.72	13.17	8.58	5.82	93.05

Italicized numbers are estimated from NAS data using simple regression technique.

TABLE A-2h
ADJUSTED MONTHLY PRECIPITATION
PAGO RIVER
USGS

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1950	*2.53*	*2.08*	*2.20*	*1.18*	*8.51*	*8.82*	*12.67*	*10.53*	*19.59*	*13.16*	*7.60*	*6.21*	95.08
1951	*5.44*	*6.66*	*4.23*	*6.41*	*1.41*	*1.91*	2.02	16.36	5.65	14.17	10.20	6.81	81.27
1952	3.38	1.83	1.58	2.07	3.51	3.92	7.14	10.29	19.28	7.28	11.45	6.81	81.27
1953	2.99	9.91	2.48	2.16	1.42	2.57	3.79	11.48	9.04	14.01	16.82	5.54	77.27
1954	6.72	1.13	2.37	1.70	3.60	6.63	3.88	14.76	16.16	8.11	12.41	6.72	83.39
1955	6.54	2.62	2.08	3.28	4.29	5.30	13.66	7.12	15.40	9.46	6.61	5.71	83.18
1956	1.48	3.04	2.48	2.50	5.90	3.11	10.43	6.75	11.38	13.41	11.18	4.16	80.52
1957	3.66	1.80	2.56	2.44	2.90	2.74	3.93	12.27	7.04	18.60	14.95	10.67	82.38
1958	6.23	2.67	0.79	2.99	3.72	10.66	12.01	12.87	15.44	9.24	9.34	3.03	75.92
1959	2.94	1.55	1.18	3.36	1.07	2.03	7.07	14.17	18.97	11.35	7.48	3.45	89.41
1960	3.07	1.34	1.45	1.78	5.69	5.30	8.72	13.57	9.05	11.54	10.45	5.12	76.29
1961	7.28	2.11	4.54	3.14	5.98	9.13	8.98	18.98	13.57	18.38	5.04	12.39	84.35
1962	1.96	6.06	1.70	2.78	5.26	11.72	22.84	24.78	17.66	14.26	11.94	4.95	102.08
1963	6.52	9.22	2.00	16.82	7.62	6.32	6.86	8.76	12.41	20.24	6.48	11.34	131.90
1964	2.64	3.75	2.37	10.54	19.20	5.21	8.53	9.05	14.29	7.20	4.62	13.44	116.69
1965	13.02	1.12	1.51	0.66	1.74	5.48	18.50	9.88	16.10	6.69	5.65	5.49	92.89
1966	1.22	0.68	1.35	0.61	1.23	7.44	5.36	17.50	17.49	15.13	7.22	2.94	85.53
1967	*4.87*	*3.19*	*7.12*	*6.67*	*4.12*	*13.76*	*12.59*	*17.42*	*18.59*	*12.84*	*9.17*	6.54	81.77
1968	*4.96*	*8.31*	*3.53*	*2.42*	*2.74*	*7.94*	*11.32*	*14.59*	*13.77*	*14.26*	*11.10*	*2.04*	112.38
1969	*2.71*	*2.18*	*2.87*	*3.04*	*4.28*	*1.61*	*12.51*	*12.02*	*9.06*	*14.42*	*9.25*	*1.78*	96.72
1970	*6.58*	*2.87*	*2.20*	*1.22*	*1.73*	*6.41*	*6.73*	*10.71*	*11.23*	*10.90*	*6.34*	*10.47*	88.42
1971	*4.85*	*5.69*	*6.94*	*3.88*	*14.30*	*6.29*	*15.93*	*15.11*	*8.98*	*10.61*	*7.00*	*4.55*	71.47
1972	*4.22*	*3.76*	*4.31*	*1.83*	*2.92*	*5.38*	*14.39*	*14.78*	*11.60*	*10.00*	*3.27*	*2.14*	101.72
1973	*1.86*	*2.02*	*1.38*	*1.15*	*2.15*	*4.14*	*5.29*	*11.59*	*8.59*	*13.50*	*3.22*	*3.44*	79.90
1974	*3.16*	*2.13*	*9.01*	*10.27*	*11.96*	*9.51*	*13.57*	*19.02*	*8.73*	*11.92*	*6.64*	*8.83*	63.72
1975	*6.67*	*0.86*	*2.00*	*2.61*	*1.82*	*2.51*	*9.56*	*14.63*	*8.47*	*12.28*	*10.61*	*6.54*	112.46
1976	*16.12*	*10.31*	*7.34*	*3.98*	*21.13*	*7.56*	*16.19*	*21.34*	*10.42*	*9.84*	*10.26*	*2.85*	74.87
1977	*2.40*	*2.29*	*3.86*	*1.30*	*4.06*	*5.18*	*5.05*	*8.29*	*13.26*	*13.47*	*9.38*	*5.65*	140.14
1978	*1.70*	*2.51*	*0.83*	*2.19*	*4.01*	*13.21*	*11.25*	*15.73*	*10.03*	*11.61*	*15.59*	*2.19*	70.73
1979	*3.13*	*1.31*	*3.54*	*1.54*	*2.10*	*3.85*	*6.92*	*12.11*	*11.42*	*16.89*	*9.28*	*4.44*	93.10
1980	*1.91*	*15.24*	*2.91*	*2.79*	*9.50*	*11.69*	*9.73*	*10.73*	*21.44*	*12.02*	*6.12*	*5.02*	77.11
												8.14	112.22
AVG	4.61	3.89	3.06	3.53	5.48	6.37	9.92	13.46	13.04	12.47	8.92	5.89	90.80

Italicized numbers are estimated from NAS data using simple regression technique.

TABLE A-3

MONTHLY MEAN TEMPERATURE

NATIONAL WEATHER SERVICE, FINEGAYAN

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1974				
Jan	83.9	70.9	77.4	0.1
Feb	84.6	72.7	78.7	1.4
Mar	82.7	72.4	77.6	-0.1
Apr	84.4	73.7	79.1	0.1
May	85.4	73.8	79.6	0.2
Jun	85.9	72.1	79.0	-0.8
Jul	85.8	71.2	78.5	-0.9
Aug	85.2	72.5	78.9	-0.2
Sept	87.0	71.1	79.1	0
Oct	86.0	73.4	79.7	0.8
Nov	85.2	73.8	79.5	0.3
Dec	83.9	73.5	78.7	0.2
1975				
Jan	83.2	72.6	77.9	0.6
Feb	84.5	70.4	77.5	0.2
Mar	85.3	69.0	77.2	-0.5
Apr	85.7	72.7	79.2	0.2
May	87.9	70.8	79.4	0
Jun	88.8	73.0	80.9	1.1
Jul	85.6	71.1	78.4	-1.0
Aug	84.0	71.9	78.0	-1.1
Sept	86.0	71.6	78.8	-0.3
Oct	85.3	72.2	78.8	-0.1
Nov	84.4	72.1	78.3	-0.9
Dec	84.2	72.2	78.2	-0.3

TABLE A-3 continued

MONTHLY MEAN TEMPERATURE - NATIONAL WEATHER SERVICE, FINEGAYAN

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1976				
Jan	82.5	69.7	76.1	-1.2
Feb	82.1	71.1	76.6	-0.7
Mar	83.1	71.7	77.4	-0.3
Apr	84.3	72.5	78.4	-0.6
May	85.0	73.2	79.1	-0.3
Jun	85.9	73.0	79.5	-0.3
Jul	- -	- -	- -	- -
Aug	- -	- -	- -	- -
Sept	84.7	72.4	78.6	-0.5
Oct	86.5	72.4	79.5	0.6
Nov	85.3	72.2	78.8	-0.4
Dec	84.4	70.8	77.6	-0.9
1977				
Jan	83.2	69.6	76.4	-0.9
Feb	83.5	70.4	77.0	-0.3
Mar	83.8	71.5	77.7	0
Apr	85.1	71.4	78.3	-0.7
May	85.4	71.4	78.9	-0.5
Jun	86.9	73.3	80.1	0.3
Jul	86.7	73.3	80.0	0.6
Aug	87.8	72.2	80.0	0.9
Sept	85.7	72.3	79.0	-0.1
Oct	85.7	72.1	78.9	0
Nov	85.0	73.4	79.2	0
Dec	84.3	72.8	78.6	0.1

TABLE A-3 continued

MONTHLY MEAN TEMPERATURE - NATIONAL WEATHER SERVICE, FINEGAYAN

DATE		AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1978					
	Jan	84.1	69.3	76.7	-0.6
	Feb	82.6	70.6	76.6	-0.7
	Mar	85.6	70.6	78.1	0.4
	Apr	86.5	73.1	79.8	0.8
	May	87.6	74.4	81.0	1.6
	Jun	87.0	72.8	79.9	0.1
	Jul	86.8	72.6	79.7	0.3
	Aug	85.0	73.1	79.1	0
	Sept	86.3	73.1	79.7	0.6
	Oct	86.2	73.1	79.7	0.8
	Nov	84.2	73.5	78.9	-0.3
	Dec	83.8	72.3	78.1	-0.4
1979					
	Jan	83.2	71.5	77.4	0.1
	Feb	84.0	70.0	77.0	-0.3
	Mar	84.1	71.3	77.7	0
	Apr	85.1	72.7	78.9	-0.1
	May	87.7	72.6	80.2	0.8
	Jun	87.2	75.0	81.1	1.3
	Jul	86.8	72.6	79.7	0.3
	Aug	85.9	71.6	78.8	-0.3
	Sept	86.5	71.2	78.9	-0.2
	Oct	85.6	72.8	79.2	0.3
	Nov	84.7	73.0	78.9	-0.3
	Dec	83.7	72.2	78.0	-0.5

TABLE A-3 continued

MONTHLY MEAN TEMPERATURE - NATIONAL WEATHER SERVICE, FINEGAYAN

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1980				
Jan	83.2	69.5	76.4	-0.9
Feb	82.7	72.1	77.4	0.1
Mar	83.4	71.7	77.6	-0.1
Apr	85.1	73.4	79.3	0.3
May	85.0	74.0	79.5	0.1
Jun	84.7	74.6	79.7	-0.1
Jul	86.0	73.1	79.6	0.2
Aug	86.9	73.4	80.2	1.1
Sept	85.5	73.2	79.4	0.3
Oct	85.9	73.6	79.8	0.9
Nov	86.3	74.4	80.4	1.2
Dec	85.2	70.8	78.0	-0.5
1981				
Jan	84.3	72.2	78.3	1.0
Feb	84.0	69.9	77.0	-0.3
Mar	84.9	71.1	78.0	0.3
Apr	86.0*	72.6	79.3*	0.3
May	86.8	73.4	80.1	0.7
Jun	87.0	73.2	80.1	0.3
Jul	86.4	72.4	79.4	0
Aug	85.5	72.4	79.0	-0.1
Sept	86.9	72.4	79.4	0.6
Oct	87.0	72.5	79.8	0.9
Nov	- -	- -	- -	- -
Dec	84.7	73.4	79.1	0.6
1982				
Jan	84.8	69.9	77.4	0.1
Feb	83.0	70.5	76.8	-0.5
Mar	84.5	70.3	77.4	-0.3

* estimated

TABLE A-4
MONTHLY MEAN TEMPERATURE
ANDERSEN AIR FORCE BASE - NOAA

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1974				
Jan	82.2	75.5	78.9	0.7
Feb	83.2	75.8	79.5	1.3
Mar	81.6	74.4	78.0	-0.5
Apr	84.6	77.0	80.8	1.3
May	85.2	77.7	81.5	1.2
Jun	84.0	76.9	80.5	-0.3
Jul	84.0	77.3	80.7	0.3
Aug	83.7	76.7	80.2	0.1
Sep	83.8	76.1	80.0	0.2
Oct	84.0	77.0	80.5	0.5
Nov	84.4	77.7	81.1	0.8
Dec	83.4	77.4	80.4	1.1
1975				
Jan	82.2	76.0	79.1	0.9
Feb	83.3	75.8	79.6	1.4
Mar	83.1	75.4	79.3	0.8
Apr	83.9	76.5	80.2	0.7
May	84.9	77.6	81.3	1.0
Jun	85.6	78.4	82.0	1.2
Jul	83.4	76.0	79.7	-0.7
Aug	83.1	75.1	79.1	-1.0
Sep	85.3	76.1	80.7	0.9
Oct	85.1	76.9	81.0	1.0
Nov	83.9	77.0	80.5	0.2
Dec	82.0	76.2	79.1	-0.2

TABLE A-4 continued

MONTHLY MEAN TEMPERATURE - ANDERSEN AIR FORCE BASE

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1976				
Jan	80.5	74.5	77.5	-0.7
Feb	79.9	74.1	77.0	-1.2
Mar	82.6	75.9	79.3	0.8
Apr	80.5	74.6	77.6	-1.9
May	81.8	75.4	78.6	-1.7
Jun	82.6	76.6	79.6	-1.2
Jul	- -	- -	- -	- -
Aug	- -	- -	- -	- -
Sep	84.0*	76.9*	80.5*	0.7
Oct	83.3	77.1	80.2	0.2
Nov	83.8	78.0	80.9	0.6
Dec	84.0	77.8	80.9	1.6
1977				
Jan	83.5	77.1	80.3	2.1
Feb	82.9	76.8	79.9	1.7
Mar	81.2	74.5	77.9	-0.6
Apr	81.4	74.5	78.0	-1.5
May	82.5	75.5	79.0	-1.3
Jun	84.0	77.2	80.6	-0.2
Jul	83.9	77.0	80.5	0.1
Aug	85.3	77.1	81.2	1.1
Sep	83.3	76.1	79.7	-0.1
Oct	83.5	76.8	80.2	0.2
Nov	83.1	77.3	80.2	-0.1
Dec	82.6	76.8	79.7	0.4

TABLE A-4 continued

MONTHLY MEAN TEMPERATURE - ANDERSEN AIR FORCE BASE

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1978				
Jan	80.8	74.4	77.6	-0.6
Feb	79.6	72.9	76.3	-1.9
Mar	81.8	75.3	78.6	0.1
Apr	82.2	75.9	79.1	-0.4
May	83.7	76.7	80.2	-0.1
Jun	82.0	75.4	78.7	-2.1
Jul	84.8	77.2	81.0	0.6
Aug	83.1	76.6	79.9	-0.2
Sep	84.4	77.0	80.7	0.9
Oct	84.1	77.1	80.6	0.6
Nov	81.6	75.9	78.8	-1.5
Dec	81.1	75.2	78.2	-1.1
1979				
Jan	80.2	74.7	77.5	-0.7
Feb	82.1	75.7	78.9	0.7
Mar	81.4	75.8	78.6	0.1
Apr	82.2	75.4	78.8	-0.7
May	83.2	76.6	79.9	-0.4
Jun	84.8	78.4	81.6	0.8
Jul	83.7	76.7	80.2	-0.2
Aug	84.6	76.9	80.8	0.7
Sep	84.7	77.4	81.1	1.3
Oct	84.8	78.2	81.5	1.5
Nov	84.1	78.6	81.4	1.1
Dec	82.7	76.9	79.8	0.5

TABLE A-4 continued

MONTHLY MEAN TEMPERATURE - ANDERSEN AIR FORCE BASE

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1980				
Jan	82.3	75.9	79.1	0.9
Feb	81.8	75.3	78.6	0.4
Mar	82.3	75.7	79.0	0.5
Apr	83.9	77.0	80.5	1.0
May	83.8	77.0	80.4	0.1
Jun	84.6	77.8	81.2	0.4
Jul	84.6	77.6	81.1	0.7
Aug	84.0	76.3	80.2	0.1
Sep	83.0	76.1	79.6	-0.2
Oct	85.0	78.1	81.6	1.6
Nov	85.0	78.7	81.9	1.6
Dec	84.0	77.5	80.8	1.5
1981				
Jan	- -	- -	- -	- -
Feb	82.8	76.3	79.6	1.4
Mar	83.6	75.9	79.8	1.3
Apr	- -	- -	- -	- -
May	86.6	78.7	82.7	2.4
Jun	85.0	78.1	81.6	0.8
Jul	83.8	76.8	80.3	-0.1
Aug	82.9	75.4	79.2	-0.9
Sep	84.1	77.3	80.7	0.9
Oct	84.7	77.5	81.1	1.1
Nov	- -	- -	- -	- -
Dec	81.7	76.5	79.1	-0.2

* estimated

TABLE A-5

MONTHLY MEAN TEMPERATURE

FLEET WEATHER CENTRAL NAVAL AIR STATION - NOAA

DATE		AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1974					
	Jan	83.7	75.1	79.4	0
	Feb	84.6	76.5	80.6	1.2
	Mar	83.5	75.1	79.3	-0.7
	Apr	85.2	77.8	81.5	0.7
	May	84.4	78.2	81.3	0
	Jun	86.5	77.8	82.2	0.4
	Jul	84.7	77.0	80.9	-0.5
	Aug	84.1	76.9	80.5	-0.7
	Sep	86.0	79.0	82.5	1.5
	Oct	87.0	79.0	83.0	2.2
	Nov	84.9	79.5	82.2	1.2
	Dec	85.0	79.9	82.5	2.3
1975					
	Jan	84.0	78.5	81.3	1.9
	Feb	83.1	76.5	79.8	0.4
	Mar	83.9	76.8	80.4	0.4
	Apr	84.1	77.8	81.0	0.2
	May	85.7	78.5	82.1	0.8
	Jun	85.4	78.8	82.1	0.3
	Jul	83.7	77.4	80.6	-0.8
	Aug	82.7	76.7	79.7	-1.5
	Sept	83.5*	76.8*	80.2*	-1.3
	Oct	84.4	76.9	80.7	-0.1
	Nov	84.6	76.6	80.6	-0.4
	Dec	84.9	77.4	81.2	1.0

TABLE A-5 continued

MONTHLY MEAN TEMPERATURE - FLEET WEATHER CENTRAL NAVAL AIR STATION

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1976				
Jan	84.3	76.9	80.6	1.2
Feb	83.7	76.6	80.2	0.8
Mar	84.0	75.2	79.6	-0.4
Apr	83.6	75.9	79.8	-1.0
May	84.6	76.5	80.6	-0.7
Jun	85.5	78.0	81.8	0
Jul	- -	- -	- -	- -
Aug	- -	- -	- -	- -
Sept	86.0	77.2	81.6	0.6
Oct	88.0	78.5	83.3	2.5
Nov	86.5	77.9	82.2	1.2
Dec	85.4	76.9	81.2	1.0
1977				
Jan	84.4	75.5	80.0	0.6
Feb	84.4	75.0	79.7	0.3
Mar	84.7	76.0	80.4	0.4
Apr	85.6	76.5	81.1	0.3
May	86.7	77.5	82.1	0.8
Jun	87.3	78.4	82.9	1.1
Jul	87.8	78.5	83.2	1.8
Aug	88.9	79.1	84.0	2.8
Sept	86.8	77.6	82.2	1.2
Oct	85.8	77.2	81.5	0.7
Nov	84.8	77.1	81.0	0
Dec	83.9	76.5	80.2	0

TABLE A-5 continued

MONTHLY MEAN TEMPERATURE - FLEET WEATHER CENTRAL NAVAL AIR STATION

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1978				
Jan	82.8	74.2	78.5	-0.9
Feb	81.8	73.1	77.0	-2.4
Mar	84.2	73.4	78.8	-1.2
Apr	86.6	77.0	81.8	1.0
May	87.8	78.5	83.2	1.9
Jun	87.3	77.7	82.5	0.7
Jul	86.5	78.0	82.3	0.9
Aug	85.4	76.9	81.2	0
Sept	87.0	76.9	82.0	1.0
Oct	86.0	78.6	82.3	1.5
Nov	84.6	77.1	80.9	-0.1
Dec	- -	- -	- -	- -
1979				
Jan	83.7	76.1	79.9	0.5
Feb	84.4	75.4	79.9	0.5
Mar	84.8	76.0	80.4	0.4
Apr	86.2	76.8	81.5	0.7
May	87.6	76.4	82.0	0.7
Jun	89.2	77.8	83.5	1.7
Jul	87.4	76.2	81.8	0.4
Aug	86.6	75.6	81.1	-0.1
Sept	89.2	76.4	82.8	1.8
Oct	88.3	76.5	82.4	1.6
Nov	86.9	76.3	81.6	0.6
Dec	- -	- -	- -	- -

TABLE A-5 continued

MONTHLY MEAN TEMPERATURE - FLEET WEATHER CENTRAL NAVAL AIR STATION

DATE	AVERAGE MAXIMUM	AVERAGE MINIMUM	AVERAGE	DEPARTURE FROM NORMAL
1980				
Jan	85.4	74.0	79.7	0.3
Feb	85.3	74.8	80.1	0.7
Mar	85.3	74.5	79.9	-0.1
Apr	86.7	77.0	81.9	1.1
May	87.3	76.9	82.1	0.8
Jun	88.1	77.9	83.0	1.2
Jul	88.9	77.0	83.0	1.6
Aug	- -	- -	- -	- -
Sept	86.7	76.1	81.4	0.4
Oct	87.3	76.5	81.9	1.1
Nov	88.1	77.5	82.8	1.8
Dec	86.4	76.3	81.4	1.2

* estimated

TABLE A-6

MEAN RELATIVE HUMIDITY-PERCENT

NATIONAL WEATHER SERVICE, FINEGAYAN

	1974	1975	1976	1977	1978	1979	1980	1981
JAN	78	81	82	79	76	79	74	83
FEB	79	75	83	78	80	76	79	73
MAR	81	76	80	80	73	77	78	77
APR	82	76	81	75	78	75	78	77
MAY	83	73	83	78	77	74	82	79
JUN	83	72	83	80	81	77	83	81
JUL	85	82	84*	81	82	81	83	84
AUG	86	86	86*	81	85	83	84	86
SEP	82	83	81	85	84	84	87	83
OCT	83	85	81	84	83	85	84	82
NOV	84	85	83	84	85	82	83	84*
DEC	82	81	81	77	80	81	82	83
ANNUAL AVERAGE	82	80	82	80	80	80	81	81

* Estimated.

TABLE A-7

MONTHLY EVAPORATION ††

NATIONAL WEATHER SERVICE, FINEGAYAN - NOAA

	1974	1975	1976	1977	1978	1979	1980	1981	AVERAGE ANNUAL
JAN	5.81	6.64*	6.27*	6.64†	7.30	7.26†	7.73	5.54	6.65
FEB	6.62	6.80	5.58	6.49	6.10	6.68	6.43†	7.22	6.49
MAR	6.90	8.08	7.22	8.20	9.46	7.76	7.85	8.94	8.05
APR	8.27	8.35	7.62	9.03	7.72	9.50	7.93	8.13†	8.32
MAY	7.21	9.01	7.37†	8.48†	8.55	10.33	8.05	8.41	8.43
JUN	5.88	9.29	7.65	7.89	6.55	8.44	6.91	7.14	7.46
JUL	6.02*	6.18	6.30*	7.83	5.90	6.44†	6.33†	6.78	6.47
AUG	5.09	5.69	5.66*	6.99	6.10†	6.34†	4.84†	6.55†	5.91
SEP	5.61†	6.14	5.47	5.24†	5.33†	5.26	5.14†	7.38	5.70
OCT	6.28	5.70	7.36	5.53†	6.32†	5.16†	5.98†	7.01†	6.17
NOV	5.73†	6.73	6.34	6.27†	5.46†	5.93	7.10	6.37*	6.24
DEC	6.93	6.39	6.56†	6.90†	5.95	6.36	6.20†	5.15	6.34
ANNUAL TOTAL	76.35	85.00	79.49	85.49	80.74	85.46	80.49	84.63	82.23

* Estimated value.

† Adjusted to a full month.

†† Measured in inches.

TABLE A-8

WATER LEVEL MEASUREMENTS - NORTHERN LENS

WELL NO.	DATE	TIME	METHOD OF MEASUREMENT	DEPTH TO WATER (ft)	ELEV. OF MEASURING POINT	ELEV. OF WATER SURFACE	CATAGORY	REMARKS
A-1	4-23-82	1435		54.86	69.97	15.11	Trans	
A-2	4-23-82	1125	S	114.79	121.44	6.65	Trans	
A-3	4-23-82	1445	E	109.40	105.28	-5.12	Parabasal	
A-4	4-23-82	1120	S	138.70	142.57	3.87	Trans	
A-5	4-23-82	1505	S	143.37	147.77	4.40	Trans	Poor Cut
A-8	4-23-82	1140	S	121.27			Trans	
A-9	4-23-82	1055	S	183.47	188.21	4.74	Basal	
	9-24-81	1055	S			6.06		
A-10	4-23-82	1020	S	186.75	191.38	4.63	Basal	
A-11	4-23-82	1520	S	141.14	172.47	31.33	Parabasal	
A-12	4-23-82	1515	S	117.74	140.02	22.28	Parabasal	
A-13	4-23-82	1025	S	128.66	133.72	4.06	Basal	
A-15	4-23-82	1600	S	195.86	199.05	3.19	Basal	
A-16	4-23-82	1555	R			3.76	Basal	
A-19	4-23-82	1415	S	133.43	136.56	3.13	Trans	
A-20	4-23-82	1400	S	103.59	141.74	38.15	Parabasal	Recorder
D-1	4-27-82	1600	S	379.55	383.10	3.55	Basal	
D-2	4-27-82	1615	S		383.03		Basal	Poor Cut
D-3	4-27-82	1645		387.40	390.18	2.78+.5	Basal	Poor Cut
D-4	4-27-82	0910	S	381.64	385.19	3.55	Basal	
D-5	4-22-82	1125	S	378.60	379.33	0.72	Basal	Poor Cut
D-6	4-22-82	1100	S	394.73	398.23	3.50	Trans	
D-7	4-27-82						Trans	
D-9	4-27-82	1425	S	386.10	389.65	3.55	Trans	
D-10	4-27-82	1430	E	388.39	391.28	2.89	Parabasal	
D-12	4-27-82	1520		419.36	422.86	3.50	Trans	
D-13	4-27-82	1510	S	399.78	401.63	1.85	Parabasal	Poor Cut
D-14	4-24-82					3.43	Basal	
D-15	4-24-82					2.98	Basal	
D-16	4-24-82					3.27	Basal	
D-17	4-27-82	1335	E	302.08	305.32	3.24	Basal	
D-18	4-24-82			313.55			Basal	
F-2	4-22-82		E			3.01	Basal	
F-3	4-21-82	1525	S	456.80	456.25	-.55	Basal	Poor Cut
	2-18-82	1400	S	453.12	456.25	3.13		

TABLE A-8 continued

WATER LEVEL MEASUREMENTS - NORTHERN LENS

WELL NO.	DATE	TIME	METHOD OF MEASUREMENT	DEPTH TO WATER (ft)	ELEV. OF MEASURING POINT	ELEV. OF WATER SURFACE	CATAGORY	REMARKS
F-6	4-21-82	1425	S	345.03	347.74	2.71	Basal	
Y-1	4-29-82	1303	S	412.47	416.76	4.29	Parabasal	
	1-22-82	1115	S			4.39		
Y-2	4-29-82	1320	S	411.60	416.83	5.23	Parabasal	Poor Cut
Y-3	4-22-82	1630	S	413.38	417.63	4.25	Parabasal	
	1-22-82		S			10		Poor Cut
Y-4	4-29-82	1400	S	395.78	399.41	3.63	Trans	
Y-5	4-30-82	1010	E	429.90	434.14	4.23	Parabasal	
	1-22-82	1025	S			4.23		
M-3	9-25-81	1030				2.88	Trans	
M-5	4-25-82					3.59	Trans	
	9-23-81	1145				3.31		
M-6	4-25-82					3.05	Basal	
M-7	4-25-82					3.52	Basal	
	9-23-81	1040	E			3.82		
M-8	4-24-82					3.30	Trans	
M-9	4-22-82		S	448.57	451.15	2.58	Basal	
M-10a	4-27-82	0824				3.07	Basal	
M-11	4-25-82		S	292.50	295.82	3.51	Basal	Recorder
M-12	4-25-82					3.31	Basal	
M-14	4-27-82	1325	S	272.34	275.84	3.50	Basal	
MW-1	4-29-82	0755	S	344.12	347.16	3.04	Basal	
MW-2	4-29-82	0820	S	347.68	349.44	1.76	Basal	
MW-3	4-29-82	0845	S	406.69	409.17	2.48	Trans	
MW-5	4-29-82	1030	S	414.00	417.23	3.23	Trans	
	2-18-82	1000	S	414.00	418.18	4.18		
MW-6	4-29-82	1015		390.65	393.90	3.25	Trans	
MW-8	4-29-82	0945	S	353.65	357.23	3.58	Trans	
EX-1	4-23-82	0840	S	90.21	97.27	7.06	Basal	
	9-15-81	0940	S			8.67		
EX-4	4-23-82		S	148.10	153.71	5.61	Basal	
	9-24-81	1520	S			6.65		
EX-5a	4-27-82			381.80	385.16	3.37	Basal	
EX-5	9-24-81	1000	S			3.94	Basal	Poor Cut

TABLE A-8 continued

WATER LEVEL MEASUREMENTS - NORTHERN LENS

WELL NO.	DATE	TIME	METHOD OF MEASUREMENT	DEPTH TO WATER (ft)	ELEV. OF MEASURING POINT	ELEV. OF WATER SURFACE	CATAGORY	REMARKS
EX-6	4-24-82			305.83	309.41	3.58	Basal	
	1-22-82	1258				3.70		
	9-24-81	0935	S			3.75		
EX-7	4-24-82			279.86	283.31	3.45	Basal	
	1-22-82		S			3.50		
	9-25-81		S			3.1		Poor Cut
EX-8	4-24-82			459.75	462.49	2.74	Basal	
	9-22-82	1310	S			2.65		
	9-17-81	0900	S			2.70		
EX-9	4-23-82	1545				3.20	Basal	
	9-24-81	1500	S			3.17		
EX-10	4-24-82	1545		345.45		3.20	Basal	
	9-24-81	1025	S			3.02		
EX-11	1-13-82		S			5.17	Trans	
H-1	4-30-82	1045	S	291.75	293.55	1.80	Basal	
H-107	4-28-82	1230	R			3.12	Basal	
147	4-23-82	0855	S	21.98	33.22	11.24		
BPM-1 (72)	4-23-82	1535	R			2.93	Basal	
Island Equip.	4-24-82		S	79.39	81.7	2.31	Basal	
AAFB BPM	4-29-82 2-18-82	1100 0930	S S	493.79 493.04	496.57 496.57	2.78 3.53	Basal	
AG-2	2-18-82	1315	E	502.94	506.2	3.08	Parabasal	
GHURA-DEDEDO	4-27-82	0855	S	391.55	393.9	2.35	Trans	
Fore-most	4-29-82	1545	S	138.66	140.41	1.75	Basal	
59	9-24-81	1545	S			8.34	Trans	

* Measurements taken by CDM and USGS
S Measured with steel tape
E Measured with electric tape
R Measured with recorder
Trans. Transitional Zone

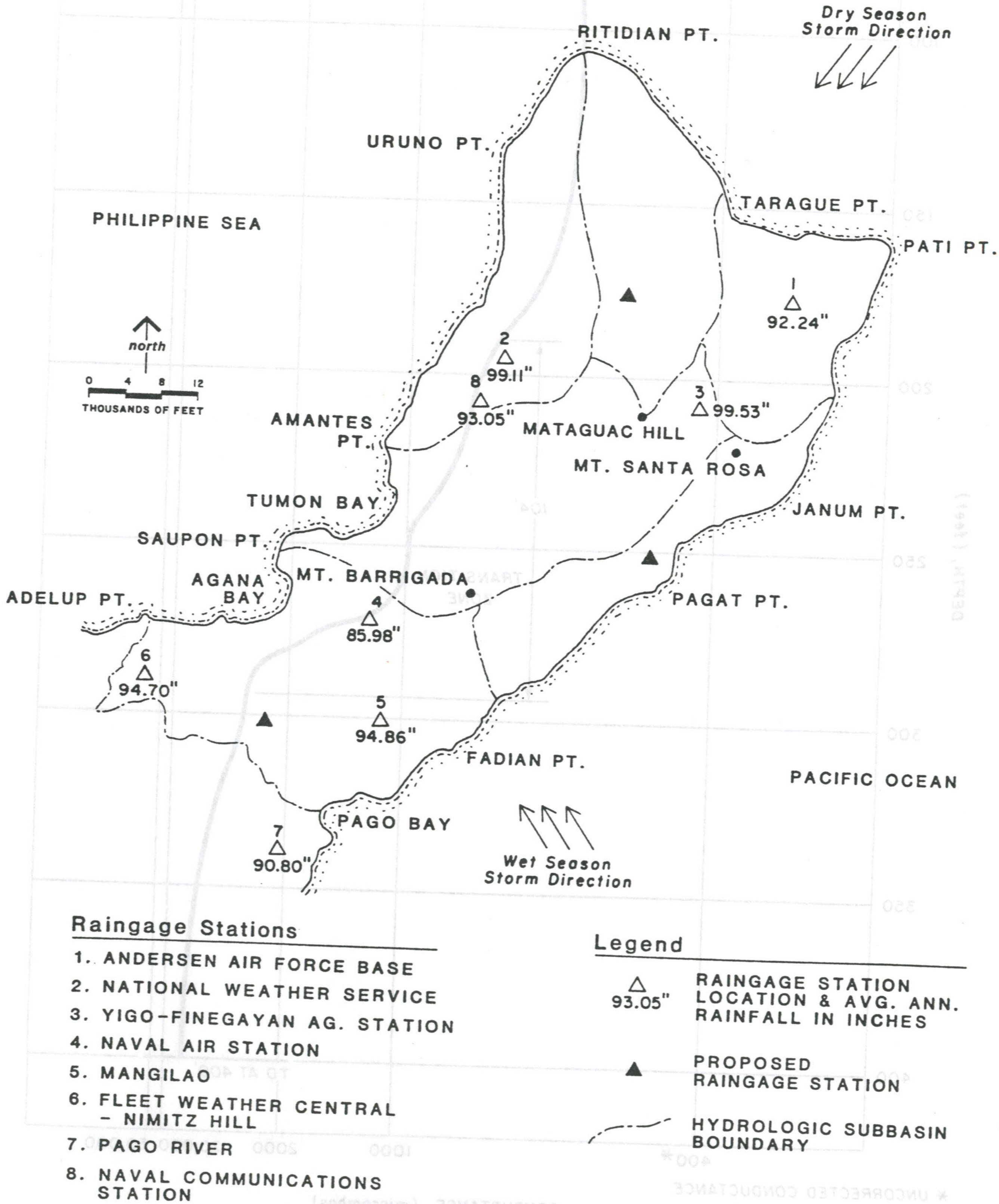
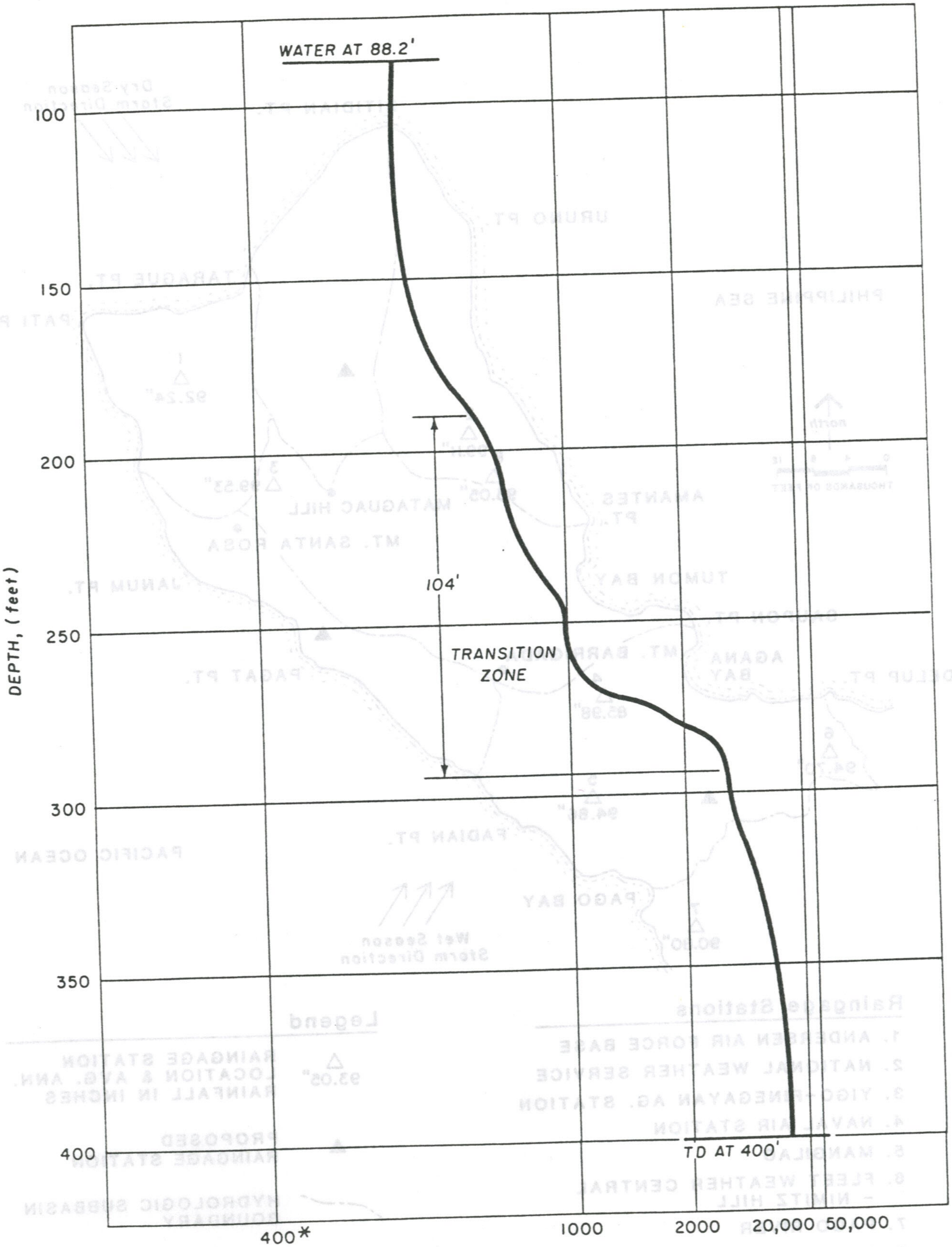


FIGURE A-1

RAINGAGE STATION LOCATIONS
NORTHERN GUAM



* UNCORRECTED CONDUCTANCE VALUES FROM U.S.G.S. LOGGER SCALE.

CONDUCTANCE, (micromhos)

FIGURE A-2
CONDUCTIVITY LOG - WELL EX-1
FEBRUARY 24, 1982

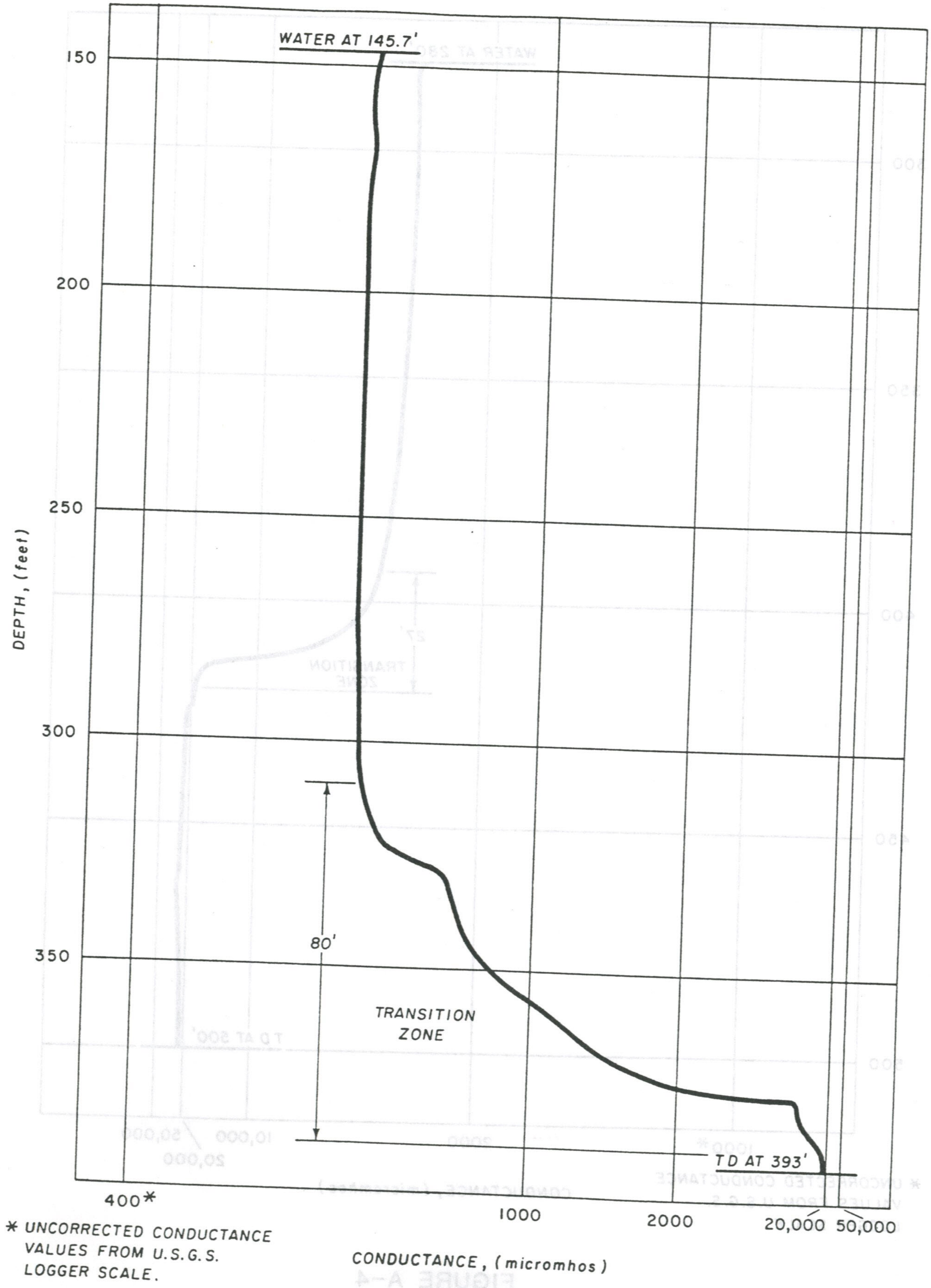


FIGURE A-3
CONDUCTIVITY LOG - WELL EX-4
FEBRUARY 12, 1982

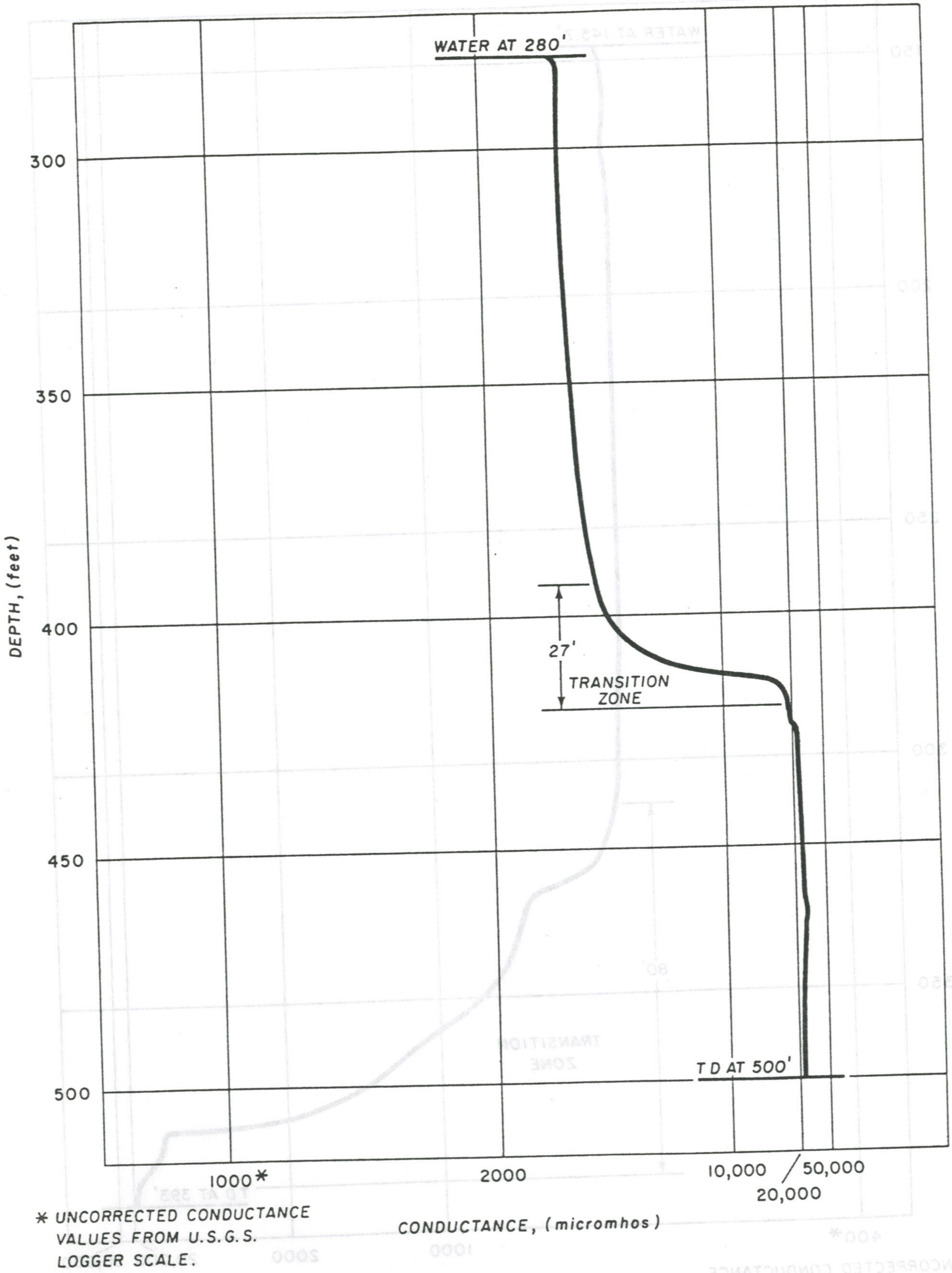
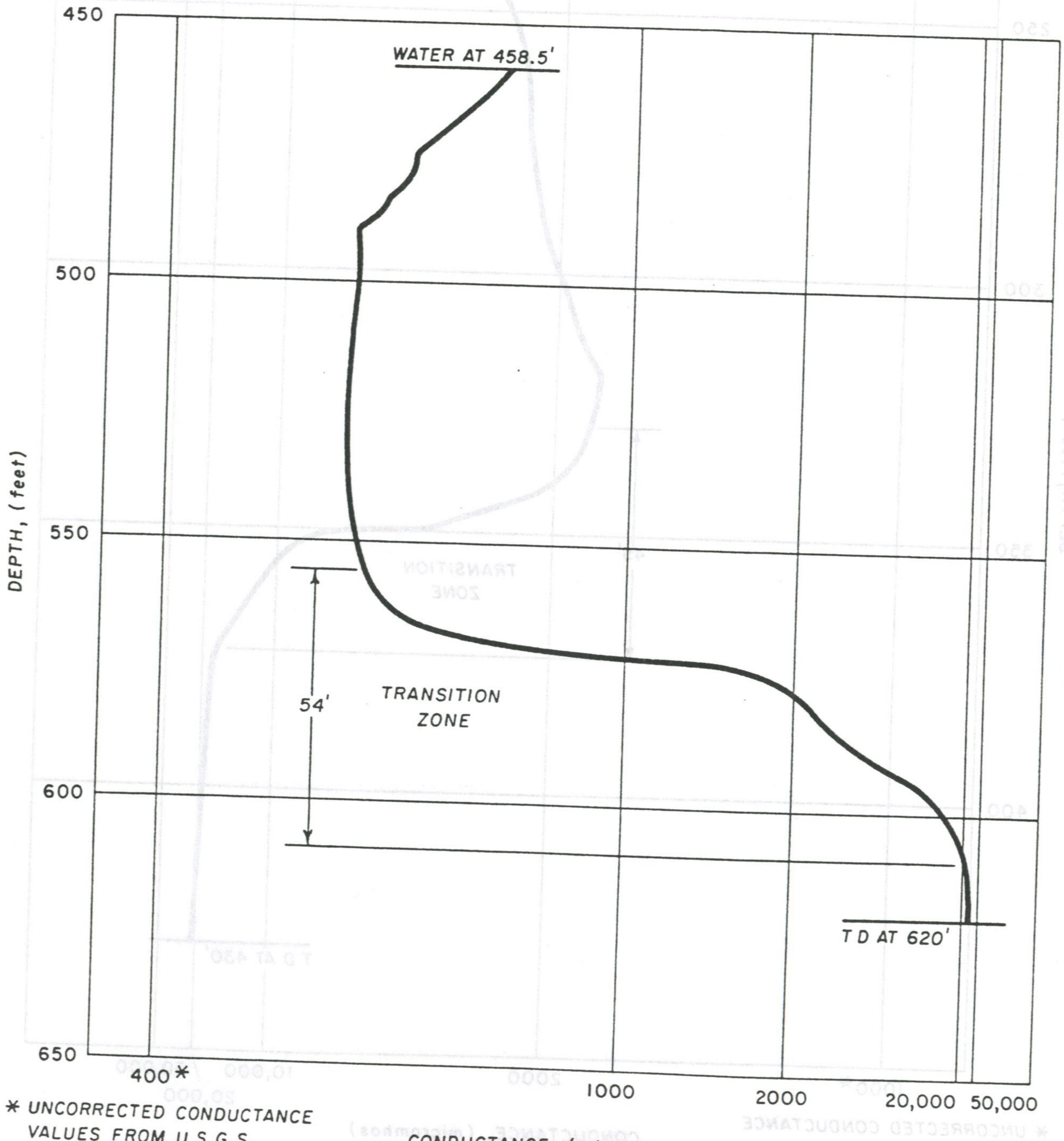


FIGURE A-4
CONDUCTIVITY LOG - WELL EX-7
FEBRUARY 10, 1982



* UNCORRECTED CONDUCTANCE VALUES FROM U.S.G.S. LOGGER SCALE.

FIGURE A-5
CONDUCTIVITY LOG - WELL EX- 8
FEBRUARY 12, 1982

FIGURE A-6
CONDUCTIVITY LOG - WELL EX-9
FEBRUARY 26, 1982

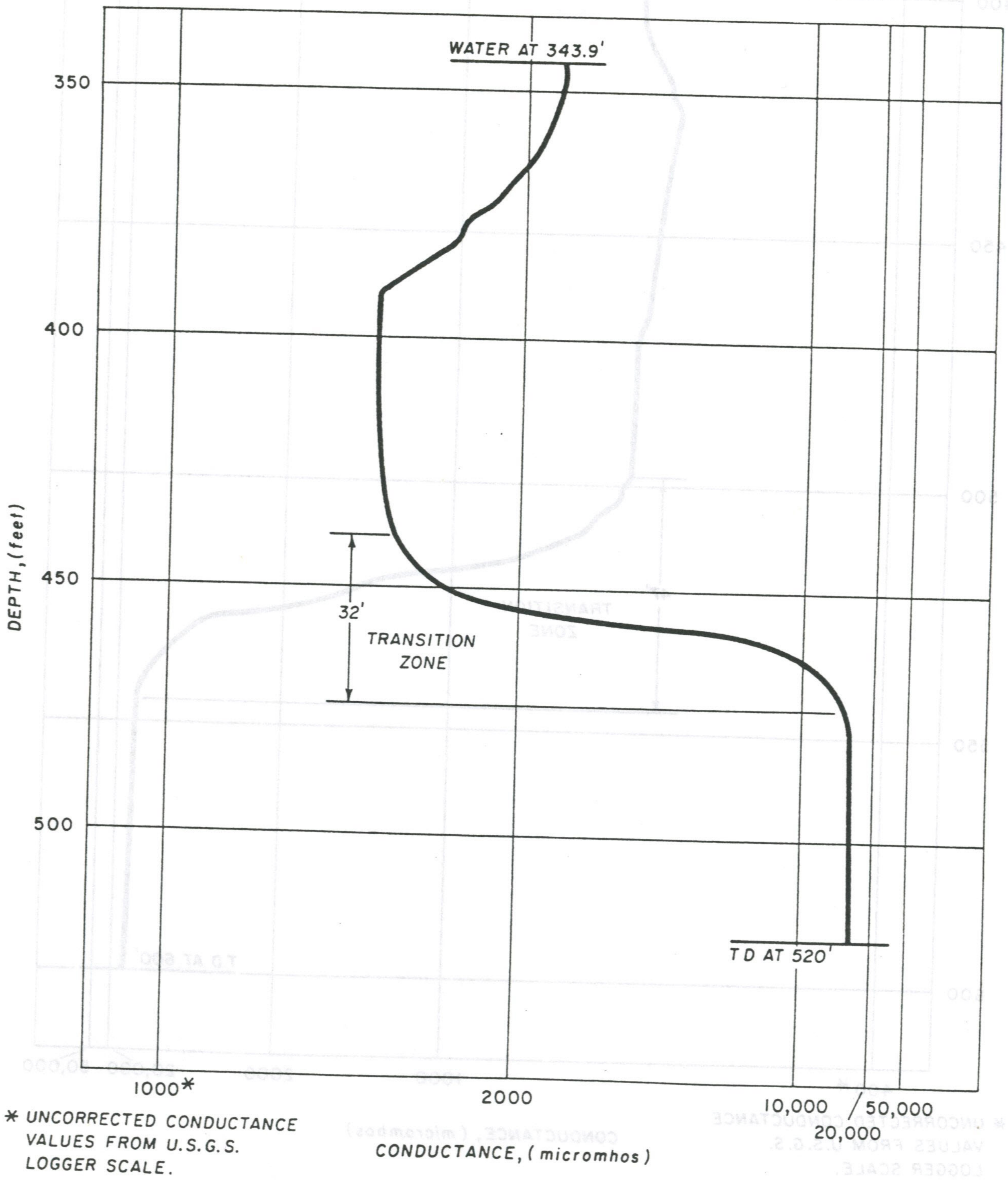


FIGURE A-7
CONDUCTIVITY LOG - WELL EX-10
FEBRUARY 16, 1982

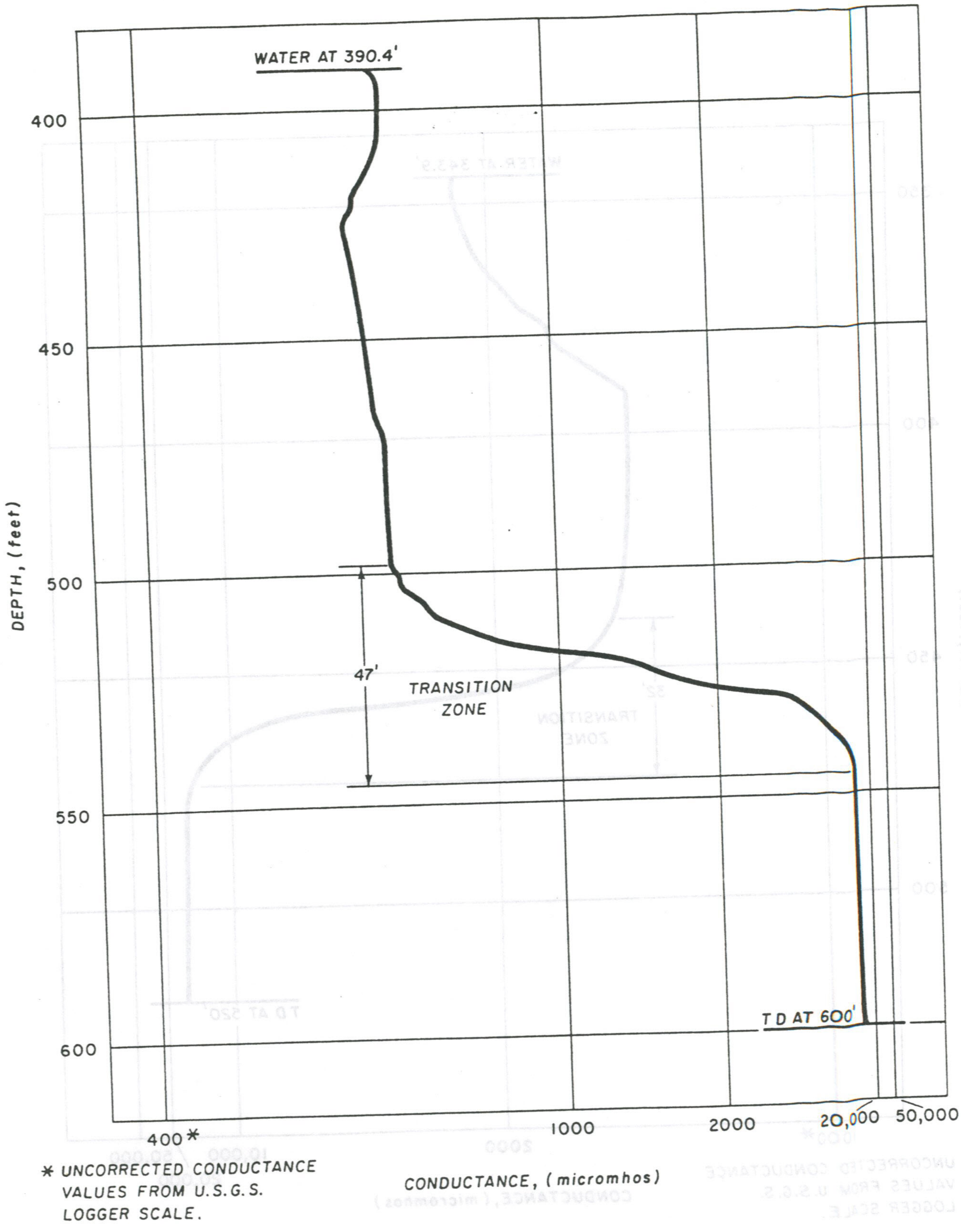


FIGURE A-8
CONDUCTIVITY LOG
GHURA - Dededo MONITORING WELL
FEBRUARY 26, 1982

DESCRIPTION OF GEOPHYSICAL EXPLORATION METHODS

By: John F. Mink

INTRODUCTION

From the earliest hydrogeologic investigations in northern Guam, it was realized that the elevation of the volcanic basement with respect to mean sea level was extremely important in defining the groundwater flow system in the limestone aquifers. Knowledge of the basement before the start of the NGLS was obtained from a few wells that penetrated the volcanics and by extrapolation of the limestone-volcanic contact from several volcanic exposures occurring at Mataguac Hill, Palii Hill, and Mt. Santa Rosa.

Geophysical techniques had long been proposed as the means of mapping the basement on a regional scale, but only in the last few years were some of these methods employed. Seismic refraction and gravity surveys were successfully conducted, while magnetic and seismic reflection techniques were tested but discontinued. The magnetic techniques were compromised by an abundance of pipes, wires and other disturbances in most areas of the north, while the success of the refraction method eliminated a requirement for the more costly seismic reflection technique. Resistivity methods were not tried because of widespread occurrence of potentially interfering artifacts and because the lithologic succession would be masked by the occurrence of salt water. Depth to the fresh water-salt water interface was not an objective to be determined by geophysical methods.

The geophysics contract was awarded to ECOsystems Management Associates of San Diego, California. The refraction survey was organized, conducted and interpreted by Dr. Shawn Biehler, and the gravity work was under the direction of Philip Walen. The surveys were run in April, 1980 and the results and interpretations submitted the following August.

A total of 56 refraction profiles were made in the 100 square miles of northern Guam. Length of the profiles averaged 2,500 feet but varied from 2,000 to 3,500 feet. The normal geophone spacing was 100 feet. Seismic waves were generated by one to three pounds of explosives placed in holes seven to twelve feet deep. Forward and reverse shots were made. Most of the crew were locally hired and trained by Dr. Biehler.

The gravity survey was carried out during the same period as the seismic work. Measurements were made at a total of 321 stations, some of which were in the south of Guam even though this area is not included in the Lens Study. These southern readings were taken to determine the continuity of structural features exhibited by work in the north.

Details and complete data for both the seismic and gravity work is given in ECOsystem's report to Guam Environmental Protection Agency entitled, "Geophysical Investigations for the Northern Guam Lens Study," on file at the GEPA office.

SEISMIC REFRACTION SURVEY

Results of Survey

The results of the refraction survey were generally satisfactory and in some instances definitive. Not enough profiles could be run to yield unequivocal knowledge of basement configuration throughout the north, but important subsurface regional stuctures have been identified and the relationships among them illuminated. The knowledge obtained is consistent with point sources of information (wells and bedrock exposures) and with the gravity results.

In most profiles three layers of distinctively different seismic velocity were encountered: the top layer of limestone, the intermediate layer also of limestone, and the bottom layer of basement volcanic rock. The first limestone layer exhibits an unusually low velocity that clearly differentiates it from the second limestone layer. In most profiles, the volcanic basement can also be differentiated from the intermediate limestone, but in several instances, the higher range of velocity in the limestone overlaps the lower velocity range of the volcanics so that judgement based on other factors must be exercised in selecting depth to basement. This is particularly the case in the Dededo well field area where the depth to basement rocks, as determined by seismic survey, does not coincide with well data. Here, seismic profiles indicate an elevation of volcanics on the order of 200 to 250 feet above sea level where several wells in the area penetrate limestones to elevations in excess of 50 feet below sea level. This inconsistency can be explained in two ways: the subsurface topography of the volcanics is extremely rugged, or what has been interpreted as volcanics is actually a third layer of limestone with a seismic velocity equivalent to that of volcanics. This particular area should be studied further in any future hydrogeologic investigations.

The velocities of the limestone are unexpectedly low when compared to results obtained in other limestone terrains. In fact, many of the contractors responding to the request for proposal believed that it would not be possible to discriminate between limestone and volcanic velocities and that the basement contact could not be identified by refraction techniques. The low velocities were a surprise because they were not predictable by reference to the literature of seismic studies. The generally available literature deals with the results of work on continental limestones, which are normally dense and compact, and submerged limestones of coasts and islands, which evidently are less porous than Guam limestones. On Guam, the limestones consist of fossil reefs and associated calcium carbonate deposits that have been raised above sea level, primarily by tectonic uplift and less importantly by eustatic sea levels associated with Pleistocene glaciation. The most likely explanation for the low velocities of the raised reefs of Guam is attenuation of the seismic impulse by relatively high porosity of the rock. Table B1-1 lists seismic velocities reported for limestones in islands elsewhere, showing they are about twice that of the upper limestone layer and normally appreciably more than the intermediate layer on Guam.

TABLE B1-1

SEISMIC VELOCITIES LIMESTONE ISLANDS
(velocities in feet per second)

Island	Data Source	Surface Layer	Type	Layer 1	Type	Layer 2	Type	Basement
Bikini	Dobrin and Perkins, 1954 USGS PP 260-J			7,000	Loose Calcareous	11,000	Compact Calcareous or Dolmite or Pyro-clastics	17,000
Barbados (note: raised reef)	Same			5,620	Reef			
Bermuda	Same			8,800				
Bikini and Kwajalein	Raitt 1954, USGS			8,200	Calcareous	9,840	Calcareous	
Eniwetok	Raitt 1957, USGS pp 260-S	6,298	Reef	8,000	Reef-Lagoon	10,000	Calcareous	13,616-26,543
Guam	Northern	3,000	Raised	6,700	Raised			9,000

Biehler interpreted his results to show that 27 of the 56 profiles did not encounter the basement because the limestone column was too thick for the profile length. Another interpretation into which well penetration and hydrologic information was integrated suggests that only 18 of the profiles did not refract from the basement. Where depth to basement is greater than about 500 feet, the survey could not discriminate the volcanics.

The three layer model of two limestone layers atop the volcanic basement is applicable throughout practically all of northern Guam. Table B1-2 is a summary of essential statistics of profiles separated by sectors in which geology and topography are similar. This arrangement of statistics shows that the velocity and thickness of layer 1 are quite uniform all over northern Guam and the velocity of layer 2 is similarly uniform. It also suggests that for those profiles where the volcanic basement was definitely encountered the thickness of layer 2 is also relatively uniform. In Table B(1)-2 only those basement velocities directly established by refraction were used for the statistics.

For layer 1, the highest average velocity is found in the A profiles located in the Chalan Pago-Ordot region. The Argillaceous member of the Mariana limestone covers the region. The clay layer, lens, and pocket characteristics of this limestone reduces its overall porosity, thereby increasing its seismic velocity. The velocity of the second layer in the A profiles is also higher than elsewhere and likely for the same reason. North of the argillaceous sector, the Mariana limestone is thought to be clean of clays and its porosity to be controlled by normal calcareous depositional and diagenetic processes.

Table B1-3 is a summary of velocity statistics of the three layers for all profiles without regard to location. As in Table B(1)-2, only definite basement velocities are considered. Included in the table are estimates of the outer limits of the velocity envelopes based on averages plus or minus two standard deviations. Assuming that individual values are normally distributed, these limits include 95 percent of all expected values. It appears that values for each layer have approximately normal distribution

TABLE B1-2

STATISTICS OF LAYER VELOCITY AND THICKNESS BY SECTORS (velocities in feet per second; thickness in feet)

Profiles	Layer 1 Avg. Vel.	Standard Deviation	Layer 1 Avg. Thick.	Standard Deviation	Layer 2 Avg. Vel.	Standard Deviation	Layer 2 Avg. Thick.	Standard Deviation	Basement Avg. Vel.	Standard Deviation
A1, A2, A3, A4, A6, A7, A8	3,560	1,293	99	38.7	7,358	495	300	119	10,614	1,211
B1, B2, B3, B4, C1, C2, C3, C4	2,666	429	113	39.8	6,495	644	314	200	9,419	715
D1, D2, D3, D4, D5, D6, D7, D8, E20	3,091	823	183	86.1	6,900	701	291	187	8,773	530
E7, E8, E9, E10, E11, F1 F2, F3, F4	3,038	475	134	50.8	6,002	1,297	278	164	8,369	615
E11, E12, E13, E15, E16, E17, E18, E19, E21	2,942	469	69	44.6	6,287	880	366	201	8,664	662
S1, S2, S3, S4, S5, S6, S7, S8	3,207	408	112	52.6	6,365	516	279	153	9,696	1,725
Weighted	3,094		126		6,670		317		9,266	

TABLE B(1)-3

STATISTICS OF LAYER VELOCITY
(velocities in feet per second)

Statistic	Limestone Layer 1	Limestone Layer 2	Volcanics Layer 3
A profiles excluded			
Number in sample (N)	52	49	32
Range of velocities	2,173-4,952	5,007-8,214	7,061-13,649
Median velocity	3,024	6,643	8,990
Average velocity (V)	3,045	6,715	9,171
Standard deviation (S)	629	882	1,114
V + 2S	4,303	8,479	11,399
V - 2S	1,787	4,951	6,943
A profiles included			
Number in sample (N)	59	56	38
Range of velocities	1,781-4,988	5,007-8,214	7,061-13,649
Median velocity	3,161	7,000	9,228
Average velocity (V)	3,106	6,795	9,398
Standard deviation (S)	742	867	1,234
V + 2S	4,590	8,529	11,866
V - 2S	1,622	5,061	6,930

because the average and the median are nearly equal, a condition of normality. In the table, two sets of statistics are given, one that excludes the A profiles and the other including them. The exclusion of the A values for layers 1 and 2 may refine the statistics for the cleaner limestones but should make no difference with respect to the basement.

The statistics show that layer 1 is distinct from layer 2. The highest velocities in layer 1 are less than the lowest velocities in layer 2, which means that only in exceptional cases could the layers be confused. The (V + 2S) statistics for layer 1 is 4,303 feet per second (fps) and the (V - 2S) statistic for layer 2 is 4,951 fps, giving a large divergence between layer velocities for all but a few percent of expected values.

The clear and significant difference between layer 1 and layer 2 velocities suggests that the layers are composed of different limestones. The low velocity of layer 1 implies high porosity, essentially unaltered reef association, while the higher velocity in layer 2 suggests a more compacted lithology characteristic of deeper water calcareous deposition. In this model, the Mariana reef limestone would be the top layer.

In most profiles where an actual layer 3 velocity was recorded, the intermediate limestone is easily distinguished from the basement. However, an overlap exists between the higher velocities of layer 2 and the lower velocities of layer 3 so that in some instances the presence of the basement must be verified by supplementary information. With the A profiles included, the (V + 2S) statistic for layer 2 is 8,529 fps and the (V - 2S) statistic for layer 3 is 6,930 fps. Thus velocities between about 7,000 fps and 8,500 fps are not diagnostic of either the basement or layer 2. Where pyroclastics dominate the upper basement, velocities are apt to be similar to those of deep limestones. Nevertheless, velocities of more than 8,500 fps are almost certainly indicative of the volcanic basement.

Interpretation of the Seismic Profiles

The principal basement features having hydrologic relevance are as follows:

1. A rise exists in the basement above sea level in a roughly elliptical area of about 10 sq.mi. between Dededo and Andersen Air Force Base. Several hundred feet of limestone overlie the basement except at small volcanic outcrops at Mataguac Hill and Palii Hill. As a rule, groundwater cannot be developed where the basement is above sea level, but this area serves as a critical source of recharge for aquifers on its flanks. Several square miles of parabasal aquifers may occur just below the sea level contour. This region may be called the "Mataguac Rise".

2. A linear subsurface ridge extends from the vicinity of Mt. Santa Rosa to Barrigada. The basement rises above sea level over a 10 mile distance as a narrow ridge varying from a few tenths of a mile to more

than a mile wide. The seismic data are consistent with the occurrence along the ridge of residual positive gravity anomalies. The ridge plunges steeply on its flanks, and at its southwest nose, drops below sea level before reaching Agana Swamp. It plunges into the Yigo Trough on the west, while on the east, the sea level contour apparently coincides with Janum Springs. All of the ridge is covered by limestone, except at Mt. Santa Rosa. The ridge is profoundly important in regional hydrology because it acts as a barrier to groundwater flow. Most groundwater is forced to drain toward the west, which substantially lowers the amount of potable groundwater supplies east of the ridge. This basement feature needs a name, and an appropriate one would be the "Santa Rosa-Barrigada Rise".

3. A subsurface low between the Mataguac Rise and the Santa Rosa-Barrigada Rise has already been named the "Yigo Trough". It extends from Tumon Bay along a gentle arc to the vicinity of the south bondary of Andersen Air Force Base and has an axial length of about eight miles. In the well defined portion of the trough, width varies from 1.5 miles at Dededo-Yigo to about half a mile at Andersen. The trough rises above sea level in its northern end, as determined by Exploratory Well No. EX-2, which effectively stops groundwater drainage between Andersen Air Force Base and Yigo Trough.

   The trough is an extremely important hydrologic feature. It receives recharge from the Mataguac and Santa Rosa-Barrigada rises and channels a large volume of fresh groundwater toward Tumon Bay. This is why the Marbo Air Force wells, many of the PUAG D and M series wells, and the Air Force Tumon infiltration gallery are such excellent groundwater production sources.

The above three major basement features dominate the location and developability of the limestone aquifers. Several subsidiary features also may play a significant role. Basement ridges seem to strike toward Ritidian and Pati Points, and a secondary trough tributary to the major Yigo Trough appears to have its axis about coincident with the Dededo well field (D series wells). Parabasal aquifers may occur on the flanks of rises where they plunge below sea level into the troughs.

Other interpretations of the seismic data may be reasonable, in particular the boundary details of the basement troughs and rises, but the four major features apparently are dominant. These features were poorly understood at the time of the writing of the last comprehensive report on the hydrology of northern Guam (Mink, 1976) but since their discovery, have greatly improved the accuracy of groundwater flow analyses for the Northern Lens. In Mink's earlier report (1976), hydrologic budget analyses assumed essentially equal groundwater flow toward the east and west coasts. The basement configuration as now known, however, indicates that at least two thirds of subsurface drainage moves toward the Philippine Sea and only one third toward the Pacific Ocean side of the island. This type of revelation, along with reasonably well defined subsurface boundaries, makes mathematical modeling of the groundwater flow system more realistic.

GRAVITY SURVEY

A gravity survey was included in the geophysical exploration program chiefly to supplement data yielded by seismic refraction. But a subsidiary purpose was to provide a reconnaissance view of gravity distribution on the island because no such survey had been done before. The normal goal of a gravity survey, which is the determination of regional gravity anomalies, was successfully accomplished. In addition, the regional bulk density of the limestone was obtained by correlating changes in free air anomalies with elevation along a linear traverse, and residual gravity values were computed by removing the regional gravity field. Bulk density of the limestone is important because, from it, an estimate of regional porosity can be calculated. The location of residual gravity anomalies trace the rise and fall of the basement.

Regional Gravity Anomalies

Over northern Guam, regional gravity varies from about 200 milligals (mgals) on the east coast to 200 mgals at the positive anomaly near Potts

Junction on Marine Drive. Although not a large gradient, it is significant. A closure of 4 to 5 mgals encircles this high in the northwest quadrant of the island. The high is not coincident with the volcanic outcrop at Mataguac Hill or the larger exposure at Mt. Santa Rosa. ECOsystems interpreted the gravity high as reflecting a deep plutonic core which is modelled as having a radius of 12,000 feet and a center of mass at a depth of 22,000 feet.

The regional gravity anomalies have not proved to be a clear guide to basement elevations, but they are indicative of primary subsurface structures. They are not as prominent as in Hawaii, where a variation of as much as 100 mgal is common, but nevertheless, ECOsystems believes they resemble the Hawaii model in reflecting concentrations of dense rock associated with volcanic rift zones. But, because Hawaiian rocks are basaltic and the rift zones radiate from calderas, while the Guam rocks are mostly andesitic with no identifiable evidence of calderas, this interpretation should be looked on as preliminary.

A second gravity high is found over Nimitz Hill. It is not as obvious as the northern one because closure is poor and incomplete. In all of Guam, the largest high lies off Facpi Point where an anomaly of 235 mgals and a closure of 5 mgals has been measured. In the vicinity of Facpi Point many dikes, which probably are part of a rift zone, have been mapped.

Determination of Bulk Density of Limestone

By correlating the change in free air gravity anomalies with differences in elevation along a line of stations, measurement of mass contained between the lowest and highest stations is made. Four traverses, mostly on Mariana limestone, resulted in density calculations ranging from 2.24 to 2.50 and averaging 2.35. From these data, approximations of the regional porosity of the limestone can be made by reference to the standard densities of solid aragonite, the mineral which calcium carbonate initially forms, and calcite, the mineral to which aragonite eventually converts. The density of aragonite is 2.930 and the density of calcite is 2.710. If all of the limestone consists of aragonite, the regional porosity would vary between

15 and 24 percent and average about 20 percent; if it consists only of calcite, regional porosity would range from 8 to 17 percent and average 13 percent. Based on gravity data, therefore, a reasonable estimate of the regional porosity of the Mariana limestone is 10 to 25 percent.

Residual Gravity Values

A technique commonly used to show relative changes in mass consists of removing the regional gravity field in order to accentuate gravity residuals. Regional separations were carried out for northern Guam and the remaining residuals computed. In many instances, the positive residuals correlate with rises in the basement and negative residuals with troughs. Not all residuals, however, follow the correlation. Interpretations of the basement configuration should be made cautiously when residuals are employed as the primary data.

DEVELOPMENT OF THE VOLCANIC BASEMENT CONTOUR MAP

The development of the Volcanic Basement Contour Map, Plate 1, which defines the lower boundary of the limestone aquifer, has significantly increased the understanding of Guam's Northern Lens groundwater system. It provides a more precise definition of the subbasin boundaries and overall geometry of the limestone aquifer. This clearer understanding of aquifer configuration has not only enhanced the estimates of sustainable yield, but has made well site selection and design far less risky.

The contour map was constructed using: 1) lithologic logs from wells; 2) seismic refraction profiles and gravity data; 3) surface geology; 4) chloride concentrations in conjunction with groundwater level elevations; and 5) surface geomorphology.

The lithologic well logs are the most definitive information for determining the top of volcanics because the penetrated volcanic rocks are visually identifiable, thus providing an exact selection of the contact. The well logs indicate the elevation at which the well intersects the volcanics, or, if the well does not penetrate volcanics, show the maximum possible elevation of the volcanics. Prior to 1981, few wells penetrated volcanics in the northern Guam because of the design criteria which stipulated that the bottom of wells should not exceed 25 feet below sea level. As a result, very wide gaps in definitive well data were evident. GEPA realized this, and as part of the Northern Guam Lens Study, drilled 11 exploratory wells in various locations in the Lens, and of those, three penetrated volcanics. These wells not only gave positive information on where the volcanics were at these locations, but also verified the validity and interpretation of the seismic refraction data. In areas of conflicting data, such as near seismic line D-1 in the Dededo Well Field (see Plate 1), the well data were given priority over other data.

Seismic refraction profiles and gravity surveys were run by ECOsystems Management Associates, Inc. Fifty-six seismic lines were run, with the lengths of the lines varying from 2,000 feet to 3,500 feet, and with geophone spacing between 50 and 200 feet. Small dynamite blasts were used as the energy source at each end of the profile. Twenty-nine seismic refraction profiles provided top-of-volcanic surface. The map, produced by ECOsystems, represented the first generation of Plate 1, which slowly evolved as new data became available. The gravity survey data, though useful in determining anomalous subsurface features, were generally not useful in determining the break between the top of volcanics and the overlying limestone.

The previously mapped surface geology was used to identify surface exposures of the volcanics. The volcanics are exposed in northern Guam at Mount Santa Rosa, Mataguac Hill, Palii Hill, and near the southern bondary of the Northern Lens, along the Pago River.

The chloride concentrations from production wells were also used in preparing Plate 1. Data were obtained from 1982 mean chloride concentrations from PUAG and United States Air Force analyses. Chloride data, from the first drilled well in 1937, through the 1950's were used for other, older wells. The chloride ion concentrations are used to divide the groundwater basin in the Northern Lens into parabasal, basal, and transitional zones. If a particular well had a chloride concentration of less than 30 mg/l, the well was considered to be in the parabasal zone; if the concentration was less than 70 mg/l and greater than 30 mg/l, the well was probably over the transition zone between basal and parabasal zones; and if it was greater than 70 mg/l, the well was in the basal zone. Chloride concentrations used in conjunction with fresh water heads and the associated fresh water-salt water interface, which was calculated using the Ghyben-Herzberg principal (which states that the fresh water-salt water interface is located at a depth 40 times that of the groundwater surface elevation), will give an approximation of depth-to-volcanics. To use this method, first, the type of lens which a particular well penetrated must be determined (i.e. parabasal or basal). For parabasal wells, the water level is multiplied by 40 and the result is the maximum depth of the top-of-volcanics. For a basal well, the water level, multiplied by 40, is the minimum depth of the volcanics.

Finally, surface geomorphology of the Northern Lens was used to interpret subsurface volcanic landform where data was insufficient to make any other, more definitive interpretation. It was assumed that the historic geomorphology after the volcanics were deposited was relatively the same as that of today. Then, contours were drawn which reflected the suspected volcanic surface. For example, at Andersen Air Force Base, the pronounced slope of the ground surface northeast toward Patti Point, as well as the prominence of Patti Point, were interpreted as reflecting a ridge line that extends from Salisbury Junction to Patti Point.

The five types of data summarized above were used together to produce the top of volcanics contour map. As new data becomes available, the map should be refined. Areas in which questionable interpetations were made are around the Dededo Well Field, northern and eastern Agana Subbasin, Andersen Subbasin, northern Finegayan Subbasin, and the Northwest Field area. The University of Guam is obtaining instruments to conduct geophysical surveys and the NGLS consultant recommends that they conduct more detailed seismic surveys in the future in these areas to further define the volcanic subsurface. In other areas, data acquired from the drilling of future production water wells will help refine the interpretation of the volcanic map.

APPENDIX C

PERMEABILITY OF THE NORTHERN LENS LIMESTONES

GENERAL

This appendix discusses several methods used to indirectly determine permeability in Guam's Northern Lens limestone aquifer. Of all the hydraulic parameters associated with the Northern Lens limestones, permeability is probably the most important, yet the most difficult to determine. Permeability (K) is a measure of the ability of a porous medium to transmit water. Permeability is defined as the rate of flow (Q) of water at 60 degrees Farenheit through a porous media having a cross-sectional area (A) of 1 square foot under a hydraulic gradient (I) of 1 foot per foot. It is represented by the variation in the Darcy equation:

$$K = \frac{Q}{IA} \qquad \text{(C-1)}$$

In the Northern Lens limestones, regional permeabilities range over three orders of magnitude, from under 10 feet per/day (ft/d) for the most argillaceous limestones in the southern part of the lens, to over 12,000 ft/d in the northern part of the lens. However, local variations in permeability are common and extreme because of the nature of the limestone matrix structure and depositional environment. Considering the types and distribution of pore space in limestone, local permeabilities may vary from near zero to 20,000 ft/d.

This extreme variation, and especially the very high values of permeability, make its precise determination by conventional pump test methods almost impossible in northern Guam. Characteristically, drawdowns in pumping wells stabilize in a matter of a few minutes. Drawdowns measured inside a pumping well are generally on the order of several feet, and in some instances tens of feet. However, aquifer drawdown calculations based on the high regional permeabilities are on the order of less than one foot. The difference between the in-casing drawdown and the corresponding aquifer drawdown indicates the relatively high head loss that occurs as the water passes from the aquifer through the gravel pack and well screen. Separating head loss through the aquifer from head loss through the well screen is nearly impossible for the wells now in production in the Northern Lens. If future wells are equipped with sounding tubes placed in the gravel pack outside the well casing, then a better estimate of water level drawdown in the aquifer will be available.

Because permeability is not easily determined using the more common pump test methods, several indirect methods are used to estimate local and average regional permeabilities. These include head gradient relationships, tidal attenuation, recovery tests, intrusion analyses, and numerical modeling techniques.

GENERAL PERMEABILITY CHARACTERISTICS OF LIMESTONE IN GUAM

The aquifer in northern Guam consists of limestone. Permeabilities and porosities in the limestone vary considerably, both locally and regionally, depending usually on the environment of deposition of the limestone. Limestone deposited in deep water is generally massive and crystalline, and more susceptible to chemical dissolution by fresh water (FUGRO, 1974), and thus have more pores and higher permeability. Limestones deposited in the near-shore lagoonal environment contain significant amounts of clay material (derived from the adjacent volcanic upland areas) which effectively reduce the potential for dissolution of the limestone and the formation of pores.

In the aquifer section associated with the fresh water lens, porosity occurs as a result of elliptical voids in the limestone as well as continuous and discontinuous passages through the limestones. These pores range in size from microscopic openings to large, well developed cavern systems. However, inspection of exploratory well cores and limestone outcrops in northern Guam indicate that the passages are generally about 1/8 to 1/4 inches in diameter.

As mentioned above, the amount of clay in the limestone also affects the magnitude of the porosity, and thus, the permeability. Permeabilities vary inversely with the amount of clay contained in the limestone matrix. In the southern portion of the lens, clay contents in the limetones are significantly higher than in the limestones further north. Correspondingly, permeabilities are generally one to two orders of magnitude lower in the southern limestones. The higher clay content is probably the result of the influx of fine-grained detrital material originating from the volcanic upland area of southern Guam and deposited in the quiet waters of a near-shore lagoonal environment.

ESTIMATES OF PERMEABILITY

The magnitude of the permeabilities in the Northern Lens cannot be directly measured. In the following sections, estimates are made of permeability using various indirect methods.

<u>Areal Variations in Fresh Water Heads</u>

Horizontal permeability within the Northern Lens can be approximated by relating fresh water head to unit flow past an observation point (located in the basal lens) and to the distance inland to the observation point. Assuming that the head is zero at the coastline and the Ghyben-Herzberg conditions apply, the basic steady state relationship is:

$$q = -41\ Kh \frac{dh}{dX} \qquad \text{(C-2)}$$

where: q = flow per unit width of aquifer past the well (dimensional units of L^2/T)

K = horizontal permeability of the aquifer (dimensional units of L/T)

X = distance from the coast to where the head measurement (h) is made, as measured along a flow line (dimensional units of L)

h = fresh water head at X (dimensional units of L)

Aquifer unit flow (q) can be estimated by:

$$q = -R(X_1 - X) \tag{C-3}$$

where: R = average annual unit recharge to the aquifer along the flow line that passes through the observation point (assuming no extraction along the flow line)(dimensional units of L/T)

X_1 = flow line distance from the ocean to the top of the drainage basin (dimensional units of L)

Combining equations (C-2) and (C-3) provides:

$$R(X_1 - X) = 41\ Kh\frac{dh}{dX} \tag{C-4}$$

Integrating equation (C-4) with the boundary condition that when X = 0, then h = 0, yields:

$$RX_1X - \frac{RX^2}{2} = 41\ \frac{Kh^2}{2} \tag{C-5}$$

Rearranging the variables in equation (C-5) gives the following expression for horizontal permeability in terms of fresh water head.

$$K = \frac{RX}{41}\ h^2\ (2X_1 - X) \tag{C-6}$$

Table C-1 shows the estimates of permeability for those wells in the basal lens based on the head measurements taken in September 1981 and April 1982. Unit recharge values are those developed in Chapter 5 (Tables 5-4 and 5-5). The areal variations in permeability are similar to those calculated using other methods discussed later in this report. Regionally, permeability increases from about 500 ft/d in the southern part of the lens to over 15,000 ft/d in the central part, and then decreases to about 2,000 to 4,000 ft/d in the northern part of the lens.

Head measurements taken at wells in September 1981 yielded lower calculated permeabilities than heads measured in the same wells in April 1982. This apparent variation in permeability is the result of using transient head

TABLE C-1

PERMEABILITY DETERMINED BY
DISTANCE-HEAD-RECHARGE RELATIONSHIP

Well No.	h Head* (ft)	X Distance** (ft)	X_1-X Distance*** (ft)	R Recharge (ft/d)	K Permeability (ft/d)
A-9	4.74	11,250	2,900	.00753	1,570
A-10	4.63	10,500	3,500	.00753	1,575
A-13	4.06	12,250	2,250	.00753	2,285
A-15	3.19	12,500	1,500	.00731	3,390
A-16	3.76	8,880	9,100	.00731	3,035
A-19	3.13	3,250	4,200	.00731	689
D-1	3.55	16,250	14,200	.00799	11,225
D-4	3.55	16,250	14,700	.00799	11,475
D-12	3.50	16,000	10,800	.00799	9,575
D-14	3.43	12,900	19,300	.00799	11,000
D-15	2.98	12,500	17,000	.00799	9,560
D-16	3.27	10,750	19,000	.00799	12,760
D-17	3.24	9,500	20,240	.00799	8,820
F-2	3.01	7,500	6,500	.00822	3,410
F-6	2.71	7,800	4,900	.00822	3,750
H-1	1.80	2,500	26,000	.00799	8,200
H-107	3.12	3,500	25,000	.00799	3,745
M-6	3.05	14,600	5,000	.00799	7,530
M-7	3.52	15,250	3,800	.00799	5,470
M-9	2.58	5,000	3,250	.00799	1,680
M-10a	3.07	7,500	12,200	.00799	4,940
M-11	3.51	11,000	23,100	.00799	9,950
M-12	3.31	9,100	21,100	.00799	8,300
M-14	3.50	7,200	23,000	.00799	6,095
MW-1	3.04	15,200	16,500	.00799	15,480
Y-4	3.63	26,500	9,200	.00799	17,590
BPM-72	2.93	5,000	8,500	.00753	2,355
BPM-AAFB	2.78	3,640	10,400	.00799	2,240
EX-1	7.06	7,200	11,600	.00776	831
EX-4	5.61	8,500	8,500	.00753	1,270
EX-5a	3.37	16,000	13,500	.00799	11,800
EX-6	3.58	11,750	11,300	.00799	6,140
EX-7	3.45	6,700	22,500	.00799	5,680
EX-8	2.74	11,220	9,000	.00799	8,510
EX-9	3.20	11,400	5,100	.00753	4,430
EX-10	3.20	8,100	17,300	.00799	6,580

TABLE C-1
(Continued)

Well No.	h Head* (ft)	X Distance** (ft)	X_1-X Distance*** (ft)	R Recharge (ft/d)	K Permeability (ft/d)
Island Equip.	2.31	3,250	11,000	.00685	2,570
Foremost	1.75	2,000	7,120	.00753	1,950
A-9	6.06[1]	11,250	2,900	.00753	960
M-7	3.82[1]	15,250	3,800	.00799	4,660
EX-1	8.67[1]	7,200	11,600	.00776	550
EX-4	6.65[1]	8,500	8,500	.00753	900
EX-6	3.75[1]	11,750	7,250	.00799	4,270

* April 1982 water levels.

** Distance from coastline to well along a flow line.

*** Distance from well to top of drainage basin along a flow line, which is equal to (X_1-X) in equations (C-3), (C-4), and (C-6).

1 September 1981 water levels.

values instead of average recharge values in a steady-state equation. Better estimates would be obtained if average annual head data were used in the calculation. However, in those areas of the Northern Lens where head variation is minimal, such as in the Yigo Subbasin, the permeability estimates provided in Table C-1 are relatively good.

Tidal Attenuation

WERI (1982) used equations developed by Ferris (1951) to estimate permeability based on tidal attentuation within the aquifer. Analyses were done at five wells throughout the lens using the Apra Harbor tidal gage data. Each of the wells, as well as the tidal gage, were equipped with continuous water level recorders for a period of 30 months. The equation used for the analysis was:

$$\frac{R_x}{R_o} = \exp\left[X \left(\frac{S}{Tt_o}\right)^{1/2}\right] \qquad (C-7)$$

where: R_x = tidal range in the observation well (dimensional units of L)

R_o = tidal range in the ocean (dimensional units of L)

X = inland distance of the observation well (dimensional units of L)

S = aquifer specific yield (which is approximately equal to porosity in the Northern Lens limestone)(dimensionless)

T = aquifer transmissivity (dimensional units of L^2/T)

t_o = tidal period (which is about half a day)(dimensional units of T)

Transmissivity (T) can be related to permeability (K) by the following expression:

$$K = \frac{T}{m} \qquad (C-8)$$

where m = thickness of the aquifer (dimensional units of L).

Therefore, combining equations C-7 and C-8,

$$K = \frac{S\,m}{t_o\left(X \text{ Log } \frac{R_x}{R_o}\right)^2} \qquad (C-9)$$

WERI (1982) calculated permeability using equation C-9 for a range of porosity values, as indicated on Table C-2. As discussed in Chapter IV, a regional average porosity in the area of the wells used for the analysis is on the order of 15 percent. Assuming a porosity of 15 percent, Table C-2 shows a range in permeabilities from 2,380 ft/d at well BPM-72, located in the Agana Subbasin (Plate 1), to 12,400 ft/d at Well No. M-11 located in the Mangilao Subbasin. The permeabilities estimated by tidal attenuation are between two and ten times higher than those calculated using variations in head discussed previously.

TABLE C-2

PERMEABILITY BASED ON
TIDAL ATTENTUATION

	Permeability (feet/day)		
Well No.	$n^* = 0.15$	$n^* = 0.25$	$n^* = 0.40$
BPM-72	2,380	3,950	6,330
H-107	5,610	9,350	14,960
M-10a	6,790	11,330	18,130
A-16	8,155	13,590	21,750
M-11	12,400	20,670	33,075

*n = effective porosity

Recovery Tests

Although pump drawdown tests are not useful in determining permeability for the limestone aquifer, pump recovery tests can be of assistance. Figure C-1 is an example of a time-recovery curve for a test conducted at Well No. F-2. The curve is used to estimate aquifer transmissivity. The equation for determining transmissivity from the time-recovery curve is:

$$T = \frac{35.3Q}{\Delta h} \qquad \text{(C-10)}$$

where: T = transmissivity, ft^2/d

Q = discharge from the well when the well was pumping, in gpm

Δh = change in head over one log cycle of time since pumping stopped, in feet

Because the wells used for this analysis only partially penetrate the aquifer (usually the upper 25 to 50 feet), transmissivity must be corrected to reflect the entire aquifer sequence. When converting transmissivity (T)

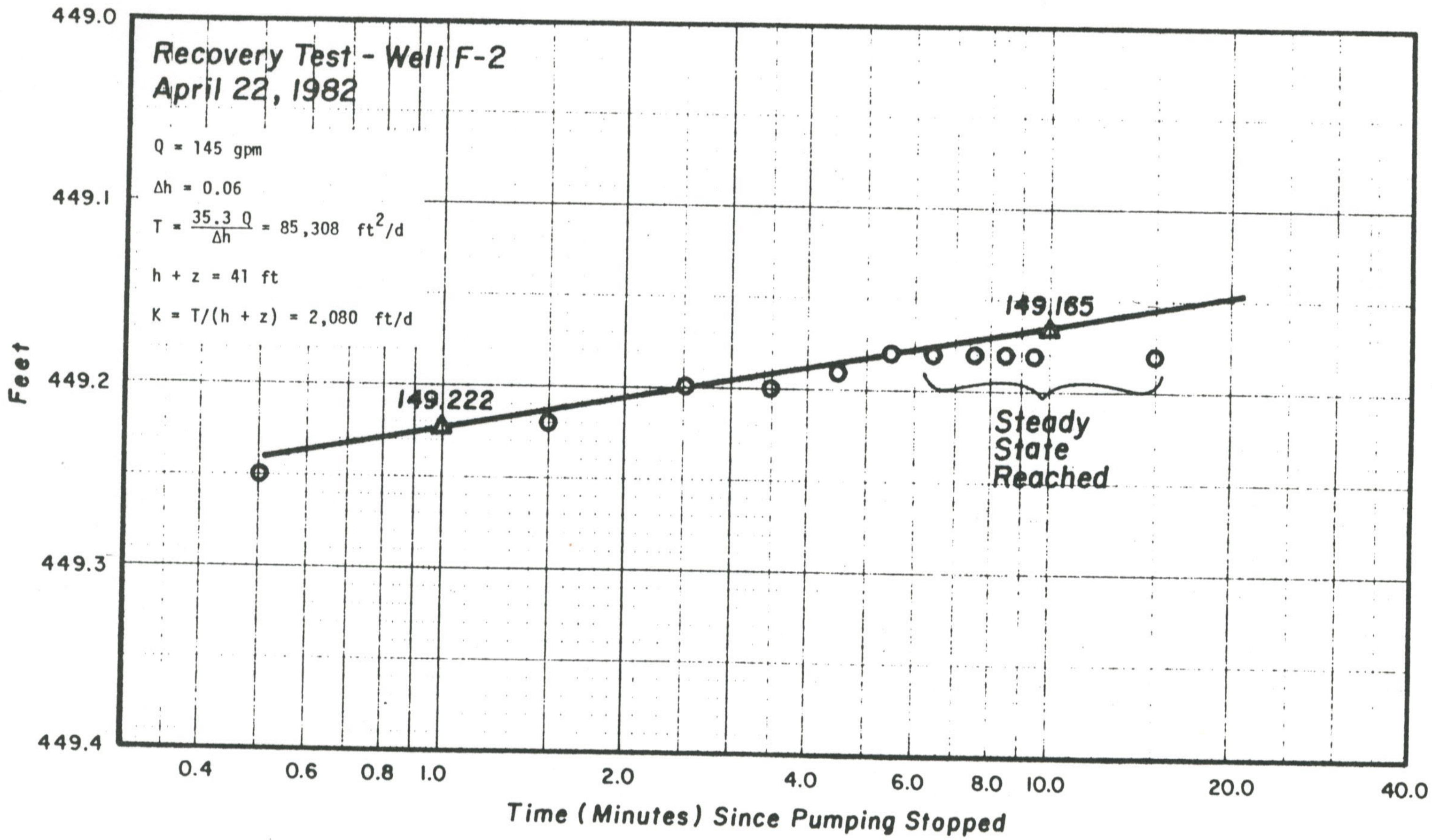


FIGURE C-1

TIME RECOVERY TEST CURVE

to permeability (K) in a fully penetrating well, T is divided by the thickness of the aquifer, as was done in equation (C-8). For a partially penetrating well, T is divided by the amount of aquifer penetrated, which equals the fresh water head (h) plus the depth of the well below sea level (z). Therefore,

$$K = T/(h+z) \qquad \text{(C-11)}$$

Table C-3 summarizes the permeabilities for each well based on the recovery test. The majority of the tests were conducted by the driller at the time of well construction prior to the initiation of the NGLS. Several tests were conducted by John Mink and CDM during the study.

TABLE C-3

PERMEABILITIES FROM
LOCAL DRAWDOWN RECOVERY TESTS

Well No.	Δh/log cycle (ft)	Q (gpm)	h (ft)	z (ft)	h+z (ft)	T (ft^2/d)	K (ft/d)
A-2	0.87	236	6.7	51	57.7	9,576	166
A-3	3.10	275	20±	306	326.0	3,131	10
A-5	0.34	225	4.4	174	178.4	23,360	131
A-7	0.69	262	10±	42	52.0	13,404	258
A-8	5.40	238	15±	173	188.0	1,556	8
A-10	0.24	215	4.6	26	30.6	31,623	1,033
A-11	12.90	164	31.3	159	190.3	449	2
A-12	3.20	252	22.3	190	212.3	2,780	13
A-13	9.50	211	4.1	194	198.1	784	4
D-4	0.16	175	3.6	26	29.6	38,609	1,304
D-11	0.31	180	3.5±	37	40.5	20,497	506
F-1	0.13	132	3.0±	35	38.0	35,843	943
F-2	0.06	145	3.0	38	41.0	85,308	2,080
M-1	0.12	194	3.0±	54	57.0	57,068	1,000
M-4	0.09	176	3.0±	50	53.0	69,031	1,300
M-5	0.10	208	3.6	131	134.6	73,424	546
M-6	0.20	194	3.1	73	76.1	34,241	450
M-7	0.08	229	3.5	51	54.5	101,046	1,850

The permeability estimates shown in Table C-3 are values for the aquifer immediately adjacent to each well, and thus, represent local permeabilities. However, the use of this method can be limited in northern Guam where aquifer permeabilities are so high. It is possible that if the permeability of the well screen and gravel pack is lower than that of the aquifer, the rise in water level within the well will lag behind the rise in the adjacent aquifer. In this case, the recovery test would be measuring the permeability of the well screen and not an accurate indication of aquifer transmissivity. If, on the other hand, the permeability of the well screen and gravel pack is higher than that of the aquifer, then the rise in water level during the test will be the same in both the aquifer and the well, thus, providing an accurate test of aquifer transmissivity. Therefore, this method of measuring permeability should be limited to those wells which do not have high in-casing drawdowns.

This method of estimating permeability shows the same areal trend and order of magnitude change over the Northern Lens as indicated by the head variation method discussed earlier in the Appendix. In the southern part of the lens, permeability ranges from 2 ft/d to 1,030 ft/day. Moving north, the permeability in the tested wells range from 450 ft/d to 2,080 ft/d.

Numerical Modeling

Two numerical groundwater models were used during the NGLS to evaluate groundwater conditions in the Northern Lens limestones. The first consisted of an intricate finite element model developed by the University of Guam. This model is described in more detail in Appendix G. The three regional permeabilities calibrated for this model were 100 ft/d in the southern part of the aquifer, 5,000 ft/d in the central part of the lens, and 10,000 ft/d in the northern part of the lens (see Appendix G).

During the NGLS, the Consultant developed a second model using a non-linear equation to determine salt water intrusion on sloping impermeable basement rock. A summary of the derivation of the basic equations of the model are provided in the following paragraphs.

Bear (1979) provides an expression which was derived by Strack (1976) for single value harmonic potential (ϕ) in the fresh water zone:

$$\phi = \frac{Q_o X}{K} + \frac{Q_i}{4\pi K} \ln \left[\frac{(X_t - x_i)^2 + Y^2}{(X_t + x_i)^2 + Y^2} \right] \qquad \text{(C-12)}$$

where:

- ϕ = function of head by the relationship $\phi = \frac{41\ h^2}{2}$ (dimensional units of L^2)
- Q_o = unit discharge through the aquifer along a flow line (dimensional units of L^2/T)
- Q_i = well discharge (dimensional units of L^3/T)
- X_t = distance inland from the coast to the salt water toe (dimensional units of L)
- Y = distance along the coast from origin of the coordinate system to the point where the salt water toe distance (X) is calculated (dimensional units of L)
- x_i = X-coordinate of the well (dimensional units of L)
- K = aquifer permeability (dimensional units of L/T)

Figure C-2 illustrates the system being described. Equation (C-12) requires modification to account for multiple wells, sloping basement rock at the base of the aquifer, and uniform recharge. To account for multiple wells, the second term on the right hand side of equation (C-12) is modified to:

$$\sum_{i=1}^{n} \left[\frac{Q_i}{4\pi K} \ln \frac{(X_t - x_i)^2 + (Y - y_i)^2}{(X_t + x_i)^2 + (Y - y_i)^2} \right] \qquad \text{(C-13)}$$

where: y_i = y-coordinate of a well (dimensional units of L)

Recharge, coming landward of the salt water toe, is introduced by modifying the first term on the right hand side of equation (C-12) as follows:

$$K\ (1 + \gamma)\ h \frac{dh}{dX_t} = Q_o + R\ (X_1 - X_t) \qquad \text{(C-14)}$$

or

$$\begin{aligned} K \frac{d\phi}{dX_t} &= Q_o + R\ (X_1 - X_t) \\ &= R\ (X_1 - L) + R\ (L - X_t) \\ &= R\ (X_1 - X_t) \end{aligned} \qquad \text{(C-15)}$$

where R = unit recharge rate (dimensional units of L/T)

L = distance from the coast to the limestone/volcanics contact at an elevation equal to mean sea level (dimensional units of L)

γ = fresh water-salt water density relationship; equal to density of fresh water divided by the difference in density between fresh water and salt water (dimensionless)

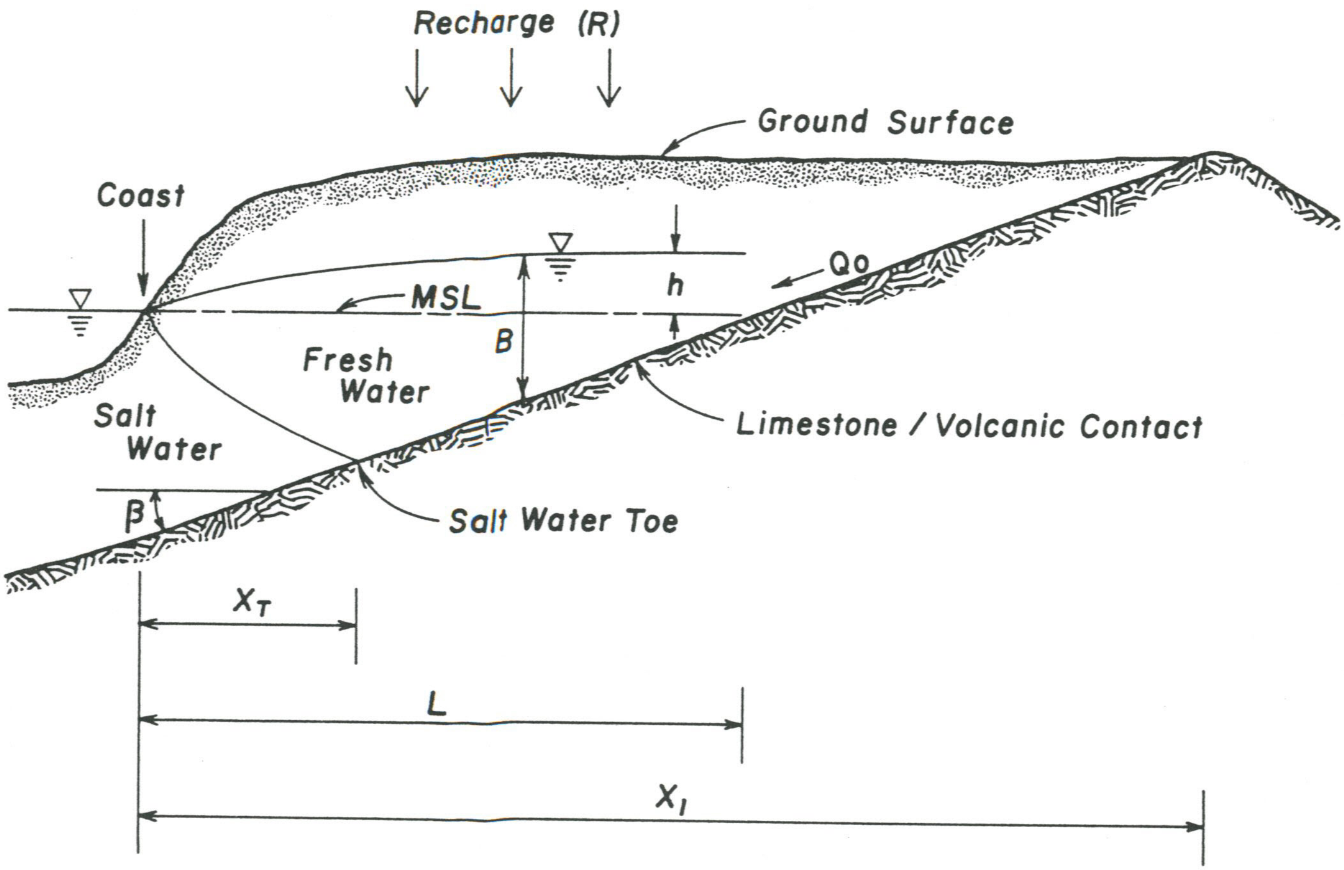
X_1 = distance from the coast to the top of the drainage basin (dimensional units of L)

Integrating the modified form of the $\frac{Q_o X_t}{K}$ term of equation (C-12) as presented in

$$\frac{Q_o X_t}{K} = \frac{R}{K} X_1 X_t - \frac{R}{2K} X_t^{2} \qquad \text{(C-16)}$$

Sloping limestone/volcanic contact is addressed next. According to the analysis by Strack (1976), the potential at the fresh water-salt water interface is given by:

$$\phi = \frac{1}{2} \left(\frac{1 + \gamma}{\gamma^2} \right) B^2 \qquad \text{(C-17)}$$



(NOT TO SCALE - VERTICALLY EXAGGERATED)

FIGURE C-2

HYPOTHETICAL DIAGRAM
OF THE SALT WATER TOE POSITION

where: B = thickness of the aquifer measured from the water table to the top of the volcanics. B can be modified to account for the slope of the limestone/volcanic contact by:

$$B = \beta\,(L - X_t)$$

Combining equations (C-17) and (C-18) gives:

$$\phi = \frac{1}{2}\left(\frac{1+\gamma}{\gamma^2}\right)\beta^2\left(L^2 - 2LX_t - X_t^2\right) \qquad \text{(C-19)}$$

Modifying equation (C-12) with respect to equations (C-13) and (C-16) and equating this to equation (C-19) yields equation (C-20) for the position of the salt water toe on the sloping limestone/volcanic contact, under the influence of a well field located landward from the toe, and with uniform recharge:

$$\left(\frac{1}{2}\ \frac{1+\gamma}{\gamma^2}\right)\beta^2L^2 - \left(\frac{1+\gamma}{\gamma^2}\right)\beta^2L^2X_t + \frac{1}{2}\left(\frac{1+\gamma}{\gamma^2}\right)\beta^2X_t^2 = \frac{RX_1X_t}{K} - \frac{RX_t^2}{2K} + \sum_{i=1}^{n}\left[\frac{Q_i}{4\pi K}\ln\left[\frac{(X_t - x_i)^2 + (Y - y_i)^2}{(X_t + x_i)^2 + (Y - y_i)^2}\right]\right] \qquad \text{(C-20)}$$

simplifying equation (C-20) in terms of X_t gives:

$$\left[\frac{1}{2}\left(\frac{1+\gamma}{\gamma^2}\right)\beta^2 + \frac{R}{2K}\right]X_t^2 - \left[\left(\frac{1+\gamma}{\gamma^2}\right)\beta^2L + \frac{RX_1}{K}\right]X_t + \left[\frac{1}{2}\left(\frac{1+\gamma}{\gamma^2}\right)\beta^2L^2\right] = \sum_{i=1}^{n}\left[\frac{Q_i}{4\pi K}\ln\left[\frac{(X_t - x_i)^2 + (Y - y_i)^2}{(X_t + x_i)^2 + (Y - y_i)^2}\right]\right] \qquad \text{(C-21)}$$

The regional permeability can be evaluated by estimating values for the position of the salt water toe and then calculating for K in equation (C-21). The position of the toe is estimated in the following manner:

1. Multiply by 40 (the Ghyben-Herzberg constant) the fresh water head measured in a basal well that is relatively close to the minus 200-foot contour line on Plate 1; this value is the depth below sea level of the fresh water-salt water interface.

2. Project the elevation of the interface onto the adjacent top of volcanics surface shown on Plate 1.

3. Where the interface intersects the top of volcanes is the estimated position of the toe.

For example, a basal well in Finegayan has a measured head of 3 feet and is situated over the minus 250-foot top of volcanics contour. Multiplying the head by 40 gives 120 feet, which is the approximate depth of the interface below sea level. The interface elevation (-120 feet) is projected onto the adjacent top of volcanics surface shown on Plate 1, and where the top of volcanics has a contour value, -120 feet is the approximate position of the salt water toe in that area.

The position of the salt water toe (X_t) is solved in equation (C-21) by Newton's method. The major criteria for use is that the toe, the zero elevation contour of the contact, and the top of the drainage area should be parallel to the coastline. The Finegayan and Mangilao Subbasins are the only areas in northern Guam that reasonably meet these criteria.

Assuming a volcanic bedrock slope of 0.103 ft/ft (measured from contours on Plate 1) and a recharge rate of 0.007 ft/d, the regional permeability for the Mangilao Subbasin in the vicinity of Well No. M-11 is about 525 ft/d. Assuming a volcanic bedrock slope of 0.075 ft/ft and recharge rate of 0.008 ft/d, the regional permeability in the Finegayan Subbasin near Well No. F-2 is about 3,300 ft/d. These results are in general agreement with those determined by recovery tests and head variation methods. However, the permeability determined by the tidal attenuation method at Well No. M-11 is over an order of magnitude higher than that determined by the numerical method.

SUMMARY

Several methods for estimating horizontal permeability in the Northern Lens were discussed in this Appendix. Generally, the results of each method concurred that aquifer permeability increases over at least an order of magnitude going from the southern to the northern part of the lens. Table C-4 summarizes and compares the results of each method at coincident observation points. As shown in the table, the recovery test results provide the lowest permeability values, and the tidal attenuation results are the highest. The numerical intrusion model provides an average regional permeability for only two subbasins. The fresh water head relationship provides what appears to be an average permeability of all determinative methods used, as well as the best indication of the areal variation in permeability over the Northern Lens.

TABLE C-4

COMPARISON OF PERMEABILITIES CALCULATED BY DIFFERENT METHODS
(units of feet per day)

Well No.	Method: Areal Variations in Fresh Water Heads*	Tidal Attenuation (n=0.15)	Recovery Tests	Numerical Modeling
72	2,355	2,380	-	-
H-107	3,745	5,610	-	-
M-10a	4,940	6,790	-	-
A-16	3,035	8,155	-	-
A-10	1,575	-	1,030	-
A-13	2,285	-	780	-
D-4	11,475	-	1,300	-
D-15	12,760	-	-	-
F-2	3,410	-	2,080	3,300
M-6	7,530	-	450	-
M-7	5,470	-	1,850	-
M-11	9,950	12,400	-	525
M-9	1,680	-	-	525
M-4	-	-	1,300	-
Y-4	17,590	-	-	-

*Permeabilities for other wells are provided on Table C-1 in Appendix C.

APPENDIX D

FRESH WATER-SALT WATER RELATIONSHIPS IN ISLAND AQUIFERS

GENERAL

Considerable research has been conducted on the interrelationship between fresh water and salt water bodies in island and coastal aquifers. Some of the more significant discussions on the subject are listed in the bibliography chapter of this report. The following discussion will examine the general relationship between fresh water and salt water in the island groundwater environment of the Northern Lens. The discussion will also evaluate salt water upconing and intrusion into the fresh water lens as a result of pumping from wells.

FRESH WATER-SALT WATER INTERRELATIONSHIP

By virtue of the density difference between fresh water and sea water, fresh water floats on salt water in a phreatic coastal or island aquifer such as exists in northern Guam. If the density of fresh water is 1.000 grams per cubic centimeter (g/cc) and the density of sea water is 1.025 g/cc, then the hydrostatic balance between the two waters results in the relationship:

$$\gamma = \frac{\rho_f}{\rho_s - \rho_f} = \frac{1.000}{1.025 - 1.000} = 40 \qquad \text{(D-1)}$$

where: γ = the density contrast between the two waters
ρ_f = the fresh water density
ρ_s = the sea water density

This relationship means that at equilibrium, for every foot of fresh water standing above sea level (h), 40 feet of fresh water exists below sea level (Z), below which, salt water is encountered. Thus,

$$Z = \frac{\rho_f}{\rho_s - \rho_f} h = 40h \qquad \text{(D-2)}$$

Equation (D-2) provides an estimate of the fresh water lens geometry in an island aquifer (see Figure D-1), which is commonly referred to as a Ghyben-Herzberg lens after the two men who discovered the relationship. Deviation from reality occurs near the coast where Dupuit conditions (flow everywhere is horizontal) are not approximated. But practically speaking, use of the 40:1 ratio is a powerful and accurate tool for estimating the thickness of the fresh water lens providing that corrections are made for transition zone effects.

Theoretically, the lower limit of the fresh water lens, as defined above by the distance Z, is an abrupt interface between fresh water (having a chloride concentration of about 100 mg/l) and sea water (having a chlorine concentration of about 19,500 mg/l). However, this ideal situation is never seen in the field because the hydrodynamic environment associated with the interface creates a transition zone that separates the fresh water and salt water (see Figure D-2). The thickness of this zone depends on the magnitude and variation with time of forces exerted on the lens. The major influences on the transition zone include:

1. Tidal and ocean level fluctuations.
2. Recharge to the aquifer.
3. Extractions (pumping) from the aquifer.

The following discussion provides an insight into the relative impact that each of these influences has on the transition zone when artifically isolated from the other influences.

Tidal Fluctuations

Tidal fluctuations in Guam are semidiurnal (with a mean range of 1.6 feet) and diurnal (with a mean range of 2.3 feet) (Tracey, et al, 1964). Because of the short period of the tidal fluctuations, the effects on the

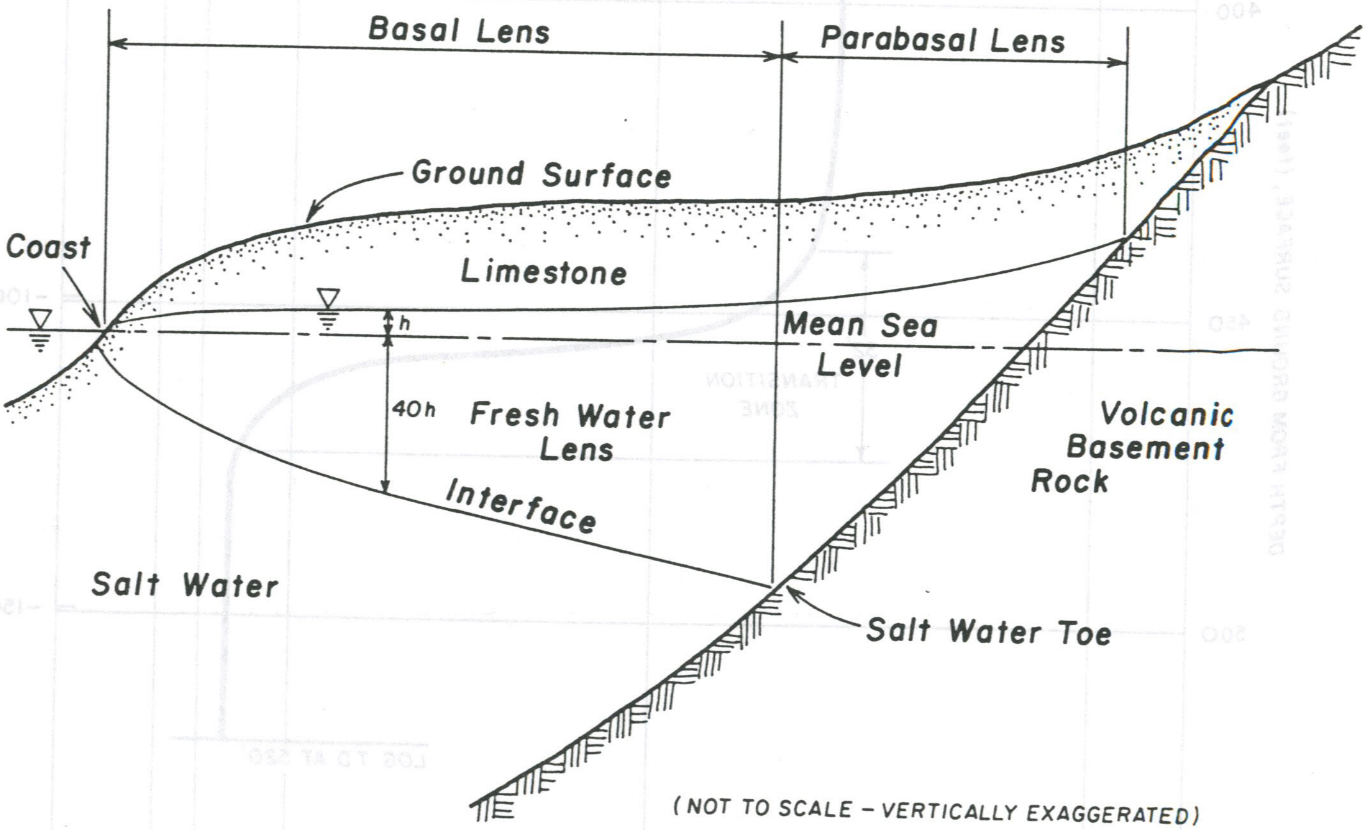


FIGURE D-1

CROSS SECTION OF FRESH WATER LENS WITH SHARP INTERFACE IN A COASTAL UNCONFINED AQUIFER

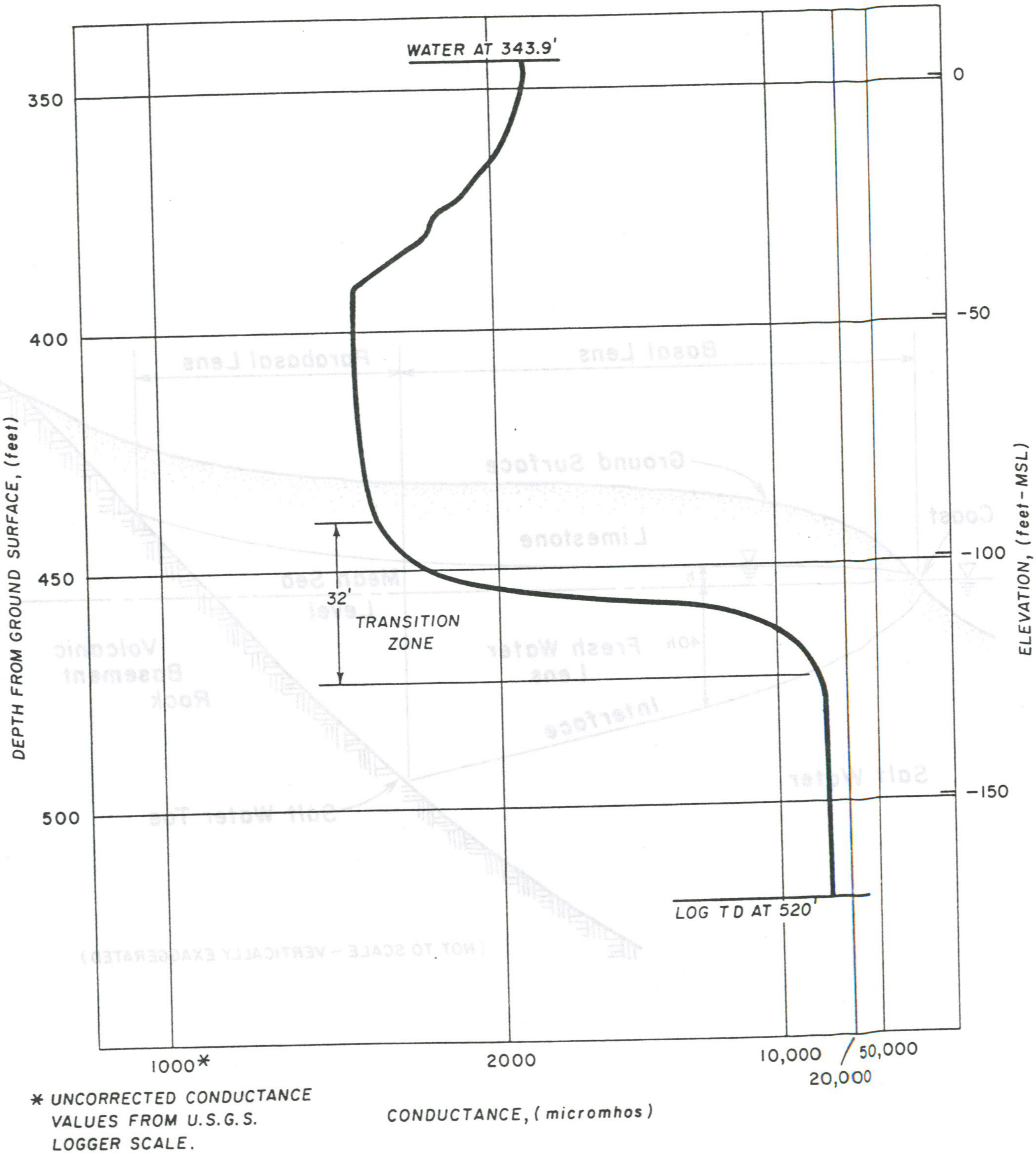


FIGURE D-2
CONDUCTIVITY LOG − WELL EX-10
FEBRUARY 16, 1982

aquifer attenuate quickly with distance inland from the coastline. Ocean level fluctuations, however, occur over a much longer period (on the order of many months) and have a range of about half a foot in Well No. 107, which is located near the coast in the Yigo Subbasin (Plate 1) (WERI, 1982). Because of the longer periods of ocean level fluctuations, their effects reach farther inland than diurnal and semidiurnal tidal effects. Ferris (1951) developed the following equation relating cyclic water level fluctuations in an open water body (e.g., the ocean) to the distance inland in a confined aquifer (WERI, 1982):

$$\frac{R_x}{R_o} = \exp \quad X \left(\frac{S}{Tt_o} \right)^{1/2} \qquad \text{(D-3)}$$

where: R_x = tidal range measured at a distance X inland from the coast,
R_o = ocean tidal range measured at the coast
S = storage coefficient of the aquifer
T = transmissivity of the aquifer
t_o = tidal period
X = distance from the coast to the observation well.

Figure D-3 is an idealized cross-section through the lens showing the relative effect on the thickness of the transition zone due to tidal and ocean level fluctuations. As shown on Figure D-3, the effect of tidal and ocean level fluctuations on the transition zone thickness decrease with distance inland.

Recharge

Seasonal variation in vertical infiltration (recharge) and lateral inflow (recharge from the adjacent parabasal areas) of rainfall to the basal fresh water lens also affects the thickness of the transition zone. WERI (1982) investigations showed that rainfall events over a 30-month period caused a water level fluctuation in Well No. 107 of about four tenths of a foot. The effect of vertical and lateral recharge on the transition is probably significant near the parabasal/basal boundary of the lens, where the inflow of recharge is greatest, and decrease slightly toward the coast, as shown on Figure D-4.

Extractions

The effects on the transition zone of pumping from a single well in the highly permeable limestones of northern Guam are generally a local condition and felt only within a few hundred feet of the well. However, the effects caused by groundwater production from an entire well field can create broad, regional declines in fresh water heads and corresponding changes in the location of the fresh water-sea water interface. The effect on the transition zone is further accentuated by the on and off cycling of well pumps. Drawdowns within the aquifer directly adjacent to a well (not to be confused with the drawdown measured within the well, which generally has a large component of head loss through the well screens) are usually less than one foot and decrease quickly with distance from the well. The corresponding upward movement of the interface (called upconing) is proportionately less than 40 feet. Figure D-5 shows the relative impact of pumping on the transition zone.

Aquifer Hydraulic Characteristics

Areal variations in the hydraulic characteristics of the aquifer are reflected in the thickness of the transition zone. For example, the thickness of the transition zone decreases with increasing permeability. This relationship is evident when comparing the conductivity logs in exploratory wells EX-1 and EX-10, both of which are about the same distance from the coast, pumping wells, and volcanic basement rocks, and both receive about the same amount of recharge. The transition zone at EX-1 is about 104 feet thick (see Figure D-6) and the surrounding aquifer has a permeability of about 800 feet per day. The transition zone at EX-10, on the other hand, has a thickness of about 32 feet (see Figure D-2) and an aquifer permeability of about 6,500 feet per day.

The conductivity logs for Exploratory Wells EX-1 and EX-10 (see Figures D-6 and D-2) illustrate the vertical distribution of salinity (as measured by

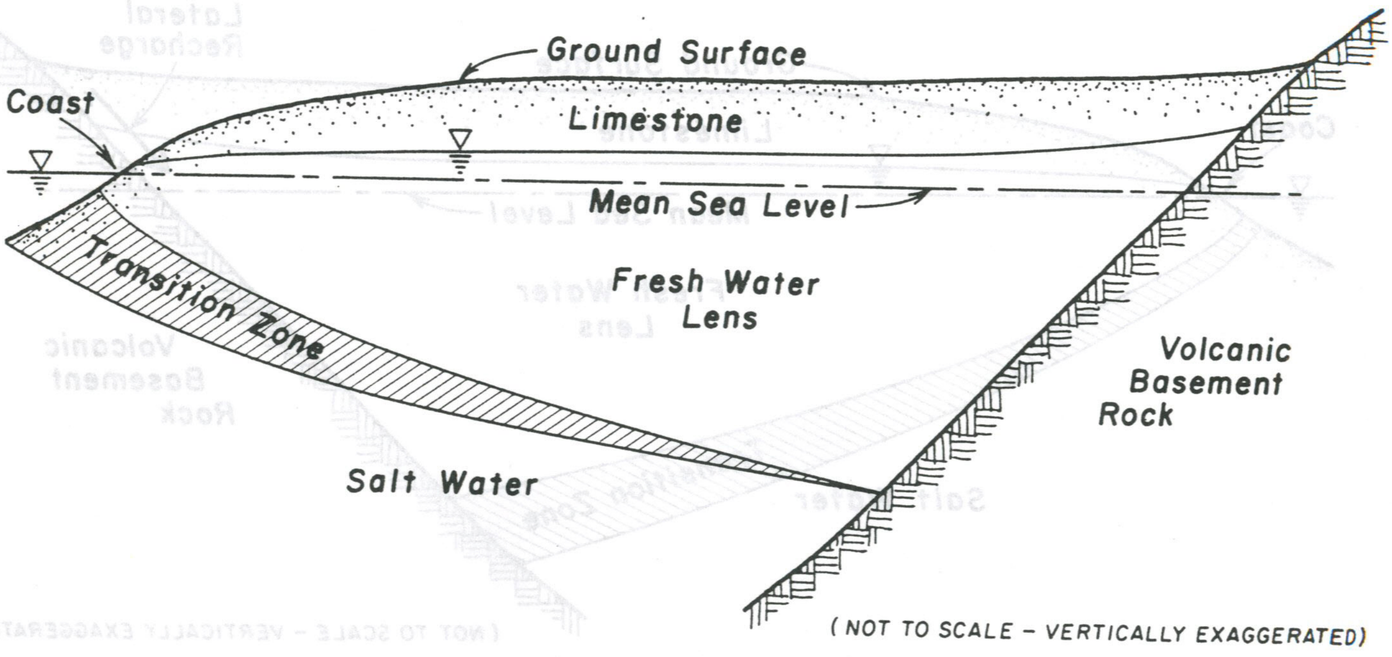


FIGURE D–3

EFFECT OF TIDAL INFLUENCES
ON THE TRANSITION ZONE

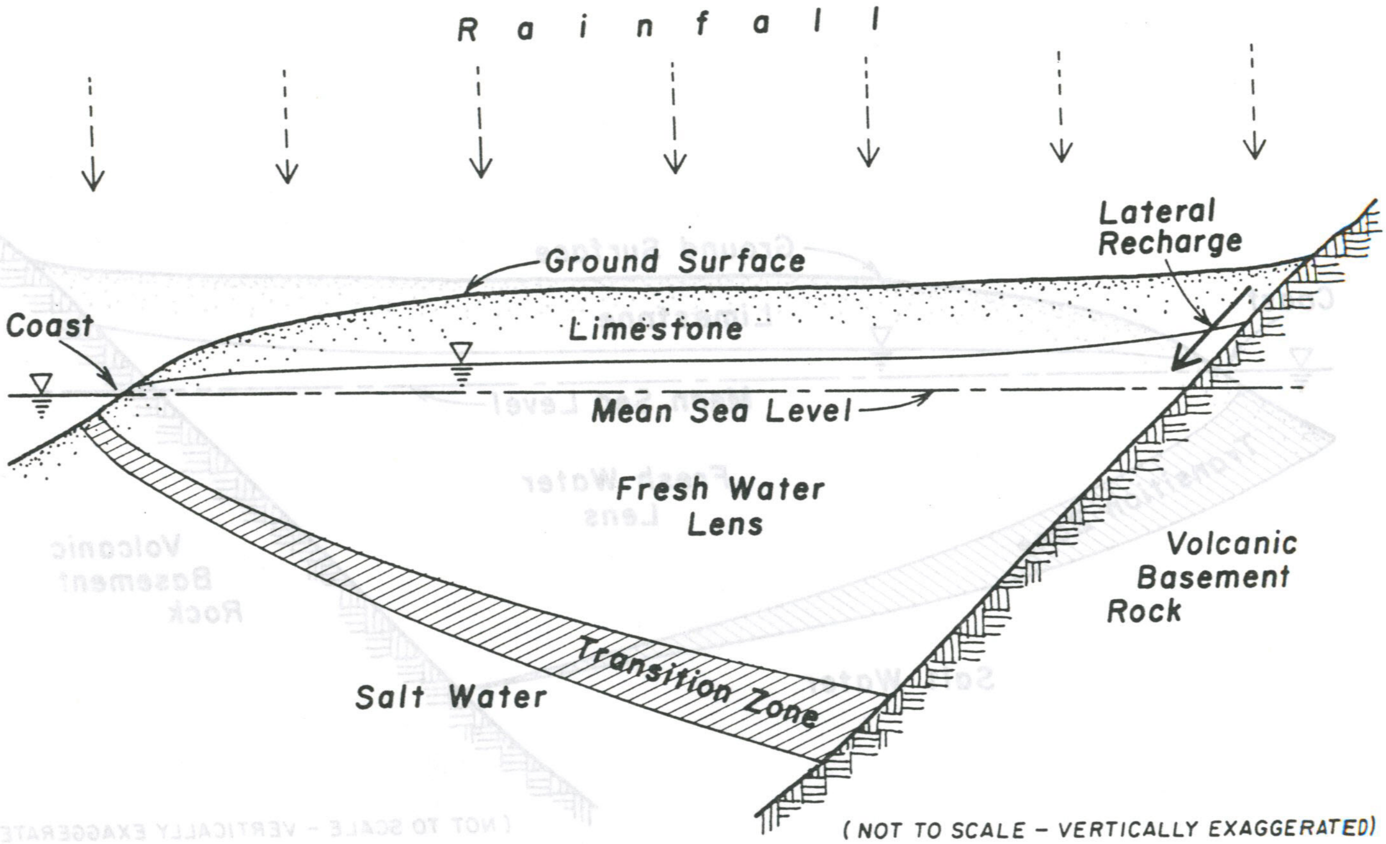


FIGURE D-4

EFFECT OF HIGH RECHARGE INFLUENCES ON THE TRANSITION ZONE

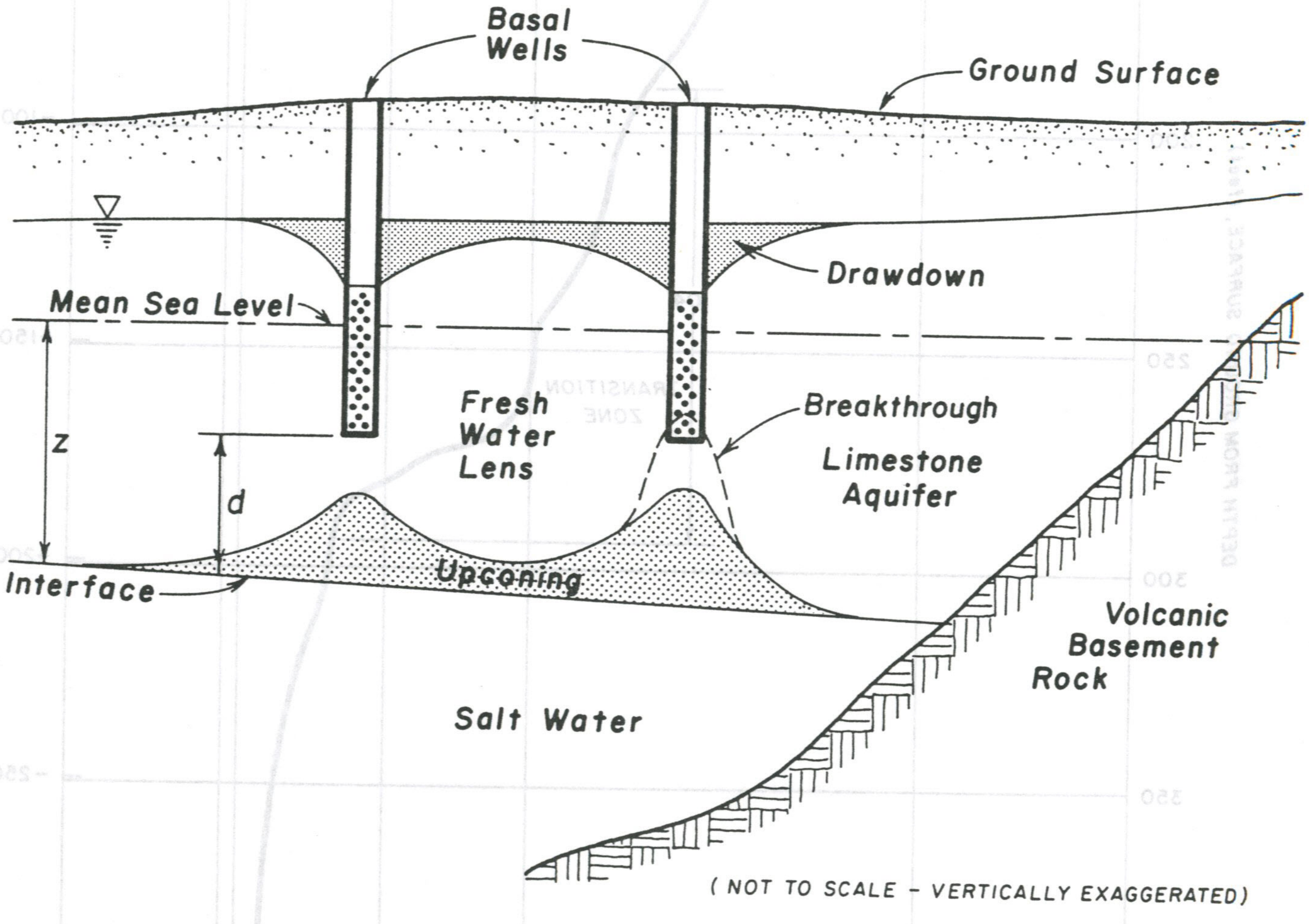
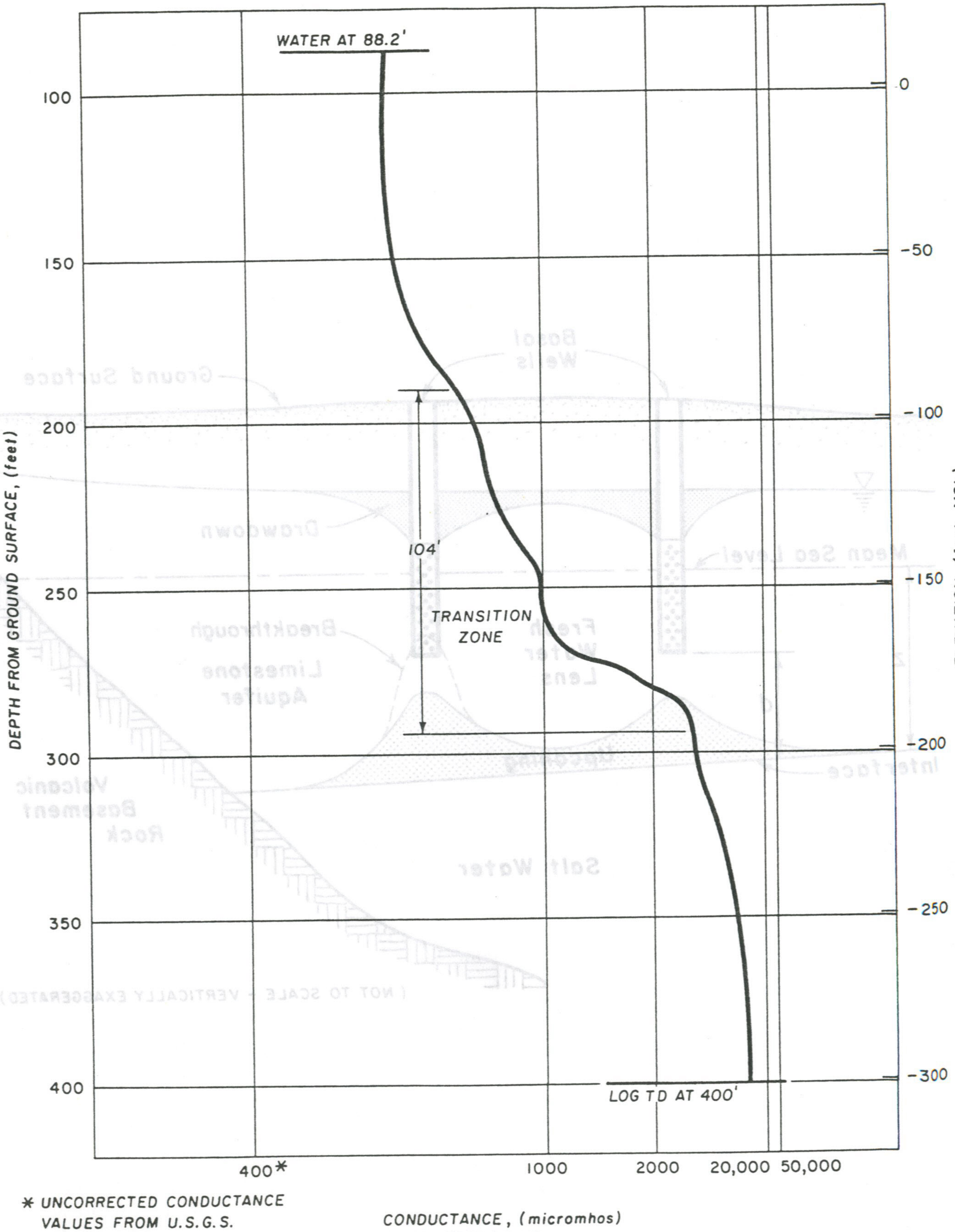


FIGURE D-5

DIAGRAM OF PUMPING INFLUENCES ON THE TRANSITION ZONE



* UNCORRECTED CONDUCTANCE VALUES FROM U.S.G.S. LOGGER SCALE.

FIGURE D-6
CONDUCTIVITY LOG - WELL EX-1
FEBRUARY 24, 1982

conductance) through the transition zone that results from the influences described above. The transition in conductance from fresh water to salt water roughly follows a normal distribution curve with the mean value representing 50 percent sea water salinity. This point is significant because it corresponds to the lower boundary of the ideal Ghyben-Herzberg lens (i.e. where the 40:1 ratio applies).

SALT WATER UPCONING

Salt water upconing occurs when pumping-induced drawdown within the aquifer causes a corresponding rise in the fresh water-salt water interface. Under steady-state conditions, this rise would be an amount equal to about 40 times h. For example, a drawdown of 1.5 feet would cause the theoretical, steady-state interface to eventually rise upward by 60 feet. This phenomenon is schematically illustrated on Figure D-4. Because the drawdown decreases with distance from the well, the corresponding upconing of the interface also decreases.

As pumping increases, upconing also increases. At a critical pumping rate, upconing accelerates, which results in a sudden rise in salinity measured in the well. The sudden increase in upconing as the critical pumping rate is exceeded is called breakthrough (as shown on Figure D-5). The increase in salinity can render the well useless unless the pumping rate is reduced in order to reduce upconing. To help prevent breakthrough, the distance between the bottom of the well and the position of the transition zone prior to pumping should be minimized. As a general design "rule of thumb", Schmorak and Mercado (1969) recommend that:

$$Z_c/d \leq 0.5 \qquad \text{(D-4)}$$

where: Z_c = magnitude of upconing at the critical pumping rate (dimensional units of L)

d = vertical distance from the bottom of the well to the interface, prior to initiation of pumping (dimensional units of L)

The magnitude of drawdown and upconing (prior to breakthrough) in an aquifer surrounding a pumping well is dependent on both the design and pumping characteristics of the well and the hydraulic parameters of the surrounding aquifer. Bear and Dagan (1964) developed several equations describing upconing Z(r,t) under various conditions. The following equations were adapted from Bear's work for the evaluation of upconing in the Northern Lens. For the transient state in an anisotropic, but otherwise Theisian aquifer, upconing of a sharp interface at a distance r from the pumping well is calculated as follows:

$$Z\,(r,t) = \frac{Q}{2\pi\,(\rho_s - 1)\,K_x d}\left[\frac{1}{(1 + R^2)^{1/2}} - \frac{1}{((1 + \tau)^2 + R^2)^{1/2}}\right] \quad \text{(D-5)}$$

where: $R = \frac{r}{d}\left(\frac{K_z}{K_x}\right)^{1/2}$

$$\tau = \frac{(\rho_s - 1)K_z t}{2nd}$$

and where:

$Z_{(r,t)}$ = upconing at distance r from the pumping well at time t since pumping started (dimensional units of L)

Q = discharge from the pumping well (dimensional units of L^3/T)

ρs = specific density of salt water (gm/cc)

K_x = horizontal permeability of the aquifer (dimensional units of L/T)

K_z = vertical permeability of the aquifer (dimensional units of L/T)

d = vertical distance from the bottom of the well to the interface (middle of the transition zone) at time t = 0 (dimensional units of L)

n = porosity of the aquifer (percent)

r = horizontal distance from the well to an observation point (dimensional units of L)

t = time since pumping started (dimensional units of T)

The magnitude of upconing, as defined by equation (D-5) is computed for the theoretical interface, or for the 50 percent relative salinity level of the transition zone. However, the chloride concentration of the water at this point is on the order of 10,000 mg/1. The recommended maximum chloride concentration for drinking water is 250 mg/1, which is significantly lower than at the interface (50 percent level). Therefore, knowledge of the upconing of the 250 mg/1 isochlor would be more helpful than the location of the interface.

Schmorak and Mercado (1969) provide the basis for determining the magnitude of upconing of the 250 mg/1 isochlor. The relative salinity within the transition zone can be estimated by:

$$\varepsilon = \frac{C - C_b}{C_s - C_b} \qquad \text{(D-6)}$$

where: ε = relative salinity

C = chloride ion concentration of interest

C_b = background chloride ion concentration of the fresh water lens

C_s = the chloride ion concentration of sea water

For example, with a background chloride concentration of 20 mg/1 and a chloride concentration of salt water of 19,500 mg/1, the relative salinity of the 250 mg/1 isochlor is:

$$\varepsilon = \frac{250 - 20}{19{,}500 - 20} = 0.0118 \text{ or } 1.18\% \qquad \text{(D-7)}$$

Assuming the chloride concentration within the transition zone has a normal distribution, the thickness of the transition zone (f) from the 50 percent relative sea water salinity level to the 1.18 percent relative salinity level is:

$$f = \theta * \sigma = 2.26\ \sigma \qquad \text{(D-8)}$$

where: σ = standard deviation of the curve that represents the transition zone salinity distribution

θ = number of standard deviations between the 50 percent and the relative salinity indicated by ε in equation (D-6); for the example given in equation D-7, θ = 2.26

The standard deviation (σ) can be estimated by plotting elevation against relative salinity within the transition zone on probability paper (see Figure D-7). From this straight line plot, the standard deviation is the change in elevation between the 50 percent and either the 84 or 16 percent relative salinity. For Well No. EX-10, as illustrated on Figure D-7, the standard deviation is about 6.5 feet. However, this standard deviation value is for static conditions and must be corrected for the effects of pumping in the following manner:

$$\sigma_\alpha = (\sigma_o^2 + (D * Z))^{1/2} \qquad \text{(D-9)}$$

where: σ_α = corrected standard deviation during pumping

σo = static condition standard deviation

D = dispersivity

$Z_{(r,t)}$ = upconing of the 50 percent salinity level calculated in equation (D-5)

Now, combining equations (D-8) and (D-9), the thickness (f) of the transition zone from the 50 relative salinity isochlor to any particular isochlor can be calculated (as long as the critical discharge is not causing breakthrough) as:

$$f = \theta \cdot \sigma_\alpha = \theta\ (\sigma^2 + (D * Z_{(r,t)}))^{1/2} \qquad \text{(D-10)}$$

For a well field, interference of upconing impacts, like drawdown, is determined by superposition. Thus, the total interface at a particular point is the sum of the individual upconing effect (calculated from equation (D-5) for each well at that point, or:

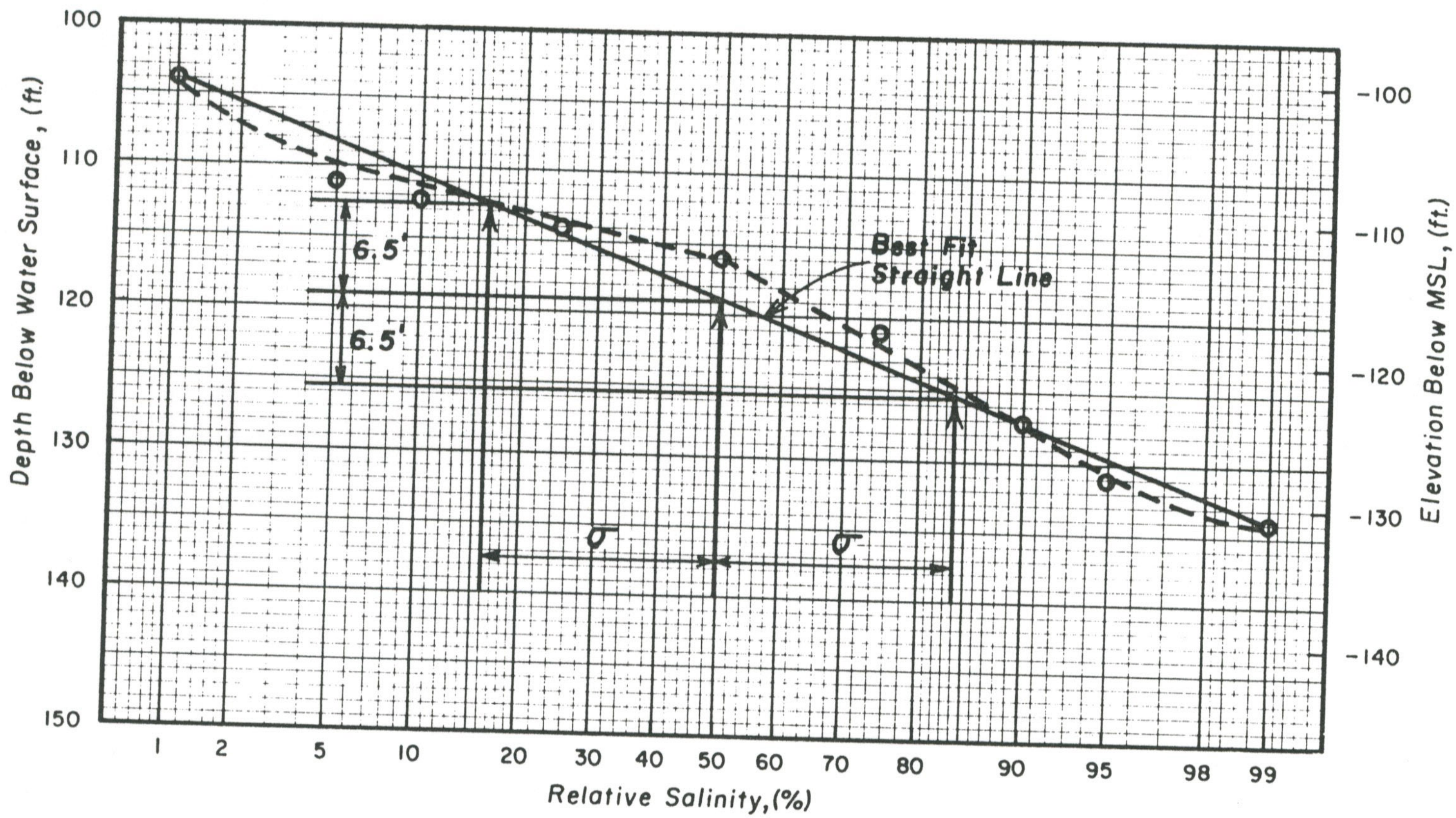


FIGURE D-7

RELATIVE SALINITY VS.
TRANSITION ZONE THICKNESS IN EX-10

$$\sum_{i=1}^{n} Z_i = Z_1 + Z_2 + Z_3 + \cdots + Z_n \qquad \text{(D-11)}$$

The total upconing (ft) for any particular isochlor caused by the pumping in a well field is:

$$f_T = \theta(\sigma^2 + (D * \sum_{i=1}^{n} Z_i))^{1/2} \qquad \text{(D-12)}$$

The upconing, as calculated using equation (D-12), will provide a very close estimate of the geometry (or change in geometry) of the fresh water lens in a well field or at an individual well. However, if breakthrough occurs in any of the wells in a well field, this analytical method becomes invalid.

SALT WATER INTRUSION

Salt water intrusion, like upconing, is a form of invasion of salt water into the fresh water lens. However, unlike upconing, which is characterized by the vertical (and usually local) movement of the interface (or transition zone), intrusion is typified by the horizontal (and regionally vertical) migration of the interface (Figure D-8). Upconing is generally the result of well or well field pumping. Intrusion, at least in northern Guam, is probably more influenced by regional and seasonal fluctuations in recharge.

The parabasal areas are most affected by horizontal intrusion. Wells located in the parabasal zone near the salt water toe can be contaminated by salt water due to the combined affect of pumping and seasonal fluctuations in recharge.

The regional position and seasonal migration of the salt water toe can be estimated using equation (C-21) in Appendix C. The relative migration of the toe can be estimated by varying the seasonal recharge rate. This estimate will indicate the potential impact that the migrating salt water toe will have on a nearby parabasal well.

Equation (C-21) was used with varying recharge rates in the Finegayan Sub-basin. The limestone aquifer in this area has relatively high permeabilities (on the order of 3,000 ft/day). The results of this analysis indicate that in order to insure that production wells remain outside the influence of the fluctuating transition zone and nearby wells, parabasal wells should (conservatively) be located at least 1,000 feet from the average toe position. In the case of a well field, where significant quantities (30 percent or more) of recharge are being intercepted, or are anticipated in future well field expansions, the wells should be located correspondingly greater than 1,000 feet away from the toe, but not more inland than the zero elevation contour of the limestone/volcanic contact. The results of this evaluation using equation (C-21) is in general agreement with the results of the regional modeling effort by WERI presented in Appendix G.

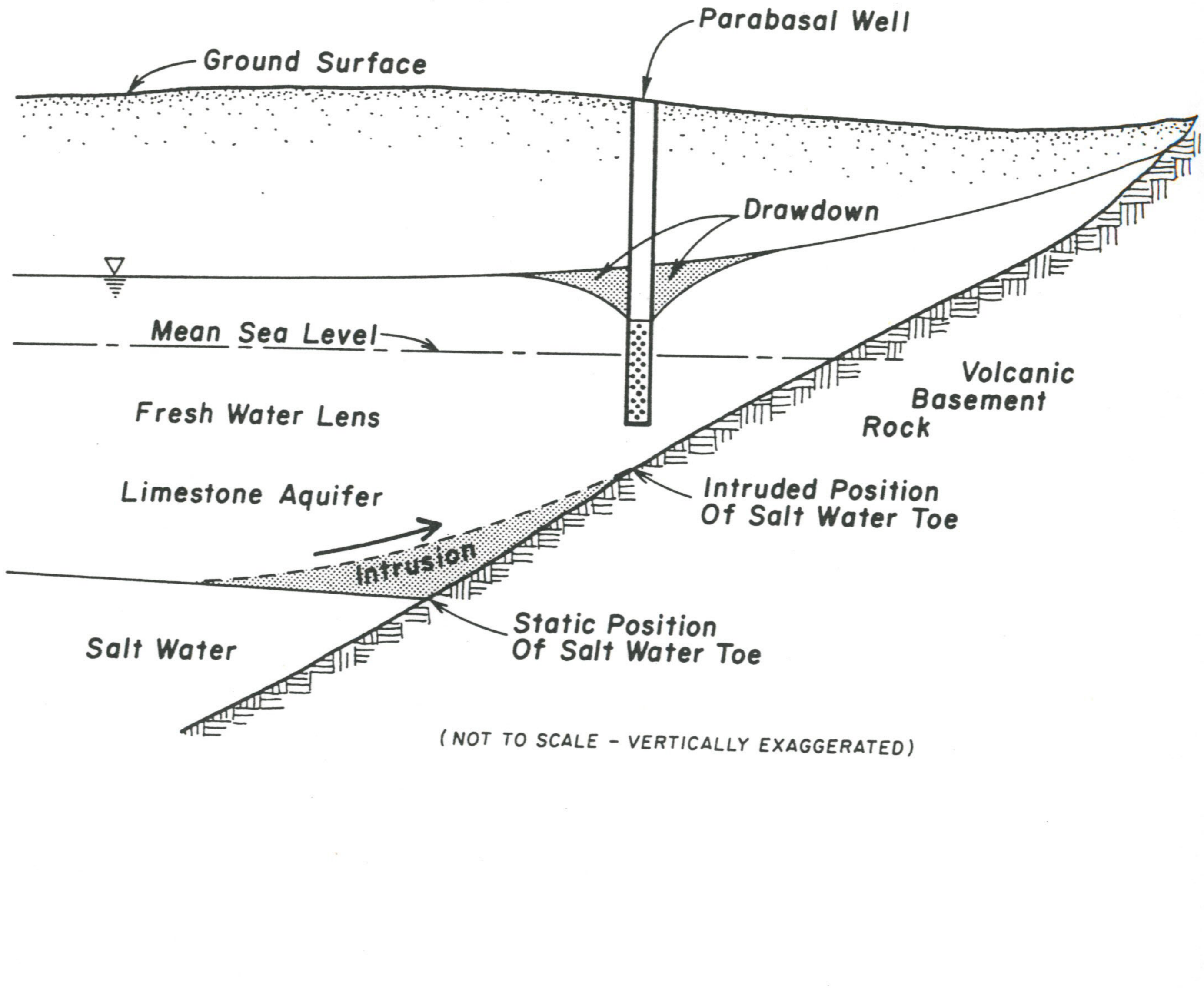


FIGURE D-8

DIAGRAM OF SALT WATER INTRUSION TOWARD PARABASAL WELL

APPENDIX E

DETERMINATION OF EVAPOTRANSPIRATION

GENERAL

This appendix contains a discussion of the various methods used to estimate the magnitude and areal distribution of potential evapotranspiration (hereafter referred to as just evapotranspiration) in northern Guam. Evapotranspiration is probably the most important factor in determining the recharge to the Northern Lens. But, because evapotranspiration has not been directly measured for any vegetation type in Guam, it must be estimated using other measured data, such as temperature, pan evaporation, and precipitation.

The major assumption made in evaluating the different methods of estimating evapotranspiration rates in northern Guam is that for tropical vegetation, it is roughly equivalent to pan evaporation. This assumption may be an over-simplification because of the wide distribution of vegetation types and cultural influences in northern Guam. However, the assumption is probably valid because in a tropical environment such as Guam, where free moisture is continually available to plants, evapotranspiration during the most intensive period of growth (the wet season) is approximately equal to pan evaporation (Mink, 1976). Research by Chang, et al (1963) supports this assumption by showing that in Hawaii, pan evaporation is approximately equal to evapotranspiration during the maximum growth period of sugar cane. But, there are significant differences in both climatic and soil conditions between Guam and Hawaii. For this reason, more research should be conducted in Guam to measure the evapotranspiration rates and areal distribution of native vegetation. Until that research is conducted, the assumptions based on Chang's work will provide a close and conservative approximation of evapotranspiration.

The remaining part of this appendix contains an evaluation of several methods of calculating evapotranspiration. The first method discussed uses precipitation data to determine the areal variation in evapotranspiration. This method was used by Mink (1976) to estimate recharge. The second method uses temperature data and common emperical equations to estimate evapotranspiration.

EVAPOTRANSPIRATION FROM PRECIPITATION DATA

Mink (1976) suggested that pan evaporation (and thus evapotranspiration) is inversely proportional to rainfall. Using rainfall records (1956 to 1972) and evaporation data (1958 to 1973) from the National Weather Service (NWS) meteorological station at Finegayan, pan evaporation values were computed from rainfall data collected at Andersen Air Force Base (1952 to 1972) and the Guam Naval Air Station (1956 to 1972). The relationship used to compute pan evaporation is:

$$E_i = \frac{R}{R_i} E \qquad \text{(E-1)}$$

where: E_i = computed pan evaporation

R_i = measured rainfall at the station in which E_i is to be computed

E = measured pan evaporation at the NWS station in Finegayan

R = measured rainfall at the NWS station in Finegayan

Table E-1 summarizes the average monthly pan evaporation as measured at the NWS and as calculated by Mink at Andersen Air Force Base and the Naval Air Station. The measured average annual pan evaporation was 72.41 inches per year at the NWS, and the calculated average annual pan evaporation was 81.23 inches per year at Andersen Air Force Base and 85.04 inches per year at the Naval Air Station.

TABLE E-1

DETERMINATION OF EVAPORATION RATES FROM RAINFALL*
(inches)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Nat'l Weather Service (Finegayan)†													
Precipitation	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
Measured 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
† Rainfall record 1956-1972; evaporation record 1958-1973.													
Andersen Air Force Base**													
Precipitation	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
Calculated 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
** Rainfall record 1952-1972.													
Guam Naval Air Station††													
Precipitation	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
Calculated 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
†† Rainfall record 1956-1972.													

* From Mink (1976), Table 2.

EVAPOTRANSPIRATION DATA FROM TEMPERATURE DATA

The more common approaches for determining evapotranspiration use monthly mean temperatures as their principal variable. The Blaney-Criddle (1950), Thornthwaite (1944), and Hargreaves (1956) methods were used to evaluate the range in ET derived by using temperature data. The results of all three methods are presented in the following paragraphs.

Hargreaves Method

The Hargreaves method uses both temperature and humidity data for determining evapotranspiration. The equation is:

$$ET = kD\,(0.38 - 0.0038H)\,(t-32) \qquad \text{(E-2)}$$

where: ET = evapotranspiration rate in inches

k = monthly consumptive use coefficient (assumed to be equal to one)

D = monthly daytime coefficient dependent on latitude

H = mean monthly relative humidity at noon in percent

t = mean monthly temperature in degrees F

The only station having both temperature and humidity data was the National Weather Service in Finegayan.

The consumptive use coefficient (k) is assumed to be equal to 1.0 based on research published by Doorenbos and Pruitt (1975). They indicate that evapotranspiration for tropical food crops, such as bananas, coffee, and sugar cane, range from .8 to 1.2 and average about 1.0. In all subsequent methods of calculating evapotranspiration, this coefficient is assumed to be equal to 1.0. The calculated monthly evapotranspiration rates at the NWS station are summarized in Table E-2. The calculated average annual evapotranspiration rate is 40.74 inches, as compared to the average annual evaporation rate of 82.23 inches at this location. To adjust the calculated evapotranspiration rate to equal the evaporation rate, the k-value

TABLE E-2

CALCULATION OF EVAPOTRANSPORATION RATES
BY THE HARGREAVES METHOD AT
THE NWS IN FINEGAYAN

Month	Temp (°F)	D[1]	H[2] (%)	ET[3] (inches)	Pan Evaporation[4] (inches)
Jan	77.4	0.98	79.0	3.55	6.65
Feb	77.4	0.89	77.9	3.39	6.49
Mar	77.7	1.02	77.8	3.93	8.05
Apr	79.0	1.01	77.8	4.00	8.32
May	79.3	1.05	78.6	4.04	8.43
Jun	79.9	1.03	80.0	3.75	7.46
Jul	79.3	1.06	82.8	3.28	6.47
Aug	79.2	1.05	84.6	2.90	5.91
Sept	79.2	0.99	83.6	2.91	5.70
Oct	79.0	1.00	83.4	2.96	6.17
Nov	79.2	0.95	83.8	2.76	6.24
Dec	78.4	0.97	80.9	3.27	6.34
Total				40.74	82.23

1 D = monthly daytime coefficient dependent on latitude (for latitude 13.5° N), from Chow (1964), Table 11-9.
2 H = the mean monthly relative humidity at noon, in percent.
3 ET = Evapotranspiration
4 For the period 1974 to 1981, measured at the NWS in Finegayan.

would have to be over 1.8, which seems unreasonably high when compared to k-values derived in research which are on the order of 0.5 to 1.2 (Chow, 1964, Table 11-3).

Thornthwaite Method

The Thornthwaite method uses only temperature to calculate evapotranspiration. However, it may be limited in its use for the tropics because it was developed for the temperate zone of the eastern United States. The equation is:

$$ET = 0.63 \left[\frac{10t}{TE}\right]^{a} \qquad (E\text{-}3)$$

where: $TE = \sum_{i=1}^{m} \left(\frac{t_i}{5}\right)^{1.514}$

$$a = 6.75 \times 10^{-7} (TE)^3 - 7.71 \times 10^{-5} (TE)^2 + 1.792 \times 10^{-2} (TE) + 0.49239$$

and where:

ET = evapotranspiration in inches

t_i = mean monthly temperature in degrees C

TE = temperature efficiency index

m = particular month for the given temperature data

Table E-3 shows the calculated evapotranspiration for the NWS, Andersen Air Force Base, and the Naval Air Station. The calculated average annual evapotranspiration value at the NWS is 59.08 inches as compared to the pan evaporation of 82.23 inches. As with the results of the Hargreaves method, these evapotranspiration values seem to be relatively low for tropical vegetation.

TABLE E-3

CALCULATION OF EVAPOTRANSPIRATION RATES BY THE THORNTHWAITE METHOD

	Naval Air Station		Andersen Air Force Base		National Weather Service Station, Finegayan		
MONTH	Temp. (°C)	ET* (in)	Temp. (°C)	ET* (in)	Temp (°C)	ET* (in)	Pan** Evap. (in)
JAN	26.3	5.04	25.7	4.69	25.2	4.42	6.65
FEB	26.3	5.04	25.7	4.69	25.2	4.42	6.49
MAR	26.7	5.35	25.8	4.75	25.4	4.55	8.05
APR	27.1	5.67	26.4	5.18	26.1	5.01	8.32
MAY	27.4	5.92	26.8	5.47	26.3	5.14	8.43
JUN	27.7	6.18	27.1	5.70	26.6	5.35	7.46
JUL	27.4	5.92	26.9	5.55	26.3	5.14	6.47
AUG	27.3	5.83	26.7	5.40	26.2	5.07	5.91
SEPT	27.2	5.75	26.6	5.32	26.2	5.07	5.70
OCT	27.1	5.67	26.7	5.40	26.1	5.01	6.17
NOV	27.2	5.75	26.8	5.47	26.2	5.07	6.24
DEC	26.8	5.43	26.3	5.10	25.8	4.81	6.34
TOTAL		67.54		62.72		59.08	82.23

* Evapotranspiration

** Pan evaporation for the period 1974 to 1981, measured at the NWS in Finegayan.

Blaney-Criddle Method

The most universally recognized method for determining evapotranspiration was developed by Blaney and Criddle (1950). Their equation is:

$$ET = \frac{kpt}{100} \qquad \text{(E-4)}$$

where: ET = evapotranspiration rate in inches per month

k = monthly consumptive use coefficient (assumed to be equal to 1)

p = percent daytime hours

t = the mean monthly temperature in degrees F

The monthly p values for latitude 13.5 degrees north are included on Table E-4. The resultant calculated average annual evapotranspiration rates for the NWS, Andersen Air Force Base and the Naval Air Station (where temperature data were available), as indicated on Table E-4, are 78.78 inches, 79.65 inches, and 80.72 inches, respectively. The calculated evapotranspiration at the NWS of 78.78 inches is relatively close to the measured pan evaporation at that station of 82.23 inches.

SELECTION OF BEST EVAPOTRANSPIRATION ESTIMATE

Using actual evapotranspiration data provides a much better estimate of recharge than calculated evaportranspiration rates. However, until actual evapotranspiration rates are measured in northern Guam, calculated rates will provide an estimate of recharge as well as illustrate the procedure for using actual evaportranspiration rates to refine recharge estimates. The best method of calculating recharge was selected based on two criteria: 1) that the method provide a conservative estimate of recharge and, subsequently, sustainable yield, until which time actual evapotranspiration rates can be used, and 2) that the method provides results which are closest to pan evapotranspiration data, which is an assumption supported by research (Chang et al, 1963).

TABLE E-4

CALCULATION OF EVAPOTRANSPIRATION RATES BY THE BLANEY-CRIDDLE METHOD

Month	U.S. Weather Bureau, Finegayan (NOAA-NWS)			Andersen Air Force Base			Naval Air Station			
	Temp. (^{o}F)	p[1]	ET[2]	Temp. (^{o}F)	p[1]	ET[2]	Temp.	p	ET	Pan[3] Evap.
Jan	77.4	8.00	6.19	78.2	8.00	6.26	79.4	8.00	6.35	6.65
Feb	77.4	7.39	5.72	78.2	7.39	5.78	79.4	7.39	5.87	6.49
Mar	77.7	8.44	6.56	78.5	8.44	6.63	80.0	8.44	6.75	8.05
Apr	79.0	8.42	6.65	79.5	8.42	6.69	80.8	8.42	6.80	8.32
May	79.3	8.93	7.08	80.3	8.93	7.17	81.3	8.93	7.26	8.43
Jun	79.9	8.74	6.98	80.8	8.74	7.06	81.8	8.74	7.15	7.46
Jul	79.3	8.99	7.13	80.4	8.99	7.23	81.4	8.99	7.32	6.47
Aug	79.2	8.79	6.96	80.1	8.79	7.04	81.2	8.79	7.14	5.91
Sept	79.2	8.27	6.55	79.8	8.27	6.60	81.0	8.27	6.70	5.70
Oct	79.0	8.28	6.54	80.0	8.28	6.62	80.8	8.28	6.69	6.17
Nov	79.2	7.80	6.18	80.3	7.80	6.26	81.0	7.80	6.32	6.24
Dec	78.4	7.95	6.23	79.3	7.95	6.30	80.2	7.95	6.38	6.34
TOTALS			78.78			79.65			80.72	82.23

1 p = Percent of daytime hours each month at latitude 13°30' from V.T. Chow, Handbook of Applied Hydrology, 1964, Table 11-4.

2 Evapotranspiration in inches/month.

3 Evaporation data (in inches/month) from the NOAA weather station (class A pan) located at the National Weather Service Station in Finegayan.

Because the Blaney-Criddle method provides evapotranspiration values that are both the most conservative and are closest to the pan evaporation data measured at the NWS in Finegayan, it was used to estimate evapotranspiration rates in northern Guam. These evapotranspiration data were then used to estimate the recharge to the Northern Lens.

APPENDIX F

CALCULATION OF RECHARGE

GENERAL

This appendix discusses two methods used to estimate recharge to the limestone aquifer of northern Guam. Several attempts have been made over the years to determine average annual recharge to the Northern Lens. These attempts have resulted in recharge estimates that range from 21 to 53 inches per year. Peterman, et al (1945) made the first estimates and reported recharge to be about 21 inches per year. Davis (1964), using seasonal variations in precipitation, estimated recharge to be about 40 inches per year. Davis and Huxel (1968) estimated recharge to the Northern Lens to be about 53 inches per year based on rainfall-runoff records for the Pago and Ylig Rivers in southern Guam. Mink (1976) (using rainfall and evaporation data) estimated a recharge range from 26 to 38 inches per year, depending on the amount of surface runoff that is assumed. Ayers (1981) estimated recharge to the Northern Lens to be about 33 inches per year by comparing the chloride ion concentration of rain water to that found in the freshest groundwater in the Northern Lens.

Because no new data were generated for the NGLS that would help in refining the results of previous recharge studies, existing data were reevaluated using two methods similar to those applied before. The first method utilized runoff data in the Pago River Basin of southern Guam to estimate recharge while the second method used evapotranspiration estimates and rainfall data to estimate recharge to the Northern Lens.

RAINFALL-RUNOFF IN THE PAGO RIVER BASIN

The Pago River drains a small basin located along the southeast boundary of the Northern Lens in the volcanic upland province of southern Guam (Plate 1) and eventually flows into Pago Bay. The USGS maintains a stream gaging station for the Pago River near Ordot located at the contact between the volcanics and the coastal limestones. This station measures the flow from a 5.67 square-mile drainage area and has daily flow records from September 1951 to the present. Because it seemed likely that the Pago River gaging station measures essentially all of the outflow from the basin (given the small capacity for subsurface outflow over the volcanics in this part of the basin), and because the river basin is adjacent to the study area, the Pago River was used in a water balance analysis to estimate recharge.

The first step in the water balance analysis was to estimate rainfall in the Pago River basin. Included in the available precipitation data are weekly rainfall records from the USGS Pago River Station, located near the Pago River stream gage, for the period July 1951 to December 1966 (Table A-2h), and daily rainfall records at the Fleet Weather Station (NAS), located on the Northern Lens north of the Pago River Station, for the period January 1950 to December 1980 (Table A-2d).

Monthly correlations between the Naval Air Station and the Pago River Station for the 1951-1966 period were used to fill in the missing Pago River Station precipitation data and to develop a complete record for the 31-year period 1950-1980. Table A-2h reports the complete, filled-in monthly precipitation record for the Pago River Station. Table F-1 lists the 31-year monthly average precipitation values for both the dry and wet seasons of the year. Table F-1 shows an average dry season precipitation of 26.94 inches and an average wet season precipitation of 63.70 inches. The estimated average annual precipitation is 90.64 inches.

The USGS has recorded streamflow data for the Pago River near Ordot since October 1951. Table F-2 summarizes these data. Average dry season streamflow for the 29-year period is 10.60 cfs and average wet season streamflow is 41.50 cfs. Average annual streamflow is 26.17 cfs. For the 5.67 square mile drainage area above the Ordot stream gage, the average annual runoff is equivalent to 62.7 inches of precipitation.

TABLE F-1

AVERAGE MONTHLY PRECIPITATION ESTIMATES FOR THE USGS PAGO RIVER PRECIPITATION STATION FOR THE PERIOD 1950-1980

Dry Season Month	Average Precipitation (inches)	Wet Season Month	Average Precipitation (inches)
January	4.61	July	9.92
February	3.89	August	13.46
March	3.06	September	13.04
April	3.53	October	12.47
May	5.48	November	8.92
June	6.37	December	5.89
Total	26.94	Total	63.70

TABLE F-2

AVERAGE MONTHLY STREAMFLOWS FOR THE PAGO RIVER NEAR ORDOT FOR THE PERIOD OCTOBER 1951-SEPTEMBER 1980

Dry Season Month	Average Streamflow (cfs)	Wet Season Month	Average Streamflow (cfs)
January	12.63	July	25.98
February	13.51	August	49.81
March	6.59	September	59.66
April	5.49	October	56.80
May	16.56	November	37.84
June	8.87	December	19.38
Average	10.60	Average	41.50

Table F-3 compares the average precipitation and runoff results and presents an estimate of actual evapotranspiration losses in the Pago River Basin above Ordot. This table shows an average annual precipitation of 90.6 inches as compared to an average runoff of 62.7 inches. The corresponding estimate of annual evapotranspiration losses is 27.9 inches. These losses are less than the evapotranspiration estimates for the Northern Lens area, and consequently, higher than the recharge estimates for the Northern Lens.

TABLE F-3

ESTIMATED WATER BALANCE FOR THE PAGO RIVER BASIN ABOVE ORDOT

Month	Average Precipitation (inches)	Average Runoff (inches)	Estimated Evapotranspiration (inches)	Average Runoff* (percent)
Dry Season				
January	4.61	2.57	2.04	55.7
February	3.89	2.50	1.39	64.3
March	3.06	1.34	1.72	43.8
April	3.53	1.08	2.45	30.6
May	5.48	3.37	2.11	61.5
June	6.37	1.75	4.62	27.5
Average	26.94	12.61	14.33	46.8
Wet Season				
July	9.92	5.28	4.64	53.2
August	13.46	10.13	3.33	75.3
September	13.04	11.74	1.30	90.0
October	12.47	11.55	0.92	92.6
November	8.92	7.45	1.47	83.5
December	5.89	3.94	1.94	66.9
Average	63.70	50.09	13.61	78.6
Annual Average	90.64	62.70	27.94	69.2

* Runoff as a percent of precipitation

Possible reasons for the difference in recharge rates between the Northern Lens area and the Pago River Basin are:

1. Runoff in the Pago River Basin is quick due to steep terrain and less dense vegetation and there may not be as much time for infiltration and subsequent evapotranspiration as on the low relief, Northern Plateau of Guam.

2. The volcanics generally support grasses rather than the dense vegetation which occurs on the limestones. The lower density vegetation should evapotranspire less.

3. Soil moisture deficiencies that occur during the dry season are greater in the Pago River Basin, where soils are thick, than on the Northern Plateau, where soils are on the order of 1 to 5 feet thick.

4. The rainfall measured at the Pago River Station may not be representative of the rainfall in the majority of the basin at higher elevation.

Until more data are generated regarding the soil moisture conditions for different areas in northern and southern Guam and the evapotranspiration rates for the major vegetation types, the value of using the water balance of river basins in southern Guam to estimate recharge rates in the north should be used with caution.

RELATIONSHIP IN NORTHERN GUAM

The evaporation and evapotranspiration information developed in Appendix E was used to estimate the magnitude and areal variation of recharge over the Northern Lens. This method of estimating recharge is conservative because evapotranspiration was derived under the assumption that is is approximately equal to pan evaporation. As discussed in Appendix E, this assumption appears valid in Hawaii during the period of most intensive growth.

However, the relatively thin soil cover in northern Guam and seasonal evapotranspiration rates that probably vary more pronouncely than the measured pan evaporation rate at the NWS Station at Finegayan (especially during the dry season) suggest that this basic assumption is conservative. But until more evapotranspiration information is available for northern Guam, estimating a conservative recharge rate is a prudent avenue to take in estimating the sustainable yield and developing a groundwater management plan.

Using the adjusted evaporation rates for the NWS Station, Naval Air Station, and Andersen Air Force Base developed in Appendix E (Table E-4) and the long-term monthly rainfall records provided in Appendix A, an estimate of the average recharge rate over a relatively large portion of northern Guam was derived. Eight raingaging stations were used to develop recharge estimates; they included the Naval Air Station, Yigo Agricultural Station, Mangailao Station, Andersen Air Force Base, the Naval Communications Center, the Pago River Station, Fleet Weather Central Station at Nimitz Hill Station, and the NWS Station at Finegayan. The most complete recent record was from the Naval Air Station and covered the 31 year period from 1950 to 1980.

The other seven stations had shorter periods of record, and they were filled in using monthly linear regression equations based on the longer Naval Air Station (NAS) record. These adjusted precipitation records are presented in Tables A-2a through A-2h.

Each rainfall station was assigned estimated evapotranspiration rates based on the proximity of the precipitation station to the neareat location where evapotranspiration estimates are available (NAS, NWS, and Andersen Air Force Base). Table E-4 contains the estimated monthly evapotranspiration rates. Then, for each of the eight rainfall records, monthly average recharge was calculated for the 31 years of record as follows:

$$\bar{R}_i = \frac{\sum_{j=1}^{n} \alpha (P_{ij} - \bar{E}_i)}{n} \qquad \text{(F-1)}$$

where: $\bar{R}_i$ = estimated average recharge (F-1) in month i (inches)

P_{ij} = precipitation in month i of year j (inches)

$\bar{E}_i$ = estimated average evapotranspiration in month i

α = 0 if $P_{ij} \geq \bar{E}$

= 1 if $P_{ij} < Ei$

i = month

j = year

n = number of years

The results of this analysis are summarized on Table F-5, which shows the average monthly recharge rate for the eight raingaging stations. The lowest recharge rate was at NAS with 28.75 inches per year; the largest rate was at the NWS Station at Finegayan with 37.97 inches per year. The average recharge rate of all eight stations was 32.97 inches per year. Recharge is seasonal, with the most amount occurring between July and December. During the dry season, recharge at the eight stations varied from 12 to 19 percent of the average monthly precipitation, and averaged 15 percent. During the wet season, recharge varied between 40 and 50 percent and averaged 45 percent.

RUNOFF FROM FONTE RIVER

For most of northern Guam, very little rainfall reaches the ocean as surface outflow. However, a notable exception is the Fonte River flow from the Nimitz Hill management zone. The river does not have a stream gage so runoff must be estimated using the stream flow data derived from the Pago River Basin. Assuming the two basins have the same outflow characteristics, then using the rainfall data from the Nimitz Hill rain gaging station, the runoff from the Fonte River Basin can be estimated, as shown on Table F-6.

TABLE F-5

AVERAGE MONTHLY RECHARGE ESTIMATES AT EIGHT RAINGAGE STATIONS IN NORTHERN GUAM (inches)

Station Location	Months												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	(Inches)
Naval Air Station	0.82	0.58	0.14	0.48	1.65	0.50	2.96	5.63	6.94	5.76	2.92	0.37	28.75
Yigo Agricultural Station	0.19	1.08	0.55	1.10	2.52	0.49	3.20	6.61	6.83	8.19	2.90	1.88	35.54
Mangilao	1.11	0.76	0.18	0.54	1.58	0.76	2.20	6.09	8.90	5.32	3.02	0.68	31.14
Andersen Air Force Base	1.04	1.22	0.76	0.93	2.41	0.28	2.91	6.24	6.34	7.04	2.61	0.95	32.73
Naval Communications Station	1.46	0.22	0.40	0.14	2.29	1.00	2.56	7.80	6.19	6.92	2.46	0.50	31.94
Pago River	0.60	0.79	0.11	0.56	1.34	1.06	3.36	6.33	6.37	5.79	2.93	1.02	30.26
Fleet Weather Central - Nimitz Hill	1.00	0.67	0.64	0.87	0.94	0.92	5.21	6.33	7.91	6.76	3.47	0.74	35.46
National Weather Service - Finegayan	1.21	1.12	0.75	0.88	2.54	0.44	3.62	7.14	8.40	7.39	3.41	1.07	37.97
										Northern Guam Average			32.97

TABLE F-6

ESTIMATED RAINFALL RUNOFF FROM FONTE RIVER

Season	Basin Rainfall* (Inches)	Runoff as a Percent of Rainfall**	Fonte River Outflow (Inches)
WET	65.74	78.6	51.67
DRY	27.72	46.8	12.97
TOTAL			64.64

* From Nimitz Hill Rain Gagin Station for base period 1950 to 1980.
** Percentages from runoff characteristics of the Pago River Basin.

The estimated average outflow for Fonte River is 64.4 inches per year. The area within the management zone covered by volcanics is about one square mile. The resulting average runoff to the limestone is about 2,160 gpm. If 50 percent of this outflow recharges the limestones prior to reaching the ocean, then roughly 1,000 gpm (or about 1.44 MGD) would be lost to the ocean.

APPENDIX G

FINITE ELEMENT MODEL OF THE NORTHERN LENS

By: D.N. Contractor

DESCRIPTION OF MODEL

This model description is intended as an introduction to solving salt water intrusion problems using the program SWIGS2D. This program and its mathematical basis have been described by Contractor (1981). A large scale application of the program to a field problem is presented in the report by Contractor, et al (1981). The model simulates an aquifer in two dimensions (plan), in which a sharp interface separates the fresh water and salt water. A finite element grid of linear triangles is used to discretize the aquifer. Appropriate boundary conditions can be specified at the nodes and along the sides of elements. Any number of pumps can be specified in the network. For these conditions, the model solves for the fresh water and salt water heads and calculates the depth of the interface, the location of the fresh water and salt water toes and the velocity in each element.

Program Capabilities

The computer program has the capacity to handle steady and unsteady flows, and analyze both confined and unconfined flows. If the aquifer is confined, the program can consider leaky and non-leaky conditions. Recharge is constant in an element but can be varied from element to element. Specified head or flow conditions can be applied at the boundaries. At a coastal boundary, a mixed or third-type boundary condition can be specified. For steady flow conditions, the salt water head can be specified to be zero along the boundary or at every node in the network. This procedure assures that the Ghyben-Herzberg condition is satisfied. The program can also be run in the unsteady mode with the Ghyben-Herzberg condition.

If the salt water head at every node in the network is specified to be much less than the anticipated fresh water head, the results of the computer program will show that the thickness of the salt water layer is equal to an arbitrarily small value. Under these conditions, the program can simulate flow in a fresh water aquifer. Use of the program to simulate fresh water aquifers is limited only by the storage capacity of the computer.

Because the heads are assumed to vary linearly across the triangular element, the velocity in each element is constant. With specific output instructions, the program will print out the velocities in the x and y directions in each element in both the fresh water and salt water layers. These velocities can then be used to calculate the flow rates across any line or boundary. The program can also determine where in the network a fresh water or salt water toe occurs. A salt water toe occurs where the interface intersects the lower impervious boundary (volcanics in the case of Guam's Northern Lens). The output provides the element number, the node numbers, and the fractional distance between the two nodes where the salt water toe occurs. The same kind of information is also provided about the fresh water toe. A fresh water toe occurs where the phreatic surface intersects the lower impervious boundary or where the interface intersects the upper impervious boundary in confined aquifers.

The program assumes that there are two independent variables at each node: the fresh water head and salt water head. After solving for the heads, the depth of the interface is determined. The location of the interface determines the thickness of the fresh water and the salt water layers. If, however, the interface is calculated to be below the lower impervious boundary, then the entire aquifer thickness will contain only fresh water and the thickness of the salt water layer should theoretically be zero. However, the program makes the salt water layer equal to an arbitrarily small value, BTOE. The permeability in the salt water thickness BTOE is made much smaller than that specified in the region where the salt water thickness is greater than BTOE. Similarly, when the phreatic surface intersects the lower impervious boundary, the fresh water layer beyond the toe is made equal to BTOE instead of zero. In the course of the program, as the interface and the phreatic surface move with respect to time, the thickness and permeability of the salt water and fresh water regions are altered accordingly.

This program uses a weighting factor which varies between zero and one. This factor is useful in regulating the stability and accuracy of the solution. When this factor is equal to zero, the problem formulation is referred to as explicit. In this formulation, the spatial derivatives are evaluated at the known time-step, t. The time-step, delta t, necessary for stable results is very small. This results in very long execution times for the program. When the weighting factor is equal to 0.5, the problem formulation is referred to as the Crank-Nicolson approximation. This approach provides high accuracy with large values of delta t, even though the results may show some numerical instability. When the weighting factor is equal to 1.0, the formulation is known as fully implicit. This formulation provides the maximum stability at a sacrifice of some accuracy. Values of the weighting factor between 0.5 and 1.0 (e.g., 0.6, 2/3, 3/4) have been used to provide the proper balance between accuracy and stability. When steady-state results are desired, the program should be run with the weighting factor equal to 1.0 and delta t equal to a very large number (e.g. 1.0E20).

The program can be run in any set of consistent units. Thus, if feet and seconds are the length and time units, the permeability and recharge must be input in ft/sec and the pump rate in cu.ft/sec. If meters and days are the length and time units, then the permeability and recharge must be input in m/day and the pump rate in cu.m/day.

When subdividing an aquifer into triangular elements, only one side of a triangle may form a boundary. The program cannot handle triangles with boundary conditions on two of its sides. The versatility of using triangles of different sizes and orientation should be taken advantage of. Place a node wherever a pump exists or is projected to be in the future. It is, however, advisable not to let the ratio of the largest triangle to the smallest triangle become too large. It will generally be the size of the smallest triangle that determines the time step, delta t, that can be used for stable results.

APPLICATION OF A SALT WATER INTRUSION MODEL TO MANAGEMENT OF THE NORTHERN GUAM LENS

The finite element salt water intrusion model described by Contractor (1981) was calibrated for the Northern Lens of Guam using hydrologic data for 1978, 1979 and 1980. The finite element network consisted of 222 linear triangular elements and 149 nodes. The porosity was held constant at 0.25 and the permeability was calibrated for the Marianna and Barrigada limestones. The results of the calibration indicated that the Marianna limestone has a permeability in the neighborhood of 1,000 ft/day. The Barrigada limestone was found to be between 5,000 and 10,000 ft/day. For the purpose of the management runs, it was decided to use a permeability of 5,000 ft/day.

The hydrologic conditions for the management scenarios were provided by the NGLS team. The aquifer was subdivided into 29 parabasal management zones and 18 basal management zones. Recharge values were ascribed to each zone, as were the projected pumping rates. The pumping rates were distributed evenly between all the nodes within each management zone. The recharge from each zone was distributed over the months of July, August, September, October and November; the remaining months of the year were assumed to have zero recharge. Three different pumping scenarios were proposed: scenario No. 1 had a pumping rate of about 60 mgd, scenario No. 2 had 80 mgd, and scenario No. 3 had 40 mgd.

Each management scenario had to start with some initial conditions. These initial conditions were taken to be the same as the initial conditions for the calibration runs, which were obtained by a steady state analysis of the first month. Each management scenario was simulated for a year. The results at the end of the year were used as the initial conditions for simulation of a second year of the same management scenario. This process was repeated until cyclic steady-state conditions were obtained.

Results

The following number of computer runs were made:

Scenario No.	Year 1	Year 2	Year 3	Year 4	Year 5
1	X	X	X	X	X
2	X	X	-	-	-
3	X	X	-	-	-

Regrettably, a large number of runs could not be made. Each run for simulating a year required two hours of execution time on the University of Guam computer (IBM 4300 series). After the ouput was obtained, the results at the end of the last month had to be input as the initial conditions for the next run. Since the format of the output was not the same as that required for the input, considerable data manipulation was required before the next run could be made.

The output of all the runs represents a large quantity of numbers distributed over space and time. It would have been desirable to be able to plot this output in 3-D diagrams. However, such facilities were not available. Consequently, one can only present results at a point as a function of time or at a number of nodes at a given time.

Figure G-1 shows the distribution of some of the nodes in the finite element grid. This figure will help in locating the nodes at which results have been plotted. In particular, the aquifer conditions have been plotted along line No. 1 with node numbers 48, 57, 67, 76, 77, 85, 92, 95, 96, 103, 109, and 111, representing a line extending from the western shore into the Yigo trough. Because management scenario No. 1 was repeated for five years, most of the plots will be given for this scenario unless otherwise stated. Figure G-2 shows the contours of the phreatic surface at the end of the dry season (June) of the fifth year of simulation. It can be seen that during this period of no recharge and heavy pumping, there is a phreatic divide roughly along the line of node numbers 90, 82, 83, 76, 68, and 69. To the left of this divide, the water flows westward toward the ocean. To the right of the divide, the water flows eastward toward the wells in the Dededo and Yigo areas. In the Yigo area, the phreatic surface will dip below mean sea level, to provide flow for the wells in that area. The phreatic surface is low over the entire aquifer. Because of these low levels, the volume of fresh water storage in the aquifer is a minimum. However, because of the low gradients, the leakage of fresh water to the ocean is also at a minimum.

During the wet season, when recharge to the aquifer is maximum, the phreatic levels are higher as shown in Figure G-3. In the Yigo area, the phreatic surface may be as high as 12 ft. above mean sea level. Because of the high levels during this time of year, the volume of fresh water storage in the aquifer is a maximum. However, because of the high gradients, the leakage of fresh water to the ocean is also at a maximum. Figures G-2 and G-3 show the aquifer conditions in the fifth year of simulation. Figures G-4 and G-5 show the aquifer conditions along line No. 1 for each of the five years of simulation. In Figure G-4, the phreatic surface in the first year dips only to MSL at nodes 103, 109 and 111. The reason the results are this way is because the program automatically made h_f (the fresh water piezometric head) equal to zero whenever a negative head resulted from the solution of the matrix. When the FORTRAN statement making this change was removed from the program, the heads at these and surrounding nodes dropped to negative values. It can be seen from this figure that the phreatic divide occurs at node 76. It can also be seen that the head varies so little from year to year that the differences cannot be seen on this scale. The interface, on the other hand, changes its elevation measurably from year to year. The change in elevation decreases every year. It is clear that the program needs to continue the simulation for several more years before steady cyclic conditions are reached. Figure G-5 shows the aquifer conditions at the peak of the wet season when recharge is a maximum. The phreatic surface is much higher. However, the interface elevations are not very different from those during the dry season. The difference in elevations of the phreatic surface between the wet and dry seasons represents a significant storage of fresh water, part of which will be lost to the ocean, but part of which will be pumped out during the next dry season.

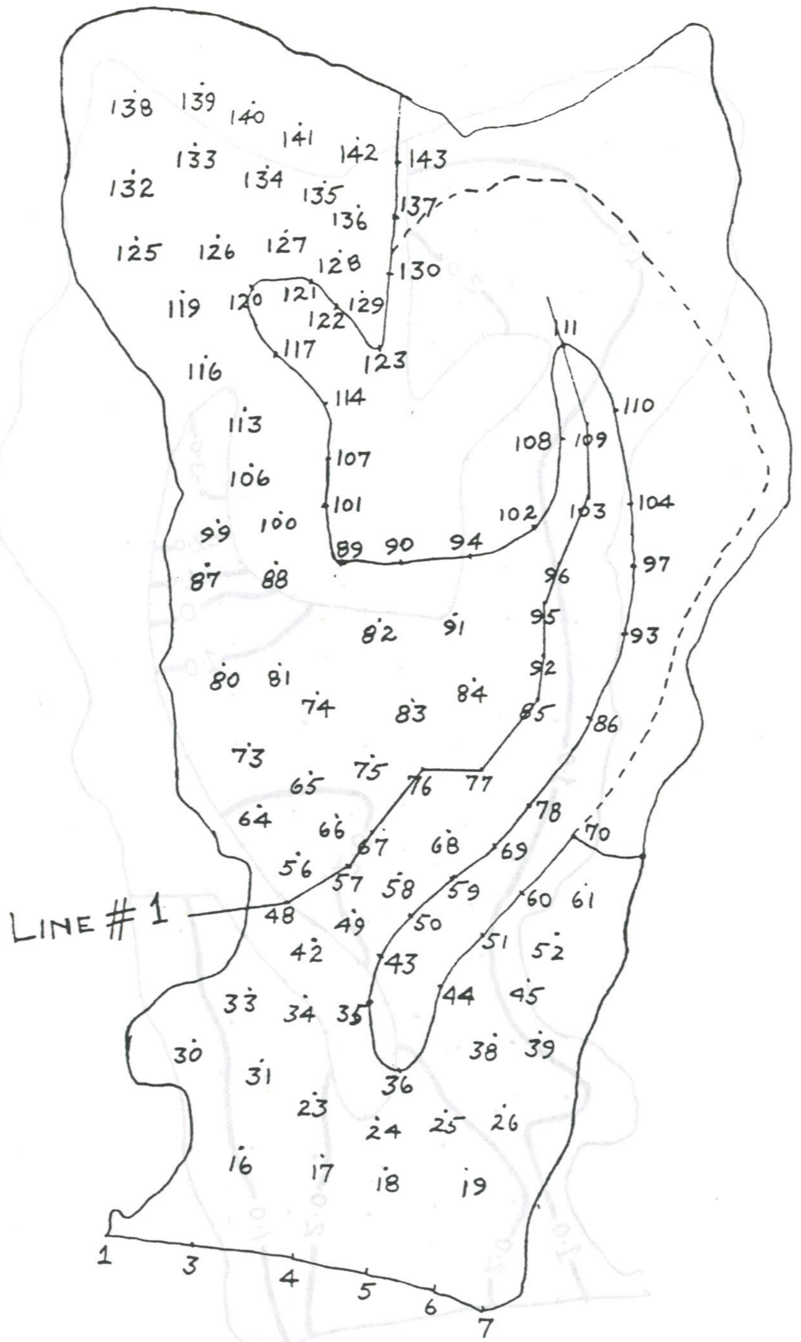


FIGURE G-1

NODE NUMBERS

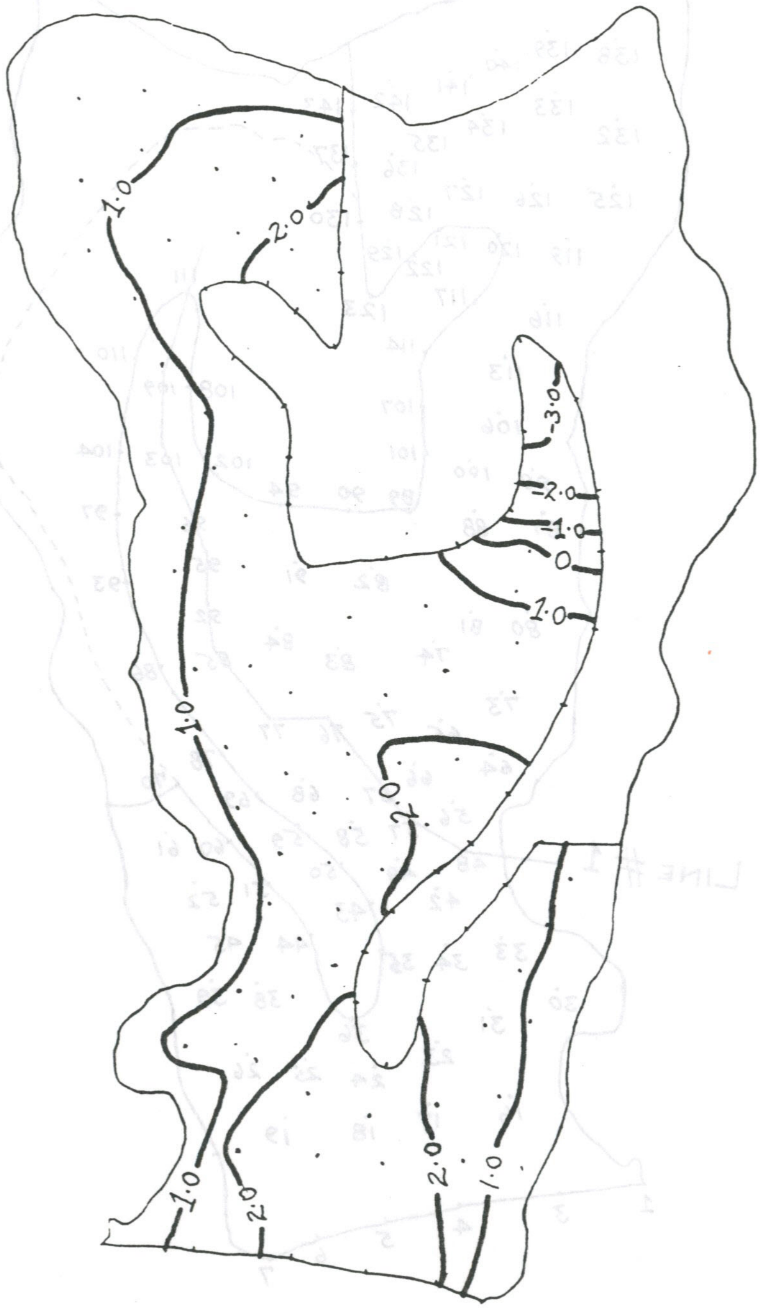


FIGURE G-2

PHREATIC CONTOURS AT END OF DRY SEASON

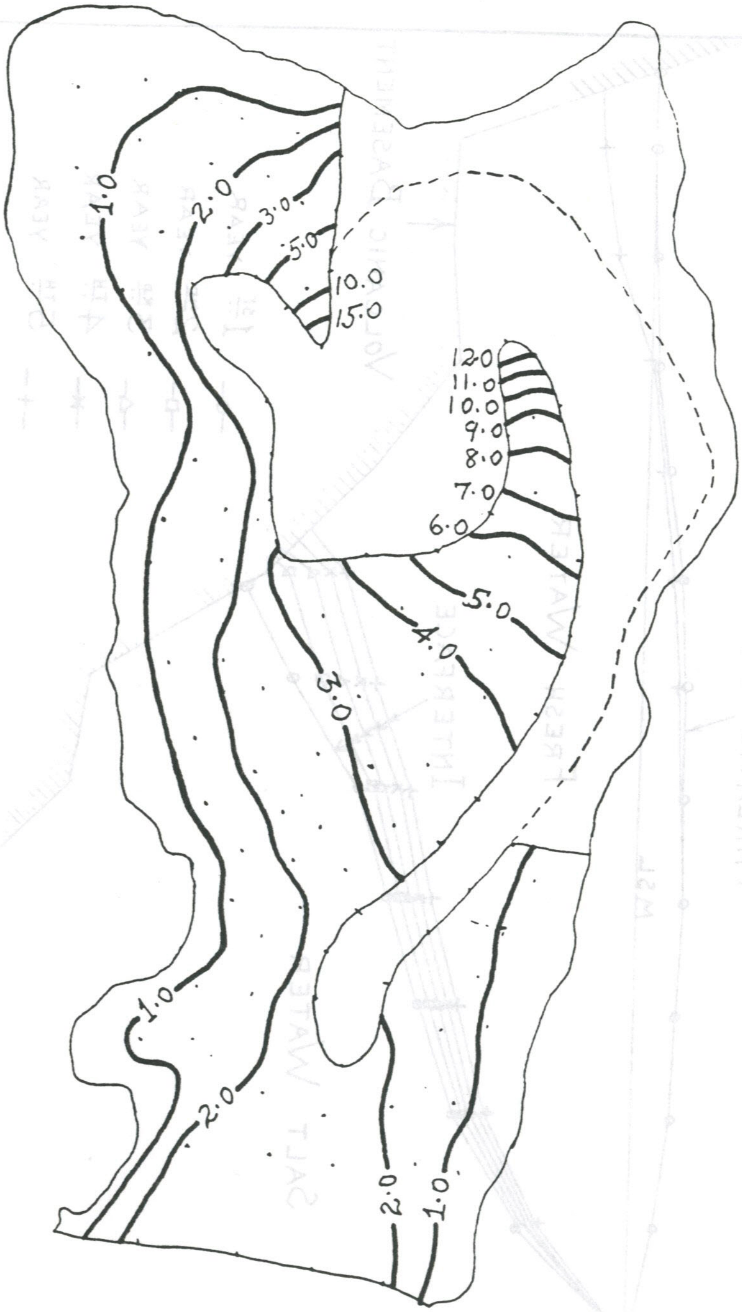


FIGURE G-3

PHREATIC CONTOURS AT END OF WET SEASON

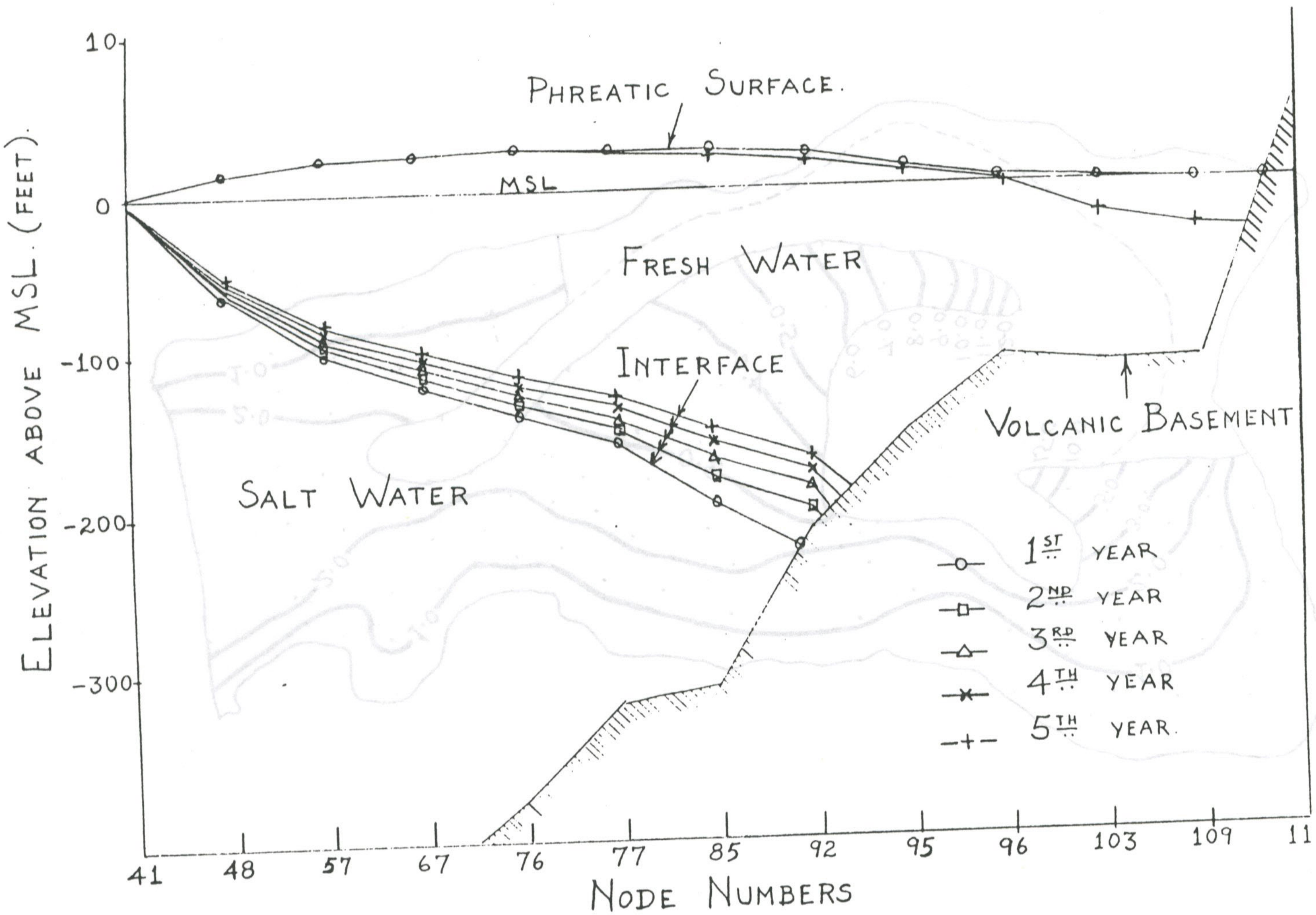


FIGURE G-4

AQUIFER CONDITIONS AT END OF DRY SEASON

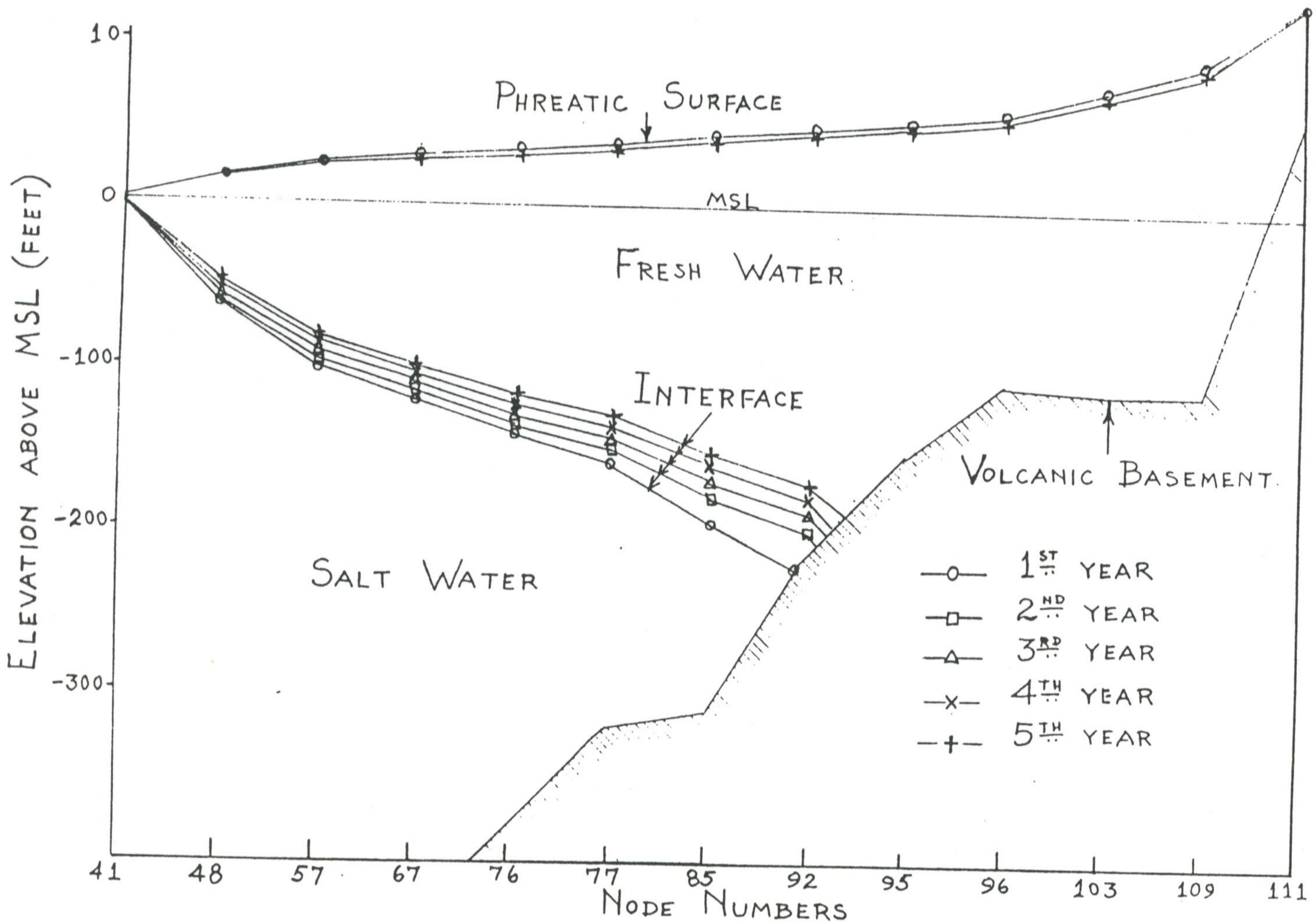


FIGURE G-5

AQUIFER CONDITIONS AT END OF WET SEASON

Figures G-6, G-7 and G-8 are plots of the elevation of the phreatic surface as a function of time at nodes 24, 76 and 95. At all three nodes, the phreatic surface rises sharply during the recharge months and drops gradually during the dry months. Over the five-year period, the head declined 0.5 feet. This decline will stop only when steady cyclic conditions prevail. The increase in elevation during the wet period is larger as one approaches the Yigo trough. Figure G-9 shows the variation of the salt water head at node 76 as a function of time. The salt water head (h_s) rose about 0.25 feet over the five year period from -1.15 feet to -0.9 feet. Because the salt water head is below mean sea level, the results show that the salt water is moving inland, which is expected. During the wet months, the fresh water head rises because of the recharge, tending to slow down the movement of the salt water inland. This can happen only when the salt water head rises during the wet season. When steady cyclic conditions are reached, the salt water head (h_s) variation during a year will be such that during the dry season, h_s will be positive, causing the same volume of salt water to move out to the ocean.

Figure G-10 shows the movement of the interface at node 76 over the period of simulation. The total rise of the interface is 35 feet. Slight variations in the elevation of the interface can be seen during a year. These variations would increase at nodes in the Yigo Trough. Because the interface is rising, the volume of fresh water in the lens will be decreasing, as shown in Figure G-11. It can be seen that the volume of fresh water in the lens has been reduced by 20 percent over five years. In general, the aquifer conditions for scenarios No. 2 and No. 3 are only slightly different from the conditions in scenario No. 1 in the first year of simulation. In the second year of simulation, some differences are observable, but are still small. The change in volume of the fresh water lens for scenario No. 2 is shown in Figure G-11. Significant changes in the aquifer conditions will occur for scenarios No. 2 and No. 3 when the simulations are continued beyond the second year. The difference in the volume of the aquifer in two consecutive months may be positive or negative. If the difference is positive, then the recharge is greater than the leakage to the ocean. If the difference is negative, then the leakage to the ocean exceeds the recharge. Figure G-12 shows the change in aquifer storage on a monthly basis for the period of simulation. It can be seen that the leakage to the ocean exceeds the gain in aquifer storage. Consequently, the volume of the storage is continually decreasing as shown in Figure G-11. When steady cyclic conditions are reached, the gain in aquifer volume will equal the net leakage to the ocean.

The last two figures show a comparison between the measured water levels in wells M-10a and M-11 from 1978 through 1980 and the third, fourth and fifth years of simulation. It can be seen that the water levels have dropped from 0.75 to 1.0 foot. Of course, the simulated water levels will be lower when cyclic steady-state conditions are reached.

Conclusions

1. For the initial conditions assumed in the management runs, five years of simulation were insufficient to reach steady cyclic conditions. Probably another five to ten years of simulation would be required. Alternatively, one can try to obtain initial conditions that are closer to the final cyclic results.

2. Despite the fact that final, steady, cyclic conditions were not reached, the computer runs do provide insight into the aquifer behavior that one can expect under these management conditions.

3. At the end of the dry season (June), the phreatic surface will develop a divide approximately along a line with node numbers 90, 82, 83, 76, 68, and 69. To the left of this divide, the groundwater will flow westward toward the ocean, and to the right of the divide, the groundwater will flow eastward toward the wells in the Dededo and Yigo areas.

4. At the height of the wet season (October), the phreatic levels will rise sharply, especially in the Yigo Trough. These high levels represent a storage volume, part of which will drain out to the ocean and part of which will be pumped out during the next dry season.

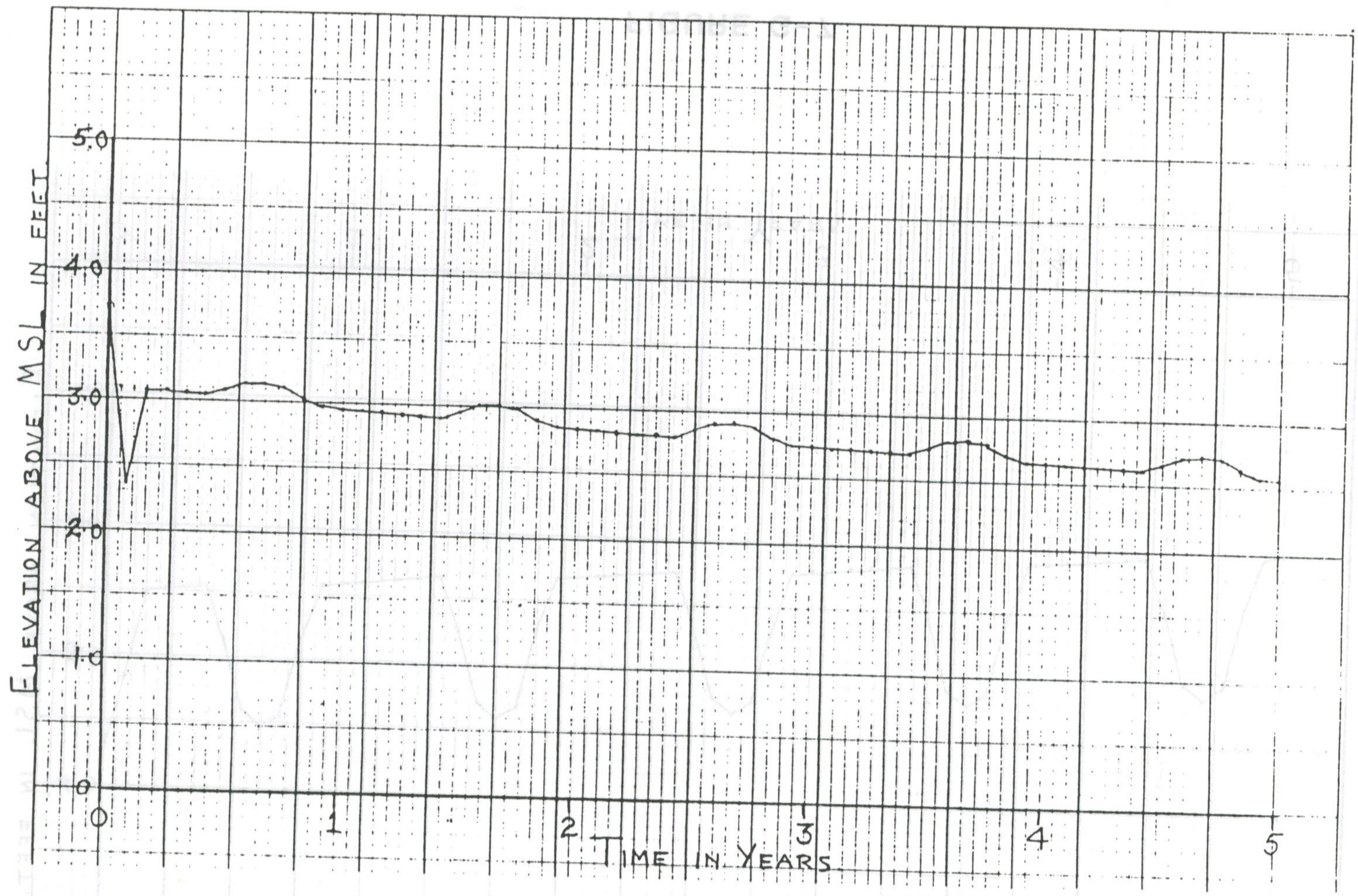


FIGURE G-6

PHREATIC SURFACE ELEVATIONS AT NODE 24

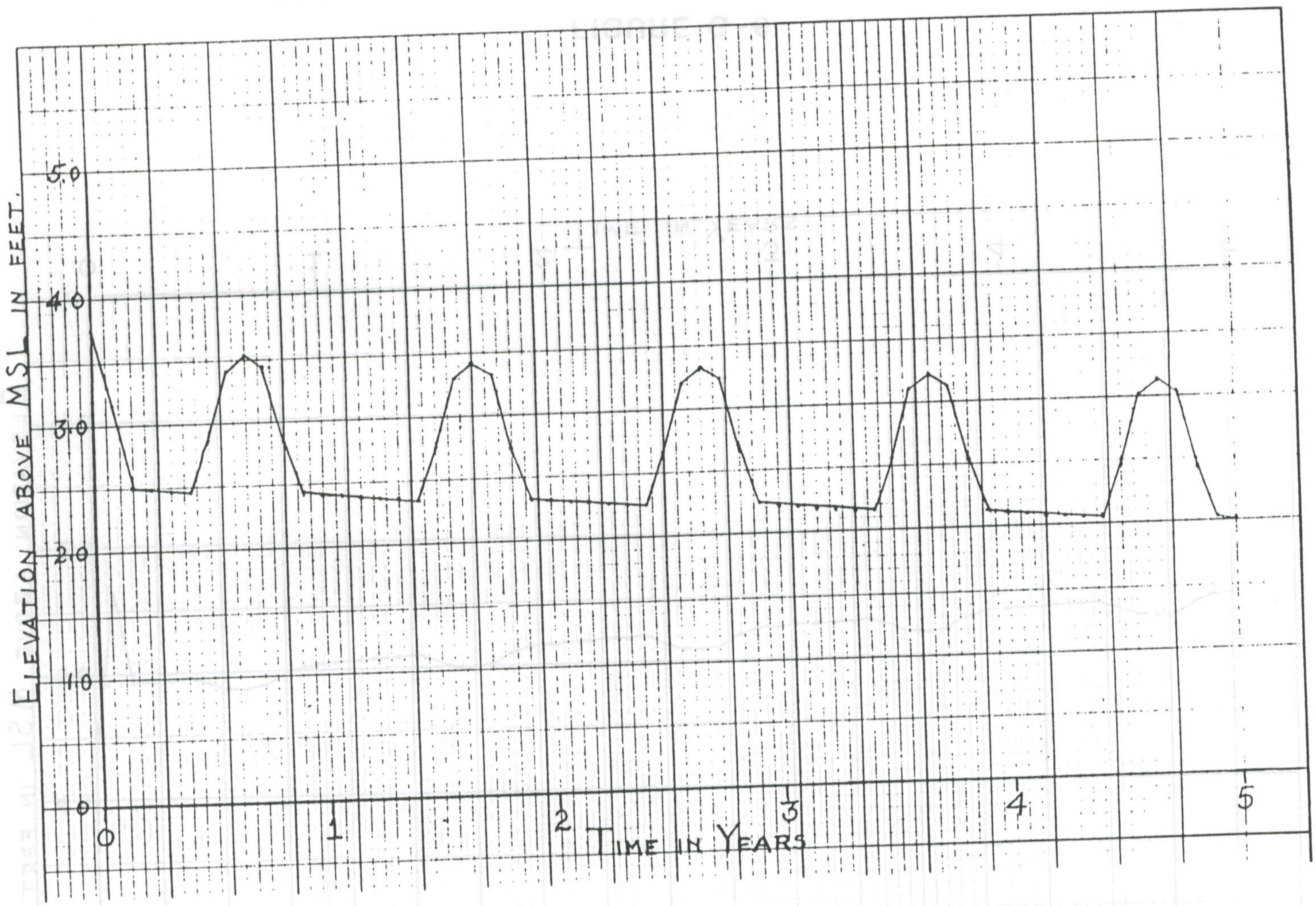


FIGURE G-7

PHREATIC SURFACE AT NODE 76

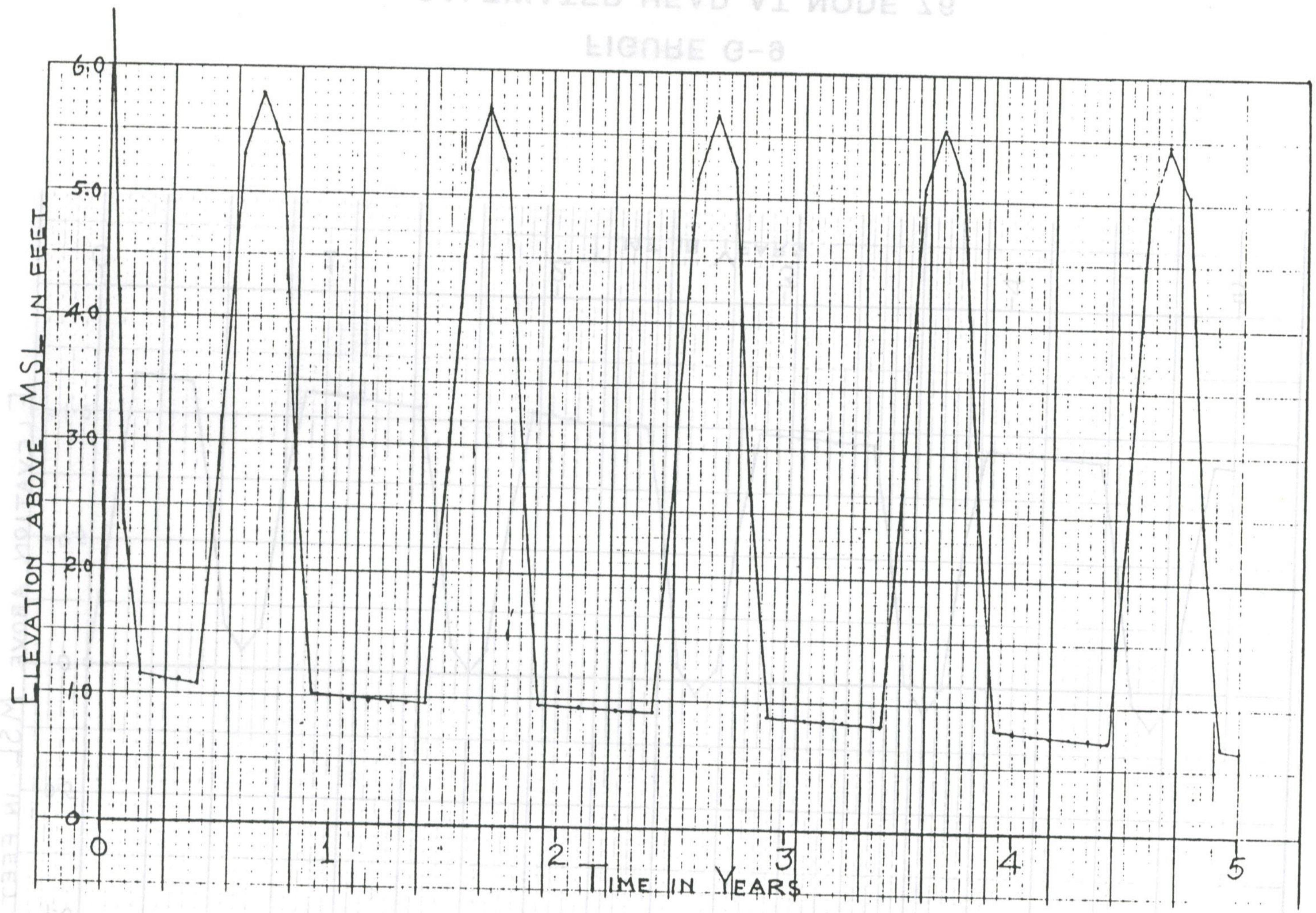


FIGURE G-8

PHREATIC SURFACE AT NODE 95

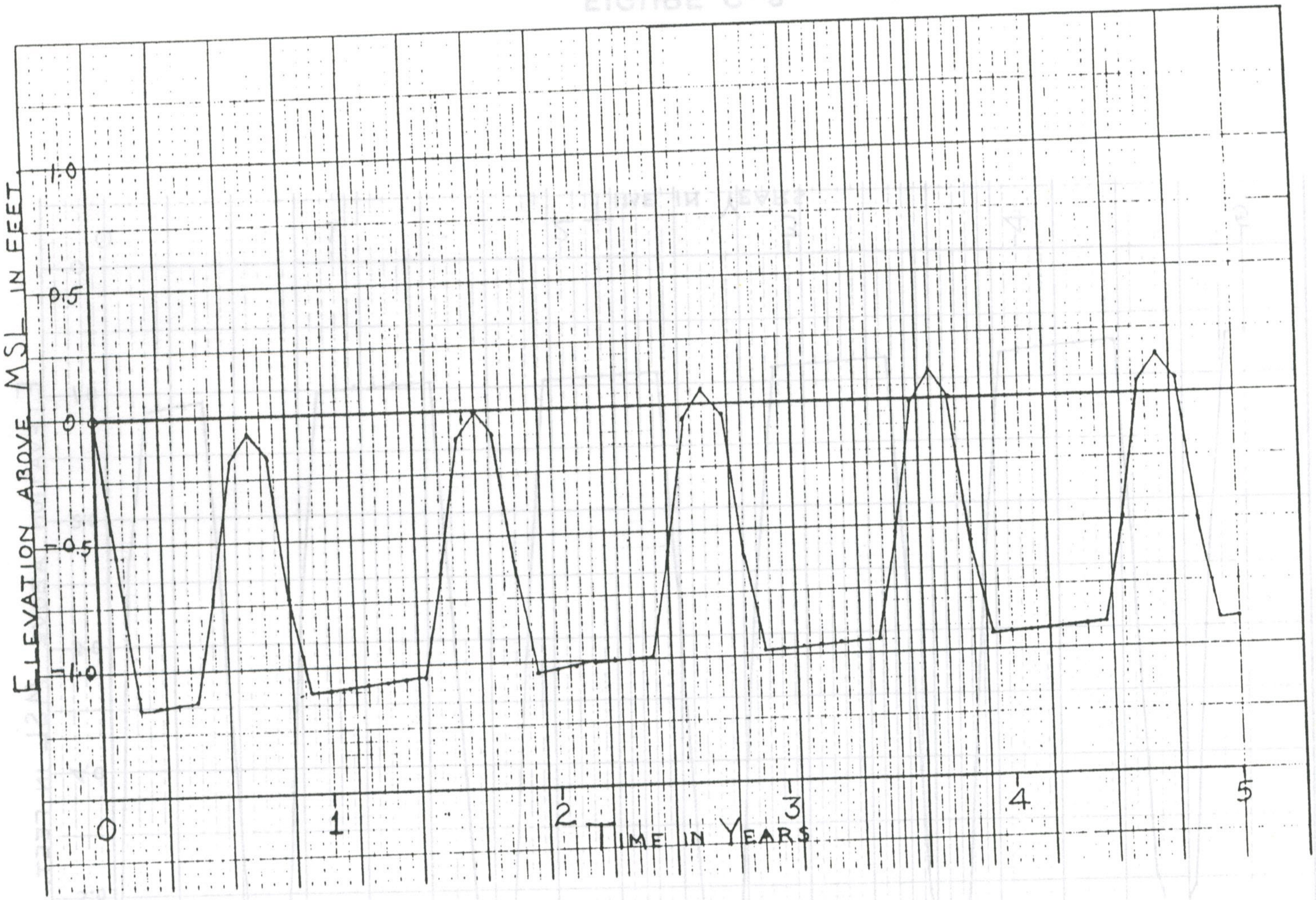


FIGURE G-9

SALTWATER HEAD AT NODE 76

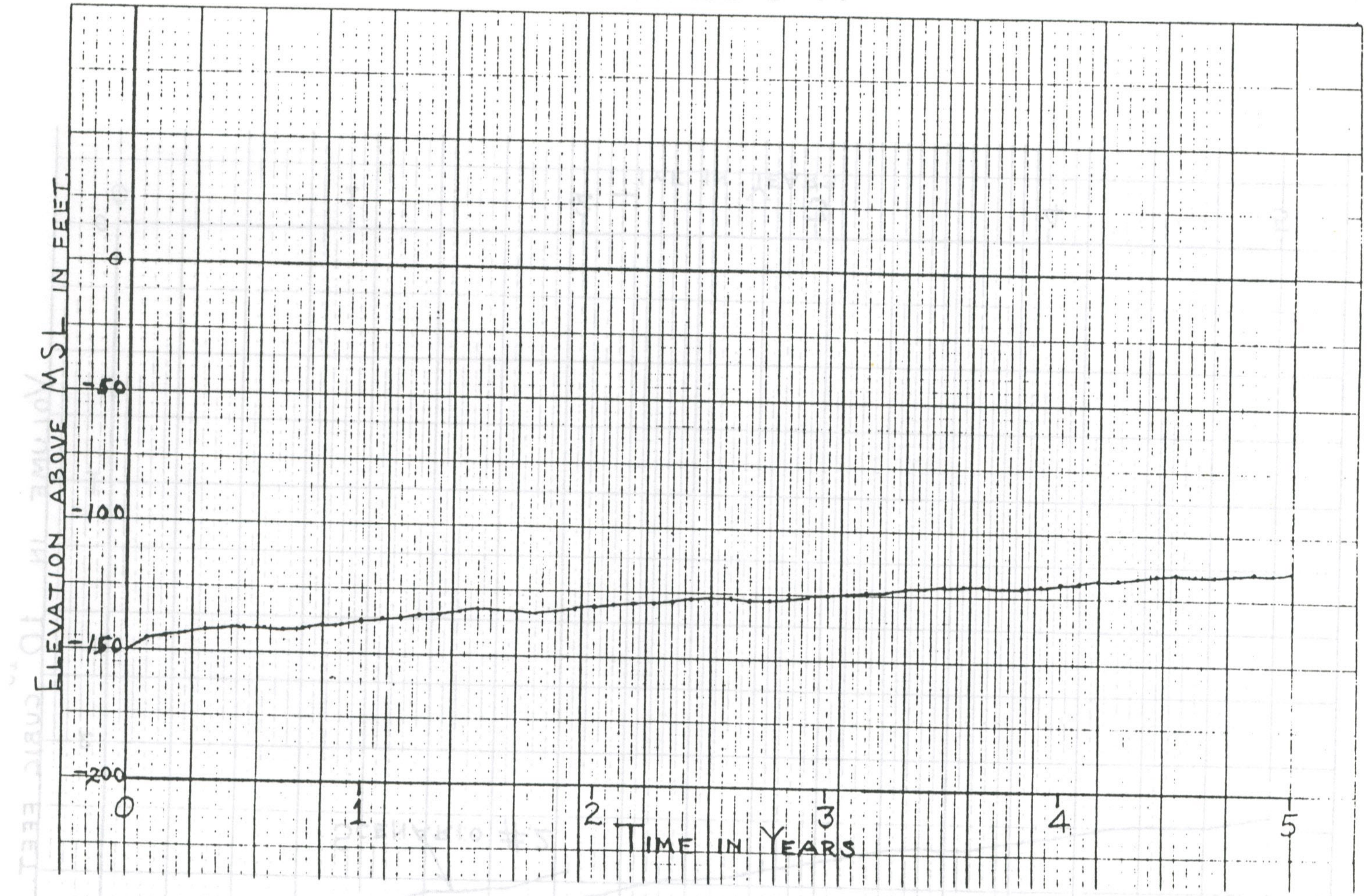


FIGURE G-10

DEPTH OF INTERFACE AT NODE 76

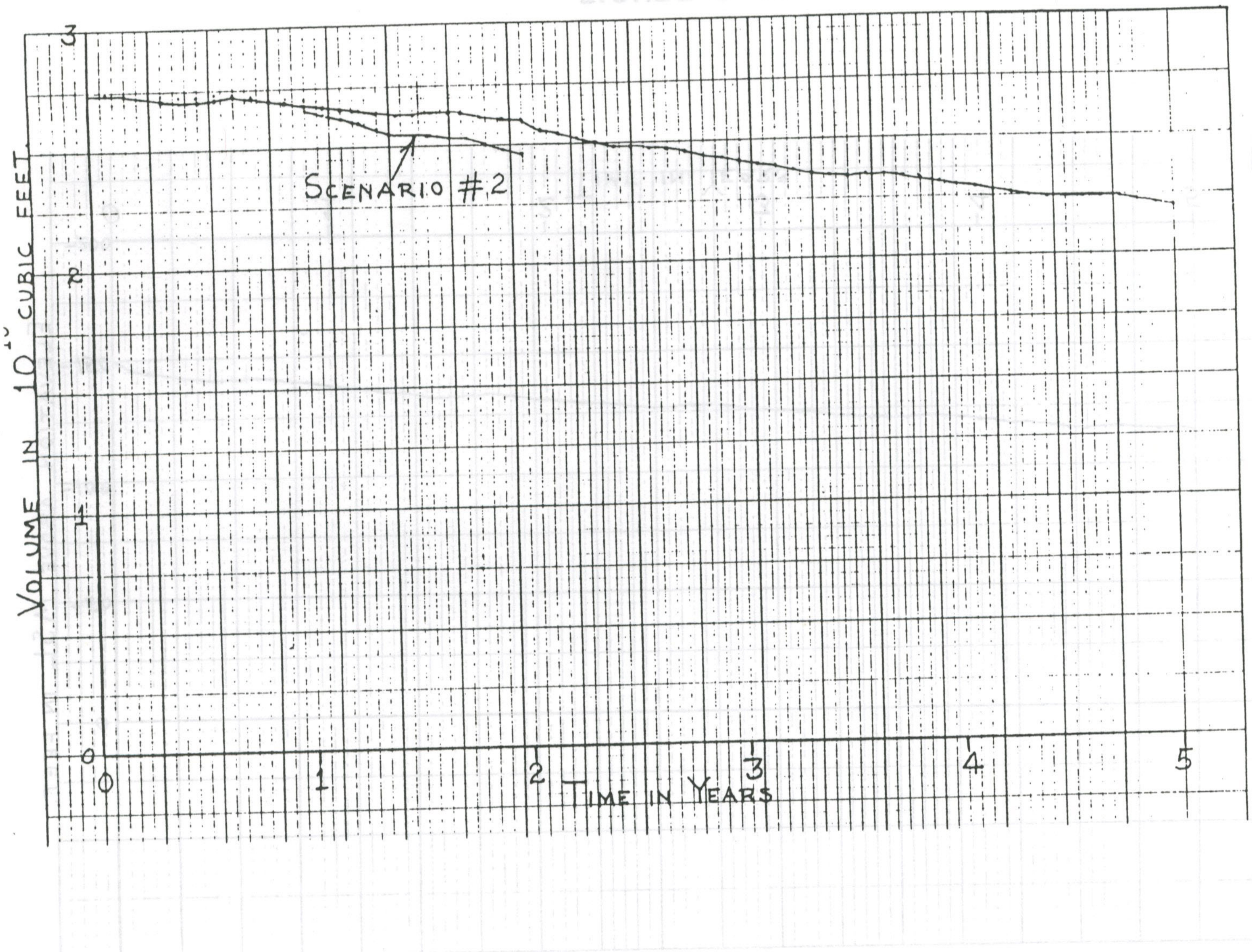


FIGURE G-11

VOLUME OF FRESH WATER STORED IN AQUIFER

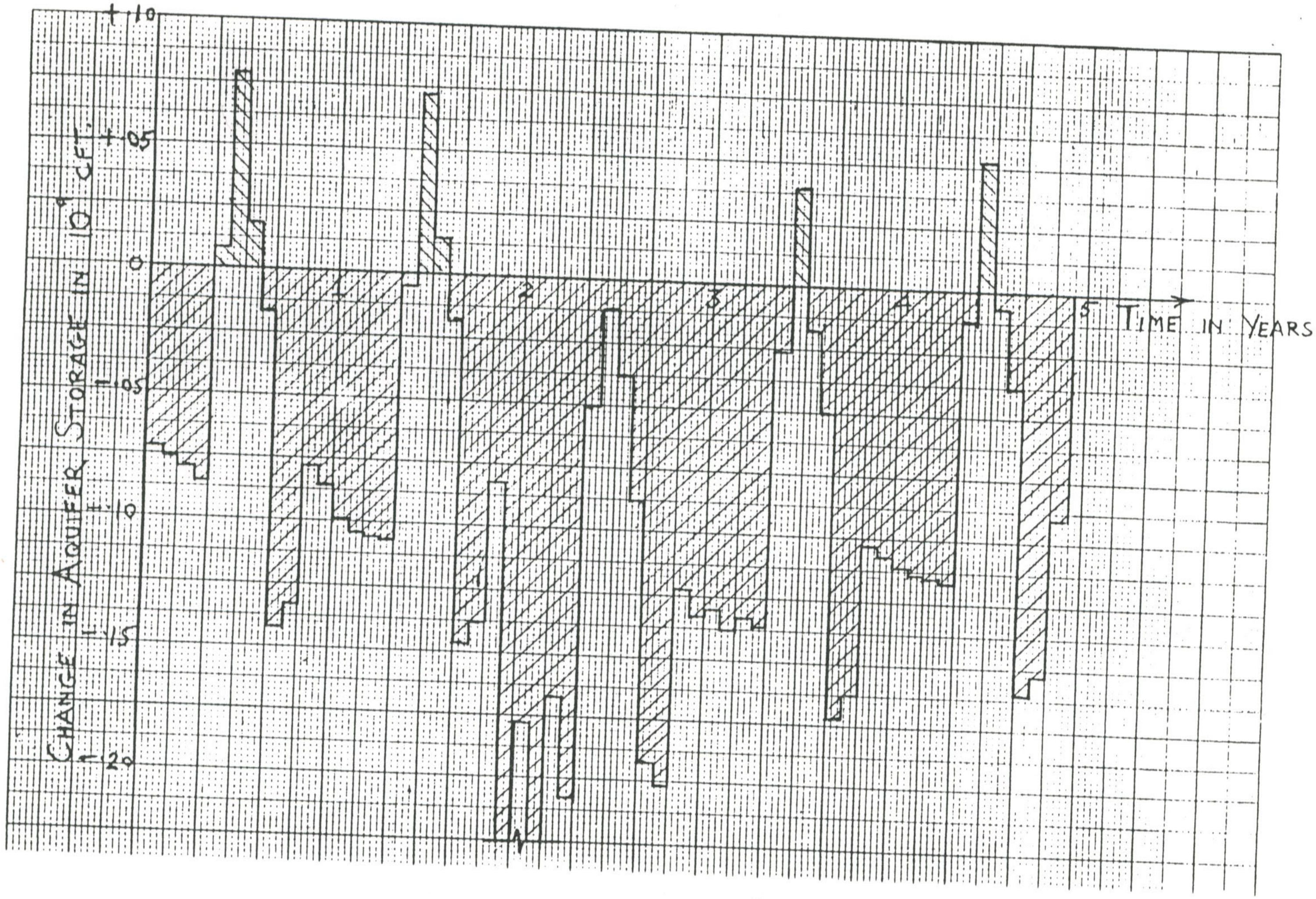


FIGURE G-12

CHANGE IN STORAGE ON A. MONTHLY BASIS

5. During the five year simulation period, the fresh water lens decreased in volume by 20 percent to 2.2E10 cubic feet (5.05E5 acre-feet).

6. Management simulations for scenarios No. 2 and No. 3 were run for two years. During this period, the results were not very different from the results of scenario No. 1. With longer simulation periods, the differences would become apparent.

Suggestions for Future Work:

1. Research work should be conducted to determine ways of reducing the simulation period requird to reach steady, cyclic conditions in the aquifer. Several ideas could be explored. First, the Ghyben-Herzberg approximation, $h_s = 0$, can be used at all nodes. With this approximation, the program may reach steady, cyclic conditions sooner and then the program can be run without the Ghyben-Herzberg approximation. Second, the salt water permeability could be artifically increased tenfold and the program run until steady, cyclic conditions result, and then the permeability decreased to its normal value. The value of these ideas and the resultant computer cost savings can only be ascertained by further research.

2. Because the main area of interest is the Dededo and Yigo areas, the aquifer network could be modified to include these areas down to the western shores of the island. This will result in a smaller number of nodes and, hence, shorter execution times for the program. Alternatively, the same number of nodes may be used in this smaller area to provide better resolution of the variables.

APPENDIX H

GLOSSARY OF TECHNICAL TERMS

Aquifer.	A formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. In Guam the aquifer is composed of limestone.
Basal.	The zone of fresh water that floats on salt water in a groundwater environment. The delineation of the zone is estimated by the Gheyben-Herzberg Relationship.
Evapotranspiration.	The combined measure of the water vapor returned to the atmosphere as evaporation from free surfaces and from transpiration by plants.
Fresh Water Lens.	The fresh groundwater consisting of the parabasal and basal zones overlying salt water.
Ghyben-Herzberg Relationship.	Fresh groundwater floats on heavier sea water in accordance with the buoyancy principal; theoretically, 40 feet of fresh water will extend below sea level for every foot of head above sea level.
Head.	The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.
Management Zone.	The parabasal and basal subdivisions of the hydrologic subbasins for which recharge and sustainable yield were determined and for which management alternatives are made.

Transition Zone.	The diffuse zone of brackish water of finite thickness that separates the fresh water and saline water. This zone develops from dispersion caused by fresh water flow plus unsteady displacements of the interface by external influences such as tides, recharge, and pumping of wells.
Upconing.	When an aquifer containing an underlying body of saline water is pumped by a well, a local rise of the fresh water-salt water interface below the well occurs. If the well is pumped at too high a rate, the interface rises to the point where the well becomes unusable due to contamination by saline water.
Volcanic Basement Rock.	An impermeable volcanic formation that is the lower boundary for the limestone aquifer.