Groundwater in Northern Guam
Sustainable Yield & Groundwater Development

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JUL 13 1992

MEMORANDUM

TO: Administrator
Guam Environmental Protection Agency

FROM: Chief Officer

SUBJECT: Groundwater in Northern Guam: Final Engineering Report prepared by Barrett Consulting Group

Attached for your review is the Final Engineering Repor prepared by the Barrett Consulting Group. The report, prepare in association with John F. Mink, was contracted by the Publ Utility Agency of Guam.

We would appreciate receiving your comments by July 30, 199 Thank you for your cooperation and assistance.

JOSEPH F. MESA

44p + Appendix

Attachments

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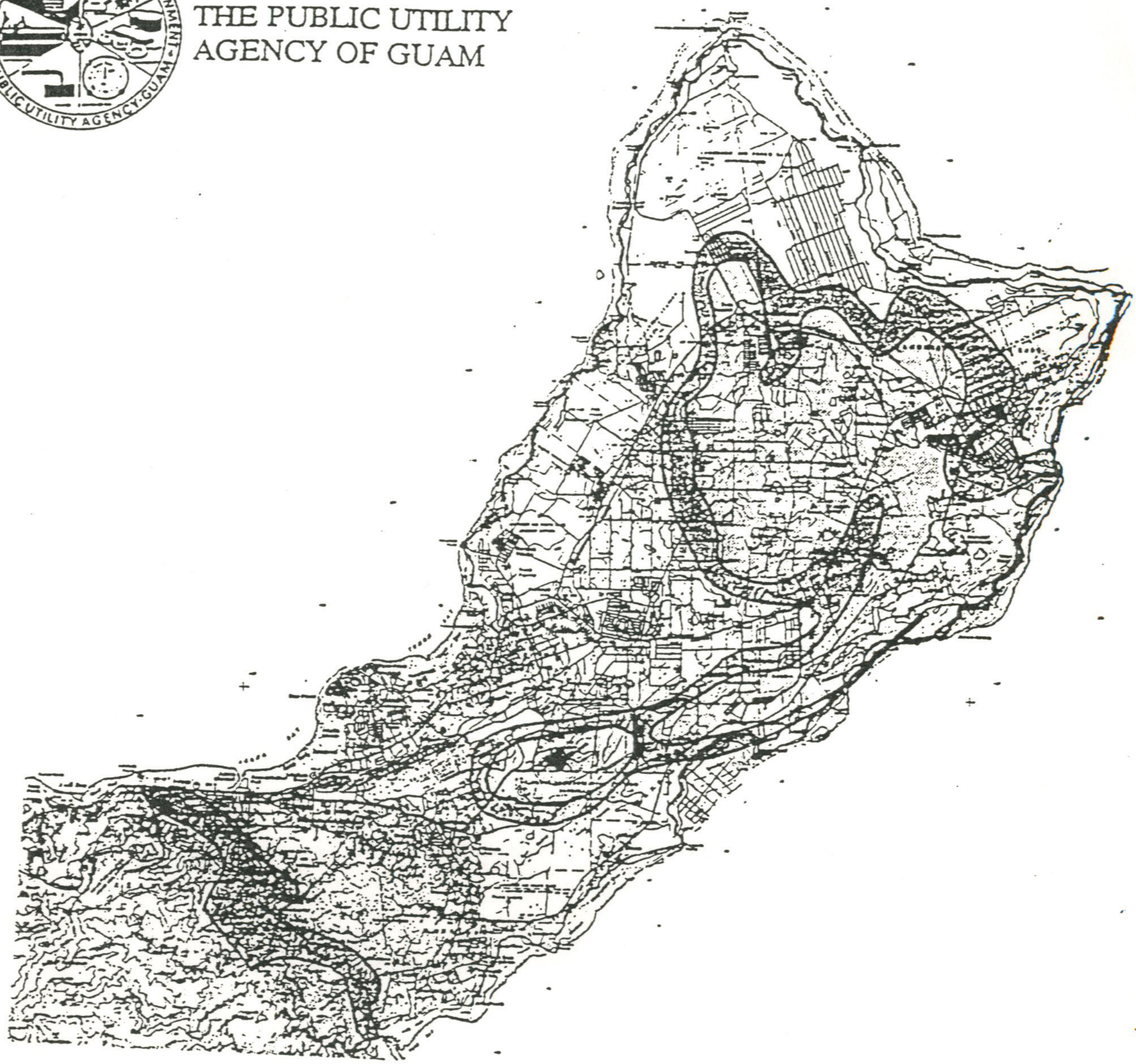
THE PUBLIC UTILITY
AGENCY OF GUAM



Final Engineering Report

GROUNDWATER IN NORTHERN GUAM
Sustainable Yield and Ground Water Development

Prepared By

BARRETT CONSULTING GROUP
AGANA, GUAM

In Association With
JOHN F. MINK

GROUNDWATER IN NORTHERN GUAM

Sustainable Yield and Groundwater Development

Final Engineering Report

Prepared For The

GOVERNMENT OF GUAM

PUBLIC UTILITY AGENCY OF GUAM

May 1992

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May 26, 1992

Mr. Joseph F. Mesa
Chief Officer
Public Utility Agency of Guam
Government of Guam
P.O. Box 3010
Agana, Guam 96910

Mr. Mesa:

In accordance with our engineering agreement dated September 24, 1990, we are pleased to submit, herewith, the final engineering report, *Groundwater In Northern Guam: Sustainable Yield and Groundwater Development*. The report represents the reevaluation by Hydrological Consultant, John F. Mink and our staff of the Northern Lens groundwater supply and proposes an overall well development program to increase the people of Guam's access to this resource.

The report presents a new basis for estimating the sustainable yield of the Northern Lens that differs significantly from the approach first applied in the 1982 *Northern Guam Lens Study* and currently used to regulate Guam's groundwater development. The proposed well development program is intended to optimize the development of groundwater resources based on this new analysis of the Northern Lens's sustainable yield and hydrodynamics.

We would like to thank PUAG, the many Government of Guam and Federal agencies whose cooperation and assistance made this report possible.

Very truly yours,

Edwin C. Pier, P.E.
Project Manager

Aziz H. Saad
Office Manager

51240E91.141/682

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY
Objectives 1-1
Conclusions 1-1
Recommendations 1-2

II. INTRODUCTION
Background 2-1

III AQUIFER CLASSIFICATION 3-1

IV SUSTAINABLE YIELD
Sustainable Yield by Aquifer Systems 4-1
Salinity-Depth Relationship to Storage Head 4-4
Sustainable Yield Determined by Transient Simulation 4-9
Recommended Average Draft by Aquifer Sectors and Systems 4-14
Summary of Draft and Sustainable Yield 4-15

V GROUNDWATER DEVELOPMENT PROGRAM
Groundwater Development Practices 5-1
Factors Affecting Well Design and Construction 5-1
Well Production by Aquifer System 5-4
Well Failure and Redevelopment 5-11
Alternative Methods of Groundwater Production 5-13
Proposed Well Development Priorities 5-15

APPENDIX
A - Hydrologic Budgets - Sustainable Yield by Steady State Model
B - Sustainable Yield, Transient Model

LIST OF TABLES

3-1 NGLS and Proposed Aquifer Classifications 3-3

4-1 Northern Guam Average Water Balance 4-3
4-2 Sustainable Yield, Aquifer Systems;
NGLS Management Zones 4-16, 17, 18
4-3 Groundwater Availability by Aquifer System 4-20

5-1 Priority Development by Aquifer Systems 5-16

LIST OF FIGURES

3-1 Northern Guam Aquifer Systems. . . . . .End of Document
4-1 Northern Guam Monitor Wells, Yigo-Tumon 4-6
4-2 Northern Guam Monitor Wells, Ex-1, Ex-4 4-7
4-3 Northern Guam Monitor Wells, Ex-8, Ex-9 4-8
4-4 Finegayan System Simulation 4-10
4-5 Yigo-Tumon Aquifer Sector Simulation 4-11
4-6 Agana Aquifer Sector: Ordot System, Hd = 45 ft. 4-12
4-7 Agana Aquifer Sector: Ordot System, Hd = 10 ft 4-13
5-1 Northern Guam Priority Well Fields . . . . .End of Document

CHAPTER I
EXECUTIVE SUMMARY

OBJECTIVES

The rapid increase in development and tourist population on the Island of Guam in recent years has resulted in a corresponding demand for infrastructure improvements and expansion. As a first step toward meeting some of these demands and anticipating the Island's future needs, the Public Utility Agency of Guam (PUAG) has initiated a number of water system improvement projects funded under the $53 million Capital Improvements Revenue Bond. A key factor in designing the projects, and in coordinating their implementation, is knowing how much water supply is available for development and where it is located. The groundwater of Guam's Northern Lens is known to be the most economically accessible water supply available. However, in light of the information collected and the advances in computer modelling and capabilities over the last nine years (since the Northern Guam Lens study was completed) many of the bases for characterizing the Lens' behavior and estimating its sustainable yield should be updated.

The objectives of this report therefore are: 1) to provide a preliminary updated estimate of the sustainable yield of Guam's Northern Groundwater Lens; and 2) outline a new program for well development based on the latest data and information connecting the lens. The update of the Lens' yield and hydrodynamics is based on the evaluation of available data obtained from well construction and monitoring conducted over the last ten years in addition to recent Time Domain Electromagnetic (TDEM) surveys.

CONCLUSIONS

Evaluation of well construction and monitoring data collected over the last ten years leads to two significant conclusions:

- First, it is now apparent that seasonal recovery of the groundwater lens does occur. Consequently, a more realistic method of analysis to determine the lens sustainable yield needs to be based on transient analytical computer modeling techniques rather than the static analytical techniques used in the NGLS ten years ago.

- Second, and perhaps more significantly, Guam's northern aquifer appears to be a much more continuous system than is implied by the system of discrete management zones proposed in the NGLS. The significance here is that the discrete management zone system from the NGLS is presently being used as a basis for regulating groundwater development in Guam. However, the available data now indicates that the lens has a capability to respond to significant water withdrawals in various areas, as a single resource.

As a consequence of these two conclusions, it now appears that the sustainable yield of the Northern Lens, *available to civilian development*, may be as much as 60 million gallons per day (mgd). Of this amount approximately 25 mgd is already being withdrawn by PUAG and private wells. An additional 35 mgd therefore remains to be developed.

RECOMMENDATIONS

A summary of the report's recommendations follows. A recommended program for overall groundwater development is discussed more thoroughly in Chapter V.

1. The system of discrete groundwater management zones presented in the *NGLS* and currently used to regulate groundwater development should be replaced with the concept of Aquifer Systems proposed in this report. Subsequently, the estimated sustainable yield of the new "Aquifer Systems" should be revised continually in light of data obtained from ongoing well development and monitoring.

2. Assuming the adoption and acceptance of the new Aquifer System for management of the groundwater resource, additional sustainable yield over that projected by the NGLS may be developable. It is recommended that the unused portion of the sustainable yield be developed in two increments. The first priority increment would be for a total of approximately 10 mgd from the Agafo Gumas, Yigo, Tumon, Gugagon and Ordot Aquifer Systems. The second priority increment would be for a total of approximately 5 mgd from the Mt. Santa Rosa, Sasajyan, Huchuanao and Mongmong Aquifer Systems. The results

derived from the development of the first 15 mgd should then determine the next set of priorities.

3. Redevelopment of existing wells should be considered but must be investigated on a case specific basis in response to actual conditions resulting from the increased production proposed in increments 1 and 2.

4. The conclusions, based on transient modeling and analysis of well data obtained since the *NGLS* was completed, strongly indicate that an update of the *NGLS* "Aquifer Yield Report" and groundwater management techniques are in order. Such an update would require a breadth of testing, modeling and analysis that is beyond the scope of this contract. However, the primary task should be the drilling of more monitoring wells and collection of data. Since data from additional monitoring wells would have to be collected over a period of at least 3 years for analyses to be really useful, this task should be pursued without delay. Additional study of actual evapotranspiration rates would also provide interesting data for future updates of the sustainable yield.

   At the same time, it should be recognized that any update of the Aquifer Yield Report must not be hastily conducted, if comprehensive, long-term conclusions are to be obtained.

CHAPTER II
INTRODUCTION

BACKGROUND

Groundwater in Northern Guam has been talked about, studied and evaluated as a premier water resource since 1937 when H.T. Stearns of the U.S. Geological Survey conducted a reconnaissance survey for the U.S. Navy. After World War II the Survey expanded efforts to full fledged geological mapping which became the basis for improved comprehension of the groundwater potential. Consulting engineers contributed to the solution of specific problems. Then in 1976 J.F. Mink summarized existing data and wrote an evaluation report for PUAG. The most comprehensive study of Northern Guam's water resources was made several years later and is commonly referred to as the *NGLS (Northern Guam Lens Study)*.

As the first comprehensive study of the Northern Lens, the *NGLS* was limited by the scarcity of long term hydrologic data then available. This was particularly true with regard to the behavior of the lens under stress--e.g. pumping from wells--and the lack of data on the salinity-depth relationship of groundwater storage head. As a consequence of this constraint, some of the bases for analysis and conclusions of the *NGLS* were, appropriately, conservative.

In order to provide a better data base for future analyses, the *NGLS* drilled several monitoring wells and recommended a monitoring program for all wells that was soon implemented by the Guam Environmental Protection Agency (GEPA). In the nine years since the completion of the *NGLS* a substantial number of new production wells have also been developed and monitored. As a result, considerably more data is now available for an analysis of the nature and productivity of Guam's Northern Lens than at the time of the NGLS. In particular, the increased number of production wells has provided the opportunity to observe the reaction of the Lens under increased stress due to pumping. The salinity-depth profiles obtained from monitoring these wells are also critical in evaluating the Lens's storage capacity. As discussed in Chapter 4, the salinity-depth relationship is a much more valuable tool in evaluating the hydrodynamics of Guam's Northern Lens than water table elevations which were all that was available at the time of the *NGLS*.

The additional knowledge of the Lens now available provides a basis for analyzing the Lens with a higher degree of confidence than was possible for the *NGLS* and allows current evaluations to depart from some of the *NGLS*'s more conservative assumptions. Advances in computer modelling of groundwater systems since the *NGLS* have also made available more practical and accurate methods of simulating lens behavior. A review and discussion of the steady-state and hydrologic budget model employed by the *NGLS* is given in Appendix A to this report. A similar review of the transient model employed by this report to derive an updated sustainable yield is given in Appendix B. Other key areas of the *NGLS* from which the current report deviates are the assumptions involved in estimating recharge of the lens and the system by which the Lens is subdivided into Management Zones to model and regulate groundwater development on Guam.

The *NGLS* organized and evaluated existing hydrologic data, made analyses relevant to groundwater production, and subdivided all of Northern Guam into Sub-Basins and Management Zones. This classification currently forms the basis of regulatory management decisions about the expansion of groundwater development.

In the *NGLS* only 67 square miles of the total of 100 square miles in Northern Guam were considered favorable for the production of potable water. This production area was divided into 47 Management Zones, each having an average area of somewhat more than one square mile. A primary function of these Zones was to produce an array of data points that would facilitate computer simulation of the Lens' behavior by numerical modelling. While the numerical method can be a powerful tool for modelling lens behavior—and was, perhaps, the best available at the time of the *NGLS*—it has some limitations with regards to application in Guam. These are discussed in Appendix B to this report. The outlines of the Zones proposed in the *NGLS* reflect hydrogeological and topographic features but each is too small to be uniquely identified by these parameters. Consequently, strict adherence to a Zone as a management unit inhibits flexibility in taking advantage of groundwater conditions.

To allow managers more latitude in initiating new groundwater developments and in revising existing ones, an aquifer classification scheme similar to but less restrictive than that in the

NGLS is proposed and will be explained later. The proposed divisions are congruent with the existing ones but are fewer in number.

The methodology employed to arrive at values for sustainable yield (SY) differs in important respects from that depended upon in the *NGLS*, especially in using groundwater flow computer simulations as the fundamental tool for allocating sustainable yield. In the *NGLS*, global hydrologic budgeting, not constrained by groundwater hydraulics, was the method employed (see Appendix A). For lack of better data, this budget assumed the sustainable yield was a conservative fraction of recharge. A preliminary finite element mathematical model was also devised by Dr. D. Contractor, then at the University of Guam, to suggest groundwater behavior. However, the model was not used in deriving sustainable yield for the NGLS effort because of inherent limitations imposed by a sparse data base and uncertainty of physical boundary conditions.

In the nine years since the *NGLS* was completed, data including well performance, salinity-depth profiles, water table elevations and groundwater quality have been regularly monitored and annually recorded by GEPA. This long term data base, unavailable for the *NGLS*, enables the use of a dynamic or transient model to predict behavior of the lens over seasonal changes and under different pumping scenarios. Although a groundwater hydraulics model depends on a water balance for values of recharge, sustainable yield is derived, in the current report, from the transient model rather than assigned a value as a fraction of recharge. More detailed discussions of the transient model used for deriving sustainable yield for this updated analysis of the lens are presented in Appendix B to this report.

CHAPTER III
AQUIFER CLASSIFICATION

The *NGLS* first divided the Northern Lens along geologic and hydrologic boundaries into subbasins. These subbasins were then further subdivided into Management Zones primarily to establish an array of data points that would facilitate numerical modelling of lens behavior. Given the modelling systems and extent of knowledge of lens behavior available at the time, the establishment of these Management Zones was appropriate when the *NGLS* was done. However, as discussed in Chapter 2 and Appendix B, the increased knowledge of lens behavior and advances in modelling techniques that have occurred since the *NGLS* now permit a more practical classification scheme for the management and evaluation of Northern Guam's groundwater lens.

The proposed division of Northern Guam into aquifer categories follows the methodology derived for Hawaii and other Pacific Islands. The divisional hierarchy starts with the Aquifer Sector, which is divided into Aquifer Systems, which in turn are subdivided into Aquifer Types. At this stage only the Sectors and Systems have been identified for Northern Guam.

An Aquifer Sector is a region within which exist similar hydrologic and geologic features and in which the direction of groundwater flow is to the same general discharge line (i.e., Pacific Ocean; Philippine Sea). A Sector incorporates one or more Aquifer Systems. In an Aquifer System hydraulic continuity exists among all groundwater components (e.g., parabasal; basal). The Aquifer Type (not defined in this report) describes specific hydrogeologic conditions of divisions within an Aquifer System.

In all instances the Aquifer Sectors correspond to the Sub-Basins of the *NGLS*, but the Agana Sub-Basin is further divided into the Agana and Fadian Aquifer Sectors to reflect the direction of groundwater flow (Agana Sector to the Philippine Sea; Fadian Sector to the Pacific Ocean). Aquifer Systems embrace a group of Management Zones. A System is a more flexible division for allocating water development than the much smaller Management Zone. System boundaries depend on geology (e.g., argillaceous versus clean limestone), basement configuration, groundwater accumulation and groundwater flow direction. Figure 3-1, located at the end of this report, is a map showing Sectors and Systems.

Correspondence between the *NGLS* divisions and the proposed classification is presented in Table 3-1.

TABLE 3-1
NGLS AND PROPOSED AQUIFER CLASSIFICATIONS

NGLS Sub-Div.	Aquifer Sector	Aquifer System	*NGLS* Mgmt. Zones
Agana	Agana	Ordot	Chalan Pago, Nimitz Hill, Anigua
		Mongmong	Toto, Agana Swamp
		Barrigada	Mt. Barrigada South, Barrigada
Agana	Fadian	Sabana Maagas	Sabana Maagas
Mangilao	Mangilao	Sasajyan	Mangilao South, Mangilao North, Adacao, Asbeco, Taguan, Sasajyan
		Pagat	Sabana Pagat, Janum
Andersen	Pati	Mt. Santa Rosa	Salisbury (1/4), Lupog
		Andersen	Salisbury (3/4), Tarague, Anao
Agafo Gumas	Tarague	Agafo Gumas	Agafo Gumas Central
		Northwest Field	Agafo Gumas West, Agafo gumas East, NW Field East
Finegayan	Finegayan	Gugagon	Callon Tramojo, Finegayan East, Potts
		Haputo	NW Field West, Finegayan West, NCS
Yigo	Yigo-Tumon	Yigo	Marbo South, Yigo East, Yigo West, Marbo North, Mt. Santa Rosa, Mataguac
		Tumon	Mt. Barrigada West Mogfog, Ysengsong, Dededo North, Dededo South, Macheche, Asatdos

CHAPTER IV
SUSTAINABLE YIELD

SUSTAINABLE YIELD BY AQUIFER SYSTEMS

As mentioned in the previous chapters, the *NGLS* was constrained by an absence of long-term hydrologic data and the uncertainty of physical boundary conditions from obtaining the sustainable yield of Guam's groundwater lens by computer modelling techniques then available. Instead, the *NGLS* derived the sustainable yield with a steady state model based on an overall hydrologic budget. Given the available knowledge and information at the time of the *NGLS*, these methods were adequate. With the tools and information available today, however, more accurate and realistic modelling of the lens is possible, particularly with regard to changes that occur in the lens over time.

Included in Appendix A of this report (see p. A-7) is a discussion of sustainable yield and its derivation by a steady state model as applied in the *NGLS*. Although the steady state provides a useful estimate of sustainable yield, it is based on timeless averages and therefore does not capture the profound role the seasons play in dewatering and replenishing the basal lenses. A steady state model is relatively simple to construct and does not require a long-term data base on groundwater behavior for application. The transient model (described in Appendix B of this report), which was developed subsequent to the application of the steady model, is considerably more difficult and relies on an extensive data base than was available at the time of the *NGLS*.

Determination of sustainable yield based on steady state equations for a given equilibrium head assumes average recharge and draft in combination with an initial head in the system before the commencement of pumping. This approach fits a situation where aquifers are very large and are sustained by uniform flux, such as is the case in the voluminous basal aquifers of southern Oahu, Hawaii. In Northern Guam, however, recharge is seasonal. Although the volumes of water in the basal lenses are large, data obtained since the completion of the *NGLS* indicates dewatering during the dry season significantly affects storage, causing a noticeable decline in head. During the wet season, recharge is great and results in sharp head recovery.

Seasonable changes in head can be simulated by a computer model employing the transient equations from which the steady state equations discussed above are derived. Initial conditions for head and volume of water in storage are required, and average draft and recharge must be assigned over a time interval. Based on the *NGLS*, the initial head for the basal aquifers of Northern Guam is taken as 3.0 or 3.5 feet, depending on the Aquifer System being modeled. Initial volume is calculated assuming a porosity of 10 percent, and the time interval is the month. The least sensitive parameter is initial volume.

For each simulation monthly draft is assumed to be constant. In fact, pumpage in Northern Guam is nearly uniform throughout the year at about 25 mgd. Recharge is calculated from average monthly rainfall minus evapotranspiration. Evapotranspiration is assigned a value of 3.3 inches in each month rainfall exceeds 5 inches, and a value of 0.73 times rainfall in those months (January through June) having less than 5 inches. The evapotranspiration values are estimates derived from water balances used in Hawaii.

Total average evapotranspiration for the year amounts to 35.3 inches, which is about half the pan evaporation rate. It is a realistic value which reflects the lack of opportunity for plants to have a continuous supply of moisture when rainfall is light or intermittent.

Total annual recharge is calculated as 53 inches, or about 60 percent of rainfall. This ratio is consistent with the probable hydrologic budget posed by Mink in the 1976 report to PUAG (see Appendix, p. A-2) in which runoff is ignored. It is somewhat greater than that employed in the steady state model (Appendix, p. A-8) in which both recharge and evapotranspiration rates are taken as 45 inches per year. The values in the transient model are more liberal than those employed in the *NGLS* because they reflect the complexity of the hydrological environment in which atmospheric conditions vary strongly between seasons, and soils on limestone are thin and unable to store all rainfall needed to sustain continuous evapotranspiration. Infiltration into the highly permeable limestone surface is the sole escape for rainfall not consumed by plants. The values of rainfall, evapotranspiration and recharge are listed in Table 4-1.

TABLE 4-1 NORTHERN GUAM AVERAGE WATER BALANCE			
Month	**Rain (in.)**	**Ev. Tran. (in.)**	**Recharge (in.)**
Jan	4.63	3.38	1.25
Feb	2.65	1.94	0.71
Mar	1.91	1.39	0.52
Apr	3.11	2.27	0.84
May	4.39	3.21	1.18
Jun	5.22	3.30	1.92
Jul	8.88	3.30	5.58
Aug	13.89	3.30	10.59
Sept	15.19	3.30	11.89
Oct	13.47	3.30	10.17
Nov	9.36	3.30	6.06
Dec	5.86	3.30	2.56
Annual	88.6	35.3	53.3

In applying the steady state model, the whole of Northern Guam is lumped in the hydrological balances and annual averages are used for recharge and evapotranspiration. But, through the application of the transient model now available for analysis the balances are determined by month for each Aquifer System. The transient model also accounts for groundwater behavior from discharge at the coastline inland to either the emergence of the basement above sea level or a groundwater divide. In a transient hydraulic model the aquifers can't be separated into non-productive coastal zones and inland producing zones as was done in the steady state model available for the *NGLS*. Groundwater is continuous and activity at one point, whether recharge or pumping, causes a reaction at all other points.

Under current average draft of 25 mgd and average conditions of rainfall, head decays during the dry season by as much as 0.5 feet, then recovers to its previous maximum during the wet season. From July through November an extraordinary volume of recharge takes place, replenishing the lens and causing a sharp increase in head.

The wet season in Guam is highly reliable. During the average five month season a total of 62.8 inches of rain falls, about 70 percent of the annual total. In the lowest wet season on record, 1973, a total of 45.2 inches fell, and in the next driest, 1966, the total was 54.6 inches. Even at these minimums substantial recharge takes place, returning head to its normal maximum.

Did he subtract the seasonal sea levels (monthly-averaged)?

He has said nothing about the influence of seasonal sea level changes,

The recoverability of the basal lenses is clearly manifested in the return of head to its annual high by October, the height of the wet season. Normally head starts to decline in December and January, sometimes as early as November, and reaches its minimum in June. The difference between the maximum and minimum heads at current draft in the principal basal lenses is 0.3 to 0.5 feet.

SALINITY-DEPTH RELATIONSHIP TO STORAGE HEAD

An even stronger manifestation of the stability of the basal lens under current operations is provided by the salinity-depth curves computed from data compiled by the U.S.G.S from monitor wells in Northern Guam starting in 1982. In a Ghyben-Herzberg lens the 40:1 ratio (40 feet of fresh water below sea level to every 1 foot above) actually applies to the depth below sea level of the middle of the transition zone, or the 50 percent sea water isochlor. Water in the lens may be fresh or brackish, but ordinarily the lens consists of a fresh water core (FWC) followed by brackish water constituting the upper limb of the transition zone (TZ). The depth of the lens water to the 50 percent isochlor is exactly 40 feet for every foot the water table stands above sea level. Below the fresh water core, the concentration versus depth curve is symmetric around the transition zone midpoint.

The midpoint rises and falls with the volume of storage in the lens. In order to depress the water table by one foot the midpoint would have to rise 40 feet. Quite obviously the midpoint is a more reliable indicator of head and volume of water in the lens than water table fluctuations. Water table measurements reflect transient perturbations, including variable recharge and pumping, which are muted or canceled before influencing the midpoint. The transition zone adjusts to long term trends rather than to the instantaneous disturbances that affect the water table.

The most reliable representation of "storage" head, defined as the head dependent on the volume of water stored in the lens, is obtained by dividing the depth below sea level to the midpoint by 40. Storage head calculated in this way is independent of broad seasonal variations in sea level because the entire lens moves in unison in response to global sea changes. Storage head as the parameter defining the status of the lens is superior to water table measurements, but monitor wells drilled through the lens are required to obtain salinity-depth curves. As a project of the *NGLS* a number of such wells were drilled, four of which continue to provide essential information about the magnitude of the lens where each is located.

Figure 4-1 is a plot of storage heads for monitor wells EX-6, EX-7, EX-10 and Ghura Dededo, all of which are located in the basal lens of the Yigo-Tumon Aquifer System. The aquifer consists of clean limestone and therefore is highly permeable. Consequently heads are less than 4.0 feet.

Storage head changes since 1982 have varied by about 0.3 feet, equivalent to a rise or fall of 12 feet at the midpoint, except at EX-7 where the data is inconsistent with the stability of the other wells. No permanent downward trend in storage head is detectable, even though lows were reached in 1984-86 at EX-6 and EX-10. Both recovered by 1988, then declined again in 1989. The midpoint of the transition zone has been remarkably stable, indicating that the present Aquifer System draft of about 11 mgd has not affected the volume of groundwater in the lens.

Figure 4-2 shows storage heads at EX-1 (Mongmong Aquifer System) and EX-4 (Fadian Aquifer System). Both wells are driven in argillaceous limestone where the hydraulic conductivity is far less than in the clean limestone of Yigo-Tumon. Storage heads are higher as a result. Water table movements in these wells may range over one foot in a year, but storage heads are stable, suggesting little impact as a result of current draft.

Figure 4-3 is a plot of storage head at EX-8 (Taragüe Aquifer System) for the available data set and at EX-9 (Agana Aquifer System). These wells, like the ones in Yigo-Tumon, are in high permeability limestone. Storage heads vary over a small range but do not display a trend.

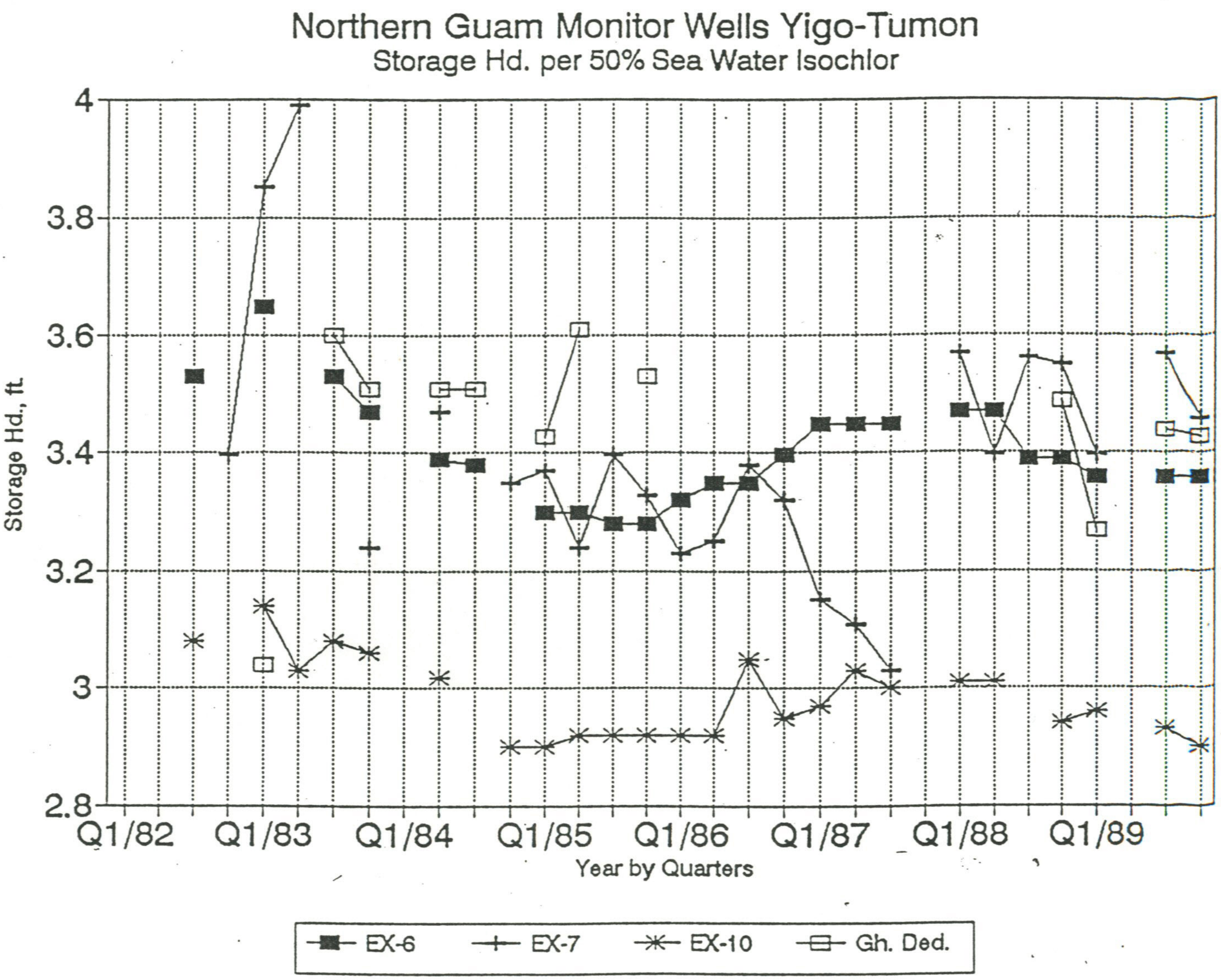


Figure 4-1
Northern Guam
Monitor Wells
Yigo-Tumon

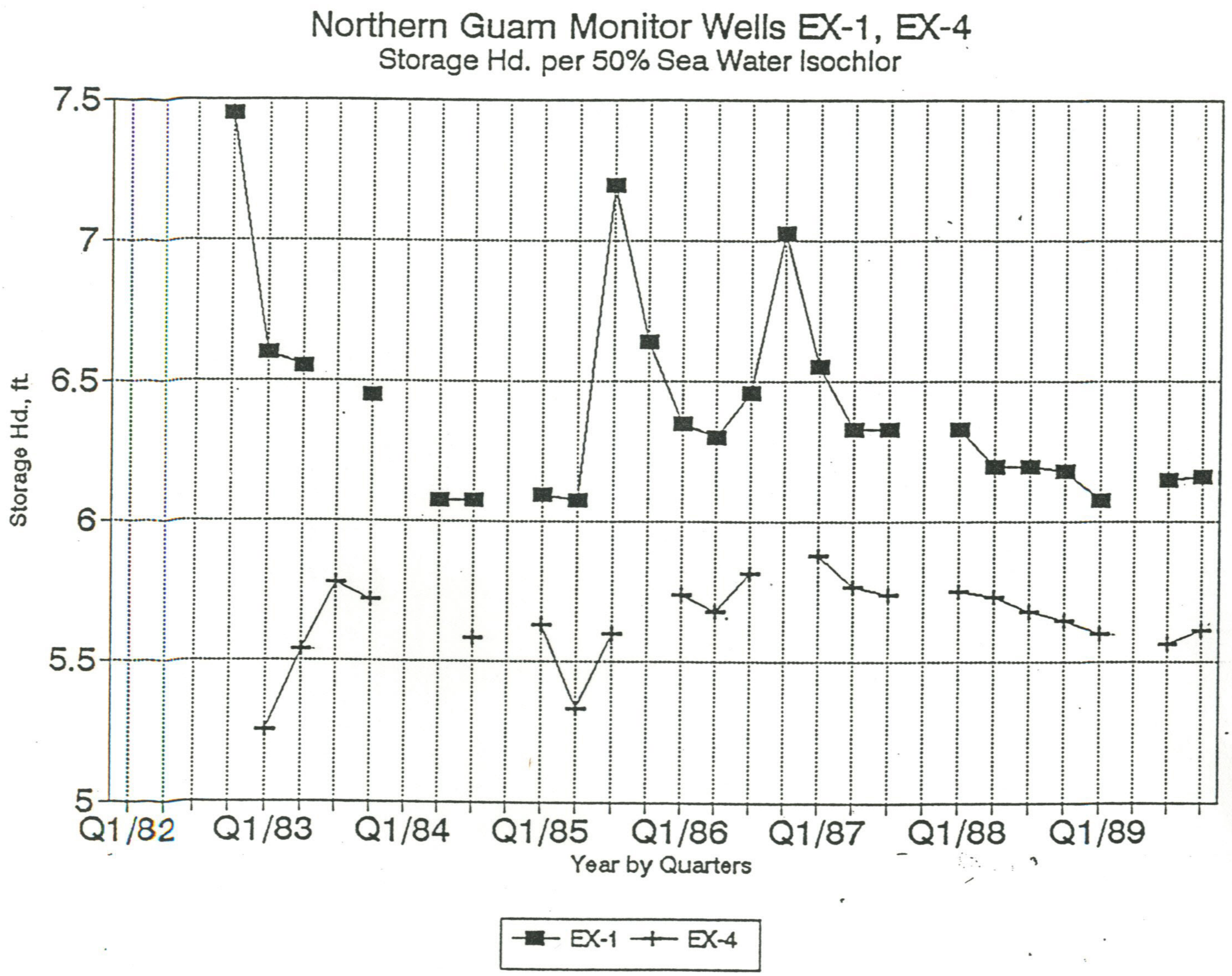


Figure 4-2
Northern Guam
Monitor Wells
EX-1, EX-4

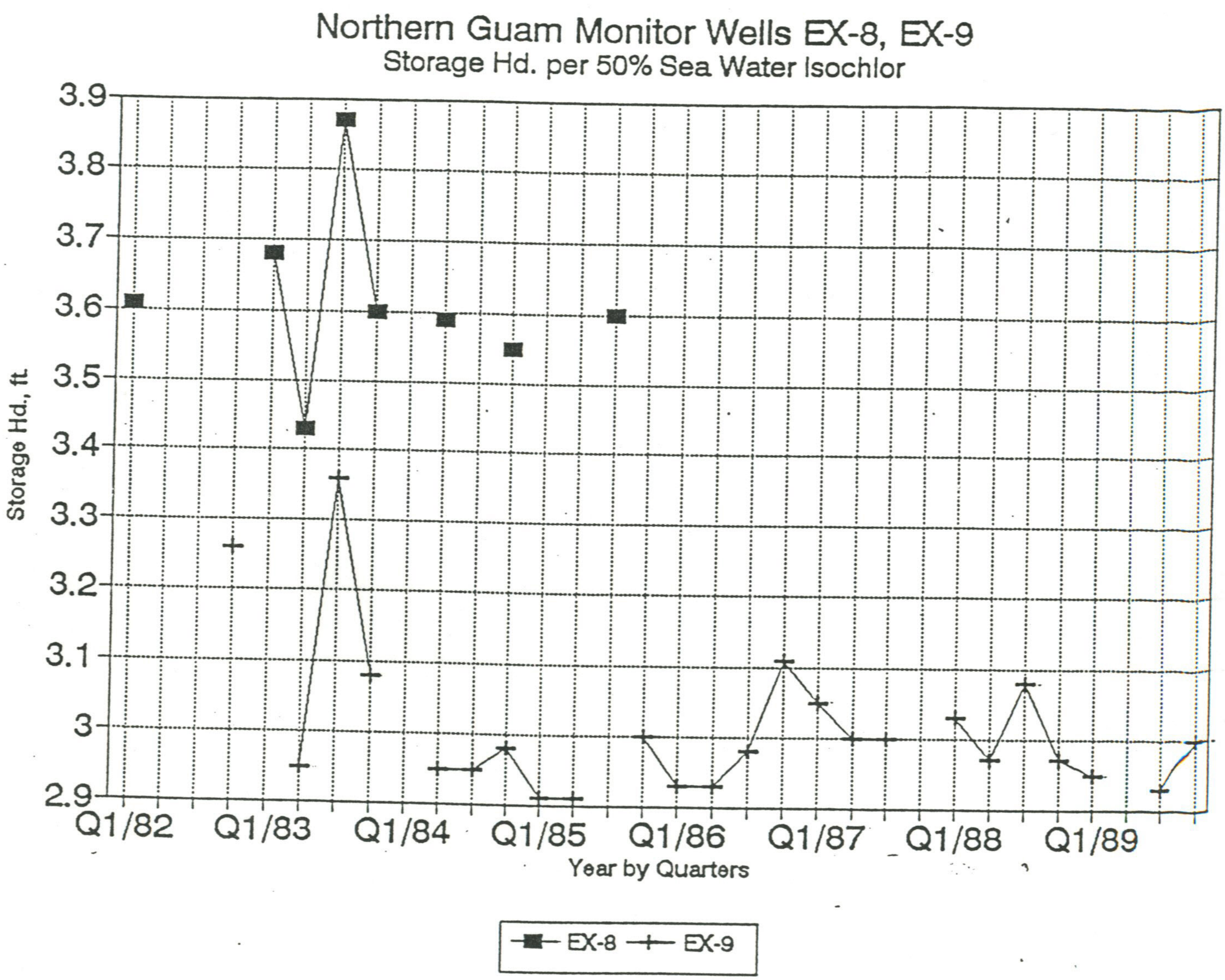


Figure 4-3
Northern Guam
Monitor Wells
EX-8, EX-9

SUSTAINABLE YIELD DETERMINED BY TRANSIENT SIMULATION

In order to test the aquifer's response to draft over time, model runs were made for two Aquifer Sectors and one Aquifer System: Yigo-Tumon Aquifer Sector; Finegayan Aquifer Sector and Ordot Aquifer System. In Yigo-Tumon and Finegayan the simulations represent behavior of the basal lenses; in Ordot parabasal water is considered.

The simulations were transient rather than steady state and are for a 12 year period at different levels of continuous average draft. The cyclical curve of head as a function of time refers to storage head. The graphs of head changes are given in Figures 4-4 through 4-7.Transient simulations do not yield single values for sustainable yield nor, for that matter, do steady state solutions. This is because sustainable yield is dependent on seasonal head change in the transient case and equilibrium head in the steady state case. A judgement must be made about an acceptable head variation for the transient simulation and a safe equilibrium head for the steady state. The annual head change or equilibrium head selected must preserve the quality and quantity of the pumped water for the given continuous average draft.

Figure 4-4 illustrates the transient case for the Finegayan Aquifer Sector. Starting with an initial head of 3.0 feet and monthly recharge rates based on Table 4-1, the head cycle for a variety of drafts to 20 mgd is simulated. As long as draft is less than recharge as an average, head will always be positive.

Head will recover each year just about to 3.0 feet if average draft is 6.0 mgd, and eventually to 2.75 feet if the average draft is 9 mgd. At a draft of 12 mgd the maximum head slips to 2.6 feet, at 15 mgd to 2.5 feet and at 20 mgd to 2.1 feet. The minimums are about 0.5 feet lower. Clearly it would be safe to pump 6 mgd from the Sector, and it is unlikely that a draft of 9 mgd would significantly affect the ability of the lens to supply good quality water. The recommended average draft is 9 mgd, but operational experience in the future may show that somewhat more draft would be allowable. The *NGLS* sustainable yield is 6.38 mgd; current draft is 3.2 mgd. An average draft of 9 mgd would account for 30 percent of the average annual recharge. The seasonal change in head is 0.5 feet.

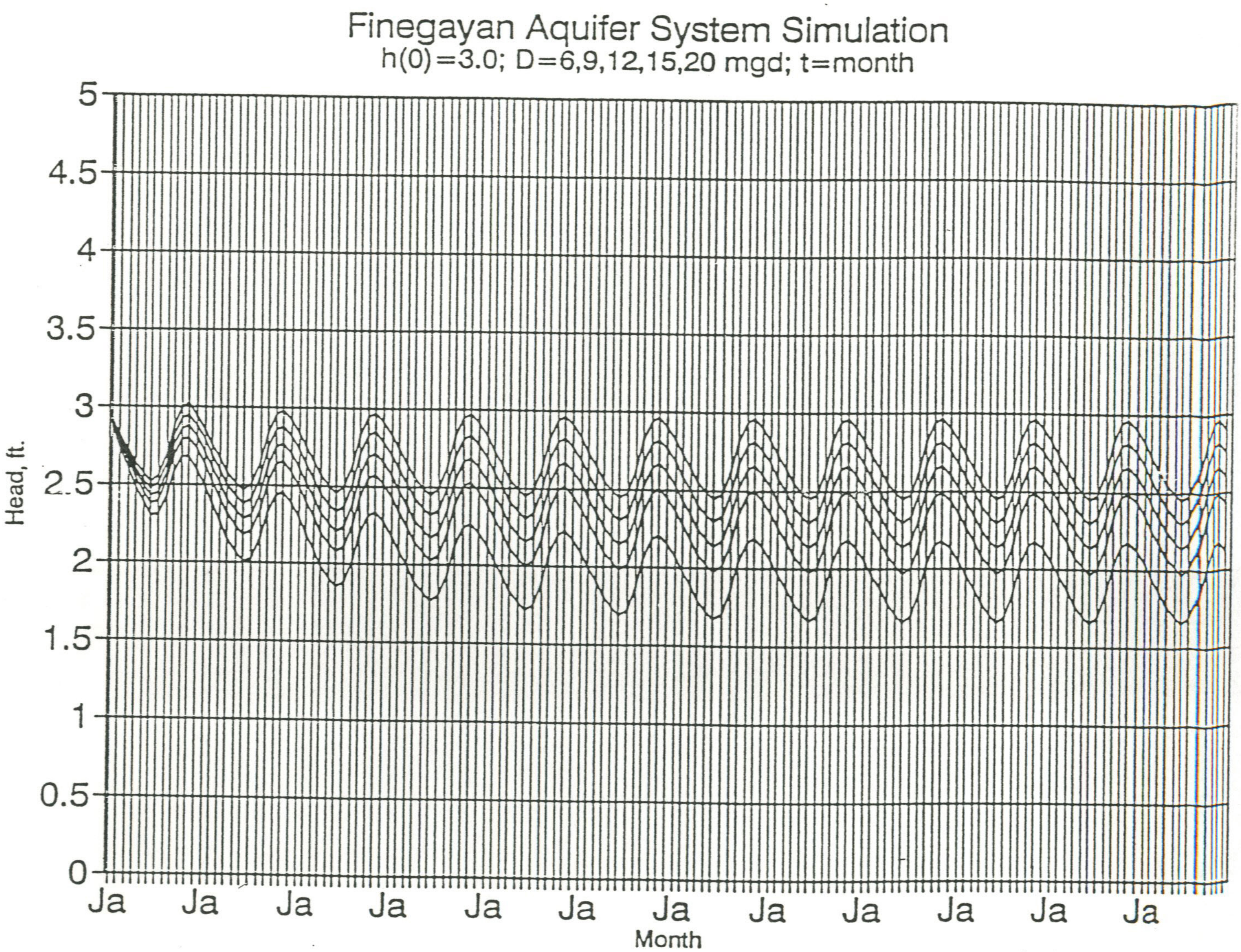


Figure 4-4
Finegayan System
Simulation

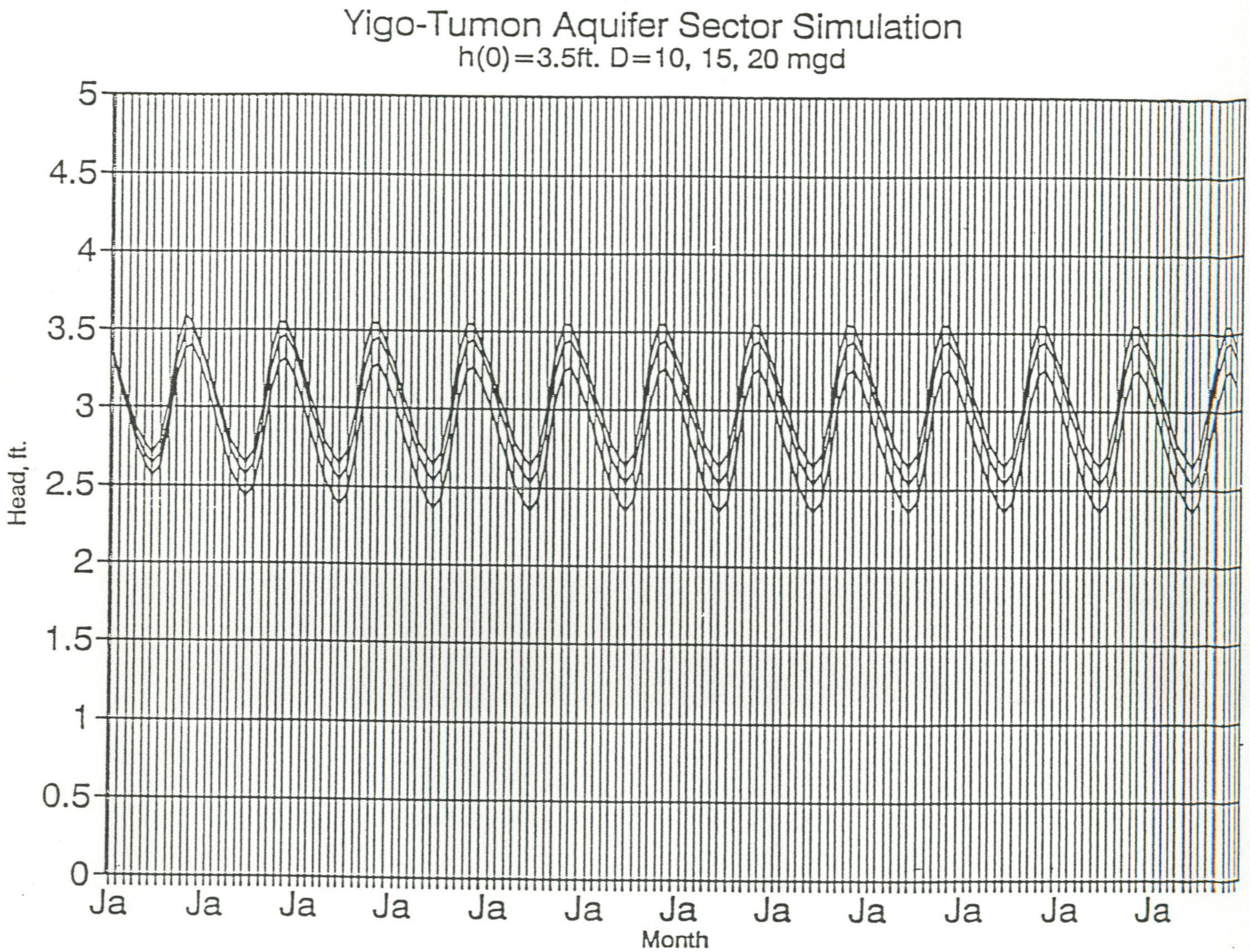


Figure 4-5
Yigo-Tumon Aquifer
Sector Simulation

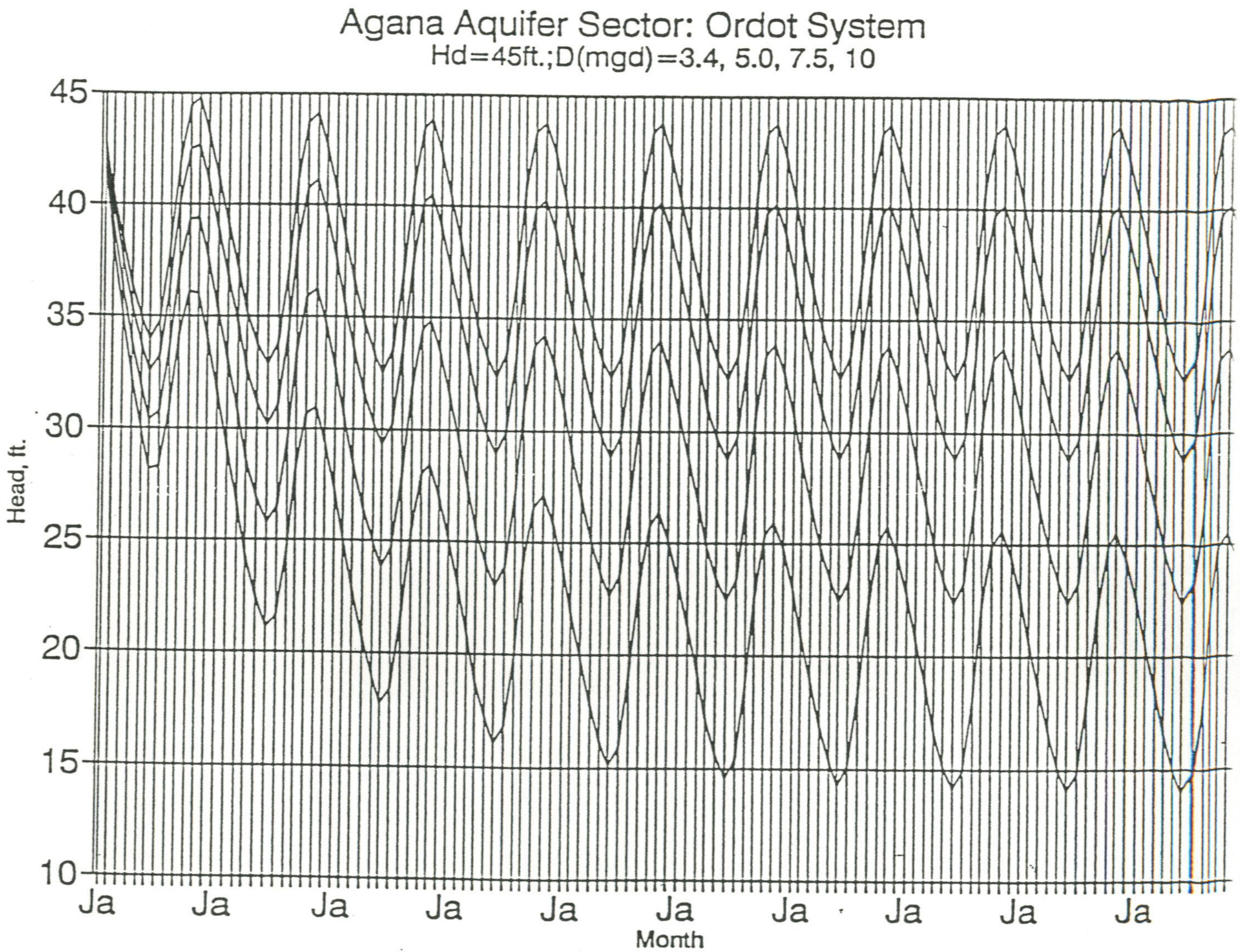


Figure 4-6
Agana Aquifer Sector:
Ordot System,
Hd = 45 Ft.

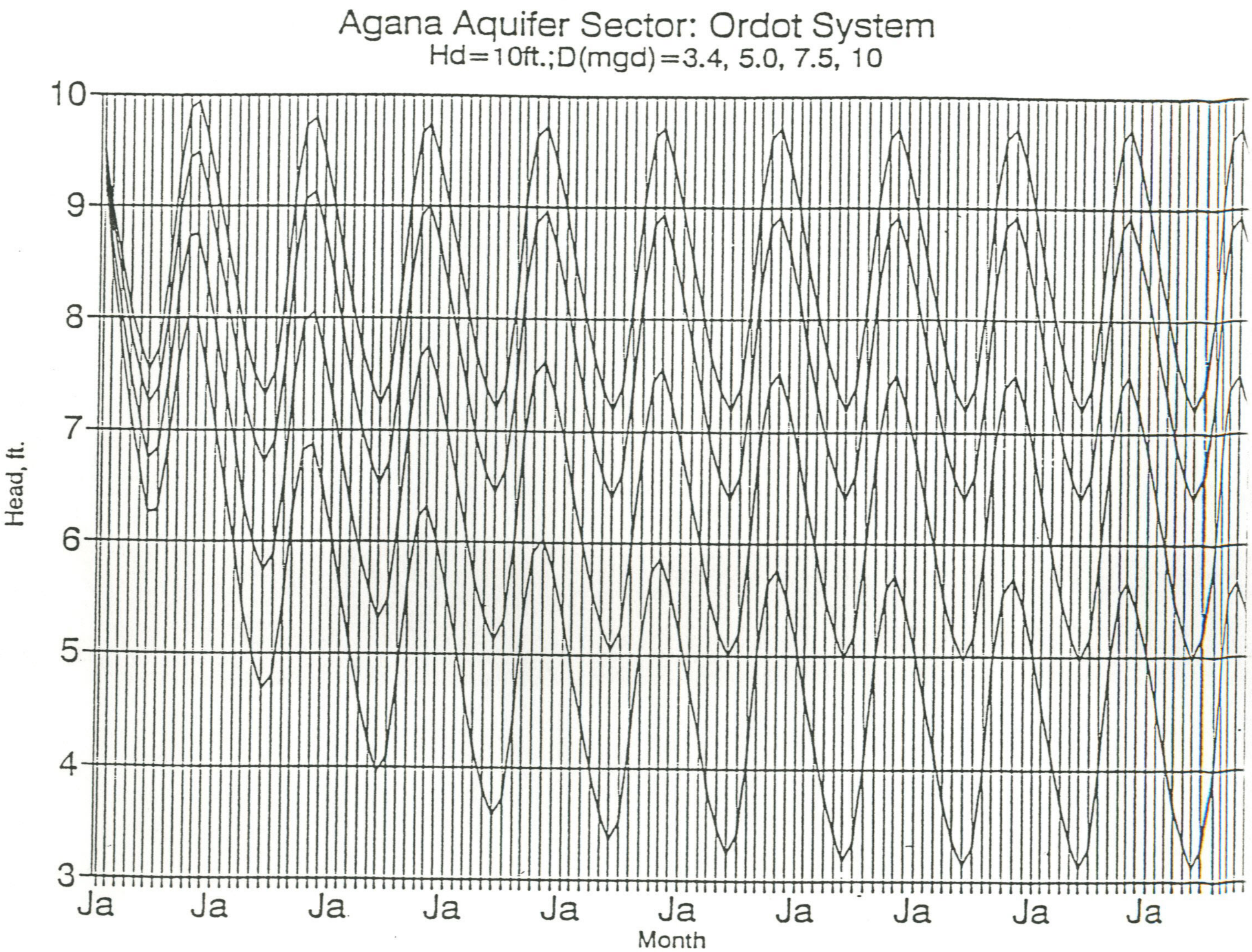


Figure 4-7
Agana Aquifer Sector:
Ordot System
Hd = 10 ft.

In Yigo-Tumon the sustainable yield of 20 mgd also amounts to 30 percent of average annual recharge. The graph in Figure 4-5 indicates that for an initial head of 3.5 feet, full recovery from a seasonal low of 2.7 feet takes place every year when draft is 10 mgd or less. At 15 mgd the low head approaches 2.5 feet and recovery peaks at 3.4 feet, while at 20 mgd the dry season minimum drops to 2.4 feet and the wet season recovery rises to 3.2 feet. Current average draft in the Sector is 11 mgd; the *NGLS* sustainable yield is 19 mgd, about the same as the recommended value.

Simulation of the parabasal groundwater in the Ordot Aquifer System is given in Figure 4-6. The head at Well A-20 is used as an index because head there has been recorded continuously for the past decade. The initial head is taken as 45 feet. The simulated yearly range is 11 feet, which matches the actual record. Decay during the dry season is similar each year unless interrupted by unusual rains. The average cycle settles at a low head of 33 feet for the average current draft of 3.4 mgd; 29.5 feet for a draft of 5 mgd; 23 feet for a draft of 7.5 mgd; and 14.5 feet for a draft of 10 mgd. In every case the head recovers by 11 feet during the wet season.

Also plotted as an Ordot graph (Figure 4-7) is the simulation for a site having an initial head of 10 feet. Because the minimum head of parabasal water is 7 feet near the margin of Agana Marsh, the sustainable yield chosen must not result in heads that would induce sea water intrusion. The simulation depicts an annual variation in head of 2.5 feet, which is characteristic of parabasal conditions where the initial head is less than about 10 feet.

The recommended sustainable yield is 7.5 mgd because at this average draft the parabasal head would be preserved even at the edge of the Marsh. The recommended sustainable yield for this parabasal situation is equal to 60 percent of average annual recharge.

RECOMMENDED AVERAGE DRAFT BY AQUIFER SECTORS AND SYSTEMS

Table 4-2, located at the end of this Chapter, summarizes the sustainable yields proposed for each Aquifer Sector and System. The model simulations for Yigo-Tumon and Finegayan Aquifer Sectors indicate that sustainable yield for a basal lens is equal to about 30 percent of recharge. This fraction is employed elsewhere in Northern Guam where basal conditions exist.

SY = .3 × R

In the *NGLS* a factor of 50 percent was used but it had no basis in hydraulic analysis. Rather, it was assumed at the time as a safety factor since so little was known about the physical boundary conditions of the lens and its response under stress. Similarity among the *NGLS* and currently computed values of sustainable yield is coincidental rather than due to application of similar methodology. The *NGLS* values depend exclusively on a water budget and apply only to that portion of the island at some distance inland where groundwater is presumed to be fresh. The current approach to sustainable yield is wedded to groundwater hydraulics analysis made possible by the monitoring of wells developed since the *NGLS* and supplemented by values for recharge obtained from a water balance. In this method an entire lens is treated as a continuum. The quality of pumped water is governed by location and rate of draft. Where conditions are favorable, good water can be pumped very close to the discharge line of the lens along the coast.

Table 4-2 lists recommended sustainable yields as well as those given in the *NGLS* along with current draft. The table identifies the fraction of sustainable yield not accessible to PUAG because it is restricted to military lands. However, except in Andersen Field, where the flow path of groundwater from origin to discharge takes place in Federal property, virtually all sustainable yield can be accessed by PUAG.

The data in the table is arranged so that the Sub-basins and Management Zones of the *NGLS* correspond to the Aquifer Sectors and Systems in the proposed classification. Consistency in names for the divisions is preserved wherever possible to avoid confusion.

SUMMARY OF DRAFT AND SUSTAINABLE YIELD

The total sustainable yield for all of Northern Guam as stated in the *NGLS* is 57.44 mgd, while in the current study the recommended value for the transient model is 80 mgd and for the steady state model, 70 mgd. In the *NGLS* sustainable yield was calculated as equal to one half the average infiltration determined by hydrologic budgeting for regions lying several thousand inland of the coast. For the current evaluations the entire Northern Guam complex of aquifers, embracing 100 square miles, is considered in the hydraulic model. The complex linkage among recharge, groundwater accumulation and flow, and groundwater extraction can't be arbitrarily limited to the region of putative potable water. The entire flow system is involved.

TABLE 4-2
SUSTAINABLE YIELD
AQUIFER SYSTEMS vs. *NGLS* MANAGEMENT ZONES (mgd)

Sector	System	*NGLS* SB	*NGLS* MZ	*NGLS* SY	Revised SY	SY from Non-Federal Lands	Draft (89)	Unused SY
Agana	Ordot	Agana	Chalan Pago	1.24			1.65	
			Nimitz Hill	2.17			1.74	
			Anigua	1.17			0	
			Total	4.58	7.5	7.5	3.39	4.1
	Mongmong		Toto	0.62			0.02	
			Agana Swamp	1.25			0	
			Total	1.87	2.8	2.8	0.02	2.8
	Barrigada		Mt. Barrigada South	0.30			0	
			Barrigada	0.37			0	
			Coastal	0.45			0.99	
			Total	1.12	3.0	3.0	0.99	2.0
			TOTAL	7.57	13.3	13.3	4.4	8.9
Fadian	Sabana Maagas		Sabana Maagas	1.73	3.0	3.0	1.89	1.1
	Huchunao		Manaca	1.67			0.15	
			Mt. Barrigada East	0.73			0	
			Total	2.40	4.2	4.2	0.15	4.0
			TOTAL	4.13	7.2	7.2	2.04	5.1
Mangilao	Sasajyan	Mangilao	Mangilao South	0.32			0	
			Mangilao North	0.42			1.01	
			Adacao	0.95			0.19	
			Asbeco	0.33			0	
			Taguan	0.30			0.62	
			Sasajyan	0.13			0	
			Total	2.45	3.3	3.3	1.82	1.5
	Pagat		Sabanan Pagat	0.79			0	
			Janum	0.66			0	
			Total	1.45	(3.3)	0	0	0
			TOTAL	3.90			1.82	1.5

* See notes at end of table.

TABLE 4-2 (Cont'd)
SUSTAINABLE YIELD
AQUIFER SYSTEMS vs. *NGLS* MANAGEMENT ZONES (mgd)

Sector	System	*NGLS* SB	*NGLS* MZ	*NGLS* SY	Revised SY	SY from Non-Federal Lands	Draft (89)	Unused SY
Pati	Mt. Santa Rosa	Andersen	Salisbury (1/4)	0.71			0	
			Lupog	1.46			0.01	
			Total	2.17	2.3	2.3	0.01	2.3
	Andersen		Salisbury (3/4)	2.14			0	
			Tarague	1.02			0	
			Anao	0.35			0	
			Andersen	0.56			0	
			Total			0	0	0
			TOTAL	6.24	(9.8)	2.3	0.01	2.3
Tarague	Agafo Gumas	Agafo Gumas	Agafo Gumas Central	4.20	5.0	5.0	0.54	4.5
	Northwest Field		Agafo Gumas West	0.86			0	
			Agafo Gumas East	1.63			0	
			Northwest Field East	3.40			0	
			Total	5.89	(7.0)	0	0	0
			TOTAL	10.09	(12.0)	5.0	0.54	4.5
Finegayan	Gugagon	Finegayan	Callon Tramojo	0.95			0.21	
			Finegayan East	1.09			0	
			Potts	0.86			0	
			Total	2.90	5.0	5.0	0.21	4.8
	Haputo		Northwest Field West	1.25			0	
			Finegayan West	0.63			2.07	
			NCS	1.60			0.72	
			Coastal				0.24	
			Total	3.48	(6.6)	4.0	3.03	1.0
			TOTAL	6.38	11.6	9.0	3.2	5.8

* See notes at end of table.

TABLE 4-2 (Cont'd)
SUSTAINABLE YIELD
AQUIFER SYSTEMS vs. *NGLS* MANAGEMENT ZONES (mgd)

Sector	System	*NGLS* SB	*NGLS* MZ	*NGLS* SY	Revised SY	SY from Non-Federal Lands	Draft (89)	Unused SY
Yigo-Tumon	Yigo	Yigo	Marbo South	0.65			0	
			Marbo North	0.35			0	
			Yigo East	1.08			1.05	
			Mt. Santa Rosa	0.76			0	
			Mataguac	0.88			0	
			Yigo West	1.90			1.75	
			Total	5.62	6.4	6.4	2.80	3.6
			Mt. Barrigada West	1.30			0	
			Mogfog	0.65			0	
			Ysengsong	3.00			0	
			Dededo North	1.93			1.63	
			Dededo South	3.46			5.92	
			Macheche	1.25			0	
			Asatdos	1.92			1.12	
			Coastal				1.34	
			Total	13.51	13.6	13.6	10.01	3.6
			TOTAL	19.13	20.0	20.0	12.8	7.2
			TOTAL			60.1	24.9	35.1

NOTES

Col.1 - Aquifer Sector: The Sector is the largest division in the proposed classification. A Sector is a region of geological and hydrological similarities.

Col.2 - Aquifer System: Each Sector contains one or more Systems. In an Aquifer System groundwater continuity exists throughout. Boundaries between Systems are related to hydrogeological features. Systems incorporate Management Zones of the *NGLS*.

Col.3 - *NGLS* Sub-Basin: The *NGLS* regional divisions corresponding to Sectors. The Agana Sub-Basin is divided into two Sectors (Agana and Fadian) along a boundary to the west of which groundwater flows toward Agana Marsh and the Philippine Sea and to the East to the Pacific Ocean. All other Sector boundaries are identical to Sub-Basin boundaries.

Col.4 - *NGLS* Management Zone: The smallest unit defined in the *NGLS*; currently the basis for allocating groundwater development. In the aquifer classification, Management Zones are subsumed in Aquifer Systems.

Col.5 - *NGLS* SY: The sustainable yield assigned to each Management Zone in the *NGLS*.

Col.6 - Revised SY: The sustainable yield derived for each Aquifer System by means of the transient simulation model. Parentheses around values means that not all of the sustainable yield is accessible by PUAG.

Col.7 - NonFed SY: Sustainable yield which is developable only in Federal lands and is presumed not accessible by PUAG.

Col.8 - Draft(89): Average 1989 pumpage by Management Zones, summed for each aquifer System.

Col.9 - Unused SY: The difference between Col.7 (NonFed SY) and Col.8 (Draft 89). The remaining undeveloped sustainable yield potentially available to PUAG.

Accessible

Not all of the 80 mgd (transient model) is available to PUAG. Development of about 20 mgd falls within Federal property, leaving a total of 60 mgd accessible to PUAG. Current total draft in Northern Guam is 25 mgd (1989), and thus PUAG can add another 35 mgd to its system under prevailing conditions of land control and water development. Experience in Hawaii and Israel suggests that, with optimal well siting and development in the highly transmissible soils of Northern Guam, virtually all of the sustainable yield could be obtained. Only the development of additional production wells and their continued monitoring, however, will determine what percentage of the remaining sustainable yield can be practically retrieved.

Additional opportunities for groundwater development available to PUAG by Aquifer Sector and System along with comments about the ease of obtaining potable water are presented in Table 4-3.

TABLE 4-3
GROUNDWATER AVAILABILITY BY AQUIFER SYSTEM

Aquifer Sector	Aquifer System	Surplus SY (mgd)	Comments
Agana	Ordot	4.1	Parabasal; easy development
	Mongmong	2.8	Basal; salinity problems
	Barrigada	2.0	Basal; salinity problems
Fadian	Sabana Maagas	1.1	Basal; salinity problems
	Huchunao	4.0	Basal
Mangilao	Sasajyan	1.5	Para & basal; good
	Pagat	0	Volc. Basement ASL
Pati	Mt. Santa Rosa	2.3	Para & basal; ?
	Andersen	0	Federal property
Tarague	Agafo Gumas	4.5	Parabasal; good.
	Northwest Field	0	Federal property
Finegayan	Gugagon	4.8	Para & basal
	Haputo	1.0	Basal.
Yigo-Tumon	Yigo	3.6	Para & basal
	Tumon	3.6	Basal
Total		35.3	

CHAPTER V
GROUNDWATER DEVELOPMENT PROGRAM

GROUNDWATER DEVELOPMENT PRACTICES

Sustainable yields are determined for aquifer systems assuming that the extraction of groundwater is accomplished optimally. For each site the extraction unit (generally a well) must be designed and outfitted to provide potable water continuously. In locations where head is low, for example, wells must not penetrate far below sea level and pump capacities need to be modest. Frequently the cost of a low capacity well will not justify drilling. Optimal wells in argillaceous limestone differ from those in clean limestone. The largest successful wells are drilled in parabasal aquifers.

These differences must be addressed when groundwater development is planned. They haven't been considered carefully in the past because a standard well for basal groundwater (depth below sea level 35 feet; pump capacity 200 gpm) generally behaved in an acceptable way. However, in order to safely take full advantage of potential sustainable yield many existing wells should be examined and tested, and for some, depth and capacity will have to be re-adjusted. Each new well will require specifications written especially for it. The standard model is no longer adequate.

FACTORS AFFECTING WELL DESIGN AND CONSTRUCTION

The standard design for a production well in Northern Guam emerged from experience with the first wells drilled for the Government of Guam in Dededo. Tests showed that 200 gpm could be pumped from a well driven 35 to 50 feet below sea level in the basal lens. Because most drilling at that time (between 1965-1975) was concentrated in Dededo, the 200 gpm well became standard for all of northern Guam.

The Dededo well field draws from an aquifer consisting of 'clean' limestone containing a basal lens having an average head of 3.0 to 3.5 feet. Clean limestone is defined as a fossil reef association in which clay is virtually absent. The clean limestones of Northern Guam are almost pure calcium carbonate. These limestones are extremely permeable on a global scale. However, on the local scale of a well bore, low permeability parts of the formation may control groundwater hydraulics. Because of the high regional permeability, heads are low in spite of the strong flux of groundwater. The 200 gpm well proved to be the optimal unit for this modest head basal groundwater environment.

Parabasal groundwater also occurs in the clean limestones of Northern Guam. In this instance the aquifers allow for considerably higher well capacities to take advantage of the high permeabilities of the formations and the absence of sea water intrusion. Parabasal wells in Agafo Gumas and Yigo prove that clean limestone wells can yield as much as 700 gpm. Unless constrained by unfavorable local geology, parabasal groundwater in clean limestone is the most favorable environment in Guam for large capacity wells. Therefore, 700 gpm should be set as the "target" capacity for the future drilling of all clean limestone wells in parabasal lenses. After drilling, testing of each well will determine if it meets the target capacity of 700 gpm. If not, a lower capacity well can be installed in the boring.

Not all of Northern Guam is underlain by clean limestone. About 14 square miles consist of argillaceous limestone of the Mariana formation. This area extends from the contact between the limestone of the north and the volcanics of the south to the 200 feet elevation topographic contour. The argillaceous limestone contains 5 to 10 percent clay intimately compounded with calcium carbonate along with lenses and pockets of clay interbedded in the limestone. The overall effect of the clay is to drastically reduce global permeability and to increase the probability of the occurrence of very low permeability on a local, or well boring, scale. Although groundwater head normally is higher in argillaceous limestone than in clean limestone because of the lower permeability, the standard well is not typically adaptable to this environment. Nevertheless, all of the wells drilled in basal groundwater in argillaceous limestone were designed as if the subsurface environment belonged to clean limestone. Eventually problems of salinity afflict these wells because 200 gpm is too high a pumping rate. When new pumps are required, most will have to be fitted with smaller pumps to ease the threat of increasing salinity.

Parabasal wells in argillaceous limestone can yield 200 gpm and perhaps more, but they can't really attain the production level of parabasal wells in clean limestone. The much lower permeability of the argillaceous limestone causes considerably greater drawdown than in clean limestone for the same pumping rate.

Thus the principal geologic factors affecting well capacity is the 'cleanliness' of the limestone and the position of the volcanic basement. The hydraulic factors are head, especially in basal lenses, and volume rate of groundwater flow. Head is the dominant control because it is a function of hydraulic conductivity, distance inland from the discharge front, usually the coastline, and groundwater flux.

Evaluation of operational data for wells in Guam and analogous situations in the Pacific Islands, including Hawaii, suggest that the following general rules should apply to well capacities in Northern Guam.

1. Condition: clean limestone; basal groundwater.
   a. $h = 3$ to 4 ft.; capacity 180 to 300 gpm.
   b. $h = 2$ to 3 ft.; capacity 80 to 150 gpm.

2. Condition: clean limestone; parabasal.
   a. $h > 4$ ft.; capacity 500 to 700 gpm.

3. Condition: argillaceous limestone; basal.
   a. $h > 5$ ft.; capacity 150 to 200 gpm.
   b. $h = 3$ to 5 ft.; capacity < 150 gpm.

4. Condition: argillaceous limestone; parabasal.
   a. $h > 7$ ft.; capacity 200 to 300 gpm.

WELL PRODUCTION BY AQUIFER SYSTEMS

The potential groundwater production of the Aquifer Systems is discussed in the following sections. The various Aquifer Systems are arranged by the Aquifer Sectors in which they are defined. Reference should be made to Figure 3-1 throughout the following discussions.

Agana Aquifer Sector - Within the Agana Aquifer Sector the Ordot, Mongmong and Barrigada Aquifer systems all have potential for groundwater production.

Ordot Aquifer System - All wells in the Ordot Aquifer System encounter parabasal groundwater in an argillaceous limestone aquifer. Salinity in each well never exceeds about 30 mg/l chloride and normally hovers around 20 mg/l. The wells include A-1, A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-11, A-12, A-23 and A-25. Flow rates range from about 140 gpm to 260 gpm, but each well was fitted with a 40 HP pump expected to produce the standard rate of 200 gpm. Some of the wells can sustain greater rates. Operationally, the most efficient manner of determining whether a higher capacity is allowable is to perform an evaluation whenever a pump is pulled from a well.

Mongmong Aquifer System - The Mongmong System has no wells producing for PUAG. Much of the area is covered by Agana Marsh, which is a groundwater sink. The entire System is composed of argillaceous limestone containing a basal lens which, surprisingly, is not being exploited. Some old wells showed high salinities, but others suggest the possibility of obtaining potable water with modest capacity pumps.

The sustainable yield is more than 2 mgd. A number of wells can be drilled, some equipped with 200 gpm pumps but most with smaller capacities. At monitor well EX-1 the head is quite high, between 6 and 8 feet.

Barrigada Aquifer System - The Barrigada Aquifer System consists of clean limestone in which groundwater occurs in a basal lens having a maximum head of approximately 3 feet. The division between the argillaceous limestone of the Mongmong System and the clean limestone in the Barrigada System roughly follows the trace of the 200 feet elevation contour.

PUAG uses only one well (A-15) in the System. Salinity of the pumped water is moderately good, between 150 and 175 mg/l chloride. Additional wells could be drilled to draw on an unused sustainable yield of 2 mgd.

The System has a reputation for yielding high salinity water, but wells with pump capacities between 100 and 150 gpm should ordinarily yield potable water.

Fadian Aquifer Sector - Within the Fadian Aquifer Sector the Sabana Maagas and Huchunao Aquifer Systems have potential for groundwater development.

Sabana Maagas Aquifer System - Of the seven active wells in the Sabana Maagas Aquifer System, five (A-13, A-14, A-17, A-18 and A-19) exhibit serious salinity problems. The other two (A-9 and A-10) yield water of less than 240 mg/l chloride, the recommended upper limit of potability, although they sometimes approach this limit. All of the wells evidently were expected to produce 200 gpm because they are fitted with 40 HP motors. Actual pumping rates range from about 150 gpm at A-19 to 220 gpm at A-14.

Every well encounters basal groundwater in an argillaceous limestone aquifer. Heads increase from about 3 feet at A-19 to about 4 feet in the vicinity of A-9, A-10 and A-13, the most inland sites. Clearly, installed pump capacity at each well is too large for the hydrogeological environment. Upon re-fitting, each well should be carefully assessed to select a capacity that will not provoke salinity problems. Very likely capacity should not exceed 150 gpm.

Huchunao Aquifer System - No wells produce water for PUAG in the Huchunao Aquifer System. Well A-22 was once active but is no longer used because it pumps too much air.

Virtually the entire System is underlain by a basal aquifer in clean limestone. Much of the land is under Federal control, but enough of an area can be accessed by PUAG to locate well sites. At present only Hawaiian Rock Products pumps water, one well (HRP-1) at about 600 gpm and the other (HRP-2) at about 250 gpm. The quality of the water is surprisingly good considering the high capacities of the wells and proximity to the coastline. GEPA reports that in 1989 a sample from HRP-2 contained 382 mg/l chloride and one from HRP-1 only 148 mg/l (the capacity of each well suggests that the values are reversed).

The System provides an opportunity for PUAG to develop additional supplies by means of wells having capacities between about 100 and 200 gpm.

Mangilao Aquifer Sector - Within the Mangilao Aquifer Sector the Sasajyan Aquifer System has limited potential for groundwater development and the Pagat system has negligible potential for development.

Sasajyan Aquifer System - The Sasajyan Aquifer System lies on the Pacific Ocean side of the subsurface ridge forming the western divide of the Yigo Trough. The divide runs from Ypao Peninsula to Mt. Santa Rosa. The System has a complicated hydrogeology that embraces both basal and parabasal groundwater.

Six M series wells along with EX-11 supply PUAG. Four of them (M-3, M-4, M-8 and M-9) and EX-11 are either parabasal or transitional between basal and parabasal. The wells were designed to yield 200 gpm but most average between 150 and 200 gpm.

Another 1.5 mgd can be pumped from the System by means of parabasal and basal wells. If basal, capacities will be 100 to 150 gpm; if parabasal, 300 to 500 gpm.

Pagat Aquifer System - Except for a narrow zone along the coast the volcanic basement throughout the Aquifer System lies above sea level, a condition which precludes the accumulation of developable groundwater. At this time there is no reason to consider the System as a potential source of groundwater production.

Janum Spring flows off the subsurface contact between the limestone and the basement volcanics. Its flow cannot be intercepted by wells placed up gradient because the volcanics rise above sea level.

Pati Aquifer Sector - The Pati Aquifer Sector is divided into two Aquifer Systems, Mt. Santa Rosa and Andersen, but only Mt. Santa Rosa is available for development by PUAG. The Andersen System lies entirely in Andersen Air Force Base.

Mt. Santa Rosa Aquifer System - No producing wells are located in the Mt. Santa Rosa System. Recent TDEM surveys suggest that both parabasal and basal groundwaters exist and are developable. Exploratory wells are needed. As much as 2 mgd may be available with properly designed wells.

Andersen Aquifer System - The entire area of the System is part of Andersen AFB. The dividing line between the Andersen and Mt. Santa Rosa Systems was drawn along the property boundary for convenience. A fine opportunity exists for the Air Force to develop water within the Andersen System.

Tarague Aquifer Sector - Like the Pati Aquifer Sector, the Tarague Sector is divided into two Aquifer Systems, one of which (Agafo Gumas) is available to PUAG for development, and the other of which (Northwest Field) lies in Federal property.

Agafo Gumas Aquifer System - In most of the Agafo Gumas System the volcanic basement lies above sea level, eliminating groundwater development opportunities. However, parabasal groundwater occurs in a subsurface trough near Route 9 and is developed by well AG-2. A well across the highway, AG-1, appears to be in groundwater transitional between parabasal and basal conditions. In addition to the PUAG wells, two golf course wells produce high quality parabasal water. These golf course wells consume an important fraction of the sustainable yield.

Wells AG-1 and AG-2 are undersized at about 200 gpm relative to the capacity of the parabasal aquifer to yield water. The golf course wells, on the other hand, successfully exploit the aquifer with 700 gpm wells. The capacity of the PUAG wells should be increased when the pumps are pulled for replacement. A capacity range of 500 to 700 gpm is justified in the parabasal area. At 10 inches in diameter, both AG-1 and AG-2 may be adequately sized to permit the desired flow of 700 gpm. However, to ensure that the diameter of the existing borings does not limit the capacity of the wells, sounding of the casings should be performed upon pulling the pumps to determine the maximum possible yield. If less than 700 gpm, the wells would need to be reamed to enlarge their diameters, then tested again to determine their increased capacities.

Details about the configuration of the volcanic basement have been revealed by recent TDEM surveys. These details will be helpful in locating exploratory and producing well sites.

Northwest Field Aquifer System - Although the Air Force does not have active wells in the Northwest Field System, opportunities for production wells exist. Both parabasal and basal groundwater may be exploited.

Finegayan Aquifer Sector - The Finegayan Sector is divided into two Aquifer Systems, Gugagon and Haputo. Both systems have potential for groundwater development although significant portions of each lie within the Andersen Air Force boundaries.

Gugagon Aquifer System - The Gugagon Aquifer System has been differentiated from the larger Haputo Aquifer System as a result of reinterpretation of the volcanic basement configuration employing original data from seismic work performed during the *NGLS* combined with recent TDEM surveys. In a large extent of the Gugagon System the basement lies above sea level, but a narrow zone evidently contains parabasal groundwater. Also within the System is an area of basal groundwater which is continuous with the basal lens of the Haputo System.

Wells F-8 and F-9, the former definitely parabasal and the other either parabasal or transitional to it, produce water for PUAG. The average yield of each is about 150 gpm, but presumably they were drilled to give 200 gpm each. Their capacities can be increased, perhaps to as much as 500 gpm.

Exploratory wells have been recommended to test for parabasal occurrences. An additional yield of nearly 5 mgd may be obtainable.

Haputo Aquifer System - Basal groundwater occurs throughout the System and is exploited by both PUAG and the Naval Communication Station (NCS). Of the nine active PUAG wells (F-1, F-2, F-3, F-4, F-5, F-6, F-7, F-10 and F-11), three (F-4, F-6 and F-10) occasionally experience salinity in excess of the recommended limit of 240 mg/l chloride, but the others yield moderate to low salinity water. The wells apparently were designed to produce 200 gpm. Average production rates are usually less than 200 gpm except for F-1 and perhaps F-2.

Where the wells are located, head in the basal lens is about 3 feet, which is high enough to allow pump capacities of 150 to 200 gpm for production of potable water.

The NCS wells are pumped at an average rate of 150 to 200 gpm and, like the PUAG wells, apparently were developed to yield 200 gpm. One of the wells (NCS1A) sometimes exceeds the recommended salinity limit, but the other two always meet the standard.

PUAG can obtain another 1 mgd from the Haputo System even though most of its area lies inside NCS and Andersen Air Force Base.

Yigo-Tumon Aquifer Sector - The most voluminous and easily developed groundwater resources in Guam occur in the clean limestone aquifers of the subsurface trough which starts at Yigo and discharges into Tumon Bay. The trough is a remarkably efficient collector and transporter of groundwater. Its axis follows an arc from about the center of the coastline at Tumon Bay through Dededo to closure between the exposed volcanic highlands of Mataguac and Mt. Santa Rosa. Recharge flows along the top of the basement volcanics where they rise above sea level to the trough axis and eventually to the sea coast as a basal lens.

The Sector is divided into two Aquifer Systems. The Yigo System constitutes the most inland portion of the trough where groundwater is predominantly parabasal. The Tumon System embraces the mid and coastal portions where groundwater is chiefly basal, though on the flanks of the trough some parabasal sections may exist.

The Sector is the primal source of water supply for Guam and its aquifers are the most intensively exploited in the island. Nevertheless a surplus of sustainable yield exists that can be developed easily.

Yigo Aquifer System - Of the nine wells in the Yigo Aquifer System, six are parabasal (Y-2, Y-3, Y-4, Y-6, Y-7 and Y-9) and the other two (Y-1 and Y-5) appear to be transitional between basal and parabasal. Wells Y-1 through Y-6 are pumped at rates of 200 gpm or less, consistent with their design. Wells Y-7 and Y-9 have larger pumps, with Y-9 pumping as much as 400 gpm.

The parabasal wells can yield more than 200 gpm, and when each needs to be re-equipped a larger pump size should be considered. In addition several new wells can be drilled to take advantage of the surplus sustainable yield of nearly 4 mgd in the System.

Tumon Aquifer System - The Tumon Aquifer System is being exploited by about 40 wells and one infiltration gallery, but its sustainable yield is still not fully developed. The infiltration gallery and eight wells supply water to Andersen and military activities associated with it. About 30 wells are used by PUAG, and the remaining few are private.

The first wells drilled for PUAG about 25 years ago were located in Dededo and belong to the D series. These wells have been extremely successful in providing low salinity groundwater at pumping rates of about 200 gpm from a basal aquifer having a head of 3 to 3.5 feet. They are placed near the axis of the Yigo Trough where the flux of groundwater in the highly permeable clean limestone is unusually strong. All of the D series wells follow the standard design for providing 200 gpm. Additional similar wells can be drilled to exploit the remaining surplus sustainable yield amounting to nearly 4 mgd.

The M series wells, along with EX-5A and GH-501, also yield low salinity water at pumping rates of 150 to 200 gpm. Like the D series, these wells take advantage of the strong flux of groundwater moving along the axis of the Yigo Trough.

The MW series, belonging to the Air Force, exploit the low salinity groundwater associated with a basal zone in close proximity to parabasal water. In spite of having pump capacities of 200 to 475 gpm, these wells yield low salinity water. At the terminus of the System near Tumon Bay the Air Force infiltration gallery supplies on the order of 1 mgd of low salinity basal groundwater.

The importance of the Yigo-Tumon Aquifer Sector can't be overemphasized. It is the heart of PUAG's water supply. It is already intensively developed, and of its estimated sustainable yield of 20 mgd, an average of about 13 mgd is being pumped. The reliability of this resource must be protected because of its dominating importance in supplying not only the civil economy of Guam but also Air Force activities.

WELL FAILURE AND REDEVELOPMENT

A well's inability to produce water of acceptable salinity (usually less than 150 mg/l chloride) at a feasible rate (usually more than 50 to 100 gpm) is normally manifested during initial testing following completion of drilling, but frequently failure takes place after a period of successful operation. A newly drilled well will fail if the position of the volcanic basement prevents the foundation of a saturated aquifer in limestone, or, should saturated limestone exist, the penetration of the well bore is either too deep, inducing upconing of the transition zone, or too shallow, not allowing sufficient surface area to accommodate inflow into the well. As a general rule, near-wasted areas are not likely to yield potable water because the groundwater in the basal lens consists mainly of the transition zone.

Wells that were initially successful but begin to fail after a period of operation often may be rehabilitated by reconfiguring well construction and reducing pump capacity. Reduction in well performance may be due to: 1) the length of time required for equilibrium between pumping rate and flow lines orientation to come about; 2) clogging of screen openings by calcium carbonate precipitation, or rearrangement of particles, including the gravel pack, at the screen interface; and 3) general failure of well construction including loss of gravel pack and collapse of the casing.

For cases where equilibrium is slowly achieved, ending in higher than acceptable chloride content, the depth of penetration of the well by back-filling with grout is a possible remedy. Where clogging is the obvious problem, acidizing the screen to dissolve calcium carbonate precipitate is the usual corrective method. The standard screen is made of stainless steel, which resists corrosion.

For wells that lose efficiency or yield brackish water as a result of general failure, abandonment and replacement with a new well is often a better resolution than attempting to rescue the failed well.

As noted earlier, the standard well capacity (200 gpm) is not suitable for all hydrogeological environments in northern Guam. When a pump fails and must be replaced, the record of well behavior should be studied before deciding on replacement capacity. In fact, upon pulling a pump the well should be sounded and the casing and screen observed by means of a TV scan to ascertain whether acidizing and other actions are justified.

The range of permissible pump capacities in northern Guam is not great, and an effort should be made to have several sizes in inventory. At the high end a 700 gpm pump in a parabasal aquifer may work, but these instances are likely to be too few to justify an inventory of extra large pumps. At the low end, however, the specification of a 100 gpm pump is likely to be frequent enough to mandate an inventory. The 200 gpm pump will continue to be the most common capacity adaptable to a wide range of conditions.

The failure of a well by no means implies the collapse in the ability of an aquifer to yield good water in reasonable amounts. The behavior of an individual well is dominated by local conditions whereas the behavior of an aquifer is a regional phenomenon. A single well in the center of a brightly productive aquifer may pump excessive salinity water if local variability promotes flow lines to travel vertically from the transition zone to the well bore, even or adjacent wells produce low salinity water. Well D-13 in the Dededo well field is a good example of this phenomenon; evidently the local permeability favors vertical movement of groundwater, perhaps by way of fractures that are not present at the other D-series wells.

Because of the dominance of local aquifer features in such a heterogeneous medium as fossil reef limestone, each well must be judged by its own performance. Adjustments are made, if needed, on this basis. Even in areas where salinity is presumed to be high because of proximity to the coast, properly designed low capacity wells often produce potable water.

ALTERNATIVE METHODS OF GROUNDWATER PRODUCTION

Except for groundwater production from the USAF Tumon Tunnel and the capture of Asan Spring flow, all potable water in Northern Guam is extracted by means of drilled wells. Asan Spring yields perched groundwater from an isolated limestone aquifer resting on volcanic rock and is not part of the Northern Guam aquifer systems. At one time several basal groundwater exposures in limestone sink holes near Tarague were tapped by the USAF. Janum and Campanaya Springs, also exposures of basal groundwater on the coastal shelf, were used by local residents. The US Navy for many years obtained a supply from parabasal groundwater springs at the margin of Agana Marsh. When the success of drilled wells was proved, spring capture was abandoned.

Basal and parabasal springs, however, are a potential source of potable water. Janum Spring in the Pagat Aquifer System has a flow estimated at 1 to 2 mgd of low salinity water. An exploratory boring was once drilled inland of the spring in an attempt to intercept groundwater but encountered the volcanic basement above sea level. The Camapanaya basal spring at the boundary of the Sasajyan and Pagat Systems was used by the Japanese occupation forces but yielded water having about 600 mg/l chloride. Better development techniques might improve output. Tarague Spring reliably provided groundwater with 300 to 350 mg/l chloride, higher than the recommended limit but indicative of an opportunity to obtain a lower salinity supply by using better techniques of withdrawal.

All of the coast of Northern Guam can be regarded as a continuum of basal springs because the lens discharges virtually at the coastline. The springs are exposures of groundwater in sink holes and caves. Where groundwater flux is strong, the "springs" yield low chloride water.

Basal groundwater springs can be created by constructing infiltration galleries. An infiltration gallery consists of tunnels and cavities excavated at about sea level. Fresh water drains into the galleries, then flows to a sump from where it is pumped. A large tunnel surface below the water table allows drainage of low salinity water from the fresh water core of the lens. The premier example of this concept, and the only infiltration gallery in use today, is the Air Force Tumon Tunnel. Its success depends on location at the terminus of the Yigo Trough where the undeveloped flux of groundwater is strong as it moves to discharge at the coast. The other infiltration gallery, the ACEORP Tunnel, is located in the Barrigada Aquifer System but is not used because of the unacceptable salinity of its pumped water. The groundwater flux passing the collection gallery is far inferior to that in the Yigo Trough.

Infiltration galleries are expensive to construct and the risk of failure is significant. They are restricted in location to coastal areas because even at short distances inland the ground surface becomes too high to permit excavation to sea level unless a deep shaft is dug. Of the few locations in Northern Guam where a successful infiltration gallery can be constructed, the most favorable is in the coastal terrace on the south side of the Tumon Aquifer System.

One more potential groundwater collecting system has merit. The Agana Marsh is sustained by groundwater from the parabasal aquifers of the Ordot Aquifer System and the basal groundwater of the Mongmong System. The parabasal groundwater was at one time developed by the US Navy at Agana Spring. Behind the Spring, drilled wells have been located to intercept a portion of the water that naturally drains to the marsh. Additional groundwater on both the parabasal (Ordot) side and the basal (Mongmong) side may be developable by means of drainage collectors.

PROPOSED WELL DEVELOPMENT PRIORITIES

The unused sustainable yield of the aquifers of northern Guam accessible by PUAG totals 35 mgd. This value is an estimate founded on the analyses discussed in the main body of the report which take into account the response of the aquifers to operation over the last decade, simulation and prediction of groundwater behavior by modeling, and TDEM surveys in some regions. Not all of the 35 mgd will be easy to develop. A portion may elude cost effectiveness and its capture may never come about. However, additional groundwater can be safely produced in the first priority increment of about 10 mgd and in the second increment, 5 mgd. When this total of 15 mgd is on line, another priority list can be established. The development of the first 15 mgd will determine the next set of priorities.

In the following table additional production is recommended by Aquifer Systems. The first priority increment includes 2 mgd from the Agafo Gumas system in the Tarague Sector; 2 mgd from the Yigo System and 1.5 mgd from the Tumon System in the Yigo-Tumon Sector; 2 mgd from the Gugagon system in the Finegayan Sector; and 2 mgd from the Ordot System in the Agana Sector. The second priority increment includes production from the Mt. Santa Rosa System in the Pati Sector, the Sasajyan System in the Mangilao Sector, the Huychunao System in the Fadian Sector and the Mongmong System in the Agana Sector. Details are listed in Table 5-1. Both first and second priority well fields are shown in Figure 5-1 at the end of this report.

TABLE 5-1 PRIORITY DEVELOPMENT BY AQUIFER SYSTEMS						
Sector	System	Unused SY (mgd)	Add (mgd)	Aq. Type	Well (gpm)	No. Wells
Priority 1						
Tarague	Agafo Gumas	4.5	2.0	PB	300	5
Yigo-Tumon	Yigo	3.6	2.0	PB/B	300	5
Yigo-Tumon	Tumon	3.6	2.0	B	200	5
Finegayan	Gugagon	4.8	2.0	PB/B	200	7
Agana	Ordot	4.1	2.0	PB	250	6
			9.5			28
Priority 2						
Pati	Mt. Santa Rosa	2.3	1.0	PB/B	200	4
Mangilao	Sasajyan	1.5	0.5	PB/B	150	2
Fadian	Huchunao	4.0	2.0	B	150	10
Agana	Mongmong	2.8	1.0	B	150	5
			4.5			21
TOTAL			14.0			49

Notes
Col. 4 (Add mgd): Recommended additional development.
Col. 5 (Aq. Type): PB = parabasal; B = basal.
Col. 6 (Well gpm): Estimated well capacity for the aquifer type. Actual installed capacity will depend on pump testing.

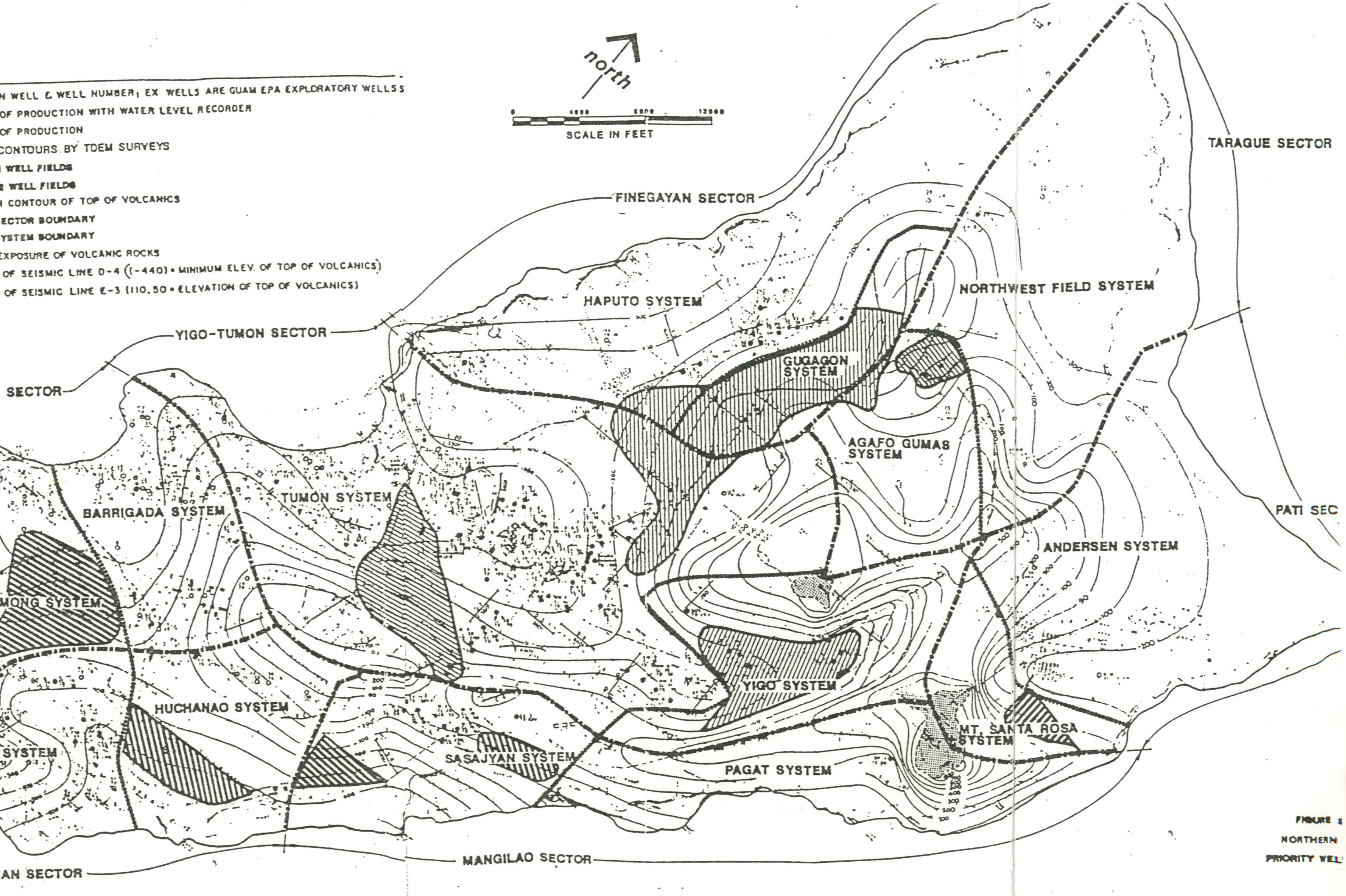
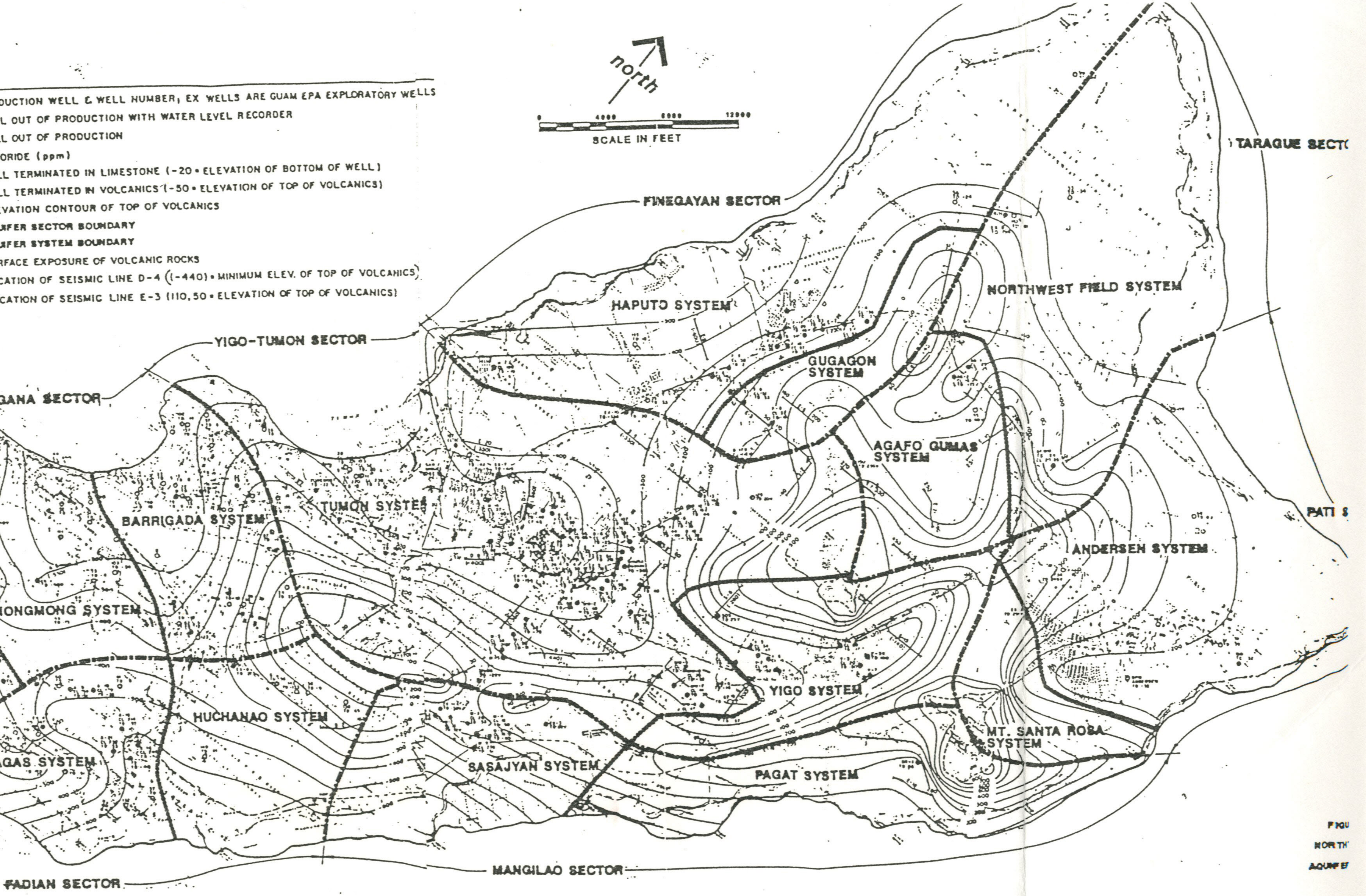


FIGURE 5
NORTHERN
PRIORITY WEL


DUCTION WELL & WELL NUMBER; EX WELLS ARE GUAM EPA EXPLORATORY WELLS
L OUT OF PRODUCTION WITH WATER LEVEL RECORDER
L OUT OF PRODUCTION
ORIDE (ppm)
L TERMINATED IN LIMESTONE (-20 = ELEVATION OF BOTTOM OF WELL)
L TERMINATED IN VOLCANICS (-50 = ELEVATION OF TOP OF VOLCANICS)
VATION CONTOUR OF TOP OF VOLCANICS
UIFER SECTOR BOUNDARY
UIFER SYSTEM BOUNDARY
RFACE EXPOSURE OF VOLCANIC ROCKS
CATION OF SEISMIC LINE D-4 ((-440) = MINIMUM ELEV. OF TOP OF VOLCANICS)
CATION OF SEISMIC LINE E-3 (110, 50 = ELEVATION OF TOP OF VOLCANICS)
north
0
4000
8000
12000
SCALE IN FEET
TARAGUE SECT
FINEGAYAN SECTOR
NORTHWEST FIELD SYSTEM
HAPUTO SYSTEM
YIGO-TUMON SECTOR
GUGAGON SYSTEM
GANA SECTOR
AGAFO GUMAS SYSTEM
TUMON SYSTE
BARRIGADA SYSTEM
PATI S
ANDERSEN SYSTEM
IONGMONG SYSTEM
YIGO SYSTEM
HUCHANAO SYSTEM
MT. SANTA ROSA SYSTEM
GAS SYSTEM
SASAJYAN SYSTEM
PAGAT SYSTEM
MANGILAO SECTOR
FADIAN SECTOR
FIGU
NORTH
AQUIFE

APPENDIX A

Hydrologic Budgets

Sustainable Yield by Steady State Model

HYDROLOGIC BUDGET FOR NORTHERN GUAM

The goal of hydrologic budgeting is to determine a mass balance among input and output variables in the hydrologic cycle. Input variables include rainfall along with other atmospheric moisture sources, and fluxes across boundaries in the region of interest. These fluxes are surface water and groundwater. Output variables consist of direct surface runoff, evapotranspiration from vegetation, and deep percolation. Rainfall and runoff are often known to some degree of accuracy as a result of measurements. Evapotranspiration is approximated from theoretical and empirical models, and infiltration is normally solved for as the unknown variable that closes the balance equation.

Islands, with their finite terminal boundaries, are good candidates for computing hydrologic budgets on a global scale because input flows across boundaries are absent, leaving atmospheric moisture as the sole input parameter. In the case of Guam, the only atmospheric moisture component of significance is rainfall.

Guam is really composed of two different islands sutured together along a geological contact extending from Pago Bay to Agana. Each unit is about 100 square miles in area, and because of geology each may be treated as a separate global entity. In the north are the great, highly permeable limestone aquifers that are the principal sources of water supply for the whole island, while the south is dominated by poorly permeable volcanics for which the most voluminous output variable is streamflow.

Groundwater resources in the south constitute only a small fraction of the island's developable water supply, but stream flow is large. Good records of rainfall and stream flow measurements are available from which hydrological principles applicable to the whole island can be extracted. In computing hydrologic budgets, the input variable rainfall and the output variable evapotranspiration are about the same for North and South Guam, but the output variables of surface runoff and groundwater flux are vastly different.

GLOBAL HYDROLOGIC BUDGET OF NORTHERN GUAM

Hydrological mass balances for Northern Guam have been proposed by numerous investigators employing a variety of methods. The balances were attempted in order to calculate the infiltration component because in the north the only developable water resource is groundwater. In 1937, H.T. Stearns, the first to attempt a hydrologic budget, suggested that 50 to 100 mgd of groundwater could be extracted from the north (H.T. Stearns, 1937, Geology and Water Resources of the Island of Guam, Mariana Islands: Manuscript Report to U.S. Navy). Shortly after World War II a U.S. Geological Survey report concluded that 15 mgd was safely developable (Ward, P.E., Hoffard, S.H., and Davis, D.A., 1965, Hydrology of Guam, U.S. Geological Survey Professional Paper 403-H).

In a study completed in 1976 for PUAG, two hydrologic budgets were calculated, one employing evaporation as the equivalent of evapotranspiration and the other deducing evapotranspiration from the water budget for Southern Guam (Mink, J.F., 1976, Groundwater Resources of Guam: Occurrence and Development: Univ. Guam Water Resources Research Center Tech. Report 1). In the *Northern Guam Lens Study (NGLS)* (1982) a budget was derived based on a theoretical determination of evapotranspiration, and as part of the study the Water, Energy Research Institute (WERI) of the University of Guam produced a partial budget in which infiltration was computed by relating the gain in salinity in groundwater to salinity in rainfall and attributing the difference to the effects of evapotranspiration.

Each method is an approximation based on assumptions combined with a body of measured data for rainfall, pan evaporation and stream flow. The unknowns in every case are evapotranspiration and infiltration. Runoff from the northern limestones is very small and is either ignored or assigned a small value. Because groundwater is the sole resource of interest, equations are solved to yield infiltration.

The fundamental balance equation for Northern Guam is:

$$P = R + ET + I$$

in which P is average rainfall, the only input variable; R is runoff, which is close to zero because of the high infiltrability of the limestone terrain; ET is evapotranspiration, or loss of moisture to the atmosphere; and I is infiltration to groundwater. This equation is for the steady state in which input is equal to output. The change in volume of groundwater does not enter the equation until groundwater withdrawals by artificial means take place.

Rearranged to solve for I the equation is:

$$I = P - R - ET$$

P is known from rain gage records, R is either ignored or taken as 5% of P, and ET is estimated by various methods. The solution for I is singularly dependent on the value assigned to ET. The differences in computed values of I among different investigators are a result of the value given to ET by each.

Table 1 is a summary of attempts to create a global hydrologic budget for Northern Guam. The budgets taken from Mink (1976) uses a total limestone area for Northern Guam of 94.6 square miles, which is virtually the entire north half of the island. The *NGLS* (1982) budget refers to only 67.24 square miles, which is the area where it was assumed that potable water is developable. Information obtained on the Lens since the *NGLS* indicates that this restriction of area understates total input. The alternate balances were recomputed from the Mink budgets by altering some parameters and employing the total area of Northern Guam (100.3 square miles), or the area inland of a zone 0.5 miles in width from the coast, leaving an input area of 80.1 square miles.

The Mink budgets are developed and explained in detail in the 1976 report. The minimum budgets assume the most conservative conditions wherein evapotranspiration is assumed to be equivalent to pan evaporation. This, of course, is not realistic because moisture is not constantly available to plants. Much of the wet season rainfall quickly transits the thin soil to infiltrate rapidly while in the dry season insufficient rain falls to support potential evapotranspiration.

TABLE 1 NORTHERN GUAM HYDROLOGIC BUDGETS					
Budget	Area (sq.mi.)	P (in/yr)	ET (in/yr)	R (in/yr)	I (mgd)
Minimum (Mink)	94.6	94.7	67.4	0	129
Minimum (Mink)	94.6	94.7	66.9	4.7	109
Probable (Mink)	94.6	94.7	42.8	0	232
Probable (Mink)	94.6	94.7	42.5	4.7	212
NGLS	67.2	94.0	59		112
Alternate 1	100.3	90.0	45	0	215
Alternate 2	100.3	90.0	45	4.5	193
Alternate 3	80.1	90.0	45	0	172
Alternate 4	80.1	90.0	45	4.5	155

Notes:
P = average annual rainfall
ET = average annual evapotranspiration
R = average annual surface runoff
I = average annual infiltration to groundwater

One of the minimum budgets assumes no runoff and the other allows for 5 percent runoff. The computed values of infiltration (129 and 109 mgd, respectively) are understated because of the excessive value assigned to evapotranspiration (67.4 in./yr.)

The "probable" budgets are a considerable improvement on the minimum budgets and are the most accurate of the postulated budgets because of the straightforward methodology employed. The balance takes advantage of the excellent USGS stream gage data for Southern Guam where 61.6 percent of rainfall leaves the land as stream flow. The stream flow is predominantly direct overland flow (about 85 percent) with the remainder derived from groundwater seepage. It is a fair assumption to equate the ratio of runoff to rainfall in the south to infiltration to rainfall in the north, leaving the balance of rain for evapotranspiration. This assumption is reasonable because only a very small quantity of groundwater escapes from the low permeability volcanic aquifers directly into the sea as seepage. Otherwise all of the output from the volcanic drainage basin is known because stream flow is accurately measured and evapotranspiration is the difference between rainfall and runoff.

The calculated evapotranspiration in the probable budget is 42.79 in./yr. This amount is consistent with values commonly assigned to humid tropical areas where average annual rainfall exceeds 60 inches (L.A. Bruijnzeel, 1990, Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review: UNESCO Hydrology Program).

Infiltration in Northern Guam for the probable budget is 232 mgd when no allowance is made for loss by surface runoff, and 212 mgd when runoff is taken as 5 percent of the rain. These values refer to a total area of 94.6 square miles.

The *NGLS* budget limits the infiltration intake area to 67 square miles, only two thirds of the total area of Northern Guam, and assigns an evapotranspiration rate of 59 inches per year. This rate is theoretical and is calculated by the Blaney-Criddle method. Both assumptions are very conservative and restrict the estimate of infiltration to only 112 mgd. Adjusted for the entire area of Northern Guam the comparable infiltration would be 167 mgd. It will become clear later why the entire area of intake must be considered when deriving estimates of yield based on groundwater flow hydraulics. Knowledge of the Lens obtained from monitoring wells not available at the time of the *NGLS* indicates that the aquifers are hydraulically continuous from the coast inland to their termination by the volcanic basement. The allowable rate of groundwater withdrawal depends on an equilibrium head which preserves the integrity of the resource. Head is therefore governed by input over the entire area of the aquifer, not just the area declared suitable for potable water development.

The evapotranspiration value used in the *NGLS* budget is high, about 88 percent of the pan evaporation rate employed in the "minimum" budget and 16 inches greater than the annual average used in the "probable" budget. The high evapotranspiration value was supported by the calculation for infiltration based on salinity of rain water and groundwater, but this calculation ignores the dry salt deposited on the surface of the ground which becomes entrained in the water that percolates through the soil to add another increment of salt to the groundwater.

The two alternate budgets essentially are recalculations of the "probable" budget substituting areas of either 100 square miles, the whole of Northern Guam, or 80 square miles, the envelope of land lying 0.5 miles inland of the coast. Evapotranspiration was assigned a value of 45 inches per year, slightly higher than the 43 inches in the "probable" budget. Calculated infiltration ranges from a low of 155 mgd for the 80 square miles area and 5 percent runoff to 215 mgd for 100 square miles and zero runoff.

SUMMARY OF GLOBAL HYDROLOGIC BUDGETS

In the budgets discussed above, calculated infiltration rates range from 109 mgd to 232 mgd for Northern Guam. The 109 mgd is from Mink's "minimum" budget and is similar to the conservative estimate of 112 mgd given in the *NGLS* report. Both are unreasonably low and reflect the limited data on the Lens's behavior available at the time.

More reasonable values fall in the range 155 mgd to about 215 mgd. For purposes of deriving sustainable yields, infiltration is given a low value of 175 mgd and a high value of 200 mgd. Note that sustainable yield is not equal to infiltration; it is only a fraction of it, and for the basal aquifers of Northern Guam this fraction is no more than about one third.

SUSTAINABLE YIELD

The hydrologic balances summarized above include very large values as groundwater recharge. Only a fraction of the infiltration, however, is developable as sustainable yield. In fact, for the Northern Guam aquifer system on a global scale, just 30 to 40 percent of the input is safely developable as potable water.

Sustainable yield is defined as "the average rate at which groundwater may be continuously pumped without diminishing either the quality or quantity of the pumped water." To achieve the hypothetically available sustainable yield, the means of withdrawal must be optimal. For most groundwater supply systems, production methods are sub-optimal and therefore the full value of sustainable yield is not available. These systems can be upgraded through re-development and by the careful location and design of new production units.

The sustainable yields discussed here are restricted to potable water pumpage. The production of additional non-potable but agriculturally acceptable water down gradient of the potable extraction units is permissible to some extent. Also, the sustainable yields are for basal water conditions where salinity is the major hazard accompanying over production. This constraint is necessary because eventually most of the groundwater in Northern Guam enters a basal lens before discharging along the sea coast, and the basal lenses are the most voluminous sources of groundwater.

Sustainable yield refers to the steady state condition when pumpage is in equilibrium with recharge, head, and leakage out of the system. To complete the argument, the initial system head is required. The relationship is expressed as (Mink, J.F., Chang, J.C., and Yuen, G.A., 1988, Review and Re-Evaluation of Groundwater Conditions in the Pearl Harbor Groundwater Control Area, Oahu, Hawaii: State of Hawaii Commission on Water Resources Management, Report R-78):

$$SY = I\{1 - [h(e)/h(o)]^2\}$$

in which SY is sustainable yield, I is infiltration, h(e) is equilibrium head for the groundwater system and h(o) is the initial pre-development head. In the above, sustainable yield is treated as a global variable, that is, it refers to an entire aquifer system. In the determination of sustainable yield that follows, the limestone aquifers of Northern Guam are considered a single, hydraulically connected entity.

Sustainable yield refers to production averaged over a time interval whose permissible length depends on the volume of groundwater in the aquifer system and the rate of replenishment to the system. If the volume is large and the replenishment high, wide swings in production rate are allowable over extended periods to make the average. In small groundwater systems, both the time interval of averaging and the range of pumping must be more tightly controlled.

Aquifer volume and replenishment rates in Northern Guam are substantial and thus averaging is allowable over relatively long periods of time. Total pumpage may also vary within a wide range. For example, if global sustainable yield is selected as 60 mgd, pumpage at a rate of 90 mgd for several months followed by pumpage at 30 mgd for an equal time may be permissible, so long as the average calculates to be 60 mgd. Optimal operation, however, would seek to stay as close to the average as possible.

In the steady state sustainable yield equation, values must be assigned for the initial head and the recharge rate, and an equilibrium head must be selected that will prevent degradation by salinity of the pumped water. The recharge rate is taken from hydrologic balance calculations, while the value for initial head must be extracted either from historical data or approximated. The choice of equilibrium head is somewhat arbitrary but needs to be guided by familiarity with the groundwater systems and by reference to analogous conditions elsewhere. This approach to sustainable yield, although constrained by assumptions, is far more quantitative than designating allowable draft as a fraction of infiltration rate.

The sets of values employed in the steady state equation from which the most probable range of sustainable yields could be chosen are as follows:

h(o): 3.5 ft.; 3.25 ft.; 3.0 ft.

h(e): 2.75 ft.; 2.5 ft.

I: 125 mgd; 150 mgd; 175 mgd; 200 mgd.

For infiltration values of 125 and 150 mgd, the sustainable yields are too small to be reasonable unless the equilibrium head goes to 2.0 ft. The best fit is for infiltration of 175 to 200 mgd, which is the probable range determined by hydrologic budgeting.

For infiltration of 175 mgd, the sustainable yield range is:

$$55 \text{ mgd} < SY < 75 \text{ mgd}$$

average 65 mgd

and for infiltration of 200 mgd,

$$60 \text{ mgd} < SY < 80 \text{ mgd}$$

average 70 mgd.

The calculations can be summarized as follows:

TABLE 2
SUSTAINABLE YIELDS AND EQUILIBRIUM HEADS

I (mgd)	SY (mgd)	h(o) = 3.5 h(e) ft.	h(o) = 3.25 h(e) ft.	h(o) = 3.0 h(e) ft.
175	70	2.7	2.5	2.3
175	65	2.8	2.6	2.4
200	70	2.8	2.6	2.4
200	65	2.9	2.7	2.5

The initial heads used in the calculations refer not to known maximum basal heads but to heads generally characteristic of basal groundwater far enough inland to yield potable water. Head varies seasonally by an average of about 0.3 to 0.5 feet in the clean limestone aquifers north of Agana Marsh so it is difficult to select an exact initial head. However, historical heads before the groundwater development of the last 15 years indicate that a reliable initial value is greater than 3.25 feet but less than 4.0 feet. An initial head of 3.5 feet is therefore a reasonable choice.

For sustainable yields of 65 to 70 mgd, regional equilibrium head will decay to 2.7 to 2.9 feet. These heads are high enough to support production of potable water from the basal lens using current methods (i.e., generally 200 gpm wells).

The sustainable yield values above refer to steady state conditions which come about when the groundwater system is in equilibrium with infiltration, head, draft and leakage. A long period of transient decay from the initial head takes place before equilibrium is achieved. The decay stage persists for many years. Equations of transient behavior are considerably more complicated than for the steady state, but tracking head change as a function of draft and time can be performed with a computer model.

Graphs of the average monthly heads recorded at various PUAG wells are presented in Figures 1 through 8 at the end of this appendix. The record of head change at the monitor wells since the end of the *NGLS* investigation in 1982 does not manifest a significant decay in head at the total pumping rate of 20 to 30 mgd. Illustrations of the stability of heads in basal lenses in clean limestone are graphs of average monthly heads for the period 1984 through 1988 (Figures 1 through 5). The most complete records are for 1985 and 1988.

Heads rise quickly in response to prolonged and heavy rainfall because infiltration temporarily accumulates at the top of the water table. This effect is particularly noticeable in the argillaceous limestone parabasal aquifer in the Chaot-Ordot region (Figure 6). The effect is less pronounced in the argillaceous limestone basal aquifer (Figures 7 and 8), and even less dramatic in the aquifers of clean limestone (Figures 1 through 5).

The graphs for clean limestone aquifer monitor wells EX-6 (Macheche), EX-7 (Wettengell), EX-8 (Northwest Field), EX-9 (Barrigada and EX-10 (Finegayan) show that heads during 1985 were lower than during 1988 by about 0.2 feet. This implies that there has not been a steady decline in head since 1984 as a result of pumping. The average heads for 1988 may be considered as equilibrium heads at the current rate of draft.

SUMMARY

The steady state model was the first model employed in an effort to quantitatively establish sustainable yields because of its simplicity. The steady state model lumps seasonal changes in recharge into the annual average, thus missing the cycle of head change from dry to wet to dry season. Subsequently a transient model was composed in which the time unit for averaging is the month, thereby incorporating the effects of seasonal recharge and outflow on the basal and parabasal resources. The transient model is discussed in the main text as well as Appendix B and recommended sustainable yields are taken from this model.

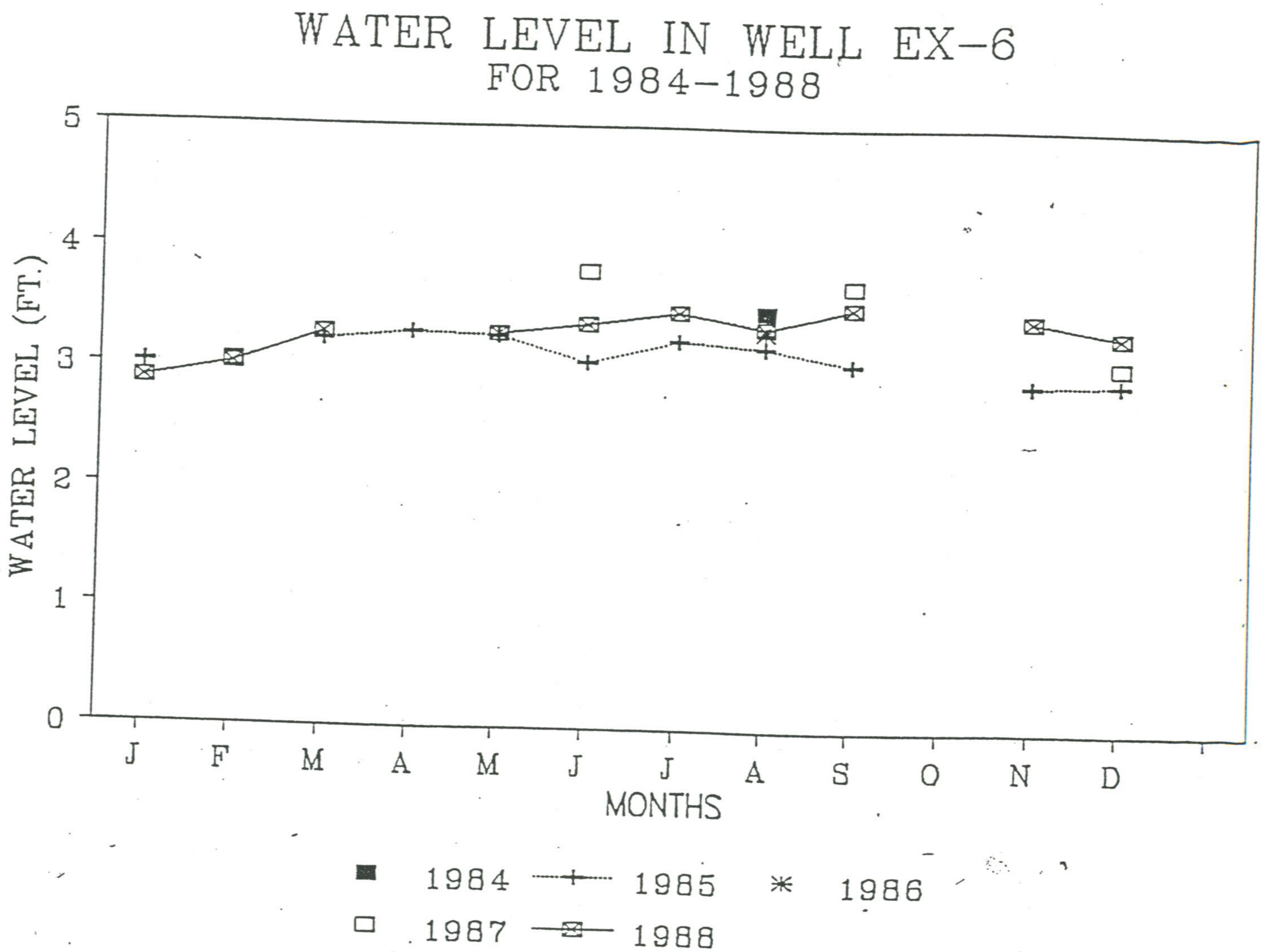


Figure 1
Average Monthly
Groundwater Elevations
Well EX-6

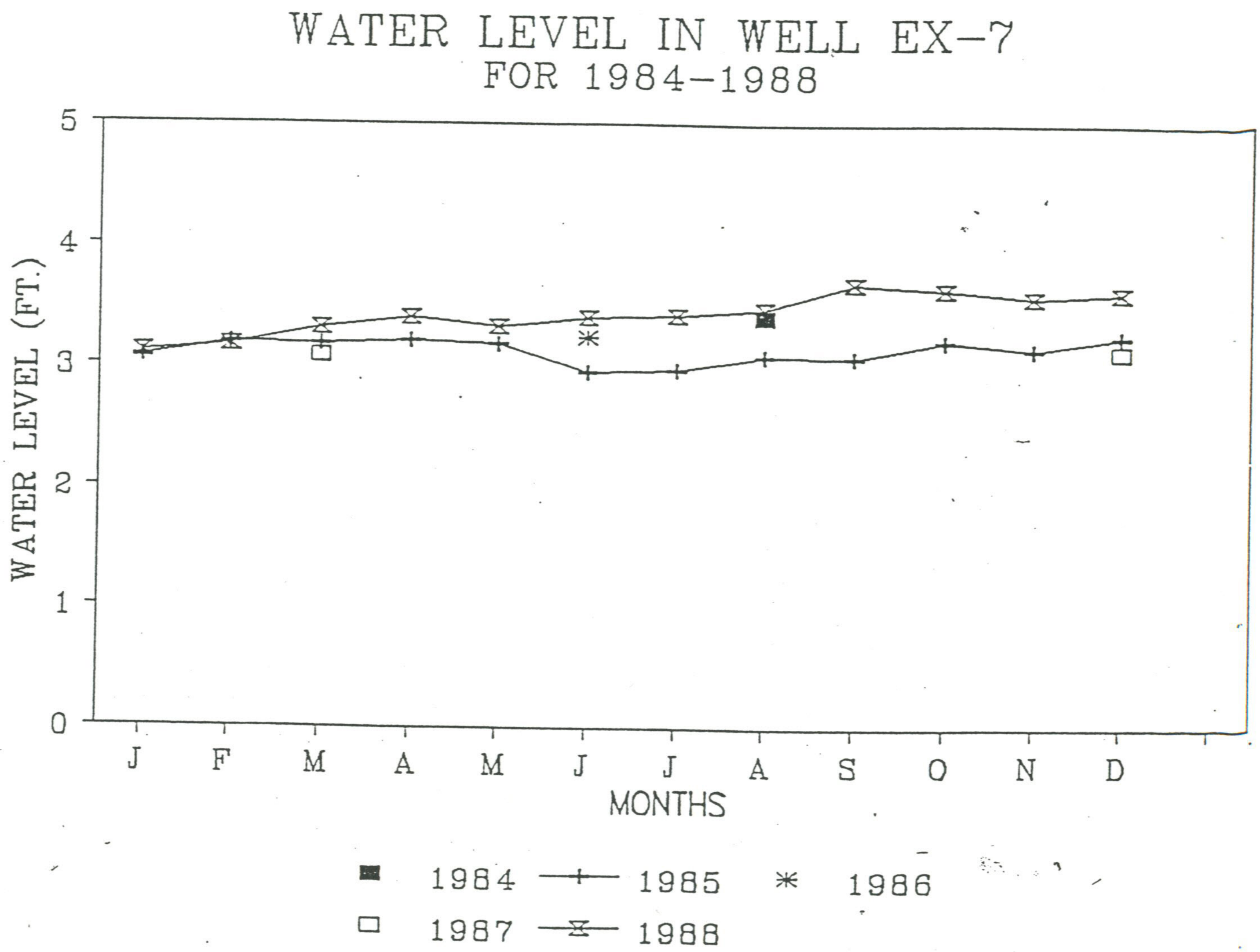


Figure 2
Average Monthly
Groundwater Elevations
Well EX-7

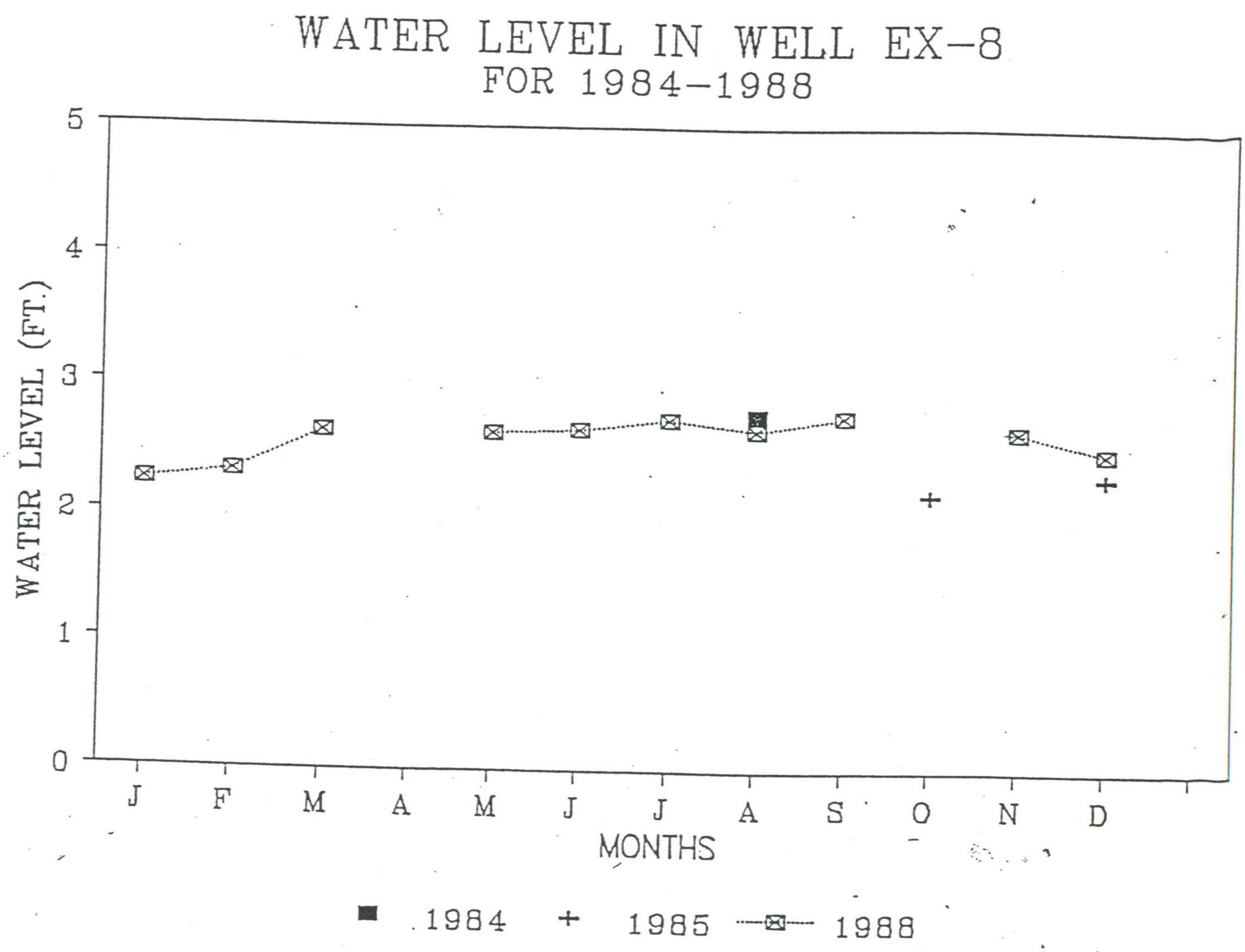


Figure 3
Average Monthly
Groundwater Elevations
Well EX-8

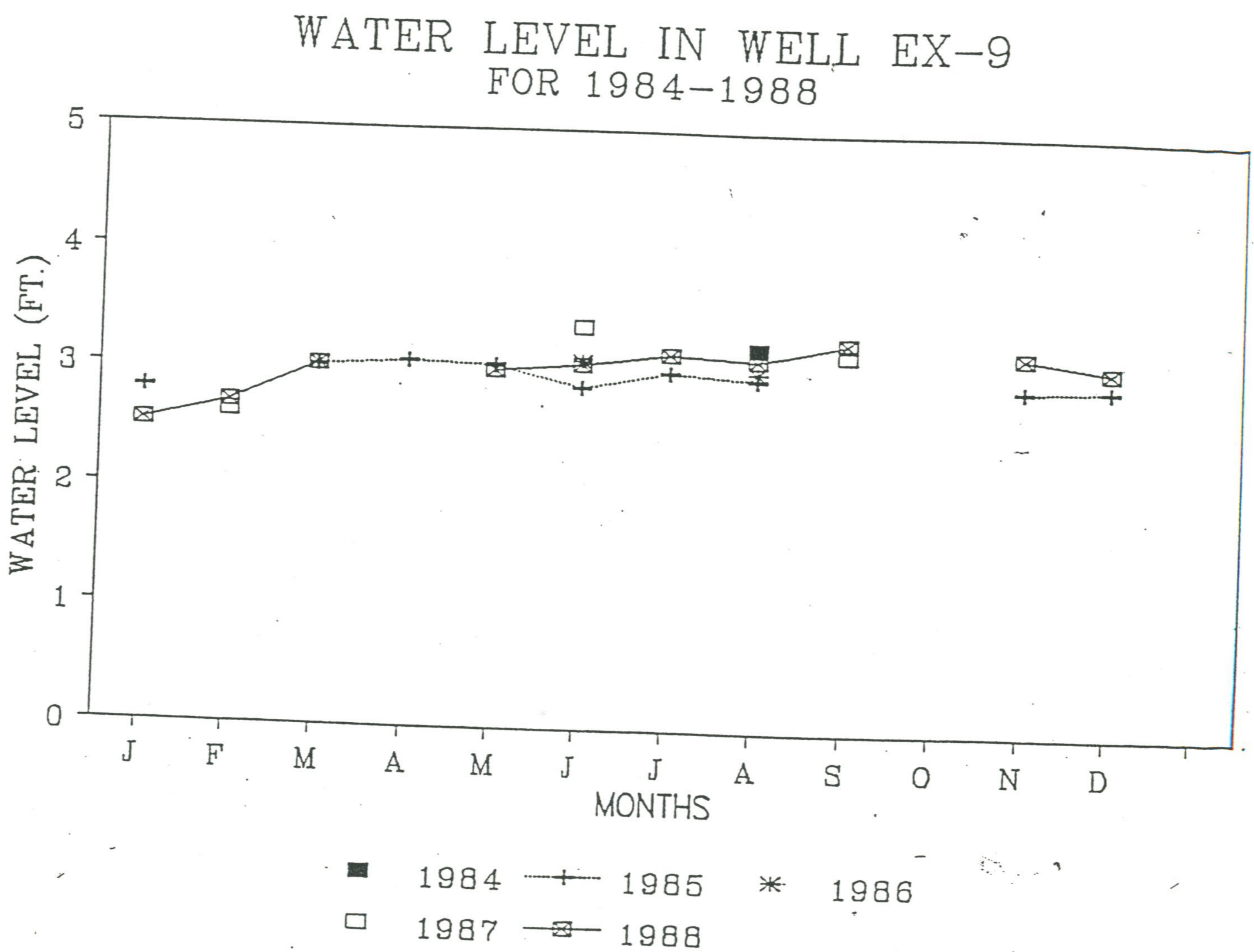


Figure 4
Average Monthly
Groundwater Elevations
Well EX-9

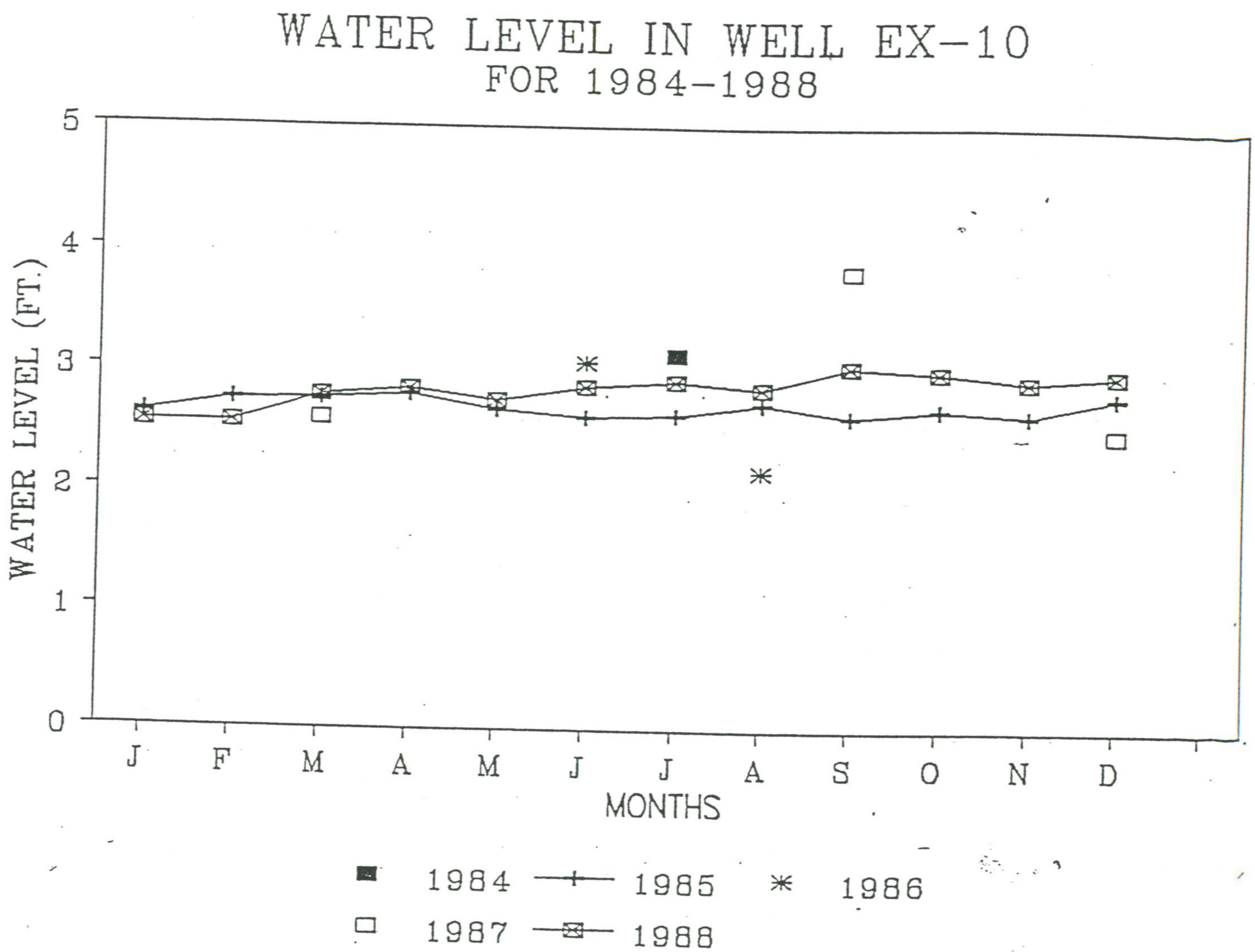


Figure 5
Average Monthly
Groundwater Elevations
Well EX-10

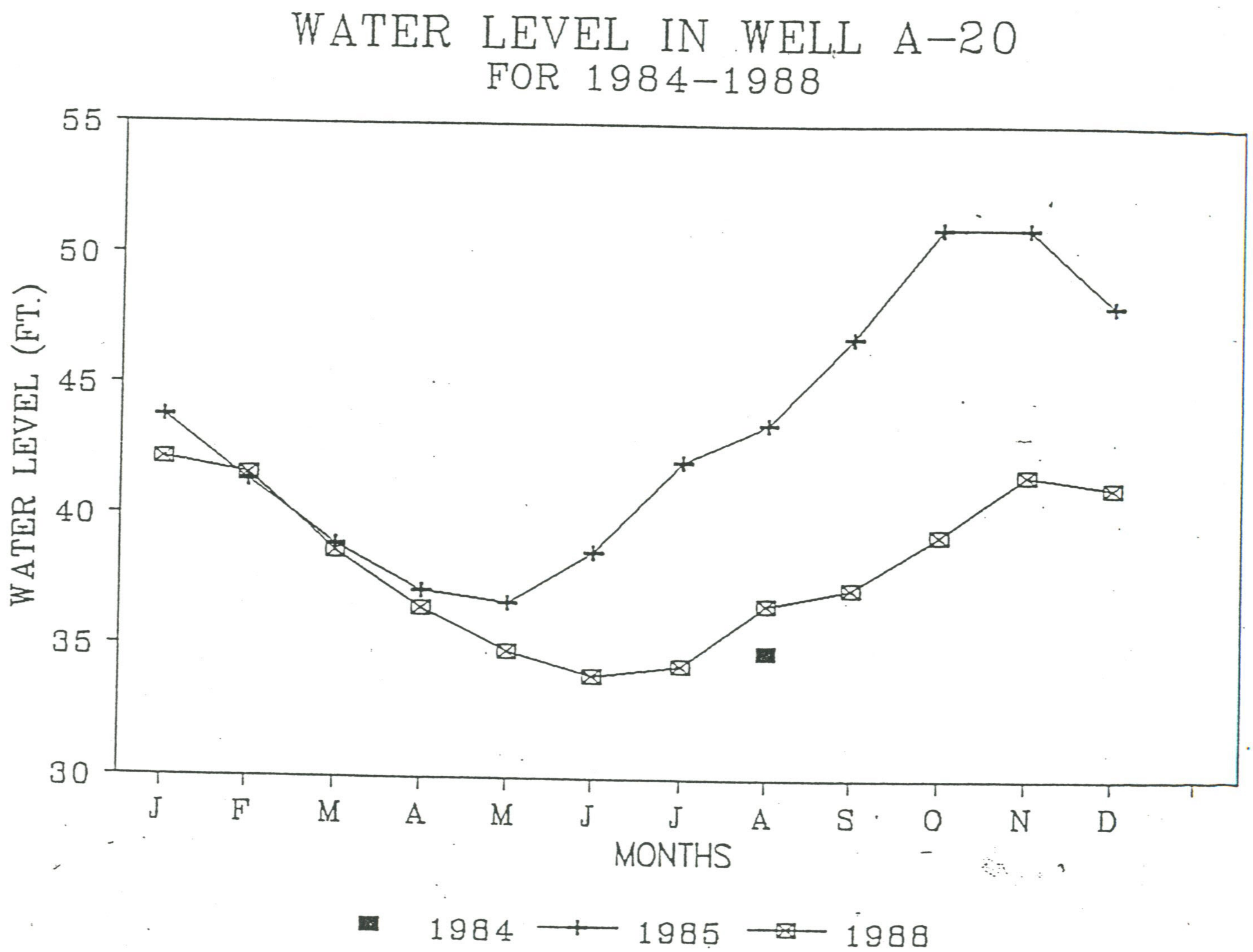


Figure 6
Average Monthly
Groundwater Elevations
Well A-20

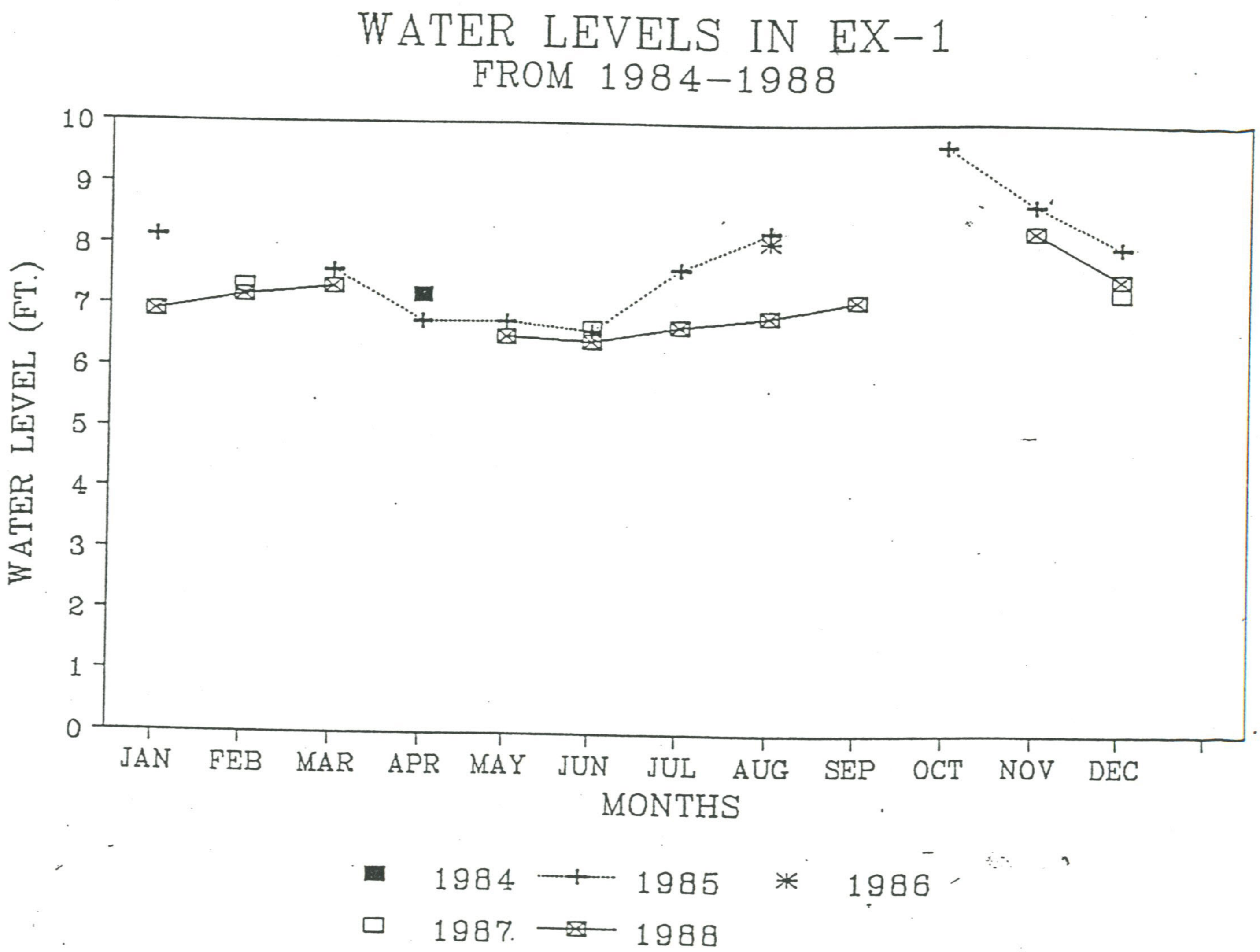


Figure 7
Average Monthly
Groundwater Elevations
Well EX-1

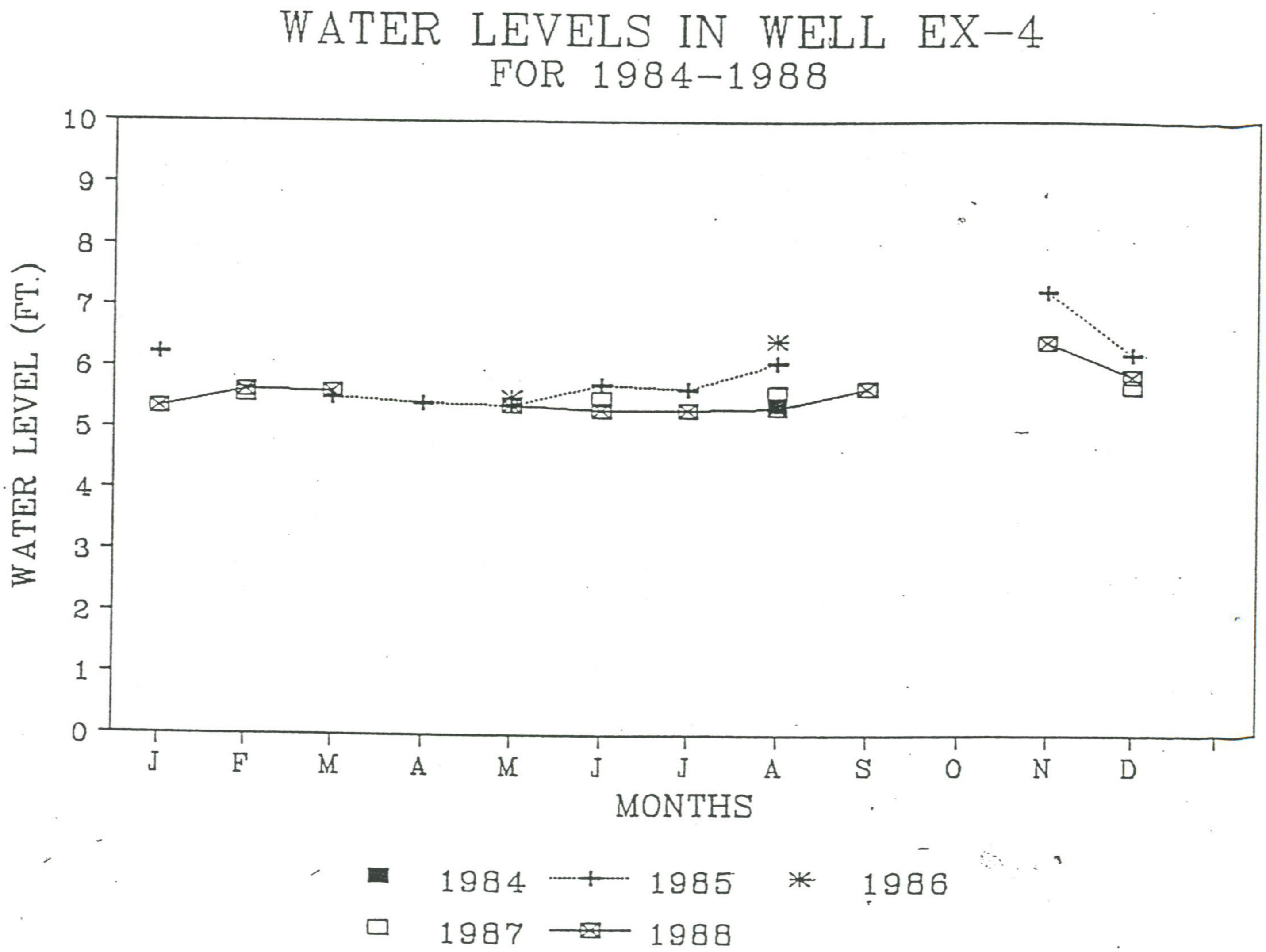


Figure 8
Average Monthly
Groundwater Elevations
Well EX-4

APPENDIX B

Sustainable Yield, Transient Model

SUSTAINABLE YIELD, TRANSIENT MODEL

Groundwater systems behave in complex ways that are difficult, if not impossible, to effectively describe in a classical analytical mathematical framework unless great simplifications are made. These simplifications, such as assigning well posed boundary conditions and linearizing the equations of groundwater flow, are useful in explaining particular aspects of behavior but generally fail if employed in describing the dynamics of the whole system. The analytical approach falters on the unsolvability of the second order non-linear partial differential equations defining flow in porous media, and on the heterogeneity of aquifer properties which frequently defies averaging.

To overcome the limitations of exact methods of solving the groundwater equations, physical and numerical mathematical models are commonly used. Physical models are highly constrained in simulating real aquifer behavior while numerical models can be made as flexible as computer efficiency allows. Numerical modeling is the preferred technique for explaining and predicting aquifer behavior because it accommodates heterogeneities and non-isotropism to whatever degree is economically acceptable by dividing the aquifer into an array of nodes or cells, each of which may display different properties. Numerical models, however, require a reliable data record of substantial length, which is not often available, for validation.

Several numerical models of Guam aquifers have been devised to help explain past behavior, to identify present status, and to predict future behavior for various development scenarios. The process of composing a model and testing it against the historical record requires a clear description of the groundwater system within a rational framework. The final objective of modeling is to promote optimal development of an aquifer.

GENERAL GROUNDWATER MODEL FOR NORTHERN GUAM

Groundwater movement is defined by hydraulic flow equations, the solutions of which usually require information obtained by composing the whole or portions of a hydrologic balance. The simplest balance consists of equating input and output for the natural, undeveloped condition of the aquifer. When groundwater is emphasized, infiltration to the saturated zone is computed as the difference between rainfall, where it is the only external source of water, and losses due to evapotranspiration and direct runoff to the sea. Expressed as a balance equation, the relationship is

1. $I = P - DRO - ET$

in which I is infiltration to the aquifer, P is rainfall, DRO is direct surface runoff lost to the sea, and ET is evaporation and transpiration lost to the atmosphere. Under development, the equation is modified chiefly by introducing pumpage as an output and irrigation return as an input. The fundamental equation applies to long term averages, but it can be applied to smaller, discrete time intervals. It may also be transformed to a transient equation by including gain or loss of storage over a time interval, for which the balance equation is

2. $L = P - ET - DRO +(-)\ dV$

where L is leakage, equal to I at initial conditions (t=0), and dV is change in storage.

A hydrologic balance is important in mathematical modeling because it yields a value for infiltration (recharge), a critical system variable. It also defines the magnitudes of system fluxes and suggests limits to groundwater development. It is usually the first computation attempted, and quits often when carefully constructed is a model of reasonable validity.

Mathematical models are actually hydraulic flow models which combine Darcy's law of flow in porous media with a continuity equation and are subject to the constraints implicit to these laws. Analytical mathematical models provide direct solutions of aquifer behavior but are limited unless simplified because the non-linear equations of complex systems cannot be solved by exact methods. Numerical modeling avoids this handicap by decomposing the governing partial differential equations into an array of algebraic equations whose solutions give an approximate description of flow. Finite difference and finite element are the numerical techniques commonly employed. The results of numerical modeling have to be tested against a historical record to ascertain the closeness of fit between actual and synthetic behavior before the model can be accepted as a valid representation of reality. If the simulation is good, the model is presumed to be capable of predicting future behavior for different aquifer scenarios.

Sufficient knowledge about and data for the Northern Guam aquifers now exist to justify hydraulic flow models which incorporate the buoyancy relationship of fresh water in contact with underlying sea water (Ghyben-Herzberg condition). It would be desirable, but is not yet practical on a regional scale, to combine a flow model with solute transport to track the dispersion of salt water in the fresh water lens. Important parameters necessary to support solute transport models, such as transverse and longitudinal dispersivities, are virtually impossible to measure directly. Consequently in most models a sharp interface between fresh and salt waters is assumed.

BASIC DARCY-CONTINUITY MODEL FOR THE NORTHERN GUAM AQUIFERS

Sophisticated numerical models for predicting the behavior of the Northern Guam aquifers have been attempted, yet even with an extensive data base and parameter identification, a fresh water—salt water system with two moving boundaries is difficult to simulate. All of the models assume instantaneous balance between the fresh and salt waters in response to removal or addition of water, but the preponderance of field evidence indicates that the top surface of the lens reacts quickly to transient perturbations while the bottom surface lags. This asymmetrical behavior is called the "bottom storage" phenomenon and was first elucidated by C.K. Wentworth in Hawaii fifty years ago.

In view of the uncertainties implicit in modeling a complicated fresh-salt water system, a simple yet exact lumped parameter model that provides global answers to water balances and aquifer behavior is a reasonable tool for management. A general mathematical model which assumes homogeneity and isotropism of the aquifer and changes which are averaged throughout the flow domain can be used to describe and predict global behavior. A model of this type was employed by Mink (1980) in southern Oahu. It relies on analytical solutions of the equations of groundwater flow in Ghyben-Herzberg system, yet is discretized by time intervals.

The model does not take into consideration solute transport but instead assumes a sharp interface between the fresh and sea waters. Although prescribed by limiting assumptions, it is straightforward and gives an exact accounting of water balances. Its applicability is less dependent than a numerical model on validation by simulation because fundamentally it is an analytical mathematical model. Even though it describes global rather than local behavior of an aquifer, it is useful in defining the limits of aquifer yield and in predicting the consequences of different levels of extraction. It is especially useful in aquifers where transmissivity is high, such as the limestone aquifers in Guam, because drawdown cones are shallow and extend great distances from the pumping centers.

The continuity equation for the groundwater balance may be as written as;

3. $Q\,dt = dV = AS\,dh$

in which Q is rate of flow; dt is change in time, t; dV is change in volume, V; A is horizontal area of the flow domain; S is specific yield or effective porosity; and dh is change in head, h. For a Ghyben-Herzberg lens the above is written as

4. $Q\,dt = AS(1+g)\,dh$

in which g is the Ghyben-Herzberg constant g(f)/g(s)-g(f), where g(f) is the specific gravity of fresh water and g(s) that of salt water.

The flow rate term, Q, can be decomposed into its balance elements to give

5. $I - L - D = AS(1+g)\,dh/dt$

in which I is steady recharge to the aquifer, L is leakage from the aquifer, and D is draft (pumpage). for normal fresh water and sea water with specific gravities of 1.000 and 1.025, respectively, the Ghyben-Herzberg constant, g, is 40, and the constant (1+g) is 41. Hereafter this value will be used in the derivations.

Combining Darcy's law with the above produces a hydraulic flow model. Darcy's law for a basal lens with undimensional flow is written as

6. $q = 41kh\ dh/dx$

where q is unit flow through the depth of the aquifer, k is hydraulic conductivity, and x is horizontal distance along the gradient. When integrated between the limits h(1) and h(2), and x(1) and x(2) the above yields

7. $q = (41k/2)[h(2)^2-h(1)^2]/[x(2)-x(1)]$.

For simplicity let h(1), x (1) be zero, which are conditions at the hypothetical discharge front, then,

8. $q = 41kh^2/2x$

This equation is valid no matter where or what the discharge front is. The actual distance x is immaterial in the final equations because it is subsumed in a constant term along with other variables.

At initial conditions leakage is equal to total input, I, and equation 8 can be restated as

9. $I = L(0) = 41kh(0)^2/2x$

in which leakage L(0) and head h(0) are initial values. In the above, 41k/2x is a constant such that $c = 41k/2x = I/h(0)^2$. This conversion eliminates k and x from the final equations but requires that I be held constant, a condition that permits transient equations to be solved.

Restating the balance equation as amended by Darcy's law gives

10. $I - D - ch^2 = 41AS\ dh/dt$

in which I includes both vertical infiltration and underflow into the aquifer, D is net extraction (net draft), and ch^2 is leakage. Designating the constant 41SA as b, the initial volume of the lens is calculated as, V(0) = bz(0), in which z(0) = f[h(0)]. For a relatively flat groundwater table, a characteristic of high transmissivity, average initial head can be used in place of z(0), giving b = V(0)/h(0). This constant does not change over time because the relationship between V and h remains constant. specific yield is eliminated from the final equations when b is used. If initial volume is computed from parabolic curvature of the lens, a head at any fixed location can be employed in b.

Equation 10 is an ordinary differential equation readily solved by separation of variables. Integration over the limits [h(i), h(i=1)] and [t(i), t(i+1)] in which h(i) is head at the start and h(i+1) is head at the end of an interval, and t(i+1)-t(i) is the fixed length of the interval, and in which the constants c and b are replaced by initial system values, yields the following equations,

11. got I>D

$$h_{i+1} = h_0 \left[\frac{I-D}{I}\right]^{1/2} \left\{ \frac{(I-D)^{1/2} + \dfrac{hi}{ho}(I)^{1/2} \exp\left[\dfrac{2t\,([I-D]\;I)^{1/2}}{V_o}\right] - (I-D)^{1/2} + \dfrac{hi}{ho}(I)^{1/2}}{(I-D)^{1/2} + \dfrac{hi}{ho}(I)^{1/2} \exp\left[\dfrac{2t\,([I-D]\;I)^{1/2}}{V_o}\right] + (I-D)^{1/2} - \dfrac{hi}{ho}(I)^{1/2}} \right\}$$

and,

12. for I<D

$$h_{i+1} = h_0 \left(\frac{D-I}{I}\right)^{1/2} \tan \left\{ \arctan \frac{hi}{ho} \left(\frac{I}{D-I}\right)^{1/2} - \frac{t\,[(D-I)\,I]^{1/2}}{V_o} \right\}$$

The steady state form of equation 11 for constant D is

13. h(e) = h(0)[1-(D/I)]^1/2

in which h(e) is the equilibrium head that eventually will become established. There can be no steady state when (I<D) and I=D).

In the above equations D may vary among intervals but I is fixed. However, variations in total recharge can be accommodated by adjusting the actual draft to reflect increases or decreases of recharge without tampering with the initial value of I.

Equations 11, 12 and 13 express global water balances in terms of head and time for variable draft. Heads are "storage heads" reflecting true thickness of the lens. The Ghyben Herzberg condition is assumed to be instantaneously established at each change in output and input. Equilibrium heads, however, are not attained at the end of an interval even though the transient head, h(i+1), is in Ghyben-Herzberg balance. Equilibrium heads do not come about until leakage combined with draft exactly equals total recharge.

For Northern Guam a model based on the above equations requires the following information and data:

1. **Total recharge, I.** Obtained from hydrologic balance calculations. If the other variables are known, I can be solved for.

2. **Initial head, h(0).** The historical record is the best source, but an approximation can be extracted from sensitivity analyses:

3. **Initial volume of fresh water, V(0).** A good estimate can be made from the initial shape of the lens and an assumed value for specific yield.

4. **Ambient head, h(i), at the start of an interval.** this is storage head, best obtained by reference to the depth of the 50 percent sea water isochlor in the lens.

5. **Net draft, D.** Obtained from pumping records corrected for return irrigation flows.

The transient model described above, like all mathematical models so far devised, assumes instantaneous balance of the upper and lower surfaces of the lens. Unlike more sophisticated models it treats the aquifer as a homogeneous and isotropic single unit in which extractions are averaged throughout the domain, and therefore it cannot predict local water table depressions or mounds resulting from pumping and local recharge.

On the other hand, the model exactly defines water balances. It provides a good estimate of the storage state of the system even though it does not take into account the transition zone. It is especially useful for predicting the overall state of the resource for different scenarios of development. The model will provide a global sustainable yield for a given equilibrium head at controlled draft.

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SUSTAINABLE YIELD OF GROUNDWATER RESOURCES

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Abstract - "Sustainable yield" is the average rate of withdrawal that does not imperil groundwater resources from an aquifer, either by diminishing the quality or quantity of water withdrawn. This is equivalent to allowable draft by means of wells, infiltration galleries, and other forced extraction. It does not include natural aquifer outflow in the form of springs and other leakages. For every exploited aquifer, sustainable yield is determined by establishing the transient and equilibrium relationships among recharge, draft, natural leakage, and storage volume in the aquifer. Sustainable yield is always less than recharge. Global equations have been derived to calculate sustainable yield based on initial conditions of head and aquifer volume with recharge and leakage varying over time.

Sustainable yield refers to the forced withdrawal of groundwater at a rate that can be sustained indefinitely without affecting either the quality of the pumped water or the rate of pumping. This a definition that was created in Hawaii in response to the need to protect the utility of groundwater resources. But it has universal application, especially in island environments where aquifers are small and salinity is a constant threat.

The word "sustainable" is used because exploiting groundwater is like exploiting the product of a natural system, such as a forest. To sustain production in a forest, a balance must be established among input (planting and seeding), growth, harvesting, and natural mortality. In the case of an aquifer, infiltration from atmospheric moisture and subsurface inflow from other sources is the input; accumulation of water in the saturated zone is growth; harvesting is removal of groundwater by pumping or other artificial means; and discharge is equivalent to natural mortality.

Other terms are often employed to convey a meaning similar to sustainable yield, but they lack comprehensiveness in definition. The terms "dependable yield" and "safe yield," for instance, are common but imprecise synonyms for sustainable yield; each lacks a clear appreciation of the time constraint. Both dependable yield and safe yield often are used to refer to a yield which is possible only for the period during which water will be needed. In other instances the definition is broadened to refer to continuous draft for an indefinite period. The definition of sustainable yield, on the other hand, unequivocally incorporates infinite time as a fundamental condition.

In Hawaii, sustainable yield has become the governing concept by which exploitation of groundwater is permitted and practiced because fresh groundwater in the most voluminous aquifers rests on sea water. Should a judicious balance among input, the volume of water stored in the aquifer, draft and natural leakage not be established, salinization of pumped water will take place when draft exceeds sustainable yield. The concept is also applicable where salt water is not a threat. In that case, dewatering is the problem.

The sustainable yield balance equation is simply stated: for an aquifer in equilibrium, the average rate of water input to the system must be equal to the sum of the average rate of withdrawal and a natural rate of discharge. In an aquifer not undergoing exploitation, the average rate of input will equal the average rate of discharge, and the average volume of storage in the aquifer will be constant. In the real world, of course, the averages are statistical abstractions of continuously varying rates within a range of probabilities. For aquifer systems with large storage, the allowable range for the rates and the length of time they persist is obviously greater than for a small system. For example, a severe drought lasting for months may have a minor effect on a voluminous aquifer while it might be catastrophic to a small one. Similarly, the effect of excessive pumping over lengthy intervals in a voluminous basal aquifer may not induce salt water to rise as high as the pump intake whereas in a thin lens, the well could easily become salinized.

The components of the elementary balance equation for the steady state are:

$$I(av) = D(av) + L(av) \tag{1}$$

in which I(av) is average input, D(av) is average rate of draft, and L(av) is average rate of leakage. In this balance, D(av) must be less than I(av). The leakage is governed by the gravity potential, or head, in the system. A common datum against which head is measured is sea level; this is the datum employed in Hawaii because of the preponderance of basal aquifers in which fresh to brackish groundwater floats on sea water as a result of density differences. Groundwater in basal aquifers is also referred to as a Ghyben-Herzberg lens. Input and draft may be made time dependent, giving the simple transient equation:

$$I(t) = D(t) + f(h) \tag{2}$$

where f(h), or function of head, replaces leakage, L. This mass balance equation combined with Darcy's law, the fundamental relationship defining hydraulic flow in porous media, leads to the sustainable yield equations.

Sustainable yield is not a fixed value but depends on the equilibrium of the state of the system at which neither the quality nor the quantity of water pumped degrades over time. Thus there is a maximum possible sustainable yield constrained by an equilibrium head that is lower than any other head. At a higher equilibrium head, a lesser value of sustainable yield would result. For example, a system in which the lowest equilibrium head meeting the conditions of the sustainable yield definition is 5 ft (16.4 m) will allow a greater draft than if 10 ft (32.8 m) were selected as the equilibrium head. The choice of equilibrium head may be constrained by factors other than hydraulics, in particular the location and depth of the extracting units. As an example, to guarantee that poorly placed and designed wells already pumping from a basal lens will continue to be useful, the selected equilibrium head must be higher than the one that would optimize aquifer draft if all wells were perfectly designed and sited.

Sustainable yield, of course, is never equal to the rate of recharge. If sustainable yield and recharge were equivalent, which is a common assumption in hydrologic budgeting, the head and volume would go to zero because a positive head would continue to force leakage. Extraction of as much water as is recharged would permit the storage volume in the aquifer to dissipate. It is therefore axiomatic that average allowable draft must always be less than average input for the system to survive.

Sustainable yield treats an aquifer as a whole unit and is computed from an elementary equation, which is:

$$D = I(1 - [h/H]) \tag{3}$$

in which D is allowable average draft, equivalent to sustainable yield; I is average input into the aquifer; h is the equilibrium head, which is chosen to maximize output; and H is the original head before draft started. This equation applies to an aquifer having at least one free surface, such as an unconfined aquifer with a phreatic upper surface, an unconfined basal lens with two free surfaces (the upper one phreatic and the lower one the interface between fresh and salt water), or a basal lens confined from above but having a free interface surface. If the aquifer is bounded both above and below and the thickness of the saturated zone is the distance between these boundaries, the applicable equation is:

$$D = I(1 - [h/H]) \,. \tag{4}$$

These equations are global, that is, they combine continuity with hydraulic flow in an entire system and assume that extraction is uniformly distributed. They do not reflect behavior at the local level of the pumping site. For this fine discrimination the equations of well hydraulics are required, or numeric modeling. Nevertheless, the computed sustainable yield, or allowable average draft, is the amount of water that can be extracted at a given equilibrium head by means of units which are optimally located and designed.

The use of the sustainable yield equation can be illustrated by employing it in reference to an aquifer with at least one unconfined surface, a common condition in southern Oahu, Hawaii, where a caprock along the coast confines the aquifer from above. In the Nuuanu Aquifer System of Honolulu, the original head was 42 ft (137.7 m) and the current average head maintained by the Board of Water Supply is approximately 22 ft (72.2 m). Thus the allowable draft, or sustainable yield, is equal to 73% of the average input. Average recharge to this aquifer system is about 20 mgd (million gallons per day) (75,700 m^3) while average draft is about 15 mgd, the same as the allowable draft for the equilibrium head. The aquifer system has been at equilibrium for many years. Thinner basal lenses would not allow the extraction of as large a percentage of input as in the thick Nuuanu Aquifer. A typical Ghyben-Herzberg lens without a caprock to inhibit outflow along the coast might have an initial head of 5 ft (16.4 m) several miles inland. If experience indicates that fresh water is not developable when the head is less than 3.5 ft (11.5 m), then the maximum sustainable yield of the system would be just 49% of the recharge.

Sustainable yield has become a fundamental tool for managing the groundwater resources in Hawaii. We are in the process of identifying the major aquifer systems in each island, then estimating sustainable yields based on hydrologic budgeting and groundwater response to exploitation. Yet even after more than a century of extensive groundwater development in the islands, only in southern Oahu and western Maui is our appreciation of groundwater behavior accurately known. In these islands the excellent records of rainfall, evapotranspiration, stream flow, and aquifer behavior in response to pumping have provided a reliable framework for computing hydrological balances and creating analytical and numerical models.