NORTHERN GUAM LENS STUDY

SUMMARY REPORT

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GUAM ENVIRONMENTAL PROTECTION AGENCY

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INTRODUCTION

Island people everywhere are highly conscious of the importance of a reliable water supply to the sustenance of normal life and in the creation of a modern economic system. On Guam this recognition is especially strong. A casual review of issues that concerned the island throughout its history reveals the crucial role of water supply.

Before World War II a supply of fresh water essentially for subsistence and the military was adequate, but following the war, and particularly since 1964 when the Territorial Government became responsible for providing water to the civilian population, a much greater demand evolved. The pace of population and economic growth pushed demand beyond the capacity of existing water sources by the 1960's, forcing the government to search for new supplies.

Groundwater in the limestone aquifers of northern Guam was the likely candidate to expand supply, yet this resource was not considered a viable alternative because of salinization that occurred from poor development practices during and just after the war. Pressed by doubt but filled with hope, the Government of Guam (GovGuam) drilled its first well at Dededo. The pumped water was clean and fresh and flowed freely from the well. Intensive development of the northern Guam aquifer (known also as the northern water lens) had started.

The success of a single well gave momentary euphoria but was no guarantee of the size of the resource. Investigations by U.S. Government agencies were started before the war, when H.T. Stearns of the U.S. Geological Survey journeyed to the island in 1937. These and later studies offered results suggesting the developability of a substantial groundwater supply, providing proper technical and management constraints were honored. Decisions about expanding the civilian water supply had to be made quickly, frequently before an appropriate data base could be established. The Government contracted with Pacific Drilling Co., then of Honolulu but later absorbed by Layne International, to help in locating well sites and to drill and equip the successful wells. While site selection was risky at first, each new well was a test of the potential of the aquifer that generated experience and data for use in subsequent decisions.

The knowledge accumulated during expansion of the water supply system, along with results of earlier investigations, was summarized, analyzed and interpreted in a Public Utility Agency of Guam (PUAG) report authored by John F. Mink in 1976 (Groundwater Resources of Guam: Occurrence and Development. Reprinted as Technical Report 1, Water Resources Research Center, University of Guam). In that report the sustainable yield of groundwater from the northern aquifers was estimated to be about 50 mgd, but it was emphasized that the estimate was highly judgemental because of the inadequacy of information concerning aquifer geometry and dynamics. The report made it evident that to arrive at a firm estimate of sustainable yield a structured groundwater investigation would have to be undertaken. Less than four years later a comprehensive investigation, the Northern Guam Lens Study (NGLS), was underway, and now, after three years of effort, the investigation is complete.

This report is a summary of the main and subsidiary reports written by the NGLS team. The main reports consist of the following (a complete listing of NGLS publications and documents appears at the end of this Report):

1. Aquifer Yield

2. Groundwater Management Alternatives

3. Groundwater Management Program

4. Technical Manuals as follows:

   a) Well Operation and Maintenance

   b) Well Operation Organization

   c) Well Construction

   d) Laws, Regulations and Agreements

5. Data Compilation

Subsidiary reports include:

1. A Preliminary Study of the Hydrogeology of Northern Guam: by the Water and Energy Research Institute, University of Guam (WERI, UOG).

2. Mathematical Model for Northern Guam: several reports by WERI, UOG

3. Data Summaries: by U.S. Geological Survey (USGS)

4. Annotated Bibliography: by USGS

5. Geophysical Investigations for the Northern Guam Lens Study: by Eco-Systems

6. Topographic Survey: by Juan C. Tenorio and Assoc., Inc.

The full range of knowledge and understanding of the groundwater system of northern Guam generated by the NGLS effort is not restricted to the above reports, however. Numerous information memoranda are in permanent file, detailed scientific description of aquifer features have been written, and, not the least important, personnel from the Guam Environmental Protection Agency (GEPA), PUAG and the USGS have gained greater experience in groundwater work. A network of permanent monitor wells has been established as a result of the exploratory well program, and about 500 feet of limestone was cored and will be available for scientific studies.

The Northern Guam Lens Study could not have been carried out without the participation and cooperation of many Government of Guam and Federal agencies. The Administrator of GEPA, Ricardo C. Duenas, provided encouragement and the full cooperation of the agency. James B. Branch, Deputy Administrator of GEPA, acted as overall Project Manager, willingly involving himself at all levels of effort. The staff of GEPA carried out many aspects of the study. Other GovGuam agencies directly involved in decisions that benefited the program were PUAG, the Department of Land Management, and the Water and Energy Research Institute, University of Guam.

The United States Air Force (USAF) and the United States Navy (USN) provided essential data and allowed entrance to, and in some cases the use of, their land. They also served on technical advisory committees.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

PHASE I
AQUIFER YIELD

Summary of Findings

The Northern Lens aquifers consist of thick sequences of porous limestones that were deposited on the submarine slopes of a volcanic mass. Mount Santa Rosa and Mataguac Hill are exposed remnants of this volcanic mass. The Barrigada and Mariana Limestones are the two primary geologic formations that comprise the aquifers of Northern Guam. These formations are thick and massive, and are interlaced with pores and channels that easily transmit water from the ground surface into the aquifers, and finally to the ocean.

Permeability of the aquifers varies both horizontally and vertically. Over northern Guam, permeability increases from the southern part of the Lens to the northern part, and ranges in value from under 100 feet per day of water movement in the Agana area in the south to over 8,000 feet per day in the Yigo and Finegayan areas in the north.

The Northern Lens consists of two basic types of aquifers: basal and parabasal. In the basal aquifers, the fresh water floats on top of saline ocean water, which has intruded into the limestone formations. In the parabasal aquifers, the fresh water overlies the volcanic formations.

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

The Northern Lens is divided into six hydrologic sub-basins, which are further subdivided into 47 management zones. For each management zone, rainfall and recharge values were calculated and a sustainable yield determined.

Total recharge to the Northern Lens is about 111.9 million gallons per day (mgd), of which about 59 mgd are available as sustainable yield. Current groundwater production is estimated to be 20 mgd (2 mgd of which is developed in the coastal areas outside of the management zones). In total, an additional 42 mgd can be safely withdrawn from Guam's northern aquifers.

Recommendations

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

- Groundwater production should be limited to the sustainable yield estimated for each management zone and hydrologic sub-basin.

For the development of basal aquifers, the following well design constraints should be imposed:

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

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

For the development of parabasal aquifers, wells should be designed for the maximum that the aquifer can deliver without exceeding the sustainable yield of the management zone and without exceeding 750 gpm. However, because of low permeabilities in many parts of the Northern Lens, the following well designs are provided as guidelines for groundwater development.

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

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

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

d. Wells should not be placed any closer than 500 feet from the salt water toe in clean limestone, and 1000 feet from the toe in argillaceous limestone.

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

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

- Three new permanent rain gaging stations should be established in Northern Guam to refine the estimates of areal distribution of precipitation. These stations should be located in Ordot, Latte Heights, and Agafo Gumas.

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

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

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

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

- Lysimeters or other similar devices should be established at locations in northern Guam so that accurate data on evapotranspiration can be obtained. Though these types of devices are relatively expensive to construct and maintain, the data will provide more accurate information on the amount of rainfall that infiltrates to the groundwater system, and thus, the amount of recharge that enters the Northern Lens. This, in turn, will lead to a better assessment of sustainable yield.

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

SUMMARY OF FINDINGS and RECOMMENDATIONS

PHASE II GROUNDWATER MANAGEMENT

Summary of Findings

The groundwater in the Northern Lens is of excellent quality and generally free of pollution as indicated by the investigation of priority pollutants. Ten sampling locations were selected that took into consideration representative coverage in terms of land use, aquifer type and distribution, and current and proposed water production. Of all the priority pollutant constituents for which analyses were conducted, only eleven constituents had concentrations above the detection limits and only one exceeded the U.S. Environmental Protection Agency (U.S. EPA) recommended drinking water limits.

Although the groundwater is of high quality, there are certain land-use practices which have the potential for contributing to future degradation of the aquifers. Some of these practices include on-site wastewater disposal systems, livestock waste disposal, industrial waste disposal, and application of pesticides and herbicides. With proper controls, these land-use activities should not cause any detrimental effects to Guam's groundwater resources.

Most stormwater runoff in northern Guam enters the ground via ponding basins or dry wells and, being of good quality, provides an excellent source of water for recharging the aquifers.

The only type of individual on-site wastewater disposal system that GEPA currently approves is the septic tank and leach field system. Because o the nature of the limestone formations on which the leach fields are constructed, these systems can have an impact on the water quality of the Northern Lens. A limit on population densities within the recharge area should be imposed unless provisions for public sewer systems are included in development plans.

Livestock wastes can contribute significantly to the concentration of nitrogen in the groundwater. Commercial swine and poultry operations constitute the largest source of livestock wastes in northern Guam. In these operations, the most potentially detrimental waste handling practices appear to be the uncontrolled runoff from livestock areas, the storage of wastes in areas exposed to weather, and the high application rates of feedlot wastes as manure.

Presently the use of pesticides in northern Guam does not appear to be a major problem. But the potential danger is great because of the thin soil cover and the characteristics of the limestone base.

A survey of well facilities revealed serious operation and maintenance problems with the wells. These problems may be attributed to design deficiencies, inadequate maintenance, lack of specificity and poor administration of the existing operation and maintenance contract between PUAG and Pacific Drilling, Inc. and poor data collection and reporting procedures.

Future well development priorities have been determined for each management zone based on a priority matrix. The issues included in the matrix are: proximity to demand; proximity to transmission and distribution facilities; land ownership; contamination potential; available yield; and maximum size of wells allowable within the management zone.

Potential Air Force and Navy well development areas have been identified. Development of wells in these areas for military water needs will allow the military commands to obtain their water at points closer to their demand centers. This should eliminate much of the military's high costs for operation of water transmission facilities. It may then be advantageous for the Government of Guam to construct new wells for military use in exchange for existing water supplies, such as the Tumon Maui Well, or for guaranteed water supplies to serve the isolated areas in southern Guam, such as in the Agat and Santa Rita areas.

Institutional and legal frameworks related to management of the Northern Lens need to be modified to provide a higher, more certain form of management of Guam's groundwater resources. The legislative acts which need to be modified include:

- The Water Resources Conservative Act (Chapter II, Title LXI)
- The Water Pollution Control Act (Chapter III, Title LXI)
- The Toilet Facilities and Sewage Disposal Act (Chapter IV, Title LXI)
- Chapters I and V of the Zoning Law (Title XVIII)
- Chapters I and II of the Subdivision Law (Title XIX)

The regulations governing well construction, operation and maintenance on Guam, promulgated by GEPA, need to be modified to improve procedures for application and granting of well drilling and operating permits, to improve requirements with respect to construction of facilities, and to provide additional reporting requirements so that data on groundwater production will be available for future studies.

Land uses within the recharge areas of the Northern Lens need to be controlled to prevent contamination of the water supply. A Groundwater Protection Zone Map will be needed to delineate the areas within which land uses must be regulated.

The Groundwater Management Program that has been proposed is an ambitious program to be undertaken by the Government of Guam. Its implementation will take a cooperative effort by the various entities of the Government of Guam, the U.S. Government and all other entities that utilize the groundwater as a source of supply or whose activities potentially impact upon the qualities of the groundwaters.

Two alternatives exist for incorporating the proposed program into GEPA's existing organizational structures: 1) To develop a new Groundwater Management Program section within the Water Program Division or 2) To expand the responsibilities of the existing Safe Drinking Water Program.

A Technical Advisory Committee is needed to provide technical assistance to GEPA in evaluating the progress and effectiveness of the Groundwater Management Program and to recommend modifications to the program to increase its overall effectiveness.

With the implementation of the Groundwater Monitoring Program, an extensive data base will allow more refined estimates of aquifer yield in the future. After a period of time, the data base should provide enough new information to reevaluate the findings of the Aquifer Yield Report.

Recommendations

- The Guam Environmental Protection Agency (GEPA) should conduct future priority pollutant investigations on a five-year frequency. Future sampling should include the same ten sites used for the priority pollutant investigations in this study.

- GEPA should continue to monitor, on a semi-annual basis, those constituents which approached or exceeded the U.S. EPA drinking water limits.

- The minimum lot size for a single dwelling within the groundwater protection zone (see figure 11), using an on-site wastewater disposal system, should not exceed one acre. Proposals for higher density developments should include provisions for public sewer systems.

- No specific groundwater monitoring measures are recommended with regard to ponding basins and dry wells. However, GEPA should maintain a reference list of these facilities and should conduct an annual inspection to ensure that responsible agencies properly maintain these facilities and to ensure that potential contamination from these facilities is prevented.

- Poultry and swine wastes should continue to be collected in the manner described in GEPA's Water Quality Plan. Liquid and solid wastes should be separated, the liquids to be transported to either the Northern District Sewer System plant or the Central Agana plant. Solids can be applied to the land as fertilizer subject to application rate limitations.

- GEPA in cooperation with the Department of Agriculture should perform annual surveys of all agricultural feedlots within the groundwater protection zone to collect information regarding the size of the feedlot, the number and kind of animals being raised, a sketch of the feedlot structures, a description of waste collection and treatment methods, and a description of ultimate disposal methods.

- PUAG should modify its well design standards to eliminate the design deficiencies which have been noted in the survey. A Well Construction Manual which also addresses design standards has been prepared as part of this study. The manual should be used to guide future designs and construction.

- PUAG should also require detailed hydraulic calculations for all well and water transmission main designs. This further ensures that design-related problems are eliminated or at least minimized.

- GEPA should conduct semi-annual well facilities inspections to identify operation and maintenance problems and ensure that corrective action is taken. Whenever a pump is removed from a well facility, video inspections of the well casing and screen should be conducted.

- Records of operation and maintenance activities performed at each well should be maintained. This will provide a history from which the condition of facilities can be determined.

- The evaluation and rating of management zones should be reviewed every five years to ensure that proper priorities are established with respect to developing wells within the various management zones.

- The hydraulic analysis performed for the Water Facility Master Plan (1979) should be revised to consider the recommendations governing well development in Guam as developed in the Northern Guam Lens Study.

- GEPA should assume responsibility for compiling groundwater monitoring data to be presented in the annual Groundwater Data Report. Precipitation, evaporation and evapotranspiration data should be compiled monthly for inclusion in the Report. An expanded and regular groundwater level measurement program should also be undertaken.

- Other data collection activities that should be under taken include monitoring of chlorides and nitrates on a quarterly basis and compilation of groundwater production data.

- The USGS-GEPA Joint Funding Agreement for Deep Well Exploratory Monitoring, Groundwater Level Observation, Water Data Management, and Technical Assistance should be continued. This agreement will provide for the collection of most of the data which will be included in the Groundwater Data Report.

- Proposed revisions of the laws are included in the Laws, Regulations and Agreements Manual presented as an appendix to the main report. These revisions should be reviewed by the Attorney General and Governor and then sent to the Legislature for enactment.

- A revised version of the Well Development and Operating Regulations is contained in the study's appendix and should be adopted by the Board of Directors of GEPA.

- An cooperative agreement should be executed between the Government of Guam, the U.S. EPA, the U.S. Air Force, the U.S. Navy, the U.S. Geological Survey and the Office of Territorial Affairs of the Department of the Interior. A suggested version of this cooperative agreement is included in the Laws, Regulations and Agreements Manual.

- The Department of Land Management should be requested to prepare a legal description of the Groundwater Protection Zone.

- GEPA should assume the role of implementing and managing agency for the Groundwater Management Program.

- The Safe Drinking Water Program responsibilities should be expanded to include the activities of the Groundwater Management Program.

A Technical Advisory Committee should be delegated by the Administrator of GEPA and at his discretion, to include members from the Guam Environmental Protection Agency, Public Utility Agency of Guam, Bureau of Planning, U.S. Geological Survey, University of Guam, the U.S. Air Force and the U.S. Navy. The Technical Advisory Committee should meet at least semi-annually and a record of its proceedings should be maintained by the Administrator.

- The Northern Guam Lens Study should be adopted quickly as an element of Guam's Comprehensive Plan. The enabling legislation to implement the program activities should be approved by the Governor and enacted by the Legislature. Program infrastructure within GEPA and PUAG can be developed to carry out the provisions of the program once the enabling legislation is enacted.

ORIGIN AND FORM OF THE NORTHERN GUAM LENS STUDY

Guam is a small but very important island whose social and economic stability is singularly important. In its 212 square miles a population of 106,000 lives, most of whom (89,000) are civilian. The remainder are part of the U.S. Defense Forces. The population is concentrated on the limestone plateau of the northern half of the island where surface water resources are virtually non-existent and visible springs are rare except in the depression east of Agana. On the other hand, it is the north where practically all of the feasibly developable groundwater resources of the island occur.

These resources are the principal source of fresh water for the island's civilian population and a singificant fraction of the military population. The importance of retaining the yield and potability of the north's groundwater cannot be over-emphasized; the island's economic welfare and its very quality of life depends on a reliable supply of this fresh groundwater.

In the south many small streams dissect the island, but these flows decay to trickles in the dry season after surging as torrents during the rainy period. The largest accumulation of surface flow is diverted to the U.S. Navy Fena Reservoir System, which yields an average of about 10 million gallons per day (mgd). The second largest accumulation drains from the Ugum River whose full development would yield an average of more than 5 mgd but less than 10 mgd. In contrast, the northern Guam aquifers already yield 20 mgd and can safely supply approximately 59 mgd on a sustained basis. The northern aquifers, for this reason, are crucial to the welfare and stability of Guam.

Recognizing the essential importance of northern Guam's water resources, GovGuam through GEPA requested of the U.S. EPA that the entire northern half of the island be declared a "principal source aquifer." This declaration was made in 1978. A year later the U.S. Congress instructed the Department of the Interior to include in the budget for Guam a sum of $476,000 for study of the adequacy of the north's resources and an additional $274,000 for drilling exploratory wells to provide critical subsurface information. In 1979 GEPA conceived the general objectives and scope of an investigation utilizing these funds, and by September of that year the project was under way. Additional funds totalling $257,051 were received as grants from the U.S. Water Resources Council, and later the U.S. EPA granted $200,000 to expand management aspects of the study, especially those dealing with groundwater quality. The total sum available for the three year effort was $1,207,051. A complete listing of the NGLS sources of revenues and expenditures appears at the end of this report.

The Project Director joined the investigation in September, 1979, and before the end of the year scopes of work had been prepared, some requests for proposals were circulated, and one contract had been signed. In 1980 activity was concentrated in field efforts, particularly in seismic, gravity and topograhic surveys, the drilling of exploratory wells and in investigation of hydrogeologic features. In addition, work was initiated on creating a mathematical numerical model of the northern aquifer system. During 1981 exploratory drilling continued, intensive data summarization and analysis was underway, and composition of the computer model proceeded. The last exploratory well was drilled at the end of 1981. Analyses and interpretations were completed by the middle of 1982, and preliminary report drafts were submitted by the end of summer.

The NGLS was organized within GEPA and carried out as a combined effort by several different entities, most of whom have a permanent presence on Guam. Those engaged in the project on a continuous basis were the Prime Contractor, Barrett-Harris Associates in association with Camp Dresser McKee, Inc; the Water and Energy Research Institute (WERI) of UOG (originally Water Resources Research Center); and the U.S. Geological Survey (USGS). Other contractors carried out the topographic survey, the seismic-gravity surveys, and the exploratory drilling.

Objectives and Scopes of Work

The NGLS was undertaken to assess the amount of groundwater that could be developed reliably and safely from the northern aquifers. The principal objectives of the study were to obtain an accurate estimate of sustainable yield, to determine the most efficient methods of extracting the groundwater consistent with need and conservation, to set out a schedule for future water development and redevelopment, to establish a code of operational rules for management, and to recommend institutional and legal arrangements for protecting the water supply. The study was divided into two phases, one of which dealt chiefly with scientific and technical aspects of water resources development and the other with management issues.

Phase I of the investigation produced an Aquifer Yield report describing aquifer boundaries, estimates of the quantity and distribution of groundwater flow, and` behavior of the groundwater under natural and exploitation conditions. Mathematical modeling, both numerical and analytical, was extensively employed. The data obtained from geophysical surveys and exploratory drilling were integrated into Phase I interpretations.

Phase II of the study was devoted to producing a groundwater management plan within the technical constraints established by the Phase I conclusions and the economic - institutional constraints inherent to Guam. The management plan considers the conservation of quantity and quality of groundwater within a framework that allows and encourages economic development to continue.

The major work sectors of the study were underway before the end of 1979. Three critical tasks had to be performed by special contractors with skills and equipment not demanded of the Prime Contractor, WERI or the USGS. The topographic survey, which was necessary to provide exact elevations above mean sea level for all water production and observation sites, was made by Juan C. Tenorio and Assoc. of Guam who completed the task early in 1980. The geophysical survey, consisting of seismic refraction and gravity measurements from which the subsurface boundaries of the aquifers could be determined, was successfully accomplished in April, 1980 by Eco-Systems Management, Inc., of San Diego, California. The exploratory well program started in the third quarter of 1980 and was completed at the end of 1981. Two Guam drilling firms, Pacific Drilling Co., Inc., and Geo-Engineering Testing Inc., were contracted to drill the wells.

Other broad work sectors included hydrogeology, aquifer characteristics and behavior, and management issues and alternatives. The hydrogeology sector, which encompassed the collection and evaluation of existing and new data in geology, hydrology and geochemistry, was initially the responsibility of WERI and the USGS, both of whom started work in the first quarter of 1980 and continued to completion of the project. The sector dealing with ascertaining aquifer characteristics and modes of behavior incorporated modeling, including a finite element model of the whole of northern Guam. The management issues and alternatives sector embraced tasks dealing with operating rules, econometric analyses, future water development, institutional and legal aspects of water development, and protection of the groundwater supply.

PHASE I
AQUIFER YIELD

The aquifer yield studies employed scientific and engineering methods to provide a comprehensive description of the Northern Guam aquifers and to determine the quantity of groundwater that reliably and safely could be developed from them. One of the most important conclusions of the studies is that the "sustainable yield" of northern Guam is 59 mgd, with about 42 mgd remaining as available yield. Sustainable yield is defined as the continuous rate of water withdrawal that would not impair either the productivity of the aquifers or the quality of the groundwater produced.

Sustainable yield, however, is not easily attained. Contributions to it are constrained by aquifer shape and characteristics and it must be carefully distributed. The program fashioned to provide a reliable estimate of sustainable yield included many tasks. The topographic survey was the first that proceeded in series and in parallel to achieve the goal. Geophysical surveys and exploratory well drilling soon followed while hydrogeological and aquifer evaluations went on simultaneously.

Topographic Survey

In groundwater systems in which fresh water floats on denser salt water the height of the water table above mean sea level (called the head) is a critical parameter because for every foot of head, 40 feet of fresh water theoretically extends below sea level. Slight changes in head cause large changes in volume and in flow rates, so that unless accurate water levels are obtained neither subsurface storage of fresh water nor its movement can be accurately determined. Chiefly for these reasons, but also to establish benchmarks for future surveys, accurate elevations at more than one hundred water production and observation sites were measured.

Heads in basal aquifers of Guam are low, normally less than four feet. Basal groundwater is defined as the lens of fresh water which freely floats on underlying salt water. In parabasal aquifers heads are higher, reaching 30 to 40 feet in the extreme case at Ordot. Parabasal groundwater is laterally continuous with basal water but rests directly on the impermeable basement.

The accurate elevations taken in the topographic survey were employed in such tasks as developing water level contour maps extending over basal and parabasal areas and in hydraulic analyses and modeling. They will serve as the elevation framework for future monitoring of the fresh water lens. A standard of care and accuracy has been set for determining elevations at all water sites to be established in the future.

Geophysical Surveys

In northern Guam limestone forms the aquifers while volcanic rocks behave as an impermeable basement. Thus the elevation of the basement with respect to mean sea level is overwhelmingly important in defining the groundwater flow system of the limestone aquifers. Before the start of the NGLS knowledge of the basement depended on a few scattered wells that had penetrated to the volcanics and extrapolation of the limestone volcanics contact from exposures situated at Mataguac Hill and Mt. Santa Rosa.

Geophysical techniques had previously been proposed as the means of mapping the basement on a regional scale, but only in the course of the NGLS were some of these methods employed. Essentially, geophysics such as seismic refraction and reflection consist of transmitting shock waves down through the earth from a known point and detecting how fast the waves return to the surface as they "bounce" off layers of rock with different densities. The shock waves are produced by small charges of dynamite and sensitive microphones placed on the ground surface detect the speed or velocity of their return. A sophisticated computer records and ultimately analyzes this information. A gravity survey detects very small changes in the earth's gravitational field at various locations due to the different densities of underground rock formations. A magnetic survey utilizes instruments which can detect the presence of rocks which contain magnetism such as iron which is present in volcanic formations. Seismic refraction and gravity surveys were successfully conducted, while magnetic and seismic reflection techniques were tested but discontinued. The magnetic techniques were compromised by an abundance of pipes, wires and other disturbances in most areas of the north, while the success of the refraction method eliminated a requirement for the more costly seismic reflection technique.

A total of 56 refraction profiles were made in the 100 square miles of northern Guam. The gravity survey was carried out during the same period as the seismic work. Measurements were made at a total of 320 stations, some of which were in the south of Guam even though this area is not included in the NGLS. These southern readings were taken to determine structural features thought to be continuous with the north.

Seismic Refraction Survey

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

In practically every profile three layers of distinctly different seismic velocity were encountered, the top layer of limestone, the intermediate layer also of limestone, and the bottom layer of basement volcanic rock. The first limestone layer exhibits an unusually low velocity that clearly differentiates it from the second limestone layer. In most profiles the volcanic basement is also differentiable from the intermediate limestone, but in several instances the higher range of velocity in the limestone overlaps the lower velocity range of the volcanics so that judgement based on other factors must be exercised in selecting depth to basement.

The velocities of the limestones are unexpectedly low when compared to results in other limestone terrains. In fact, many of the contractors responding to the request for proposal believed that it would not be possible to discriminate between limestone and volcanic velocities and that the basement contact could not be identified by refraction techniques. On Guam the limestones consist of fossil reefs and associated calcium carbonate deposits that have been raised above sea level. The most likely explanation for the low velocites of these raised reefs is that the highly porous rock decreases the seismic shock waves.

The three layer model of two limestone layers atop the volcanic basement is applicable throughout northern Guam. The basement could not be identified in all cases, however; 18 of the profiles did not refract from the basement because its depth is greater than 500 feet, the limit of discrimination at these locations.

The velocity and thickness of layer 1 are quite uniform; the average thickness is 126 feet and the average velocity 3,106 feet per second. The velocity of layer 2 is similarly uniform, and for those profiles where the volcanic basement was definitely encountered the thickness of layer 2 is also relatively constant. Average velocity of layer 2 is 6,795 feet per second and average thickness 317 feet. Using only those basement velocities directly established by refraction, average basement velocity is 9,171 feet per second.

Table 1 is a summary of velocity statistics of the three layers for all profiles without regard to location. Only definite basement velocities are considered. Included in the table are estimates of the outer limits of the velocity envelopes based on averages plus or minus two standard deviations. Assuming that individual values are normally distributed, these limits include 95 percent of all expected values. It appears that values for each layer are approximately normally distributed because the average and the median are nearly equal, a condition of normality.

The statistics show that layer 1 is unambiguously distinct from layer 2. In most profiles where an actual

Table 1

Seismic Refraction
Statistics of Layer Velocity

(velocities in feet per second)

Statistic	Limestone Layer 1	Limestone Layer 2	Volcanics Layer 3
number in sample	56	56	38
range of velocity	1,781-4,988	5,007-8,214	7,061-13,649
median velocity	3,161	7,000	9,228
average velocity (V)	3,106	6,795	9,398
standard deviation (S)	742	867	1,234
V + 2 S	4,590	8,529	11,866
V - 2 S	1,622	5,061	6,930

layer 3 velocity was recorded the intermediate limestone is usually distinguishable from the basement. However, an overlap exists of the higher layer 2 velocities with the lower layer 3 velocities so that in some instances the basement must be verified by supplementary information.

Figure 1 is a map illustrating the important regional features of the basement as interpreted from results of the refraction survey. Contours of the basement as elevations relative to mean sea level are shown. Where the basement is more than 150 feet below sea level parabasal conditions form. Where the basement rises above sea level, developable groundwater is unlikely to occur.

The principal basement features having hydrologic relevance are as follows:

1. Mataguac Rise : a rise in the basement above sea level in a roughly elliptical area of about 10 square miles between Dededo and Andersen Air Force Base. Several hundred feet of limestone overlie the basement except at small volcanic outcrops near Mataguac. This area serves as a critical source of recharge for aquifers on its flanks.

2. Santa Rosa - Barrigada Rise: a linear subsurface ridge extending from the vicinity of Mt. Santa Rosa to Barrigada. The basement rises above sea level over a 10 mile distance as a narrow ridge varying from a few tenths to more than a mile wide. The ridge plunges steeply on its flanks, and its southwest extension drops below sea level before reaching Agana Swamp. It plunges into the Yigo Trough on the west, while on the east the sea level contour coincide with Janum Spring. It is profoundly important in regional hydrology because it acts as a barrier to groundwater flow. Most groundwater is forced to drain toward the west.

3. Yigo Trough: a subsurface low between the Mataguac Rise and the Santa Rosa-Barrigada Rise. It extends from Tumon Bay along a gentle arc to the vicinity of the south boundary of Andersen over a length of about eight miles. Inland width varies from 1.5 miles at Dededo-Yigo to about half a mile at Andersen. The trough rises above sea level in its northern end, separating groundwater drainage beneath Andersen air field from that moving toward Yigo. It is an extremely important hydrologic feature that accumulates and channels the largest flux of groundwater in Guam.

The above three major basement features dominate the location and developability of the limestone aquifers north of the Agana region. A fourth important feature is the rise in the basement between Agana Swamp and the limestone - volcanic rock contact that separates Guam into north and southern halves. An appreciable parabasal sector rests on the basement reaching across the island from Pago Bay to Agana.

The basement configuration indicates that at least two thirds of subsurface drainage moves toward the Philippine Sea and only one third to the Pacific Ocean sides of the island. This sort of revelation, along with reasonably well defined subsurface boundaries, makes mathematical modeling of the groundwater flow system more realistic.

Gravity Survey

A gravity survey was included in the geophysics sector chiefly to supplement data yielded by seismic refraction, but an ancillary purpose was to provide a reconnaissance view of gravity distribution of the island because no such survey had been done before. The normal goal of a gravity survey, which is determination of regional gravity anomalies, was successfully accomplished. In addition, the regional bulk density of the limestone was obtained by correlating changes in free air anomalies with elevation along a linear traverse, and residual gravity values were computed by removing the regional gravity field.

Over northern Guam regional gravity varies from about 200 milligals (mgals) on the east coast to 220 mgals at the positive anomaly near Potts Junction on Marine Drive. Although not a large gradient, it is significant. A second gravity high is found over Nimitz Hill. It is not as obvious as the northern one because closure is poor and incomplete. In all of Guam the greatest high lies off Facpi Point where an anomaly of 235 mgals was measured.

By correlating changes in free air gravity anomalies with differences in elevation along a line of stations, measurement of mass between the lowest and highest station is made. Four traverses resulted in density calculations averaging 2.35. By referring this density to that of solid calcite limestone, the porosity of the actual limestone can be calculated. An average porosity of 13 percent was computed, which is consistent with values determined by other methods.

Exploratory Well Program

An essential work sector of the NGLS was the siting and drilling of exploratory wells to obtain critical information about the subsurface environment and the dynamics of groundwater flow in it. The concept of an exploratory well program predated formulation of the NGLS and, in fact, was required in the funding legislation.

Exploratory wells are borings that probe into the fresh and salt water portions of an aquifer and occasionally reach to the volcanic basement. Hydrologic information is directly obtained in contrast to conclusions which must be derived from geophysical surveys. Eleven exploratory wells were originally planned and eleven were completed.

The principal objectives of the exploratory program were as follows:

1. Verify and expand knowledge of subsurface geology
2. Define aquifer characteristics
3. Evaluate dynamics of groundwater flow
4. Obtain water samples of various depths for chemical analysis
5. Serve as observation sites to monitor long and short term changes in groundwater behavior and character.

The wells had a simple design and were left uncased except in the argillaceous limestone, which ordinarily is unstable. One well (Ex-5) was cored from the surface to its full depth, while in other wells two separate five feet cores were taken, one at the water table and the other in either the transition zone (where the fresh and salt water interface) or the salt water underlying it. Examination of these cores, in particular to estimate porosity, were made for the NGLS. The cores will be available for future research.

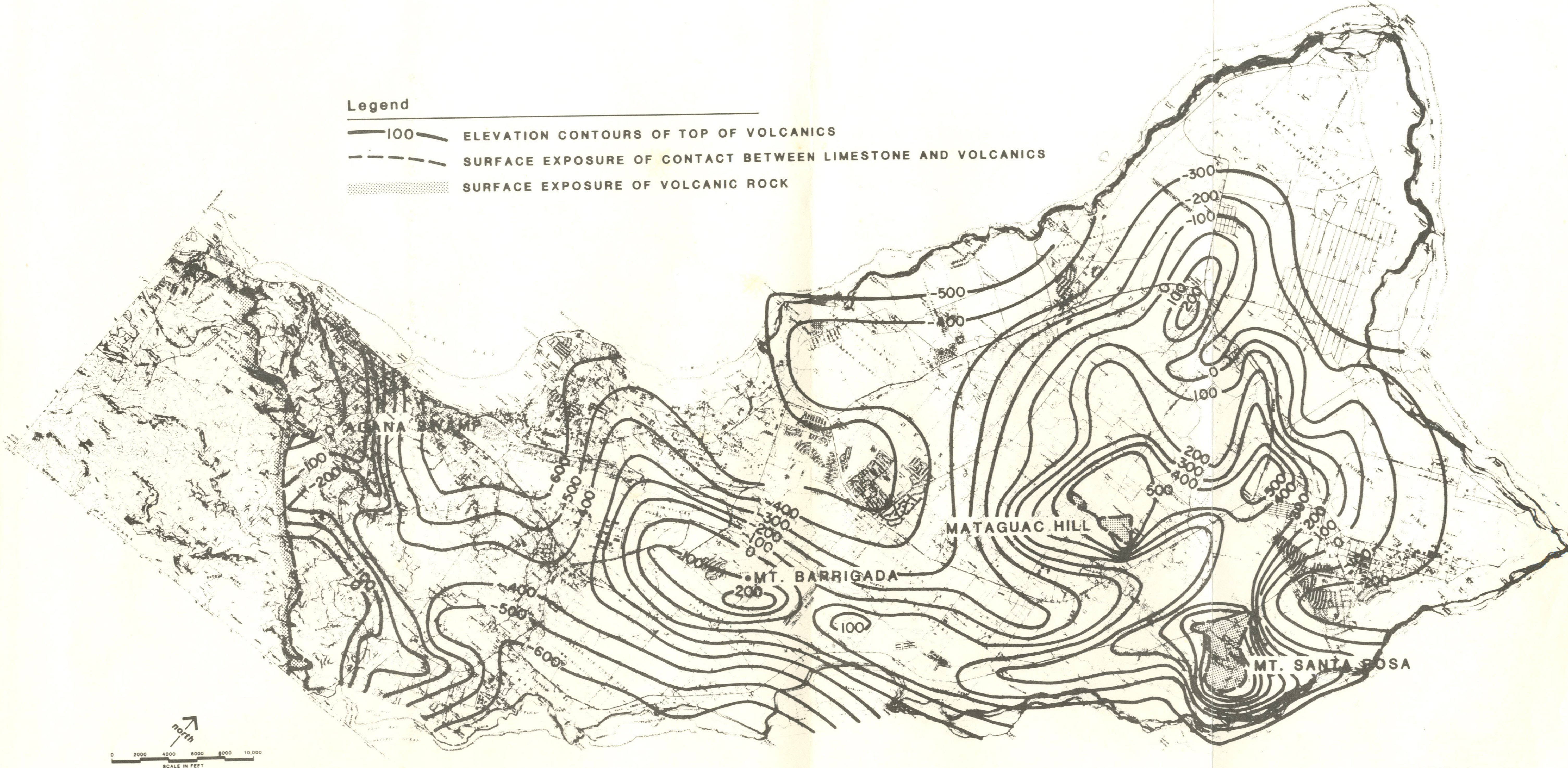


FIGURE 1
CONTOUR MAP
OF THE VOLCANIC BASEMENT

Table 2 lists the exploratory wells and some essential data for each one. Ex-5A was drilled within 50 feet of Ex-5 because the driller could not properly complete Ex-5. Actual drilling in Ex-6 was only 50 feet because the exploratory well was located to take advantage of an existing abandoned well, M-11A, which was already 413 feet deep. Total footage drilled for all wells was 6,140 feet, and approximately 1,000 feet of casing was installed. The wells have already provided much valuable information, yet they will continue to be important as data gathering sites for as long as they remain accessible. A monitoring network centered on these wells will guide future groundwater development.

Table 2

Exploratory Wells

Well	Location	Ground Elevation (ft)	Drilled Depth (ft)	Bottom Elevation (ft)	Volcanic Basement Elevation (ft)
Ex-1	Mongmong	97	597	- 500	
Ex-2	Andersen-Yigo Boundary	564	300	+ 264	+ 291
Ex-3	Adacao	447	535	- 88	+ 82
Ex-4	Father Duenas School	154	400	- 246	
Ex-5	Dededo	387	570	- 183	
Ex-5A	Dededo	385	600	- 215	
Ex-6	Macheche	309	463	- 154	
Ex-7	Wettengel Junction	283	698	- 415	
Ex-8	Northwest Field	462	658	- 196	
Ex-9	Barrigada	239	513	- 274	
Ex-10	Finegayan	349	705	- 356	
Ex-11	Latte Heights	390	513	- 123	- 50

Hydrogeology

The hydrogeology sector, which incorporated tasks in geology, hydrology and geochemistry, was a joint effort of WERI, the USGS and the Prime Contractor. It went on continously, spanning the full period of the investigation because its conclusions depended in large measure on data generated by other work sectors.

Throughout all discussions concerning the aquifers, four fundamental descriptive terms frequently appear. Two of the terms, argillaceous limestone and clean limestone, broadly describe aquifer lithology, and the other two, basal water and parabasal water, stipulate the mode of groundwater occurrence. Argillaceous limestone refers to the formation that contains enough clay to profoundly influence aquifer characteristics and behavior; clean limestone refers to formations in which clay and other impurities are virtually absent. Basal groundwater refers to fresh water floating on sea water while parabasal groundwater refers to fresh water hydraulically connected with basal water but lying directly on the impermeable basement. These features of groundwater occurrence are illustrated in figure 2.

Argillaceous limestone aquifers extend from Barrigada south to the end of the limestone platform below ground elevation of approximately 200 feet; clean limestone aquifers exist north of Barrigada. The basal and parabasal groundwater zones depend on the configuration of the basement; the widest known extent of parabasal water crosses the island as a strip a mile or less in width along Route 4 from Agana toward Pago. Elsewhere basal conditions dominate groundwater occurrence.

Basement configuration and aquifer geology vary over short distances. To enable the major variations to be integrated into a management scheme, northern Guam was divided into six major sub-basins (see figure 3). The chief determinant of sub-basin boundaries are the buried rises of the volcanic basement. The subbasins are further separated into basal and parabasal sectors. Basal sectors are restricted to distances greater than 4,000 feet inland while the parabasal sectors are considered exploitable from the nearest incursion of salt water to a basement divide. For management control purposes, each sub-basin is partitioned into zones. A total of 47 of these management zones has been assigned to northern Guam.

The restriction of a 4,000 foot wide buffer zone between exploitable basal aquifers and the sea leaves approximately 70 square miles as the zone of recharge. Rainfall over the limestone plateau averages between 85 and 100 inches per year, of which the recharge portion has been calculated to be about 33 inches, or 111.9 mgd. Somewhat less than half of this quantity is safely developable.

Aquifer Features

All of the aquifers of northern Guam are composed of limestone but a marked difference in characteristics and behavior exists between the argillaceous limestone aquifers and the clean limestone aquifers. Porosity, one of the intrinsic parameters governing flow behavior, is less in the argillaceous limestone but not extravagantly so. On the other hand, permeability, the most fundamental parameter, is greater by an order of magnitude in the clean limestone.

Core porosity analyses by WERI of an argillaceous core (Ex-1) showed typical porosity to be less than 4 percent while examination of a clean limestone core (Ex-5) indicated average porosity of about 13 percent

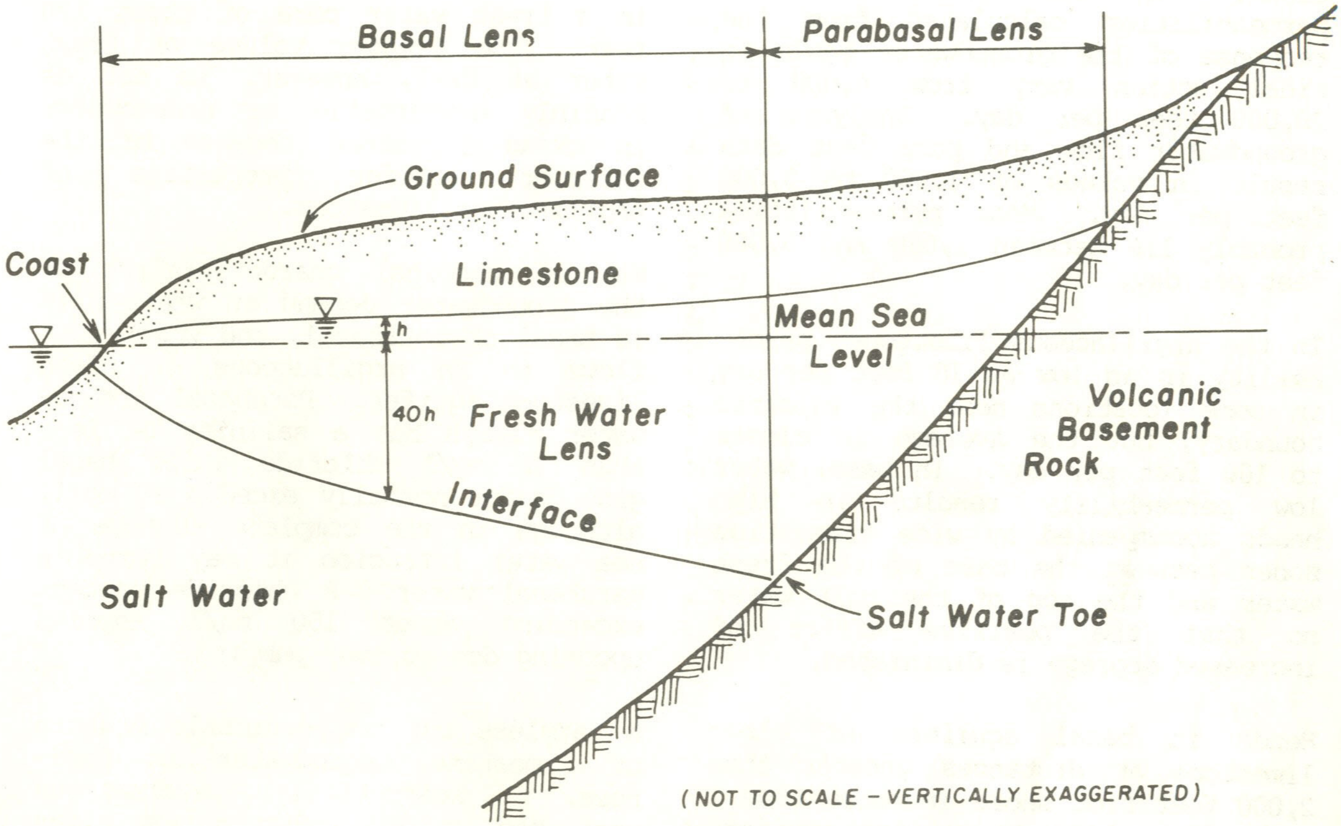


FIGURE 2

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

above the water table and 21 percent below. These higher values conform to the conclusions of the gravity survey.

Permeability, also called hydraulic conductivity, varies over a wide range within each rock type, but the lower limit in clean limestone is equal to or greater than the higher limit of the argillaceous formations. In the clean limestone permeabilities calculated from the response of the groundwater table to tidal action vary from 4,000 to 20,000 feet per day. Analysis of groundwater flow and pump test data result in values of 1,000 to 3,000 feet per day. Most permeabilities probably lie between 1,000 and 5,000 feet per day.

In the argillaceous limestones permeability is as low as 10 feet per day in some locations near the volcanic boundary, but the average is closer to 100 feet per day. In basal water low permeability results in high heads accompanied by wide transition zones between the base of the fresh water and the top of the salt water so that the positive effect of increased storage is diminished.

Heads in basal aquifers of clean limestone at distances greater than 2,000 feet from shore increase from 2 to 4 feet while in similar aquifers in argillaceous limestone they are 4 to 10 feet. The transition zone in clean limestone has a half width (extending from the 50 percent sea water isochlor to the potable isochlor of 250 mg/l chloride) averaging 15 to 20 feet, while in the argillaceous limestone the half width typically exceeds 50 feet. For instance, at Ex-9 in clean limestone the head is 3.0 to 3.5 feet and the half width of the transition zone is 20 feet, yielding a fresh water core of 110 feet (based on application of the 40:1 ratio to the 50 percent sea water isochlor). At Ex-1 in argillaceous limestone the head is about 8 feet and the half width of the transition zone about 100 feet, resulting in a fresh water core of about 220 feet. The greater volume of fresh water at Ex-1, however, is not as feasibly developable as groundwater in clean limestone because of the inferior aquifer properties of argillaceous limestone.

Natural chemical characteristics of the groundwater depend on whether it is basal or parabasal, and whether it flows in an argillaceous or clean limestone aquifer. Parabasal groundwater always has a salinity of less than 30 mg/l chloride while basal groundwater normally exceeds 70 mg/l, although in the complete absence of sea water intrusion it may resemble parabasal water. A chloride content exceeding about 150 mg/l implies upconing due to over pumping.

A harmless but not desirable feature of limestone groundwater is hardness. Statistical evaluations performed by WERI indicate that clean limestone, in the absence of sea water intrusion, carries water having less hardness and total dissolved solids than argillaceous limestone under the same constraint. Table 3 briefly summarizes water quality in the various limestones.

Legend

GROUNDWATER SUBBASIN BOUNDARY

72 WELL No. 72

FIGURE 3

SUBBASIN LOCATION MAP

Table 3
Water Type
(Parabasal)

	pH	Hardness mg/l	Chloride mg/l	Conductance micromhos per cm
Clean limestone	7.4-7.7	170-220	15-25	365-450
Argillaceous limestone	7.1-7.2	260-320	15-25	522-625
Intermediate	7.4-7.5	220-240	20-25	455-495

Assessment of groundwater quality for aquifer contamination was included in the Phase II portion of the NGLS, but the level of pollution reflects upon the purifying efficiency of the limestone. Analyses were made of water from ten well sites in an attempt to identity "priority pollutants" comprised of 114 organic compounds, 17 metals and asbestos fibers. Groundwater in northern Guam was shown to be essentilly free of measureable contamination. Table 4 gives the level of contamination found at each sampling site for selected pollutants. All contaminant concentrations, except for selenium in well A-17, are below formally designated or presumed harmful levels. In A-17 the selenium level of 13 micrograms per liter exceeds the safe level of 10 micrograms per liter. No explanation for this has been found.

Mathematical Model of Aquifer Behavior

A popular technique for describing and predicting groundwater behavior under different conditions of development is mathematical modeling in which numerical methods for solving arrays of complicated differential equations are employed. The application of the method to fresh water-salt water systems has evolved rapidly in the last few years. During the NGLS a finite element model of groundwater flow was devised by Dr. Dinshaw Contractor, visiting professor at the University of Guam, as part of the WERI contribution to the investigation. The model is one of the first anywhere to successfully simulate behavior of a basal-parabasal groundwater system.

Solutions have been produced that predict responses of salt water underlying the fresh water lens for different conditions of recharge and pumping. The model shows that in an unconstrained basal lens the water table reacts to recharge rapidly, that is in days or weeks, while the fresh water-salt water interface at the base of the lens responds very slowly, in years. This is a revelation that, though not unexpected on the basis of other forms of analysis, is at odds with a common belief that the lens contracts quickly and substantially during periods of low recharge. Under parabasal conditions the model indicates that upward movement of the water table in response to impulse recharge and its decay during drought happens rapidly.

Table 4

Priority Pollutant Constituents with Detectable Concentrations

Constitutent	Concentration (micrograms/liter) by Well										
	A-6	A-15	A-17	AG-1	D-1	F-1	H-1	M-1	Y-2	Tumon Maui Well	Recommended Drinking Water Limit
Inorganics											
Arsenic	- -*	7	18	- -	- -	- -	- -	- -	- -	- -	50†
Iron	4	13	6	6	4	4	5	5	8	152	300†
Lead	- -	- -	- -	6	- -	- -	- -	- -	- -	28	50†
Maganese	- -	- -	- -	- -	- -	- -	- -	- -	- -	5	50†
Selenium	- -	7	13	- -	- -	- -	7	- -	- -	- -	10†
Zinc	4	- -	- -	9	- -	7	9	- -	- -	21	5000†
Organic											
Dieldrin	- -	0.06	0.02	- -	- -	- -	- -	- -	- -	0.01	17††
Methoxychlor	- -	- -	- -	- -	0.54	- -	- -	- -	- -	1.9	100†
Methylene Chloride	- -	- -	- -	- -	- -	- -	- -	302	- -	- -	100**
Trichlorethylene (TCE)	35	- -	- -	- -	- -	- -	- -	- -	- -	- -	100**
Trichlorofluoromethane (Freon 11)	- -	- -	- -	- -	- -	- -	- -	29	12	- -	80**

* Constituent concentration less than the limits of detection.

† U.S. EPA recommended drinking water limit.

** No specified limit, but above this number, there should be concern.

†† California (1972) limiting concentration (No EPA limit set).

Reports dealing with calibration of the model and simulation of groundwater development scenarios have been submitted to the NGLS and published by the University of Guam. In addition, Dr. Contractor has prepared a User Manual for the Model.

The model is highly sophisticated and not likely to be of direct assistance in development of groundwater without substantial further refinement. Even when it is perfected, exceptional skill and effort will be required to properly utilize it.

Sustainable Yield

One of the primary objectives of the NGLS was determination of the sustainable yield of the northern Guam aquifers. The concept of sustainable yield incorporates all aspects of the proper development of groundwater including well location and construction, and rates and distribution of draft. Sustainable yields were computed for each of the 47 management zones included in the six major sub-basins. Table 5 lists these values along with the portions remaining for further development. A brief description of each sub-basin and its sustainable yield is given below.

Agana Sub-basin

The basin is divided into five basal and six parabasal management zones. Total sustainable yield is 13.1 mgd (or 11.7 mgd if 1000 gpm flow recharging the Fonte River is excluded), of which 5.0 mgd is currently being produced. The basin covers 16.1 square miles, equally divided between basal and parabasal sectors south of Barrigada Hill.

Mangilao Sub-basin

The basin has an area of 4.4 square miles divided into three basal and five parabasal zones - about three fourths of the area is parabasal. Total sustainable yield is 3.9 mgd, of which 1.40 mgd is being pumped.

Andersen Sub-basin

The basin includes an area of 6.8 square miles of which less than two square miles is thought to be basal. It is divided into three parabasal and two basal management zones. Although its sustainable yield is 6.2 mgd, no groundwater is being exploited.

Agafo Gumas Sub-basin

This basin contains 11.7 squre miles, more than half of which is parabasal. Sustainable yield is 10.1 mgd, but only 0.4 mgd is presently being produced. Division has been made into three parabasal and one basal management zone.

Finegayan Sub-basin

The basin is divided into three basal and three parabasal zones sectored out of a total area of 7.6 square miles. Nearly twice as much is basal as parabasal. Sustainable yield is 6.4 mgd of which 2.6 mgd is being developed.

Yigo Sub-basin

This basin is the largest and most productive in northern Guam. It includes 21.2 square miles, 11.0 square miles of which are parabasal. The basin is divided into nine parabasal and four basal zones. Current production is 8.6 mgd while sustainable yield is 19.1 mgd. The Yigo sub-basin, which essentially coincides with the Yigo Trough, has great potential for innovative methods of water development, such as the use of large capacity wells.

Table 5

Summary of Sustainable Yield

Sub-basin and Zone	Aquifer Type	No. of Existing Wells	Average Annual Well Production (mgd)[4]	Estimated Sustainable Yield (mgd)	Remaining Available Yield (mgd)
Agana					
Pago Bay	PB	1	0.17	0.45	0.28
Chalan Pago	PB	5	1.40	1.24	(0.16)
Nimitz Hill	PB	2	0.49	2.17[3]	1.68
Anigua	PB	0	0	1.17	1.17
Mt. Barrigada South	PB	0	0	0.30	0.30
Mt. Barrigada East	PB	0	0	0.73	0.73
Barrigada	B	2	0.26	0.37	0.11
Toto	B	0	0	0.62	0.62
Agana Swamp	B	2	0.61	1.25	0.64
Sabanan Maagas	B	8	2.07	1.73	(0.34)
Manaca	B	0	0	1.67	1.67
Sub-Total		20	5.00	11.70[3]	7.20[1]
Mangilao					
Mangilao South	PB	0	0	0.32	0.32
Mangilao North	PB	5	1.17	0.42	(0.75)
Adacao	PB	0	0	0.95	0.95
Sabanan Pagat	PB	0	0	0.79	0.79
Janum	PB	0	0	0.66	0.66
Asbeco	B	0	0	0.33	0.33
Taguan	B	1	0.25	0.30	0.05
Sasajyan	B	0	0	0.13	0.13
Sub-Total		6	1.42	3.90	3.23[1]
Andersen					
Tarague	PB	0	0	1.02	1.02
Salisbury	PB	0	0	2.85	2.85
Lupog	PB	0	0	1.46	1.46
Anao	B	0	0	0.35	0.35
Andersen	B	0	0	0.56	0.56
Sub-Total		0	0	6.24	6.24
Agafo Gumas					
Agafo Gumas West	PB	0	0	0.86	0.86
Agafo Gumas Central	PB	2	0.38	4.20	3.82
Afafo Gumas East	PB	0	0	1.63	1.63
Northwest Field East	B	0	0	3,40	3.40
Sub-Total		2	0.38	10.09	9.71

Summary of Sustainable Yield

Sub-basin and Zone	Aquifer Type	No. of Existing Wells	Average Annual Well Production (mgd)(4)	Estimated Sustainable Yield (mgd)	Remaining Available Yield (mgd)
Finegayen					
Callon Tramojo	PB	2	0.50	0.95	0.45
Finegayen East	PB	0	0	1.09	1.09
Potts	PB	0	0	0.86	0.86
Northwest Field West	B	0	0	1.25	1.25
Finegayen West	B	7	1.59	0.63	(0.96)
NCS	B	3	0.50	1.60	1.10
Sub-Total		12	2.59	6.38	4.75(1)
Yigo					
Mt. Barrigada West	PB	0	0	1.30	1.30
Mogfog	PB	0	0	0.65	0.65
Marbo South	PB	0	0	0.65	0.65
Marbo North	PB	0	0	0.35	0.35
Yigo East	PB	2	0.18	1.08	0.90
Mt. Santa Rosa	PB	0	0	0.76	0.76
Mataguac	PB	0	0	0.88	0.88
Yigo West	PB	4	0.71	1.90	1.19
Y-Sengsong	PB	5	1.04	3.00	1.96
Dededo North	B	1	0.18	1.93	1.75
Dededo South	B	22	4.68	3.46	(1.22)
Macheche	B	1	0.03	1.25	1.22
Asatdas	B	7	1.81	1.92	(0.11)
Sub-Total		42	8.63	19.13	11.72(1)
TOTAL		82	18.02(2)	57.44(3)	42.85

(1) For areas exceeding sustainable yield, remaining available yield considered as zero.

(2) Excludes well production and yield estimates for coastal areas (4000 ft. buffer).

(3) Excludes 1000 gpm (1.44 mgd) of sustainable yield that currently recharges the Fonte River.

(4) Average annual well production based on production records for 1981.

PHASE II
GROUNDWATER MANAGEMENT

In 1978 the groundwater resources of northern Guam were designated a "principal source aquifer" in recognition of their extraordinary importance as the primary source of drinking water for about three fourths of the island's population. The designation noted that the aquifers are vulnerable to contamination and consequently require constant attention to protect against degradation. It was implicit in the official designation that a management framework for groundwater protection is necessary.

Some management aspects were included in the original scopes of work for Phase I of the NGLS, but it soon became clear that expansion of the management sector was desirable. In early 1981 the U.S. EPA granted GEPA $200,000 to enhance management studies, especially with respect to protection of the aquifer from contamination, and subsequently the NGLS was restructured by adding Phase II in which management, institutional and financial issues were joined.

The main objectives of Phase II were to produce a comprehensive groundwater management plan and implementation manuals for stipulating rules of performance relating to water development operations. The results of Phase I were essential to creating a realistic final management plan. The principal tasks undertaken in Phase II included the following:

1. Source control for priority pollutants
2. Review of operating procedures
3. Detailed review of laws and regulations
4. Analysis of land use and related environmental issues
5. Preparation of technical manuals
6. Preparation of management and institutional manuals
7. Preparation of groundwater management plan and report

The Phase II program resulted in the following written contributions to the NGLS, but it should be noted, as it was in the discussion of Phase I, that the benefits of association and experience of GEPA and other GovGuam personnel were also an important product of the investigation.

1. Groundwater Management Alternatives
2. Groundwater Management Program
3. Operation and Maintenance Manual
4. Well Operation Organizational Manual
5. Well Construction Manual
6. Laws, Regulations and Agreements Manual

State of the Groundwater Resources of Northern Guam

The extent and features of the groundwater resources of northern Guam are described in the Aquifer Yield Report of Phase I. Efficient management of a groundwater system depends on a clear understanding of the limits of the resources. Figure 4 shows the location of the basal and parabasal aquifers, and in figure 5 cross-sections of representative aquifers are given for the transects shown on figure 4. The aquifers have been successfully exploited since 1965, but deterioration of groundwater quality has occurred in some places and could be expected to expand in the absence of a set of management constraints.

Of special importance in Phase II was the determination of the condition of the aquifer with regard to contamination by non-natural substances. A program for detecting "priority pollutants" was initiated. Ten sampling locations were chosen that took into consideration representative coverage in terms of land use, aquifer types and distribution, and current and proposed production. The first sampling run was made in September, 1981, and a follow-up on several sites was done in July, 1982.

The results of the survey showed the groundwater of northern Guam to be of excellent quality, unusally free of pollutants. Several priority pollutants were detected but only one (selenium) in one well was found to be somewhat in excess of the U.S. EPA recommended limit. Table 4 lists the detected pollutants by location and gives the recommended limits of acceptance.

A peculiarity of the limestone aquifers of northern Guam is the relatively high concentration of nitrogen (N) in the groundwater. The concentration of nitrogen is by no means near the unacceptable limit of 10 mg/l, but its normal range between 1 and 3 mg/l is five to ten times greater than in typical groundwater. Because waste disposal into the ground is a common source of nitrogen in groundwater, a mass balance calculation was made of probable human and animal contribution to the nitrogen load. Although the computed concentration is only half of what occurs, the model suggests that waste disposal must be controlled to minimize further increases in nitrogen.

Except for unusual circumstances, bacterial contamination in the groundwater of northern Guam does not occur. At most of the wells in which coliform bacteria were detected, the concentrations are so low that they are not health hazards. Three wells (A-6, A-13 and Y-3) have shown significant positive pollution which, however, is readily controlled by chlorination.

The aquifers of northern Guam store and transmit great volumes of good potable water, but since they are composed of limestone (calcium carbonate) they impart to the water much dissolved calcium, a key ingredient of hardness. The mixture of even a small amount of sea water with fresh water sharply increses hardness. This consequence of northern Guam's groundwater is the inevitable consequence of its mode of occurrence. Hardness is not a concern with respect to potability of groundwater; its presence is usually observed as residues that form during cooking and cleaning.

The mixing of sea water, even in minute amounts, contributes many dissolved constituents to the fresh water. Chloride content is the best indicator of sea water intrusion. Where the chloride exceeds about 30 mg/l, the addition of sea water is almost certain to have occurred. A chloride content of 250 mg/l, equal to a mixture contining 1.25 percent sea water, is the recommended upper limit for drinking water. Some wells, especially in the basal sector of the argillaceous limestone, have experienced chloride in excess of 200 mg/l, but mixing in the transmission-storage system keeps the distributed water appreciably below 200 mg/l. Sea water intrusion is one of the serious constraints considered in the determination of sustainable yield.

Groundwater Demand and Production

The 1980 census reported a total population for Guam of 106,000, of which 89,000 are resident civilians and the remainder part of the military forces. By the year 2000 the civilian population is projected to be 167,000 while the military is expected to remain the same as now. To serve the current total population, approximately 30 mgd is produced daily, about 20 mgd from northern aquifers for the civilian population and part of the military, and 10 mgd for military installations from a surface water reservoir (Fena) in the south. Table 6 gives the total water production for the years 1974-1977.

Of the 20 mgd of groundwater produced in the north, PUAG accounts for 16 mgd and most of the remainder is pumped by the USAF with a small amount taken by the USN. Private wells pump less than 1 mgd. Production in each sub-basin is shown in figure 6. The Yigo sub-basin produces an average of 8.7 mgd, much of it from the Dededo well field, and is the largest supplier. The Agana sub-basin produces an average of 5 mgd.

Per capita use by the civilian population averages 115 gallons per day, a reasonable consumption behavior. This rate is not expected to increase substantially in the future. Agricultural demand is variable but greatest during the dry season from January to June. Current usage is probably less than 1 mgd but demand is increasing sharply. Industrial water consumption is small at present but can be expected to rise as the economy of Guam expands.

Table 6

Historical Water Production

By Operating Agency

Agency	1974	1975	1976	1977	Average	Percent
	Production in mgd					
Government of Guam	13.79	15.30	15.13	15.23	14.85	51.9
U.S. Air Force	2.93	3.48	3.37	3.45	3.31	11.6
U.S. Navy	9.67	9.68	9.47	9.58	9.60	33.6
Private	1.12	1.02	0.67	0.53	0.83	2.9
TOTAL	27.51	29.48	28.64	28.79	28.59	100.00

SOURCE: Water Facilities Master Plan, 1979

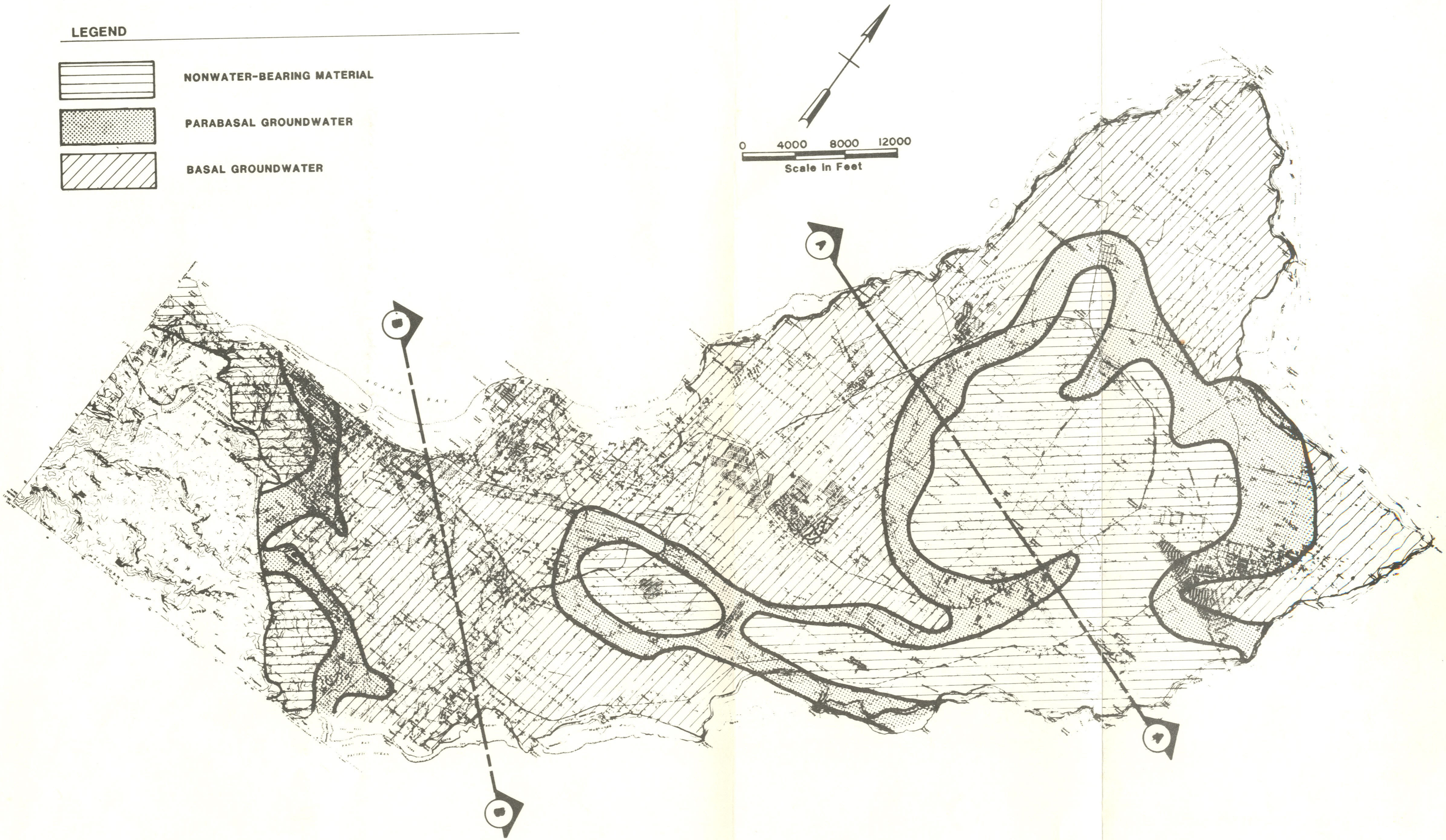
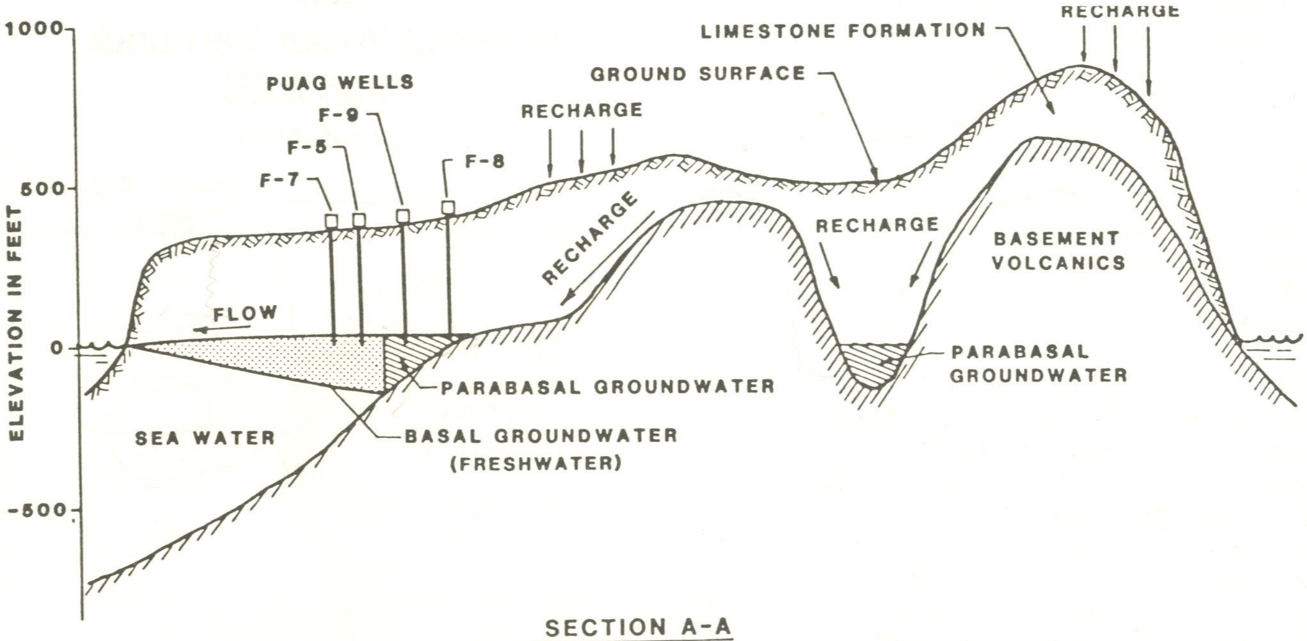
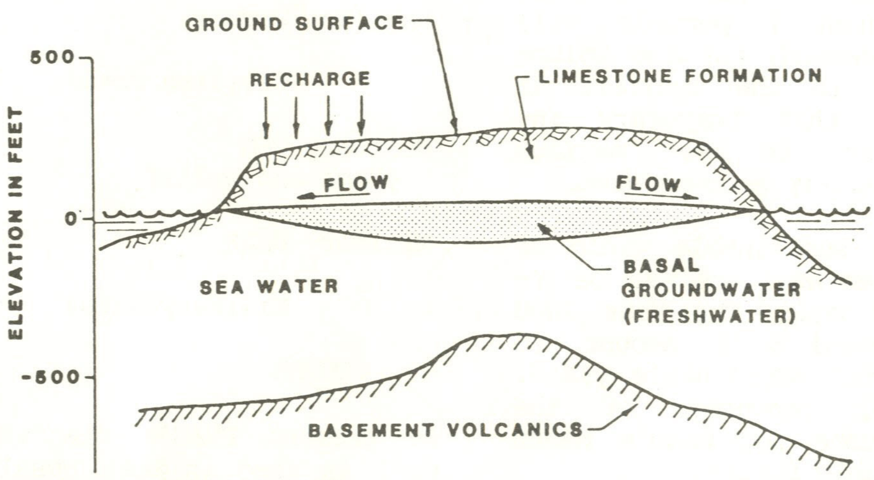


FIGURE 4
GROUNDWATER CONDITIONS



SECTION A-A



NOTE: SEE FIGURE 4-4 FOR LOCATION OF CROSS-SECTIONS

SECTION B-B

FIGURE 5
GROUNDWATER CROSS-SECTIONS

Present demand of the military sector is about 12.5 mgd, of which 9 mgd is produced by the US Navy, chiefly from Fena Reservoir, and 3.5 mgd is pumped by the U.S. Air Force from the Yigo sub-basin. Some of the Navy's production is diverted to the PUAG system. Navy demand is expected to increase another 5 mgd by the year 2000 while Air Force demand will remain the same.

Total average annual water demand in the year 2000 for all sectors of the economy is expected to average 43 mgd. Nearly 10 mgd of this total will be produced from the USN Fena system, leaving a draft requirement on the northern Guam aquifers of 32 to 35 mgd. PUAG will produce nearly 30 mgd of this groundwater total. Table 7 lists expected demand in the year 2000 by sectors, and figure 7 is a graph showing increases over the next two decades. Maximum daily demand for extended periods will exceed average demand, but the volume of fresh water in the aquifers is very large so that temporary increases in draft to meet maximum demand will be easily accommodated.

In Phase I the sustainable yield of the northern Guam aquifers was determined to be 59 mgd. The Year 2000 groundwater demand will amount to about half of the sustainable yield. The groundwater resources of the north are adequate for Guam's needs for the foreseeable future.

Methods of Groundwater Production

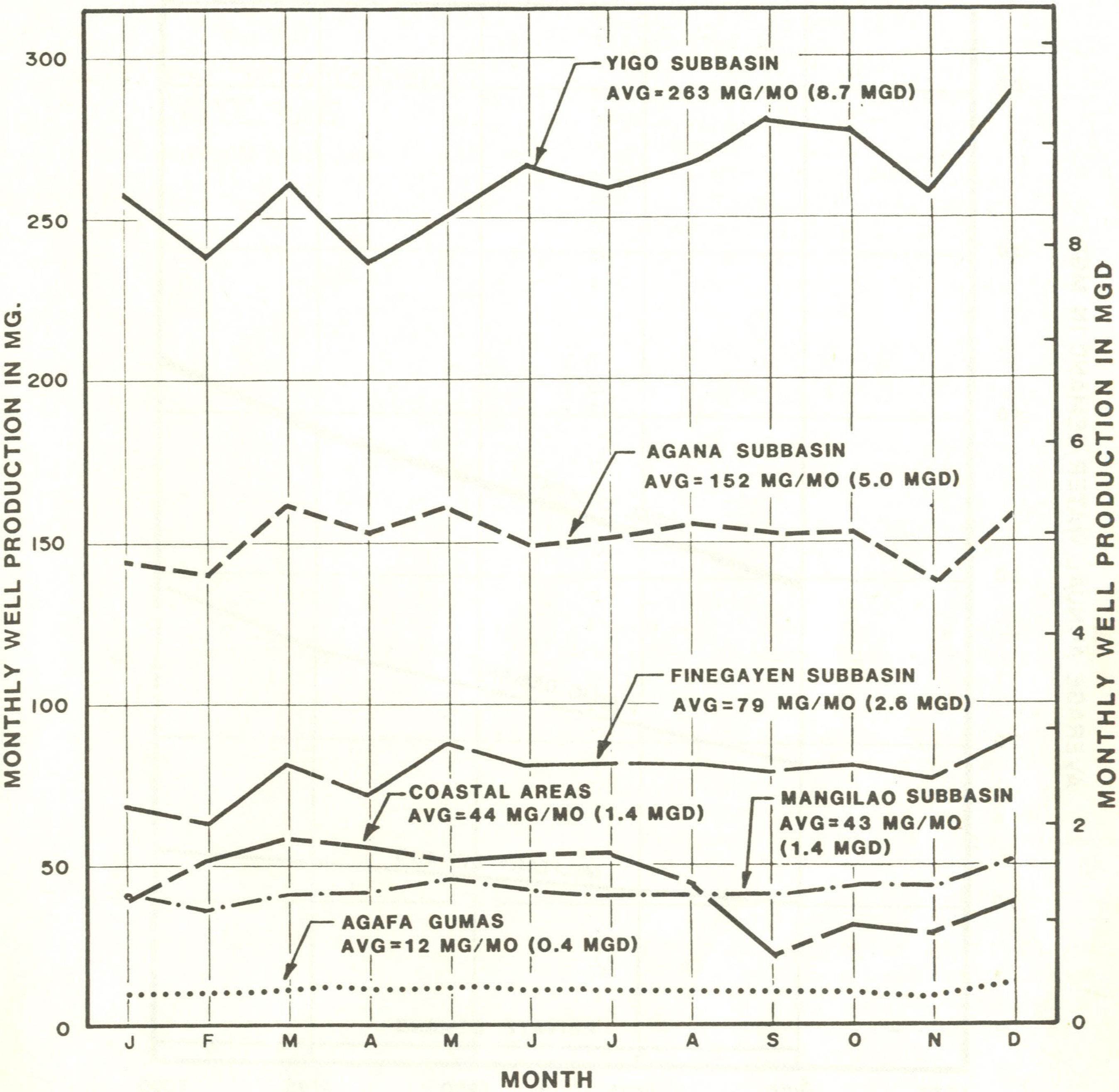
Groundwater in the northern Guam aquifers is developed for use by means of 87 drilled wells and one infiltration gallery. PUAG owns 71 wells, the USAF maintains 8 wells and the gallery (Tumon Maui Well), the USN operates 3 wells, and private companies control 5 wells. The PUAG wells were designed to yield 200 gpm while the Air Force wells produce up to 350 gpm.

Table 7
Projected Water Demands
Year 2000
Island-Wide

Sector	Averaged Demand (mgd)
Civilian Domestic	24
Civilian Industrial	
Guam Power Authority	0.4
Commercial Port Complex	0.6
Fish Cannery	0.2
Industrial Park	1.2
Civilian Agiculture	3.0
Civilian Prvate	0.5
Civilian Total	30
Military USN (Fena and wells)	9.6
Military USAF	3.5
Military Total	13
TOTAL	43

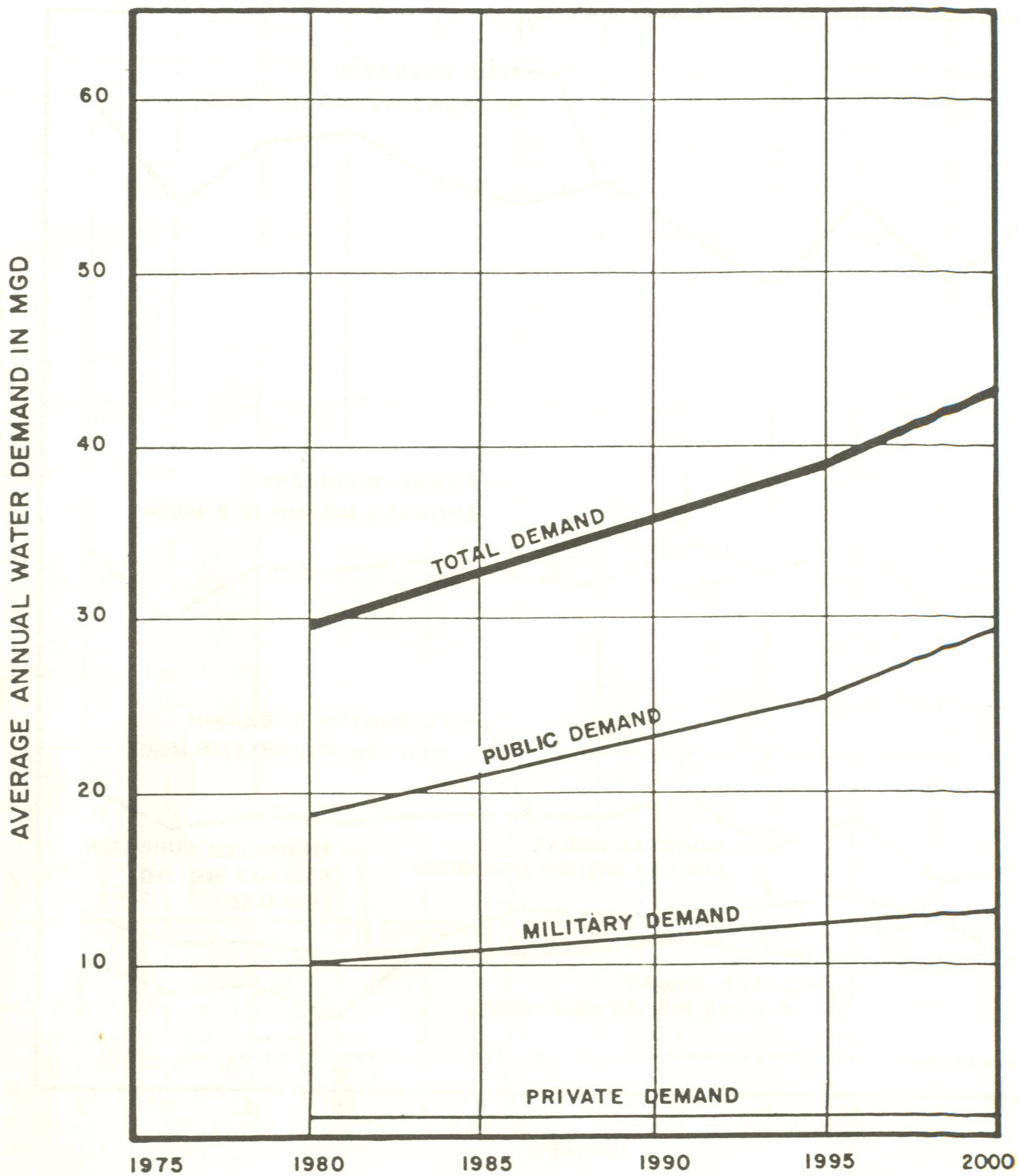
At present PUAG's standard 200 gpm well is used in both basal and parabasal portions of the aquifers. It will continue to be the standard for the basal portions, but larger wells, up to 750 gpm, will be constructed in parabasal regions. Figures 8 and 9 illustrate conditions which occur after excessive pumping in basal and parabasal situations. Sea water intrusion is more readily controlled in parabasal sectors.

The efficiency of groundwater development as practiced today is considerably less than optimal. Inefficiencies are graphically expressed in



DATA TAKEN FROM USGS
RECORDS FOR 1981

FIGURE 6
SUBBASIN WELL PRODUCTION



NOTE: ASSUMES REDUCTION IN PUAG UNACCOUNTED-FOR WATER FROM 30 PERCENT IN 1980 TO 15 PERCENT BY 1995.

SOURCE: WATER FACILITIES MASTER PLAN, 1979

FIGURE 7

ISLAND-WIDE WATER PRODUCTION REQUIREMENTS figure 10 which shows the record of pump efficiencies and actual flow rates of the PUAG standard 200 gpm wells. About one third of the pumps operate at efficiencies below 70 percent; only 19 of the 56 wells measured yielded a flow rate greater than 180 gpm.

An important objective of the Management Program is to improve pump and well efficiencies. Existing wells may have to be repaired when pumps are replaced, and the design and construction of future wells will follow strict specifications. Table 8 lists the standard capacity per well and minimum standard spacing between all new wells.

Table 8

Well Capacity and Spacing

Aquifer Type	Minimum Capacity (gpm)	Minimum Spacing (ft)
Basal		
Groundwater heads <4'	200	300
Groundwater heads >4'	350	300
Parabasal		
Regional permeabilities <500 ft/day	350	300
Regional permeabilities between 500 and 2,000 ft/day	500	300
Regional permeabilities >2,000 ft/day	750	300

Management Alternatives: Technical Manuals

The conclusions of the Aquifer Yield studies and the discussion of management issues and needs led to the identification of alternatives to be considered in selecting an optimal program of groundwater development and management. The categories of needs for which alternatives have been identified are:

1. Physical solutions to the aquifer yield problem

2. Monitoring programs to guide management decisions

3. Laws and regulations required to protect the principal aquifer

4. Appropriations required for water development

5. Sources of revenue

A total of 47 alternatives are considered and evaluated. The results of this evaluation are discussed in the Phase II "Summary of Findings and Recommendations," section of this report.

Technical manuals have been written to provide a summary set of instructions for developing, operating and protecting the groundwater resources. The manuals are listed as appendices to the main reports and consist of the following:

1. Well Construction Manual: includes basic design criteria and specifications.

2. Operations and Maintenance Manual: gives guidelines for operation and preventative maintenance of existing PUAG well facilities.

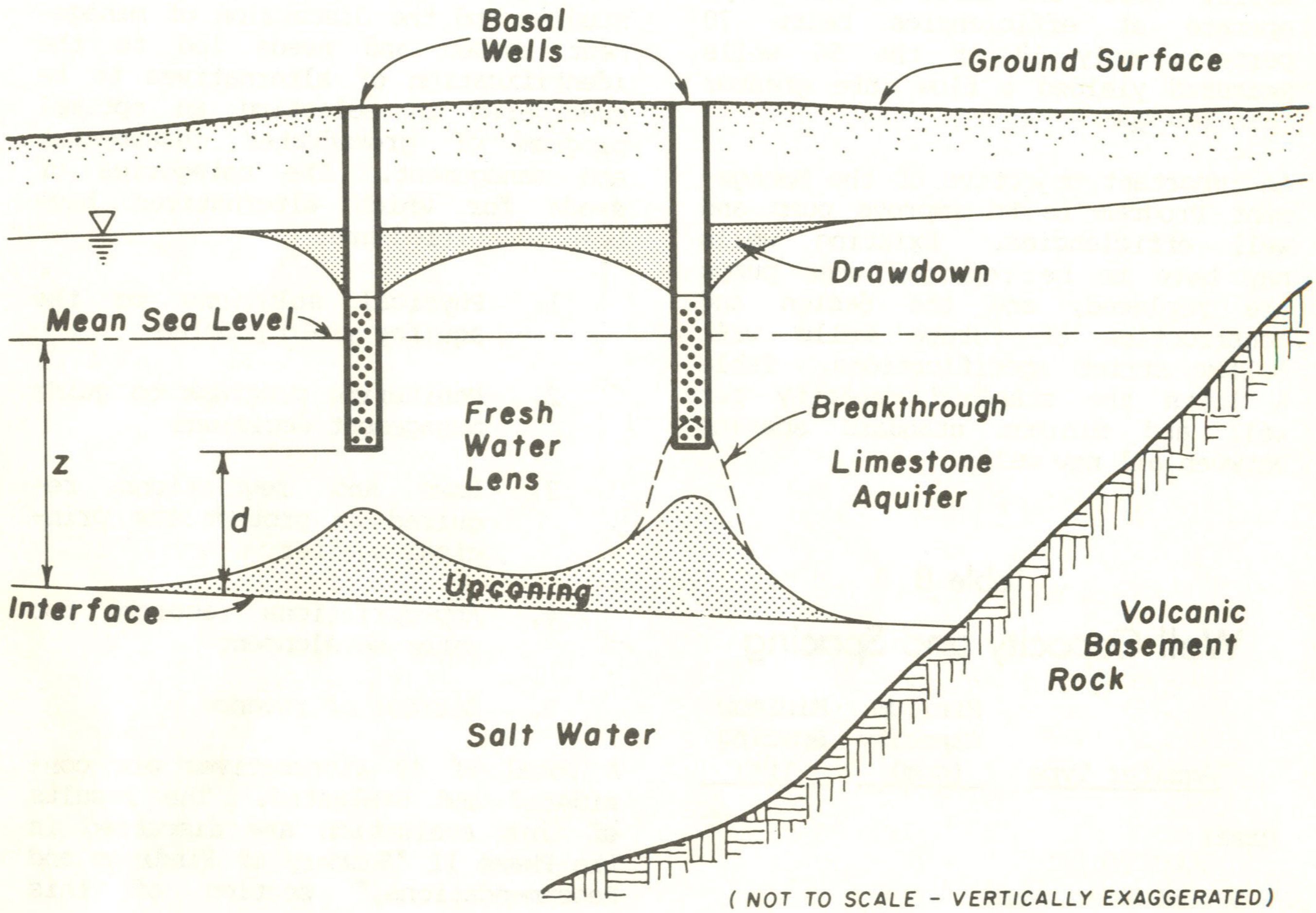


FIGURE 8

DIAGRAM OF PUMPING INFLUENCES ON THE TRANSITION ZONE

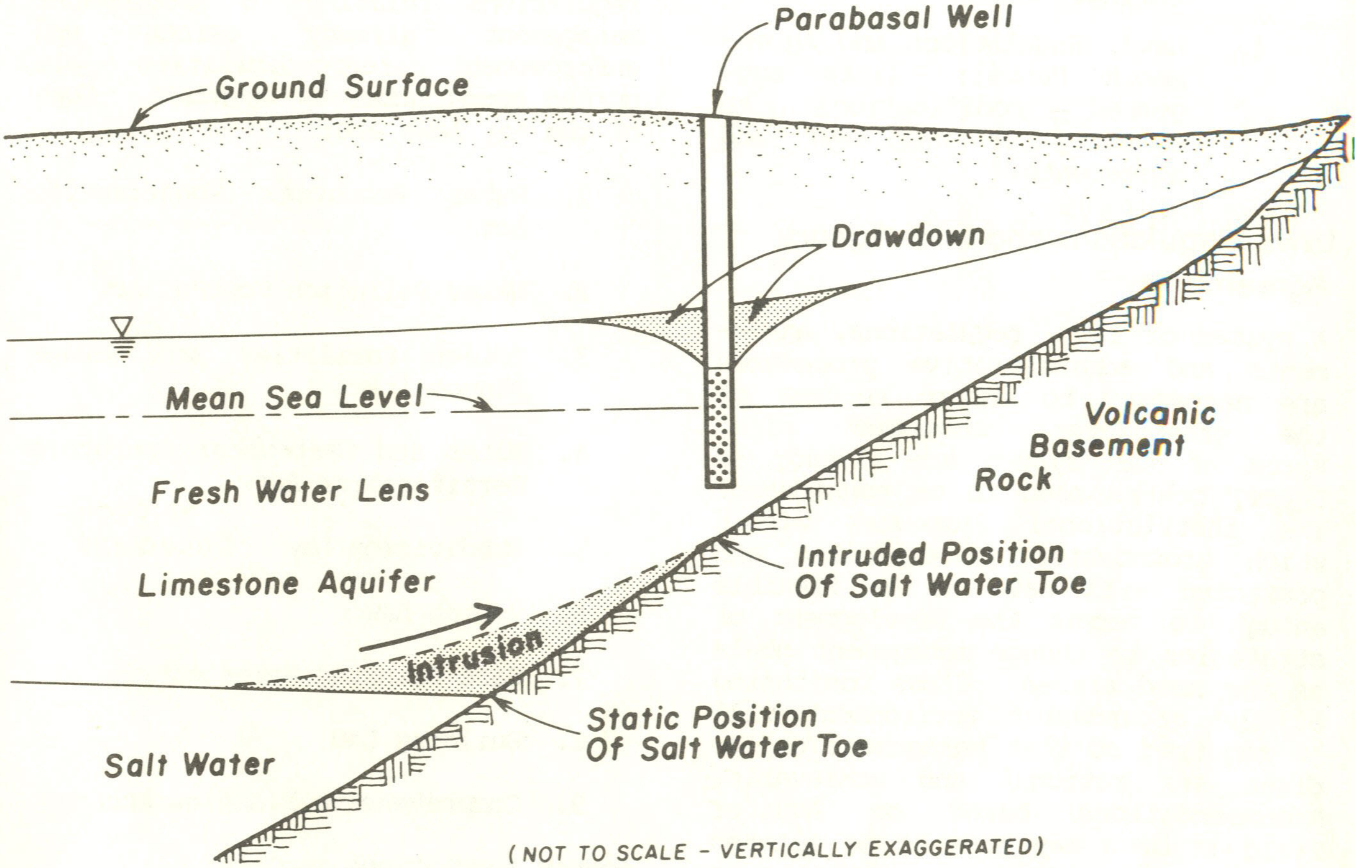


FIGURE 9

DIAGRAM OF SALT WATER INTRUSION TOWARD PARABASAL WELL

3. Well Operations Organization Manual: details personnel requirements for PUAG and suggests organizational changes needed for operation, maintenance and monitoring.
4. Laws, Regulations and Agreements Manual: lists suggested modifications to existing or new laws and agreements.

Laws, Regulations and Inter-Agency Agreements

A system of laws, regulations, agreements and administrative procedures are necessary to ensure success of the groundwater management plan. Parts of the system are already in force, others need to be considered. The institutional framework within which groundwater is exploited and protected will have to be flexible enough to permit the development of strategies to change management goals as the need arises. Close monitoring of the groundwater environment will be required so that management objectives are rational and achievable. Recommendations based on Aquifer Yield studies may have to be altered as new information and experience is gained.

Numerous GovGuam agencies are concerned in direct ways with the management of groundwater. GEPA and PUAG are most overtly involved, but others include the Department of Public Works, Bureau of Planning, Department of Agriculture, Department of Land Management, Territorial Planning Commission, Subdivision Development and Review Committee, and the University of Guam. On the Federal level the Air Force and Navy have a direct concern with the manageement of groundwater, and the USGS is specifically charged with data collection and analysis of the resources. The incorporation of all of these groups into a groundwater management framework is no easy matter, but it is necessary and can best be accomplished under the guidance of GEPA.

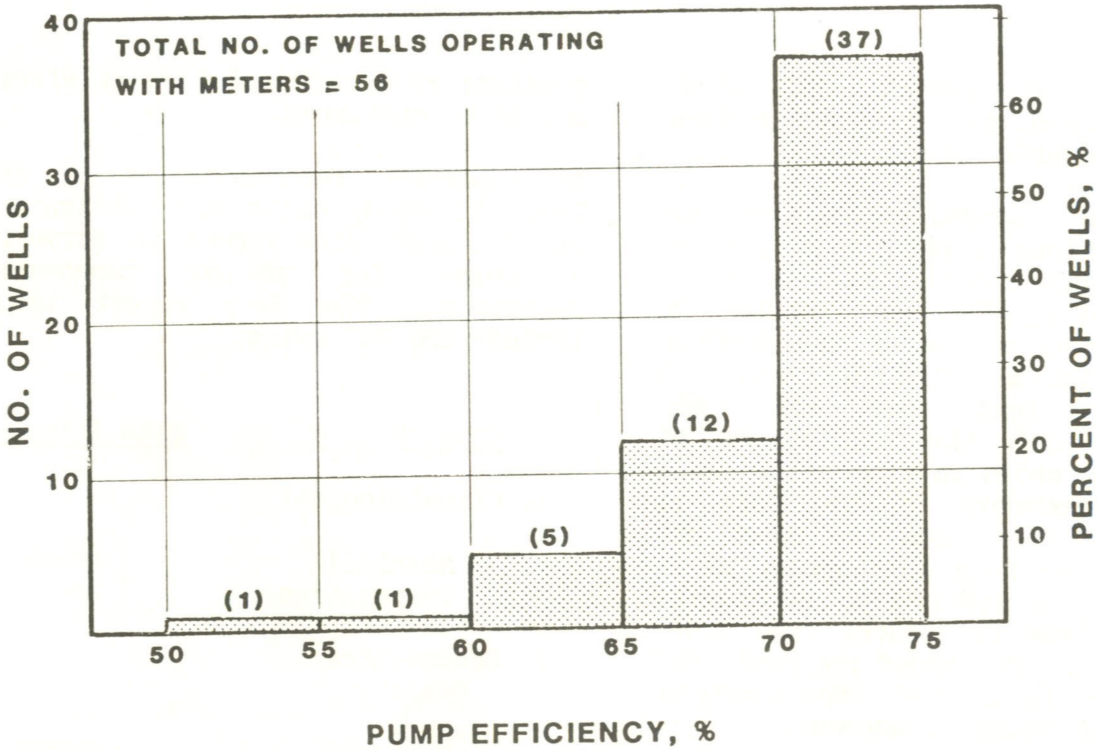
A sizeable body of GovGuam laws and regulations relating to groundwater management already exists and enforceement responsibilities are spread among numerous agencies. Some of the key laws are:

1. Water Resources Conservation Act
2. Water Pollution Control Act
3. Toilet Facilities and Sewage Disposal Act
4. Water and Wastewater Operators Certification Act
5. Subdivision Law
6. Zoning Law
7. Safe Drinking Water Act
8. Building Law
9. Comprehensive Planning Act

Agency regulations include:

1. Underground Injection Control (GEPA)
2. Rules for the Protection, Development and Conservation of Water Resources (GEPA)
3. Safe Drinking Water Standards (GEPA)
4. Water Quality Standards (GEPA)

Designation of Northern Guam as a principal source aquifer is the result of a memorandum of agreement between U.S. EPA and GEPA. A recent memorandum of understanding (1981) between GEPA and PUAG stipulates that



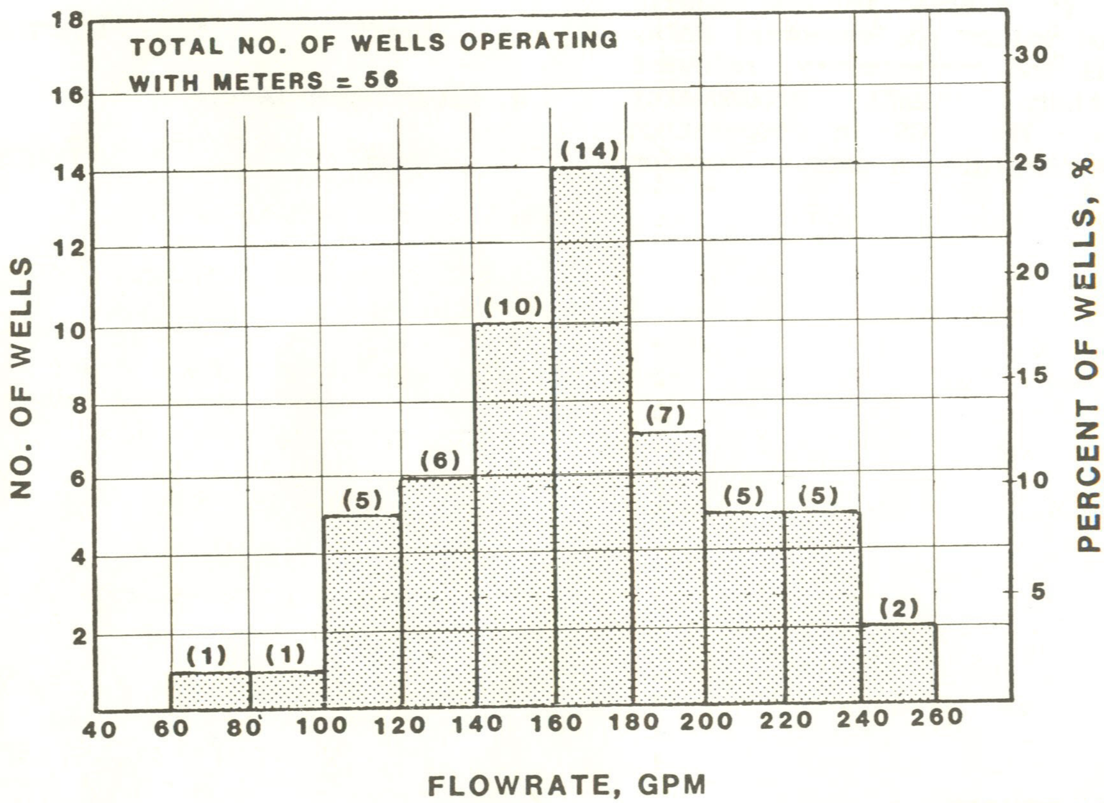


FIGURE 10
CLASSIFICATION OF
WELL FLOW RATES

groundwater development initiatives will be agreed upon by both parties before being undertaken.

Many of the proposed changes in laws and regulations refer to a groundwater protection map. This map is to be prepared by GEPA in response to proposed modification of the GovGuam Water Pollution Control Act. A groundwater protection zone map consistent with the conclusions of the NGLS is shown in figure 11. As a rule the boundary of the zone is drawn 4,000 feet from the coast but exceptions occur in some areas, as in the Agana and lower Yigo sub-basins where the line is greater than 4,000 feet inland. The added non-protected area is not of crucial importance to proper groundwater management.

Data Report

Included with the Aquifer Yield Report is a comprehensive data report. It places in one easily accessible volume the essential data, historical and contemporary, relevant to northern Guam's groundwater resources. The USGS in cooperation with GEPA maintains a data collection program; this successful joint effort should be continued.

An important recommendation of the Phase II study calls for publication of an annual data report to serve as a guide for making management decisions. The data report would include the following:

Type of Data	Data Interval
1. Climatological	
Rainfall	1 month
Evaporation	1 month
2. Groundwater Quality	
Nitrogen	3 months
Chloride	3 months
3. Groundwater Production	
Draft	1 month
4. Groundwater Levels	
Head	6 months

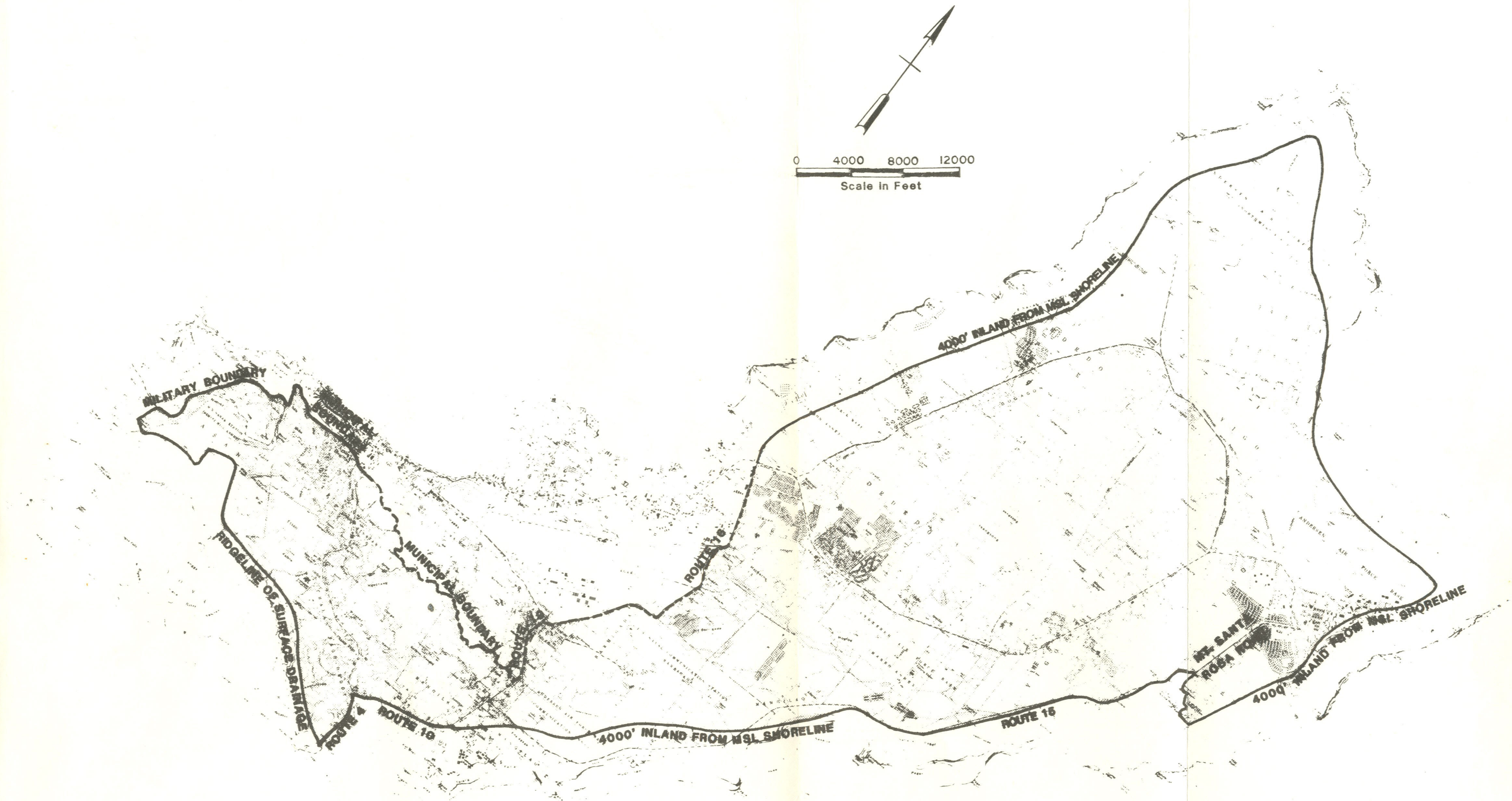


FIGURE 11

GROUNDWATER PROTECTION ZONE

LIST OF NGLS DOCUMENTS & PUBLICATIONS

Grant Applications

Application for Financial Grant Under Title III, Water Resources Planning Act U.S. Water Resources Council, for Northern Guam Lens Study (FY 1980), GEPA, January, 1980.

Application for Financial Grant Under Title III, Water Resources Planning Act U.S. Water Resources Council, for Northern Guam Lens Study (FY 1981), GEPA, December, 1980.

Application for Federal Assistance under Section 208, Water Quality Management Planning, Clean Water Act, U.S. Environmental Protection Agency, for Northern Guam Lens Study, GEPA, January, 1981.

Progress Reports

Project Description, Northern Guam Lens Study, Presented to the Department of Interior, Office of Territorial Affairs, GEPA, March, 1980.

Status Report to the GEPA Administrator and Board of Directors, Northern Guam Lens Study, GEPA, January, 1981.

Status Report to the GEPA Administrator and Board of Directors, Northern Guam Lens Study, GEPA, January, 1982.

Quarterly Reports of the Project Director, NGLS, Report 1 (December, 1979) through 12 (September, 1982), GEPA.

Technical Memoranda for the Record, by the Project Director, NGLS, Memorandum 1 (October, 1979) through 32 (August, 1982), GEPA.

Technical Reports

Determination of Elevations of Groundwater Production Sites, Tenorio and Associates, NGLS, July, 1980.

Geophysical Investigations for the Northern Guam Lens Study (including data appendices), Ecosystems, Inc., September, 1980.

A Preliminary Study of the Hydrogeology of Northern Guam, Final Report for the NGLS, Hydrogeology Sector, Water and Energy Research Institute, University of Guam, September, 1982.

Final Report for the Northern Guam Lens Study Mathematical Modeling Sector, Water and Energy Research Institute, University of Guam, September, 1982.

A One-Dimensional, Finite Element Salt Water Intrusion Model, by Dinshaw N. Contractor, Water and Energy Research Institute Technical Report No. 20, NGLS, University of Guam, February, 1981.

A Two-Dimensional, Finite Element Model of Salt Water Intrusion in Groundwater Systems, by Dinshaw N. Contractor, Water and Energy Research Institute Technical Report No. 26, NGLS, University of Guam, October, 1981.

Numerical Modeling of Salt-Water Intrusion in the Northern Guam Lens, by Dinshaw N. Contrctor, Jerry F. Ayers, and Stephen J. Winter, Water and Energy Research Institute Technical Report No. 27, NGLS, University of Guam, August, 1981.

Aquifer Yield Report of the Northern Guam Ground-Water Lens (including Data Report), Barrett, Harris and Associates, Inc., and Camp, Dresser and McKee, Inc., NGLS, December, 1982.

Groundwater Management Alternatives, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp Dresser and McKee, Inc., December, 1982.

Groundwater Management Program, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp Dresser and McKee, Inc., December, 1982.

Operation and Maintenance Manual, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp Dresser and McKee, Inc., December, 1982.

Well Operations Organizational Manual, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp Dresser and McKee, Inc., December, 1982.

Well Construction Manual, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp, Dresser & McKee, Inc., December, 1982.

Laws, Regulations and Inter-Agency Agreements Manual, Northern Guam Lens Study, Barrett, Harris and Associates, Inc., and Camp Dresser and McKee, Inc., December, 1982.

NORTHERN GUAM LENS STUDY

EXPENDITURES BY FISCAL YEAR

Organization	Year 1 (FY 79/80)	Year 2 (FY 81)	Year 3 (FY 82/83)	TOTAL
Project Director (John Mink)	$ 26,796 (DOI-A)	$ 28,500 (DOI-A)	$ 28,500 (DOI-A) 3,500 (DOI-B)	$ 87,296
Topography Contractor (Non-government)	16,538 (DOI-A)			16,538
Seismic & Gravity Contractor (Non-government)	182,270 (DOI-A)			182,270
Water Resources Research Center (Government of Guam)	30,000 (WRC-80)	30,000 (WRC-81)	30,000 (DOI-A)	90,000
U.S. Geological Survey (Federal Government)	36,647 (DOI-A)	56,850 (DOI-A)		93,497
Prime Contractor (Non-government)				
I. Aquifer Yield Phase I	119,600 (WRC-80)	22,387 (WRC-81) 59,393 (DOI-A)	68,620 (DOI-B) 13,400 (WRC-81)	283,400
II. Groundwater Management Plan, Phase II		80,500 (EPA)	119,500 (EPA)	200,000
Mathematical Modeling Consultant (Non-government)		5,000 (DOI-B)		5,000
Drilling Contractors (Non-government)				229,705
Ex-1 (Pacific)	30,180 (WRC-79)			
Ex-2, Ex-3, Ex-4 (Pacific)		55,500 (DOI-B)		
Ex-5 (Geo)		39,420 (DOI-B)		

Organization	Year 1 (FY 79/80)	Year 2 (FY 81)	Year 3 (FY 82/83)	TOTAL
Ex-5A (Change Order #1)			1,789 (DOI-B) 4,139 (WRC-81)	
Ex-6, Ex-7, Ex-8 (Geo)		47,392 (DOI-B) 1,471 (WRC-79)		
Ex-7 Redrill (Pacific)		7,200 (DOI-B)		
Ex-9, Ex-10 (Pacific)		31,740 (DOI-B)		
Ex-9, Ex-10 (Change Order #1)		996 (WRC-81)		
Ex-11 (Pacific)			4,878 (WRC-81) 5,000 (DOI-B)	
Travel (off-island)	2,862 (DOI-A)	1,200 (DOI-A)		4,062
Printing, Summary Report			1,090 (DOI-B)	1,090
Miscellaneous (advertising, maps overseas calls, surveying)	2,441 (DOI-A)	1,436 (DOI-A)	1,626 (DOI-A)	5,503
Unexpended funds			8,690 (DOI-B)	8,690
TOTAL	$447,334	$468,985	$290,732	$1,207,051

PROJECT FUNDING SOURCES:

Department of Interior Study Grant (DOI-A)	$ 476,000
Department of Interior Drilling Grant (DOI-B)	274,000
Water Resources Council (FY-79 Carryover)	31,651
Water Resources Council (FY-80)	149,600
Water Resources Council (FY-81)	75,800
U.S. Environmental Protection Agency (EPA)	200,000
	$1,207,051

NOTE: Fiscal Year: October 1 - September 30