GROUNDWATER RESOURCES OF GUAM: OCCURRENCE AND DEVELOPMENT

John F. Mink

WERI
WATER AND ENERGY RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

Technical Report No. 1
September 1976; reprinted May 1991

GROUNDWATER RESOURCES OF GUAM:

OCCURRENCE AND DEVELOPMENT

by

John F. Mink

Technical Report No. 1

September 1976

Reprinted May 1991

Project Completion Report

for

GUAM GROUNDWATER ASSESSMENT AS OF 1975

OWRT Project No. A-001-Guam, Grant Agreement No. 14-31-0001-5054

Principal Investigators: John F. Mink and James A. Marsh, Jr.

Project Period: June 1, 1975 to September 30, 1976

The research reported herein was funded by the Public Utility Agency of Guam. Funds for the printing of this report were provided by the United States Department of the Interior as authorized under the Water Resources Act of 1964, Public Law 88-379.

Report 1 was unique in the universality of its coverage and in being written to appeal to a literate audience who could employ the information and analyses in making decisions or arriving at opinions about water supply.

The report was completed and published before the avalanche of models, data bases, graphs, and other wonders of presentation which accompanied the proletarianization of computers. In this respect, also, it marks the end of an era. The next major water resources investigation, the Northern Guam Lens Study (NGLS), grew out of Technical Report 1, but by then the age of microcomputers had arrived.

Technical Report 1 is reprinted as originally written, without revision. It remains a useful compendium of discussions, analyses, data collections, and illustrations. Perhaps a revised edition will be possible for the next printing. There is much more to discuss.

John F. Mink

May 1991

PREFACE, 1991 REPRINTING

In 1975 when Technical Report 1 was written, the island of Guam was already embarked on a vigorous economic and social evolution that was to shed the smothering embrace of paternalism in which the island's people had been trapped for so many years. The civil government, thrown on its own not too many years before, was told to develop its own infrastructure, and provision of a clean water supply was one of the fundamental utilities it had to master. This report in every respect acknowledges the willingness of the Public Utility Agency of Guam (PUAG) administrators of that time not only to carry out their responsibility to supply water to the civil population but also to commission a study aimed at elucidating the nature and extent of the water resources.

Just after the report was completed, the University of Guam Water Resources Research Center (now the Water and Energy Research Institute--WERI) was created, and the Guam Environmental Protection Agency (GEPA) had come into existence. The report, then, marked the end of an era when water supply concerns were examined problem by problem, usually by consultants, and the beginning of an island-wide approach to water supply by PUAG in cooperation with WERI and GEPA.

The report was not the first general discussion of water resources occurrence and behavior in Guam. The U.S. Geological Survey (USGS) had made studies and published professional papers that became the basis on which subsequent studies depended. The USGS continues to be involved in data collection and ancillary evaluations in coordination with GEPA. Nevertheless, Technical

PREFACE

Since 1964 the Government of Guam has been engaged in the development of groundwater to supply the domestic needs of the civil sector of the island. Demand has grown in excess of projections, requiring intensive effort on the part of the Public Utility Agency and its groundwater supply contractor, Singer-Layne International, to satisfy the increasing call for water all over the island but especially in the north.

The Government's actions to meet demand have generally been based on careful consideration of the nature of groundwater, but the pace of development has been so rapid that no time had been devoted to comprehensively documenting and evaluating the groundwater resources based upon the working experience of the last decade. Without a probing evaluation of the extent and exploitability of the resources, speculation often replaces rational analysis as the instrument of decision making, leading to inefficient investment and possible irreparable damage to the resources.

Based primarily on the information which has accumulated in the last 10 years in conjunction with earlier documentations and analyses, I have attempted to evaluate the groundwater resources of Guam, in particular those of northern Guam, in a manner which provides a utilitarian framework for decision-making by government agencies concerned with water supply. The report that follows meets the goals which I set and in my proposal to the Government, which are:

1. Review and critique all of the available literature on water resources and their development in the island of Guam, and to relate the recommendations of the previous reports to the status of knowledge at the time they were written.

2. Review of past ground water development (prior to the start of the Government of Guam's activities in 1964) and the history of water usage.

3. Description and analyses of ground water resources and the environments in which they occur. This evaluation to be comprehensive and to include analyses of climate, geology, aquifer characteristics as determined from pump tests, extent and available quantities of ground water, sustainable yields, quality, pollution dangers and other items relevant to a full understanding of the ground water systems.

4. From the descriptions and analyses given in part 3, to evaluate the means of developing the resources so as to maximize sustainable yields within reasonable technical and economic constraints.

5. Review and critique of current development practices and locations of producing stations.

6. Recommendations of standards of development.

7. Proposals of methods of providing ground water for future growth on a sustainable yield basis.

The report also meets the general goal of the contract agreed upon by myself and the Public Utility Agency of Guam, which stipulated that the consultant "provide documentations to the groundwater resources of the island of Guam, their present development and their potential for future development." In addition the scope of services listed in the contract has been complied with. The scope of services is as follows:

1. Prepare water level and salinity maps of northern Guam, representing at least two periods of measurement. From these draw interpretations and descriptions of (a) direction and gradient of ground water movement; (b) lens thickness and changes in thickness and position; (c) location of hydrologic discontinuities which may compartment the aquifer, and (d) changes in regional water level as it may relate to quantities of fresh water and intrusion of salt water.

2. Identify effects of hydrologic stresses such as pumping, tidal changes and variation of recharge. Correlate these stress effects with fresh water head changes.

3. Compare the current data with past records of water level, rainfall, tidal effects and pumping to identify and describe response of the fresh water body to long term stresses.

4. Identification of areas of thick limestone aquifer containing fresh water under true lens conditions and areas where bedrock is shallow enough to prevent lens formation and to cause variations in groundwater response to hydrologic stress.

5. Preparation of description of the occurrence and behavior of the fresh water lens and other groundwater bodies as reflected in present pumping areas and natural discharge.

6. Preparation of sections and descriptions of subsurface geologic and hydrologic conditions controlling occurrence and movement of the fresh water body.

7. Description of the manner in which rainfall replenishes the groundwater, including descriptions of recharge areas as they relate to principal areas of groundwater pumping.

8. Preparation of recommendations for the siting of new production wells, and for management practices to allow maximum use of the groundwater resource.

9. From the data available, determine the need and most suitable sites for deep, multiple tube wells for monitoring the position and movement of the freshwater and salt water transition zone and changes in the configuration of the lens.

10. Design of a long term water data monitoring network.

11. Upon approval of completed documentations and relevant materials, deliver to the Government a set, of good quality, suitable for reproduction.

An important aspect of ground water resources not mentioned in the above scope of services but included in the report because of its significance to water standards and pollution control is the geochemistry of the waters.

The report is structured in accordance with my proposal, that is, it consists of two principal parts, the first a predominately narrative evaluation for general use by decision-makers, and the second a compendium of analyses, data summaries, and relevant graphics. A main objective is to provide a document which can be used by both interested laymen and technical experts.

The chief sources of data for the report were:

1. Singer-Layne International -- well logs, drilling information, pump test data, water analyses, etc.

2. U. S. Geological Survey -- water levels, water analyses, geology, previous reports and evaluations.

3. Public Utility Agency -- engineering reports, transmission and storage plans, consumption, etc.

4. Micronesian Area Research Center (MARC) -- historical data, botany, general information on the environment.

I was greatly assisted n initiating the study and structuring it by Barnabe Paulino, Acting Director of PUAG, and John San Agustin, former Director of PUAG. Dr. O. V. Matarajan of Guam EPA was in large measure responsible for promoting the investigation because of his interest in the total water environment. Atilano Halili, Chief Engineer of PUAG guided me to much information in his office. Doug Creddick, Larry Gavin, and Ted Lund, all former managers of Singer-Layne International, provided information and suggestions during their years on Guam, as has Les Lien, the current manager. Chuck Huxel of the U. S. Geological Survey not only made much data available but helped clarify many areas of confusion with his critical discussions.

My special gratitude goes to Stanley Sumida for all of the graphics and to Terry Sumida for having suffered through typing the entire manuscript.

John F. Mink

TABLE OF CONTENTS

Text

Page

Page

<u>Text Figures</u>

Page

Text Tables

Appendix A

Analyses

Appendix B

Tables

Page

Maps

History of Water Development

The discovery of Guam by Magellan in the early 16th century alerted its people to a world about which they could have had but very little knowledge. Magellan found a society in equilibrium with its environment in an early stage of material development. The people lived in huts resting on pillars of stone called "latte," probably for protection against flooding and dampness. Subsistence was gained by wet land farming of taro, gathering of wild plants, and fishing. No common meat animals are native to the island.

The hamlets, now called "latte" sites by archaeologists, were located near running water, either streams or fresh water springs discharging near the ocean. It is also likely that the natives dug shallow wells to ground water on the low coastal plain, such as near Agana. Apparently the proximity of visible fresh water was the determining factor as to where settlements were made. The fertile high northern limestone plateau had few settlements because no streams occur there whereas the coastal lowlands of southern Guam had many sites because of the abundance of small streams. Archeological studies are showing that latte sites also occur on the coast in the north opposite nearly every break in the reef. These sites probably were associated with ground water that surfaces as springs at the shore.

Prior to Magellan's arrival the largest community on the island was Agana where a large spring issues into a swamp about one mile from the coast. Nearby is another large spring, Asan, which gushes from a steep limestone slope more than 100 feet above sea level. The Spanish concentrated their forces at Agana and also utilized the village of Umatac on the west coast of south Guam as an administrative center. Passing through Umatac is a perennial stream with a substantial base flow. Umatac was also a center of inhabitation in pre-Christian times. These two sites, important because of their water, fostered Spanish activity throughout the Marianas.

Although the Spanish left no sizable water development constructions, it is interesting to note that one of the Governors gave a description of ground water springs along the coast of northern Guam which manifested such keen observation that it could very well be used in a modern hydrology textbook. Governor Don Felipe De La Cortes in his memoirs which cover the period 1855-1866 remarked, "In the northern part ..... water percolates through the porous, or even cavernous strata down to sea level and comes up through the sand of the little beaches between the headlands as springs of sweet water; some are uncovered only at extreme low tide when they make runnel in the wet sand; when covered with salt water they are often betrayed by rising bubbles."

On June 21, 1898, a U. S. Navy vessel sailed into Apra to conquer the island in an extension of the Spanish-American War. It was saluted by a feeble cannonade from the ancient fort overlooking the bay. The Governor came to pay his respects to the unexpected visitors. The Americans, surprised at the Governor's courtesy, seized him and took possession of Agana. The Spaniards quickly surrendered without argument. The following year the United States formally purchased the island from Spain, ending more than 300 years of European imperialism.

On the U. S. S. Yosemite, the conquering warship, was a distilling unit for use by American forces who were to occupy Agana. Recognition of the reliability of Agana and Asan Springs soon eliminated the need for the unit, but at Apra, slated to become the American military fortress and harbor, no easily accessible source of water was in sight. The first identifiable water plan on record for Guam was drawn by the U.S. Navy in 1902 for the supply of the new naval station. In the report (Guam Survey Board, 1902) it was noted that cisterns might solve the problem and that wells on the coast near the foot of the hills were worth trying, but pointed out that such wells "were never known to have been driven."

The principal recommendation of the report was a dam on the Paulana River about 5000 feet from the naval station. No meteorological records were available to the engineers who wrote the report; their assumption of 60 inches of rain per year was reasonable under the circumstances. An available supply of 120 million gallons per year was predicted, sufficient for 6000 people at 50 gallons per person per day. The total cost of the dam and pipeline was estimated a $105,000.00. Neither the dam nor any other substantial recommendation in the report was undertaken.

Records of the naval water supply for the first few years of the century are sparse or difficult to obtain. Apparently nearby springs were sufficient for the station's needs. In 1910 a small dam was built on the Fonte River at elevation 395 feet in the volcanic highlands just south of Agana and formed a reservoir with a capacity of 2.5 million gallons. So much confidence was placed in the new dam that all shallow wells in Agana were ordered filled as a sanitary measure. The expected reliable flow of the system was 0.2 mgd, but a drought in 1912 quickly modified such optimism. The failure of the Fonte reservoir to provide a sustainable yield coupled with continued growth of the station forced new efforts to develop a water supply. In 1914 pumps were installed at Agana Springs to supply up to 2 mgd to the coastal plain and Navy Headquarters. The pump remained in operation until early in the 1950's, and although abandoned now, nebulous plans to install new pumps occasionally arise. In 1915 a dependable flow of 0.2 mgd from Asan Spring was added to the system.

In April 1937 the Navy brought a drill rig to the island and bored the first well the following month at Wettengel School near Barrigada (USGS Well 6), striking fresh ground water (15 mg/l chloride). A second well (USGS no. 9) was quickly drilled near the old Dededo village behind Tumon and encountered water with 50 mg/l chloride. A third well (USGS 74) followed closer to the shore at Ilipog giving water with 104 mg/l chloride. The widespread occurrence of fresh ground water was proved.

Also in 1937, shortly after the initiation of drilling, H. T. Stearns of the U. S. Geological Survey made a reconnaissance investigation of the geology and water resources of Guam at the request to the U. S. Navy. His efforts were the first attempt to evaluate island-wide water supplies. For those areas having difficulty with a reliable water supply he recommended the following:

1. An infiltration tunnel at Agana Springs with wells drilled in the tunnel.

2. Spring water for Agat-Sumay, near Apra Harbor.

3. A small diversion dam on the Masso River to provide 35,000 gallons per day to the town of Piti, near Apra. Such a dam, or larger, had been suggested as an alternative in the 1902 Navy report.

4. Drilled wells at Machanao on the limestone plateau.

5. Spring water at Mataguac where the volcanics rise above the limestone of the northeast.

6. Drilled wells at Yigo, Dededo, Barrigada, Sinajana, and Ordot, all of which are on the limestone plateau.

Stearn's recommendations were the first to include drilled wells to tap the groundwater of the north. The sites of the wells attempted before his arrival were selected in a random manner. All of his recommendations were eventually followed in some form except for the infiltration tunnel at Agana Springs.

In a classified report for military purpose only he recommended the use of the large springs draining the limestone cap on mountains in the south. These springs at elevations of about 300 feet were five to seven miles from the naval base, but in spite of the high cost their development was initiated before the war because of the rapid build-up in troops. They now feed into the naval water system.

During the Japanese occupation from December 1941 to July 1944 little was done to change the existing water systems. In the South Pacific islands, including their own territories, the Japanese eschewed large scale water development, relying instead upon small local works. Their approach apparently was successful for their purposes, which were aimed mainly at establishing a self sufficient agricultural economy with surpluses for export on each island.

Re-conquest by U. S. forces brought a peak of 30,000 men to occupy Guam. Military installations spread throughout the island whereas in pre-war days they were restricted to the Agana-Apra region. To supply the need for water, diversion structures were built on many small streams, and wells were drilled where troops were billeted. Two infiltration galleries were also built, one (Tumon) a success, the other (ACEORP) a failure from the start when its pumped water contained 500 mg/l chloride. Some coastal springs, such as Tarague on the north coast near Andersen Air Force Base, were exploited, though the quality of the water was unreliable.

Evidence of the small diversion dams can still be found and a few are still used. The locations of many of the wells are known today, but quite a few have been lost. Several of the successful wells continue to be used, and one of the infiltration galleries (Tumon) now helps to supply the Air Force. Nevertheless, the attempt to supply the troops and population with groundwater from the limestone aquifers of the north failed, not because of the failure of the resource but because of the failure of the methods of exploitation.

The indiscriminate drilling of wells throughout the island reflected the immediacy of the need for water before proper investigation or planning could be undertaken. Many of the wells were failures when drilled, and many more failed because of salt water intrusion induced by heavy pumping. By 1947 records show that 7 mgd were being produced from the limestones of northern Guam by the wells and infiltration gallery that maintained potable water quality. In addition Agana Springs produced up to 3 mgd and the springs and streams of southern Guam an unknown amount, perhaps in the neighborhood of 5 mgd. However, the supply was not considered reliable, particularly in view of the salinization that had taken place in the north. The U. S. Navy, who had again assumed sole administrative authority over the island, sought new sources for long term development.

The Navy solution was to construct a large dam and reservoir in the Fena basin at the headwaters of the Talofofo River system where several small tributaries and high limestone springs converge. The cost of the dam and water distribution system to the Agana-Apra region 10 to 12 miles away was very high for a limited water supply and reflects an expediency and desire to solve the problem once and for all. Economic considerations were not fundamental factors in the decision.

The Fena reservoir drains 5.8 sq. mi. and has a reliable yield of 15 mgd, although work in progress or recently completed suggests this value is too high by several mgd. The dam has an earth-filled core faced with concrete and rests on volcanics of the

Umatac formation. Since Guam is subject to frequent earth tremors, a real fear exists that a severe earthquake may someday rupture the dam.

Currently between 5 and 10 mgd is withdrawn from Fena reservoir for use. In addition to the Fena flow, the system also collects an average of 2.5 mgd from Almagosa Spring and 0.75 mgd from Bona Spring. Some of the Navy supply is diverted to civilian use, but with growing Navy demand the portion allocated to the civil sector, now about 3 mgd, will decrease. The Air Force, whose commitment on Guam is considerably less than the Navy's, obtains its water from several wells and the Tumon tunnel to satisfy a total consumption averaging about 3 mgd.

Until 1950 Guam was administered under the firm hand of the U. S. Navy. Following the formal initiation of a civil government in 1951, the Navy understandably started to withdraw certain of the perquisites the people enjoyed, such as a ready made and managed water supply. Within a decade the new government was faced with a water problem but lacked an infrastructure able to handle the situation. The Navy reluctantly continued to sell water to the government, generally accompanied by warnings of impending shortages of its own. In 1963 a destructive typhoon, Karen, swept over the island, flattening much of Agana and destroying civil works. An appeal was made to Washington for help. The Federal Government came through handsomely with rehabilitation funds so that the Government of Guam was able to initiate planning and construction over a wide range of services. Water supply was one of the first areas into which the new funds were directed.

In 1964 the government contracted with Kennedy Engineers to draw up a master plan for water development. The firm had submitted a plan in 1955 but no action was taken on it. The new plan was to cover the period at least until 1980. Kennedy Engineers carefully cataloged the existing water systems and made a refined accounting of the amounts of water produced and consumed. They tabulated total water production of 5 mgd satisfying the civil sector population of 44,892. Of the total production, 3.5 mgd was diverted from the Navy system, 0.3 mgd from the Air Force, and the government supplied 1.2 mgd. For 1980 a civil population of 76,300 and a water demand of 11.09 mgd were projected. Like so many other projections made before the start of the economic boom in the mid-1960's, the Kennedy figures for 1980 were low. The civil sector demand today is already exceeding the 1980 projection of 11.09 mgd.

In their report, Kennedy Engineers concluded that groundwater was unreliable as a source and recommended as the principal project the construction of a dam on the Ugum River, 12 miles by pipeline from Agana. They also proposed extension of the Navy system to the civil sector, the re-building of the ACEORP infiltration gallery, several small river diversions, the re-fitting of Agana Springs with pumps, and the development of 3 mgd from wells in the Dededo-Harmon area. The total cost of their recommendations, discounted at the unrealistically low interest rate of 2%, was $9,444,000, which would provide 15 mgd by 1980.

In their evaluation of the water resources of the island, Kennedy Engineers ignored the enormous quantity of ground water potentially available in the north where most of the consumption takes place, believing that salt water intrusion and possible surface pollution compromised its value. The costs of water development under the Kennedy plan were so great that when Pacific Drilling Company of Honolulu proposed drilling a well at Dededo to supply new housing projects with water, the government accepted the risk. The venture was a success and a study initiated by Pacific Drilling recommended many more wells and stated that the requirements of the entire civil population could be supplied by groundwater.

Within a year 10 wells, all successful, were drilled, supplying up to 20% of demand. The well-drilling program has continued since then so that by the summer of 1974, 57 wells were withdrawing about 15 mgd from the limestone aquifers of northern Guam.

There is no doubt that ground water is the premier water resource of the island. Much of this report is devoted to showing that at least 50 mgd can be taken from northern Guam under proper development and management methods.

Environmental setting

Geography

Guam is a small elongate island in the northern tropics of the Southwest Pacific whose main port, Agana, lies 13°30′N and 144° 45′W. Although encompassing only 212 sq. mi., it is the largest and most important of the Mariana Islands. Its main axis runs NE - SW over a total length of 30 miles. Its maximum width is 11.5 miles but at its narrow waist it is only 4 miles wide. Guam is one of an arc of islands lying immediately west of the deep Mariana Trench into which the Pacific lithospheric plate is being subducted.

The island is sharply divided across its narrow waist into nearly equal halves. The northern half is an undulating limestone plateau sloping to the southwest that precipitously abuts against the sea or a narrow coastal plain. The limestones are emerged massive fossil reef deposits which include the entire spectrum of reef facies from argillaceous lagoonal sediments to compact fore reef strata. In the northeast the uniformity of the plateau is broken by several small protuberances of volcanic rocks at Mataguac and Mt. Santa Rosa. Elsewhere the surface slopes along the long axis of the island from a maximum elevation of about 600 feet in the north to elevations of 100 to 200 feet near its abrupt southern boundary. The limestone is so permeable that a normal stream drainage pattern has not been able to form. Instead, a gentle karst topography has developed and drainage takes place directly into the ground or through sink holes. Thick, nearly impenetrable shrub-like jungles cover the uncleared portions of the plateau.

The southern half of Guam has few affinities with the north. It has a rolling to sharply dissected terrain consisting of extrusive and pyroclastic volcanic rocks fringed by rough fossil reef limestones along some portions of the coast. A narrow band of limestone also caps the highest mountain range which lies several miles inland and parallel to the western coast of the island. The highest peak, which is also the highest point on the island, reaches 1,334 feet above sea level. The limestone caps and coastal fringes carry a heavy foliage in contrast to the coarse sword grass which dominates the volcanic rocks. Alluviated stream valleys and coastal lowlands also are densely vegetated. The common shrub, tangan-tangan (Leucaena glauca), will not grow on the infertile volcanic formations but thrives on limestones, providing a nearly precise indicator of the contact between limestone and volcanic rocks.

Two different drainage patterns, separated by the high mountain range paralleling the west coast, occur in southern Guam. Drainage to the west is by steeply sloping parallel streams; to the east the drainage pattern is generally dendritic with modifications imposed by faulting and lesser structural features. As in the north, limestone areas have no extensive drainage patterns.

Climate

Guam is warm and humid throughout the year but nevertheless has two distinct seasons, one wet and the other dry. The mean annual temperature is 81°F about which daily maximums and minimums vary no more than 10°F. The relative humidity ranges from an average of 65 to 80 percent in the afternoon to 85 to 100 percent at night. A sub-tropical high pressure area lying north of the island throughout much of the year results in a dominant air flow pattern characterized by trade winds, but frequent storms in the summer and fall disrupt the pattern. These storms sometimes intensify to typhoons which cause excessive damage to the island.

From January through May the constant trade winds result in a well defined dry season broken only by occasional showers. July through November is the wet season during which the trades are frequently interrupted by tropical storms with heavy rains. The months of June and December are transitional. About two thirds of the annual precipitation falls in the five month wet season. There is no certainty to the wet season; droughts are common and severe droughts are not unusual.

The mean annual rainfall over the island ranges from 85 inches on the west coast near Apra to about 115 inches on the jagged limestone peaks of southern Guam. On the north plateau an average of 85 to 100 inches occurs. Variations from year to year may be large; for instance the maximum recorded annual rainfall near Agana is 119.35 inches (1916), while the minimum is 57.14 inches (1926). Table 1 (appendix B) tabulates the statistics of rainfall for four stations in northern Guam.

General geology

Tracey, et al (1964) made a thorough study of the geology of Guam, and the descriptions that follow are in large measure a summary of their findings but with emphasis on hydrogeologic relationships.

The island is sharply divisible into two major nearly equal geologic provinces, a limestone plateau in the north and a dissected volcanic upland in the south (see geologic map 1). The volcanics preceded the limestones in time, and the volcanic surface had been normally eroded before limestone emplacement so that gross unconformities separate these distinctly different rock types. The earliest identifiable rocks were erupted from a volcano located west of Guam in early Eocene time. Thick sequences of flows and pyroclastics accumulated nearly to sea level and were followed by weak limestone growth. A second volcano in the southwest yielded lavas and extensive pyroclastic deposits until its final collapse in early Oligocene time. Sedimentary deposition from the collapsed volcano continued through the early Miocene. From this time on the volcanoes were dormant, and deposition of limestones in massive sequences proceeded.

In late Miocene and throughout Pliocene time extensive lagoonal and reef limestones had formed over the volcanics. A general period of emergence followed with accompanying weathering and erosion. The island was again submerged in Plio-Pleistocene time during which the final limestone cover on the north plateau formed. Prior to this deposition the major structural events had taken place but minor earth movements have continued into the present. The middle and late Pleistocene was characterized by changing sea levels.

The earliest volcanic rocks are called the Alutom formation. They form a sequence 2000 to 3000 feet thick of water-laid tuffaceous shales, sandstones and conglomerates in which lava flows, breccia and fragments of reef limestone are intermingled. The Alutom formation is highly weathered from its surface to a depth of up to 100 feet and is poorly permeable throughout both the weathered zone and the fresh rock. It outcrops over about half of southern Guam, comprising the region between the Talofofo River and the northern limit of the volcanics.

Following the Alutom, the Umatac volcanic formation was deposited. It has a thickness of over 2200 feet and includes lavas, tuffaceous shales and sandstones, volcanic conglomerate, and lenses of limestone. In general the formation has a low permeability except for the small limestone lenses which are moderately permeable. The Umatac covers most of Guam south of the Talofofo River, thus making up the southernmost fourth of the island.

The Dandan basalt of the Umatac formation was the last volcanic rock extruded on Guam. It was followed by a series of limestones laid down from late Miocene time into the Pleistocene. From hydrologic considerations the most important limestones are those of the Alifan, Barrigada and Mariana formations. The Barrigada and Mariana cover most of the north plateau and constitute the principal aquifers. Mariana limestone also forms a band along the east coast of south Guam. Alifan limestone caps the higher portion of the mountain range in the south central part of the island.

Tectonism throughout Tertiary time resulted in three readily identifiable structural provinces. The northern plateau of limestone is the largest. It was apparently tilted toward the southwest and lightly faulted in post-Tertiary time. The U. S. G. S. team identified a fault extending from Tamuning to Yigo which displaced the Barrigada limestone but occurred before Mariana deposition. The throw of the fault is difficult to measure but is probably small, perhaps less the 100 feet in vertical movement.

The central structural block, named the Tenjo Block, is clearly separated from the limestone plateau by a contact, which may express a fault trace, extending across the waist of the island from Adelup, somewhat south of Agana, to Pago Bay. The contact is considered by Tracey, et al (1964) as evidence of faulting which occurred before Mariana time. The Tenjo Block consists chiefly of Alutom volcanics and is much deformed by small normal faults, thrusts and local folding.

The southern structural province, called the Bolanos Block, meets the central block at the Talofofo River, where a major fault extends across the island. This province is composed mainly of the Umatac formation and is also folded and faulted but to a lesser degree than the Tenjo Block.

The island's land forms are closely correlated with the structural provinces. The limestone plateau is gently sloping and featureless but locally extremely rough where limestone solution features are not covered by soil. The dissected volcanic uplands of the south have well entrenched streams, some of which flow in small canyons. The region between the central and southern structural provinces, which includes most of the drainage of the Talofofo River, is sufficiently unique to be called a separate geomorphic unit. It is a deep basin that extends inland from the east coast to the mountain range parallel to the west coast. The basin is covered with deep alluvium, which reaches a thickness of 200 feet at Talofofo Bay, over much of its extent. Around the south half of the island coastal lowlands merge into valley floors except where remnant Mariana limestone directly faces the sea. The north half in general has a narrow sandy coastal plain but many stretches of coast consist of bare limestone cliffs.

General hydrology

The approximately 100 sq. mi. area of south Guam is drained by 40 streams emptying into the sea. On the limestone of the north only one waterway is long enough to be called a stream., It originates in the volcanics just south of the contact line dividing the island, then flows intermittently over a clayey member of the Mariana limestone to a depression behind Agana.

The streams of south Guam are flashy, responding immediately to rainfall but declining rapidly afterwards. Flows during the wet season are substantially higher than in the dry months. Most of the streams are reduced to a trickle by the end of the dry season and in some periods many of them have no flow.

Drainage areas are small, ranging from much less than one square mile to a maximum of about 20 sq. mi. for the Talofofo basin.

The major streams drain areas between two and six sq. mi. Talofofo's average flow of 41 mgd is the greatest for the island. The smallest streams have average flows in the neighborhood of or less than one mgd.

Stream pattern and flow is determined by geological conditions, particularly the composition of the rocks and their structural arrangement. On the Tenjo Block drainage is controlled by slope, resulting in an irregular pattern. The major streams on the Bolanos Block follow structural lines. The Talofofo River drains most of the Interior Basin, which originally formed as a structural depression.

The Alutom, the principal formation of the Tenjo Block, is quite impermeable and its streams display the most extreme ranges of flow. Toward the end of the dry months even its large streams may go dry. The Umatac volcanics, which make up most of the Bolanos Block, are also poorly permeable but within the sequence are thin lenses of limestone which are moderately permeable. The base flows of the Umatac streams are relatively substantial and never reach the vanishing point. Table 6, Appendix B, summarizes flow data for the major streams of the south, and Analysis 5, Appendix A, discusses characteristics of flow.

While the limestone plateau of north Guam boasts of little or no surface drainage to the sea, it contains a bountiful supply of ground water. The limestone surface is extremely permeable and rainwater moves quickly downward to the zone of saturation. The ground water occurs as a lens of fresh water floating on sea water except between Highway 4 and the Adelup-Pago contact, where the volcanic basement rises above the theoretical depth to salt water, and in the northeast where volcanics rise above the surrounding plateau.

The lens of fresh water is essentially continuous north of Highway 4 and has a maximum head of five to six feet (elevation of the water table above sea level), suggesting from the buoyancy principle that it extends a maximum of 240 feet below sea level. This is by no means strictly true, however, because the water in the lens is in constant motion, causing a deepening of the freshwater and also a mixing with underlying salt water. Discharge takes place along the coast, often in concentrated streams through cavernous openings in limestone. Analysis 1 and 2, Appendix A, discuss the formation and shape of a fresh water lens floating on sea water in a permeable aquifer.

Groundwater is limited in occurrence in south Guam. Where exploitable aquifers exist they are small in extent and thickness. As a general rule the volcanic rocks are poor water-bearers, either containing no water at all or yielding it very slowly. In a few locations small limestone aquifers are encased by volcanic rocks. The limestones along the east coast are potential aquifers and a successful attempt has been made at Togcha to utilize such an aquifer. The remnant high limestones lying unconformably on volcanics inland often serve as porous reservoirs for springs that issue at the contact of the formations.

Groundwater Resources

In the natural hydrologic cycle the rain which ultimately infiltrates into the ground past the root zone most commonly drains into rock formations whose porosity and permeability allow water to accumulate and to slowly move along a gravitational gradient. The favorable rock formations are called aquifers and the water which saturates them is called groundwater. Permeability is the property of the aquifer which permits the transmission of water under gravitational force. The porosity of significance to groundwater is the fraction of void space through which the groundwater can freely pass and is called specific yield, or effective porosity.

The fundamental law of groundwater motion in porous media (i.e., an aquifer) was empirically established by Darcy and is named after him. It is a simple rule, expressed as:

(1) $$v = -k \frac{dy}{dx}$$

in which v is bulk velocity in ft/d (feet per day), k is hydraulic conductivity in ft/d, and $\frac{dy}{dx}$ is the gradient, or the change in water level over a horizontal distance, and is dimensionless. In the coordinate system to which the above equation refers, the horizontal axis is the x direction, the vertical is the y direction, and the negative sign signifies motion down gradient.

Equation (1) may be altered to represent the specific flow rate over the thickness of the saturated aquifer as follows:

(2) $$q = -k\ y \frac{dy}{dx}$$

in which q is the volume rate of flow over a one foot wide strip of aquifer and y is aquifer thickness. The term (ky) is also referred to as transmissivity, T.

The Darcy, or bulk, velocity refers to the volume movement of water as if the aquifer were 100% porous; the actual velocity of a particle of water in the real aquifer, called particle velocity, is given as:

$$(3) \quad v = \frac{-k}{m}\frac{dy}{dx}$$

where m is the effective porosity. Thus in the limestone aquifers of northern Guam, in which the average gradient is about 0.5 ft/1000 ft, the hydraulic conductivity is about 2000 ft/d, and the porosity is estimated at 10%, the bulk velocity of the water is about 1 ft/d while the particle velocity is approximately 10 ft/d. A drop of rain infiltrating the limestone 10000 feet from the coast would take 1000 days (2.74 years) to discharge in the springs along the coast under natural conditions. Appendices A-1 and A-2 discuss ground water flow in some detail.

The limestone aquifers of northern Guam effectively store an enormous volume of ground water and in fact behave as vast reservoirs which are relatively drought resistant (see Appendix A-4 for a detailed analysis of this concept). Using proper techniques of development coupled with rational management, the ground water resources may be exploited to supply the domestic requirements of the civil sector far into the future.

Ground water has been used in Guam from earliest times, long before the arrival of Magellan. Springs and streams, which at base flow carry only ground water, served the ancient culture, whose people probably also invented the dug well which reaches to the water table. However, not until 1937 was a deliberate attempt made to evaluate and exploit the ground water resources. H. T. Stearns conducted the first significant hydro-geological investigation in that year and identified five types of groundwater as: 1) basal water in limestone, 2) perched water in limestone, 3) dike water, 4) water in the bedding planes, fault zones, and joints of volcanic rocks, and 5) water in alluvium. Only categories 1 and 2, basal and perched water in limestone, are of actual importance at this time. Basal water refers to the fresh water which floats on sea water in the subsurface (see Appendix A-1 for definitions and analysis), and perched water refers to groundwater accumulated in limestone lying on an impervious basement of volcanic rock at elevations high enough to permit sub-aerial drainage of the water (see Appendix A-9).

In addition to the basal and perched groundwaters noted by Stearns (1937), a third type has been identified (Mink, manuscript reports to Layne International) which occurs in continuity with basal water but rests on the impervious volcanic basement rather than sea water because the theoretical thickness of the fresh water column exceeds the thickness of the limestone aquifer. This type of fresh ground water may be called para-basal water because its flow and potential field is an extension of the basal water field.

Stearns' category 3, dike water, refers to ground water trapped between nearly impermeable dikes, which are the feeder conduits of the original volcano. Very little developable dike water occurs on Guam. His category 4, water within structures of volcanic rocks, is important locally but grossly inferior in exploitability to limestone ground water and is not of significant interest at this time. Neither is category 5, alluvium water, which is limited in extent and quality characteristics, and in developability.

Following the War, an extensive survey of the water resources of Guam was undertaken by the U. S. Geological Survey and was reported in Ward, et al (1965). Stearns concluded that 50 to 100 mgd of ground water could safely be extracted from the limestones of northern Guam, but the Ward, et al, report was somewhat more conservative. However, since 1964 the successful exploitation of ground water to a present production of about 16 mgd suggests that at least the lower estimate of Stearns is obtainable. The analyses and evaluations given in this report sustain that estimate.

Hydrogeology

Practically all of Guam can be described in terms of two general rock types, limestones and volcanics. In a relative sense the volcanics are aquicludes when associated with limestones; in an absolute sense both the limestones and volcanics are aquifers, but the characteristics to store and transmit water are magnitudes more favorable for the limestone.

The early geologic history of Guam was dominated by volcanic activity, but during quiet intervals thin, discontinuous limestones were deposited, though they are of no hydrologic significance now. However, toward the end of the life of the last volcano moderately thick lenses of limestone formed during quiescent periods, and although scattered and relatively small in extent these limestones, called the Maemong member of the Umatac formation, carry groundwater and yield appreciable quantities to springs or wells. The Maemong is restricted to southern Guam and occurs as lenses encased in volcanic rocks in some of the valleys that drain to the southwest coast of the island, as pointed out by Tracey, et al (1964), and in the Bolanos member of the Umatac at Malolo, and perhaps other locations not yet discovered, as noted by Mink (manuscript reports to Layne, International).

The last phase of volcanism was followed by deposition of the Bonya limestone, a formation of little significance to groundwater development. After the Bonya the Alifan limestone formed and today is the aquifer rock for many perched springs of the south, such as Almagosa and Asan, but as far as is known does not underlie the northern plateau. A major limestone formation of the north, the Barrigada, succeeded the Alifan and may underlie much of the northern plateau, although it is exposed chiefly in the Dededo-Yigo-Northwest Field region. The most recent emerged limestone, and the most widespread, is the Mariana limestone which covers about 80% of the northern plate. and a significant band along the east coast of southern Guam. Both the Barrigada and the Mariana formations are of paramount importance as groundwater aquifers.

Limestones

Compared to limestones, volcanic rocks have rather uniform aquifer characteristics over wide areas and among rock varieties. Limestones, on the other hand, are highly variable, ranging from cavernous barrier reef facies to fine lagooonal sands and muds. The variety of limestone types and their short range of persistence, vertically and horizontally, is especially significant with regard to groundwater exploitation and the possibility of pollution from external sources. Typically near the coasts of northern Guam the limestone cliffs are the remnants of barrier reefs which contain large openings characteristic of massive coral growth, often enlarged by solution. These exposed sections have dominated observers' impressions, which are then commonly extrapolated to all of the island. In fact, however, behind the exposed fossil barrier reefs is the fossil lagoonal facies, making up most of northern Guam, which consists of heterogeneous detrital deposits, often cemented and filled with fine calcareous mud. In these deposits infiltrating water follows tortuous channels to the water table in contrast to possible direct vertical movement through the barrier reef sections.

The vertical and horizontal heterogeneity of the limestones gives rise to aquifer parameters which are most usefully defined on regional and local scales. The total flow of groundwater is described on a regional scale, the aquifer parameters for which represent an average between impermeable rock and open caverns. Groundwater flow to a line or point sink, such as a gallery or well, is described by local aquifer characteristics in the immediate vicinity of the sink. Regional parameters are skewed toward favorable conditions for flow; local parameters, especially hydraulic conductivity, are skewed toward the lower range of values. The section on Hydrologic Budget derives a value for regional hydraulic conductivity of approximately 2000 ft/d; from well tests local hydraulic conductivities typically fall between about 20 ft/d and 200 ft/d, although in some tests conductivities exceeding even 2000 ft/d were encountered.

Hydraulic conductivity is profoundly affected by the quantity of clay mixed with the limestone components. Argillaceous limestones contain up to 10% clay and have local hydraulic conductivities as low as 20 ft/d compared to clean limestone local hydraulic conductivities in the neighborhood of 200 ft/d. For well productivity computations it is convenient to classify the limestones and assign an average hydraulic conductivity, based on pump test analyses, to each as follows:

clean limestone: $k = 190$ ft/d

probable limestone: $k = 120$ ft/d

argillaceous limestone: $k = 52$ ft/d

very argillaceous limestone: $k = 26$ ft/d

The Maemong and Alifan are argillaceous to very argillaceous limestones; the Barrigada is a clean limestone; and the Mariana is subdivided into an argillaceous member lying between Barrigada and Pago-Agana and a clean member covering the remainder of northern Guam (see map 1).

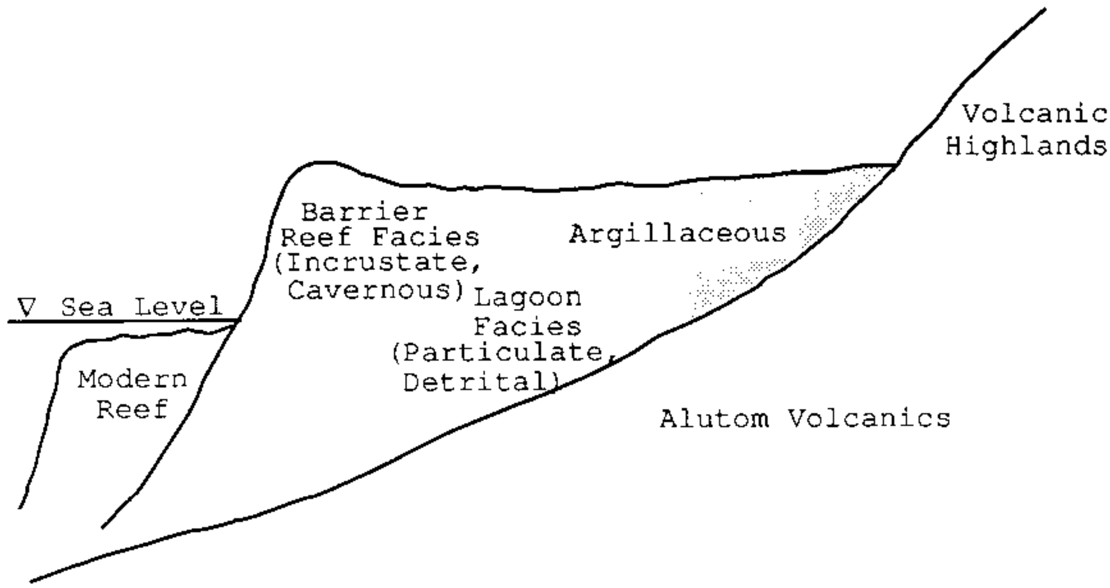
Porosity varies over short distances but on both a regional and local scale probably averages closer to 10% than to a larger figure. In primary carbonates before diagenesis porosity ranges between 40 and 70% (Bathurst, 1971), which reduces to 36 to 57% when primary aragonite recrystallizes to calcite, as it has in the limestones of Guam (Schlanger, 1964). The deposition of marl and calcite from solution into the matrix of the original carbonate further reduces the porosity, so that an estimate of 10% is reasonable.

At the water table porosity may increase greatly because of solution of the limestone by infiltrate charged with carbon dioxide but is generally unaffected below. During the drilling of wells it is not unusual to encounter cavernous limestone and the saturated zone simultaneously.

With reference to the basal groundwater of northern Guam, the limestones of chief interest are the Barrigada and the Mariana. Schlanger (1964) describes the Barrigada as a massive gray to white, indurated to friable, dense to porous fine grain detrital limestone which was deposited in deep water. Many drilling logs confirm the occurrence of this type of limestone in the interior of northern Guam.

The Mariana limestone is actually an emerged barrier reef and lagoon. The barrier reef facies is composed of incrustable limestone formed by colonial corals, coralline algae, and incrusting foraminifers. It is generally massive in structure with large openings and solution channels and forms the steep cliffs along the coasts of northern Guam. The lagoon facies, comprising the bulk of the plateau, consists of particulate limestone, which originated as the accumulation of fragmental coral debris, shells and other calcium carbonate detritus. It is extremely heterogeneous; driller's logs suggest a complicated history of formation which led to beach sands, marls, and lignitic material (from near shore swamps) as common components.

The lagoon facies nearest the volcanic highlands of southern Guam received a significant input of volcanic sediment which became incorporated into the carbonate detritus of the lagoon to form an argillaceous limestone, called the Agana argillaceous member of the Mariana limestone. This member covers the area between the limestone-volcanic contact extending from Pago Bay to Adelup and the 200 feet elevation contour near Barrigada. The clay content of the limestone is greatest nearest the volcanics and decreases toward Barrigada. The hydraulic conductivity of the Agana member is considerably smaller than for the remainder of the lagoon facies. A rough sketch of the distribution of the components of the Mariana reef now forming the northern plateau of the island is given below.



Volcanics

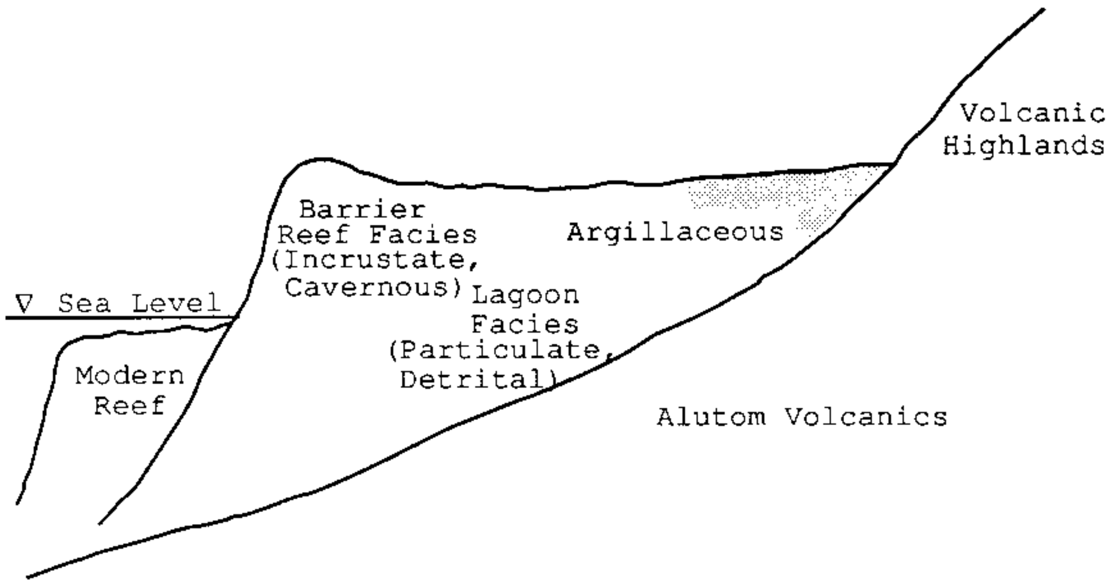
All of the volcanic rocks of Guam were erupted beneath the sea, giving rise to a variety of basaltic-andesitic rocks ranging from dense pillow basalts and andesites to compacted fine grain pyroclastics. Not any of these rocks can be regarded as suitable for easily exploitable aquifers. Even in the primary state their hydraulic conductivities are very poor, and with the pervasive secondary mineralization which occurred subsequent to their deposition the conductivities became even poorer.

Ground water occurs in the bedding planes and fractures of the volcanics. The water table stands very high, generally within 50 feet of the ground surface and conformable with it, and drainage to streams is slow. Approximately 50 to 100 mgd of ground water drains from the volcanics as seepage to stream valleys (see Appendix

A-5 for a discussion of ground water in the volcanics as determined from stream flow analysis).

Two geologically distinct volcanic formations, the Alutom and the Umatac, cover southern Guam but their gross hydrogeologic characteristics are similar. The Alutom is an undifferentiated succession of mixed pyroclastic and flow units which often carry appreciable carbonate detritus, while the Umatac is subdivided into the early Facpi basalt member, the Bolanos pyroclastic member, and the hydrogeologically insignificant Dandan basalt member. The aquifer parameters of the volcanic formations are so poor that where limestone aquifers occur the volcanics may be treated as impermeable boundaries.

A carefully conducted bail test in the Bolanos member of the Umatac formation in the Malolo area gave a hydraulic conductivity of .034 ft/d, and a pumping test of the RCA Pulantat well, which penetrates the Alutom formation, yielded a hydraulic conductivity of .036 ft/d. These values, more than a thousand times inferior to argillaceous limestone, are probably characteristic of the normal volcanic sections. At the Guam Oil Refinery well, however, a transmissivity of 522 ft^2/d was determined, equivalent to a hydraulic conductivity of about 2.6 ft/d. It is not clear why this particular section of the Alutom formation should have such an unusually high hydraulic conductivity, but the chemistry of the pumped ground water suggests the presence of buried limestone. The water contains about 50 mg/l of calcium, several times the normal content of volcanic ground water (see fig. 8, Appendix B).



Volcanics

All of the volcanic rocks of Guam were erupted beneath the sea, giving rise to a variety of basaltic-andesitic rocks ranging from dense pillow basalts and andesites to compacted fine grain pyroclastics. Not any of these rocks can be regarded as suitable for easily exploitable aquifers. Even in the primary state their hydraulic conductivities are very poor, and with the pervasive secondary mineralization which occurred subsequent to their deposition the conductivities became even poorer.

Ground water occurs in the bedding planes and fractures of the volcanics. The water table stands very high, generally within 50 feet of the ground surface and conformable with it, and drainage to streams is slow. Approximately 50 to 100 mgd of ground water drains from the volcanics as seepage to stream valleys (see Appendix

A-5 for a discussion of ground water in the volcanics as determined from stream flow analysis).

Two geologically distinct volcanic formations, the Alutom and the Umatac, cover southern Guam but their gross hydrogeologic characteristics are similar. The Alutom is an undifferentiated succession of mixed pyroclastic and flow units which often carry appreciable carbonate detritus, while the Umatac is subdivided into the early Facpi basalt member, the Bolanos pyroclastic member, and the hydrogeologically insignificant Dandan basalt member. The aquifer parameters of the volcanic formations are so poor that where limestone aquifers occur the volcanics may be treated as impermeable boundaries.

A carefully conducted bail test in the Bolanos member of the Umatac formation in the Malolo area gave a hydraulic conductivity of .034 ft/d, and a pumping test of the RCA Pulantat well, which penetrates the Alutom formation, yielded a hydraulic conductivity of .036 ft/d. These values, more than a thousand times inferior to argillaceous limestone, are probably characteristic of the normal volcanic sections. At the Guam Oil Refinery well, however, a transmissivity of 522 ft^2/d was determined, equivalent to a hydraulic conductivity of about 2.6 ft/d. It is not clear why this particular section of the Alutom formation should have such an unusually high hydraulic conductivity, but the chemistry of the pumped ground water suggests the presence of buried limestone. The water contains about 50 mg/l of calcium, several times the normal content of volcanic ground water (see fig. 8, Appendix B).

A well drilled in the Facpi member of the Umatac formation near Merizo showed an immeasurably small hydraulic conductivity. The pillow basalts of this member are apt to have the lowest hydraulic conductivity of any rock on Guam.

In general terms, the volcanic rocks of Guam are extraordinarily poor aquifers not worthy of exploitation within normal economic criteria.

Occurrence and Extent of Groundwater

Although ground water underlies all of Guam, only in the limestone plateau of the north is it extensive enough to be developable on a large scale. The largest resource consists of basal water which extends from the near vicinity of Highway 4, where it connects Agana and Chalan Pago, northward to the extremities of the island. Basal water also occurs in the Mariana limestone along the east coast of southern Guam. Appendices A-1 and A-2 define and describe basal water, also called Ghyben-Herzberg water after the investigators who first recognized that fresh groundwater floats on heavier sea water in accord with the buoyancy principle. Because the density of fresh water is 1.000 and that of salt water is 1.025, for static conditions, which approximate ground water flow, theoretically 40 feet of fresh water will extend below sea level for every foot above sea level. This ratio does not hold exactly under natural conditions because of the complexity of the ground water flow system, but it is a good approximation.

Second in importance to basal water is the para-basal water resource extending from the Adelup-Pago contact to approximately Highway 4. This type of resource also occurs to an unknown extent in the vicinity of Barrigada Hill and around Mataguac and Mt. Santa Rosa but its exploitability has not been tested in either of these regions.

Following para-basal water in importance is high level perched spring water, much of which is already obtained from the

Almagosa springs complex by the U. S. Navy from Asan Springs by PUAG. Other sources serve local needs but are probably inefficiently exploited.

The limestone lenses in the volcanics of southern Guam have been inadequately explored but their probable yields could be expected to be sufficient only for local demands. At this time, the groundwater in the volcanics of southern Guam is the least important of all the ground water resources of the island.

Basal Water in Northern Guam

The extent of basal water in northern Guam, from the Agana-Ordot-Chalan Pago region northward to the extremities of the island, is shown in map 2. Throughout this entire region a continuous lens of basal water occurs, interrupted only in the Barrigada Hill region by the elevated volcanic basement and in the northeast by the buried volcanic mountains manifested by Mataguac and Mt. Santa Rosa. The basal water region is subdivided into four sectors, called areas 2, 3, 4, 5 (see map 3), for hydrologic budgeting and for descriptive purposes. Area 1 is the para-basal water region falling between the basal water, with which it is in hydrologic continuity, and the Adelup-Pago contact, the absolute southern boundary of the limestone plateau.

The measurable indices of the basal lens, in particular the heads and to a lesser degree the chloride content of the fresh water, have not changed significantly within the accuracy of measurements between the drilling of the first well in 1937 and the present.

Heads apparently have been stable, although expectably they should have dropped somewhat because of current draft, but the theoretical decrease at current average draft of 16 mgd would be 0.5 ft. or less, an amount probably beyond the discrimination of presently used measuring techniques. Appendix A-8 analyzes the effects of natural leakage and draft on basal heads, pointing out that it would take a development of about 50 mgd from northern Guam to cause the 5 ft. equipotential (line of equal head) to drop to 4 ft.

The first head measurements in the basal water of northern Guam were made in 1937 when the first deep wells were drilled and when Stearns undertook his investigations. These measurements reflect the condition of the basal lens before any exploitation by pumping was started. Stearns recorded heads and chloride content for 12 wells drilled in central Guam and drew an isopiestic map which is surprisingly modern in concept (fig 1). He postulated a maximum head of about 8 feet near Mataguac and normal maximum of between 5 and 6 feet along the long axis of the island. His suggested normal maximums have been substantiated by many measurements over the years and continue to prevail even today.

Actually the highest head noted by Stearns was 19.2 feet in the para-basal water near Chaot, though he was unaware of the existence of such ground water. He assumed the high head to be the result of flow in a poorly permeable argillaceous section of the limestone aquifer. The first well for PUAG in para-basal water was drilled in 1964 within a few hundred feet of the well Stearns reported and showed a head of about 20 feet, the same as that encountered in 1937.

The chlorides reported by Stearns are typical of undisturbed basal water and continue to prevail where the lens has been properly developed. Chlorides generally are higher within about 2000 feet of the coast than in the interior of the island. A tongue of high chloride water, however, has encroached from Ypao Peninsula on the west coast in to Barrigada.

Table 1 summarizes Stearns' records of heads, chlorides and computed gradients, all measured in 1937, and these measurements may be treated as the approximate initial boundary conditions of the basal lens and the para-basal water. The heads are probably accurate to within 0.5 ft. but the gradients may not have been computed for the actual groundwater flow paths and therefore are only approximations. The chloride concentrations are accurate because the test is simple and standardized. Column 1 in the table lists Stearns' numbering system while column 2 is the well numbers assigned in the initial USGS report (Ward, et al, 1965). The new USGS numbers may be obtained from the cross-reference tables recently published by the USGS.

Table 1

Measurements of heads and chlorides of wells in northern Guam in 1937 as reported in Stearns (1937)

Well (Stearns no)	Well (USGS no)	Name And Location	Static Water Level above MLLW	Gradient ft/mi	NaCl gr/gal	Cl mg/l
1	9	Dededo	2.8	3.7	5.5	55
2	74	Ilipog	1.6	3.2	12.0	120
3	6	Barrigada	4.0	2.3	1.9	19
4	42	Canada 1	5.7	3.4	1.3	13
5	64	Canada 4	6.3		8.9	90
6	43	Canada 2	6.3			
7	45	Canada 3	6.3			
8	88	Ordot	18.2	9.1	1.7	17
9	19	Price 1	4.9	6.4	2.7	27
10	41	Price 2	4.2	4.9	1.7	17
13		Tumon Farm	1.6		14.9	150
14	120	Chaot	19.2		4.6	46

Note: Stearns also reported that 3 holes were drilled in a gulch just SE of Agana Swamp, each showing a 6 ft. head.

Following Stearns the next attempt at depicting the isopiestic surface of the basal lens was made by Piper for the period 1944-45 (Pacific Island Engineers, 1948). His map (fig. 2) is inferior to Stearns' in conceptualizing the ground water surface but like Stearns he recognized that the normal maximum heads fell between 5 and 6 feet.

The water table contours of the lens under current development are shown in map 2 and are based chiefly on data collected during the last ten years by Layne International, PUAG, and the USGS. Maximum heads in the strictly basal lens sector are between 5 and 6 feet.

The direction of flow is at right angles to the isopiestic lines, which in a general way run parallel to the coastal outline of the island.

The ground water gradient averages about 0.55 ft/1000 ft but is flatter in the northern portion of the plateau where the flow path is longest. The water table is parabolic in shape and the approximate head relationship between two points on the water surface is given by:

$$h_2 = \left[\frac{x_2}{x_1} \right]^{0.5} h_1$$

in which x_1 and x_2 are distances from the discharge line at the coast measured inland and normal to the water table contours to points where the heads are h_1 and h_2, respectively. Using this relationship for heads in the Dededo region (well M-10) gives a maximum head on the axis of the island of 6 to 6.5 feet; inland of ACEORP ınnel near Barrigada the maximum head computed in the same way is 5 to 6 feet. The low flow gradient relative to the large volume of ground waters which must discharge implies a very high hydraulic conductivity.

The lens is sustained by direct rain water infiltration and by subsurface flow from the para-basal sector (area 1) and from Barrigada Hill and Mataguac-Mt. Santa Rosa where the volcanic basement rises above the theoretical bottom of the lens. Discharge takes place as springs and seeps along the coast and in Agana Swamp.

The lens may carry fresh water practically to the shoreline, but as a general rule in a band extending about 2000 feet inland the ground water is slightly brackish as a result of mixing of the fresh water with underlying sea water induced principally by tidal movement. Appendix A-1 discusses this mixing and the creation of the "zone of transition" in the lower part of the fresh water lens. The brackish water band expands and intrudes as a roughly triangular salient from Ypao Peninsula on the west coast to the center of the island at Barrigada. This wedge of high chloride water apparently formed shortly after ground water development began and has not dissipated since. Normally the high flux of ground water would eventually flush away such a wedge under natural conditions, which prevailed for many years after the wedge initially formed. The apparent stability of the salient suggests abnormalities in the characteristics of the limestone aquifer in the region.

Brief Description of Basal Water Areas

The basal water areas of northern Guam are designated as areas 2, 3, 4, 5 on map 3 and in the hydrologic budget calculations given later. Area 2 extends northward from Highway 4 to Barrigada as a highly karstic argillaceous limestone terrane contained within the 200 feet elevation contour. The maximum basal water head is near 8 feet where the volcanic basement truncates the fresh water-sea water interface of the lens (see fig. 3, cross-section BB') but reduces to the normal maximum of about 6 feet toward Barrigada.

Figure 4 (cross-section CC') illustrates the occurrence of basal water in area 2 across the island from the west to the east coast. The volcanic basement probably lies at least 300 feet below sea level, allowing a normal lens to form. Figure 5 (cross-section DD') shows the relationships between the volcanic basement and the free basal lens in the vicinity of Agana Swamp. The head at Agana Spring is usually about 10 feet, suggesting that it lies in the transition area between the free basal lens seaward of the swamp and the para-basal water of area 1.

Area 3 includes the region between area 2 and a line connecting Ypao Beach, the scarp on the northern side of Barrigada Hill and Pagat Point on the east coast. The aquifer consists of clean limestone, mostly belonging to the detrital lagoon facies. In a small portion of the area, as an envelope around Barrigada Hill, the volcanic basement rises above sea level, although it does not surface (map 2). The scarp on the north face of Barrigada Hill has been classified as a fault by Tracey, et al (1965), but it may simply be an expression of reef geomorphology.

Figure 6 (cross-section EE') shows a section through the Ghyben-Herzberg lens extending from Tumon Bay southeastward across the waist of the island to Huchunao. The volcanic basement lies far below the interface and the lens is continuous across the island. The maximum head in the middle of the section is 5.5 to 6 feet.

Ypao Peninsula and the tongue of saline water with its apex at Barrigada is included in area 3. Elsewhere the groundwater has chloride content of 50 to 100 mg/l, characteristic of uncontaminated basal water.

Area 4 extends northward from area 3 to an arbitrary boundary which connects Uruno Point on the northwest coast and Janum Point on the east coast. The northern boundary was selected primarily because it differentiates the Andersen Air Force Base complex, which is unavailable to PUAG as a source of ground water, from the Dededo-Yigo region, in which appreciable ground water development has taken place. Additionally, the Uruno-Janum line roughly follows the sub-surface drainage divide of the elevated volcanic basement which culminates in Mataguac and Mt. Santa Rosa; drainage south of the line finds its way to the lens in the Dededo-Yigo region while to the north of the line it flows to the north coast.

The Mariana formation predominates in area 4 as elsewhere in northern Guam but a band of Barrigada limestone up to $1\frac{1}{2}$ miles wide surrounds the isolated sector of Mariana limestone through which the volcanic rocks of Mataguac and Mt. Santa Rosa project. All of the limestones can be classified as clean, though vertical sections display mixed modes of deposition. Much of the Mariana limestone was formed under lagoonal conditions but near the present coasts fossil barrier reefs dominate. The Barrigada formation is a deep water detrital limestone.

Approximately 16 sq. mi of volcanic basement rise above sea level around Mataguac and Mt. Santa Rosa (see map 2). These small peaks may be envisioned as eroded volcanic remnants which lay as islets around which an enormous lagoon formed during the late Pliocene - early Pleistocene time. The orogeny of the early Pleistocene raised the lagoon above sea level, and eustasy during the Pleistocene terraced the raised barrier reefs forming the coastal escarpments.

The basal lens wraps around the elevated basement on the west but is terminated on the east where the basement rises to Mataguac-Mt Santa Rosa. The maximum basal head near the elevated basement is 6 to 7 feet, about equal to Stearns' estimate.

Figure 7 (cross-section FF') illustrates the lens in the southern part of area 4 near the presumed Tamuning-Yigo fault; to the north of the scarp the ground water is entirely basal, while just to the south it is para-basal where the volcanic basement rises in the vicinity of Barrigada Hill.

Figure 8 (cross-section GG') is a section across the island from west to east through Mataguac and Mt. Santa Rosa. It shows the complexity of ground water occurrence where the volcanics rise above sea level. In the buried valley between Mataguac and Mt. Santa Rosa the volcanic basement sits well above sea level and a small area of para-basal water occurs, which drains to the basal lens near the town of Yigo. Figure 9 (cross-section HH') is a north-south transect through Mataguac, showing the transition to basal conditions both south and north of the mountain. Figure 10 (cross-section II') illustrates the Yigo subsurface valley as it deepens to basal water conditions and the geohydrologic conditions at Janum Spring. This large spring apparently discharges subsurface drainage at the limestone-volcanic contact just above sea level.

In area 5, the northernmost sector of the island, the basal lens is continuous on the west with the basal lens of central Guam but is truncated on the east by the elevated basement. The limestone is clean, mostly Mariana Formation with some Barrigada. The maximum basal head is above 6 feet and ground water quality is good. Large basal springs at Tarague occur on the north coast in the fossil barrier reef facies.

Brief Description of Area of Para-basal Water

Area 1, the approximately 5 sq. mi. region lying between the Adelup-Pago lithologic contact and the vicinity of Highway 4, consists of argillaceous to very argillaceous limestone of the Agana member of the Mariana formation, all of it lying below 200 feet elevation. Underlying the limestone at elevations sufficiently high to prevent the occurrence of a Ghyben-Herzberg lens is a volcanic basement which slopes about 3° to 5° to the north. The basement is irregular, however, representing the old eroded volcanic surface before submergence.

Several wells have penetrated the limestone to the underlying volcanics. At A-11, about 1500 ft. from the contact, the basement lies at -170 ft.; at A-3, about 3500 ft. from the contact, it lies at -260 ft. Where the basement lies deeper than -250 to -300 ft., a Ghyben-Herzberg lens forms. This generally occurs about 1000 ft. north of Highway 4. The contour surface of the basement, drawn from the sparse data available, is shown in map 4.

The water table of area 1 drops from somewhat more than 40 ft. above sea level near A-11 to 8 to 10 ft. where para-basal conditions change to basal conditions (map 4). The sharp increase in head from the basal sector results not only from the effect of the rising basement but also from the reduction in hydraulic conductivity of the aquifer as it becomes more argillaceous nearer the volcanic highlands.

Because sea water intrusion cannot affect para-basal water, the chloride content in area 1 is very low, between 15 and 20 mg/l.

Figure 11 (cross-section AA') shows a transect across area 1 from the limestone-volcanic contact forming its southern boundary to upper Agana Swamp, which lies in the basal water region. Figure 3 (cross-section BB'), a section extending from Famja to Lates Point, also illustrates the relationship between the basal lens and para-basal water, as does figure 5 (cross-section DD') in the vicinity of Agana Swamp.

Heads recorded by Stearns in 1937 in para-basal water near Ordot and Chalan Pago were 18 to 19 ft.; slightly higher values were recorded in 1965 when the first producing wells were drilled in the region. In recent years heavy pumping has reduced local heads, but unfortunately non-pumping observation wells have not been installed to test whether the regional head has also suffered a decline.

Basal Water in the Limestones of Southern Guam

An unbroken rim of Mariana limestone up to 2.5 miles wide forms the east boundary of southern Guam from Pago south to the Talofofo River, then continues beyond Talofofo valley to the Paulilac and Inarajan Rivers, over a total distance of about 10 miles. Typically the limestone displays a marked terrace at 100 ft. elevation, the result of the Kaena stand of the sea of about 450,000 years before present. Between elevations 100 and 200 feet the slope is quite steep, some flattening takes place at 200 feet, then the slope again rises steeply to 300 feet elevation where the surface forms a karstic plateau. Maximum elevations are 340 to 350 feet.

The distinct 100 ft. elevation break in slope suggests that the relatively flat limestones below this elevation were formed some time after the main Mariana formation. The steep slopes above 100 feet are fossil barrier reefs which were formed above sea level in early Pleistocene time. The small amount of data available indicates that the volcanic basement beneath these reefs lies above sea level, thus preventing the formation of a Ghyben-Herzberg lens or para-basal water.

The limestones of the 100 ft. terrace, however, extend below sea level and may carry basal water. Unfortunately, the 100 ft. contour extends far enough inland in only a few places to allow the formation of a fresh water lens. The deepest penetration inland of limestones lying below an elevation of 100 ft. is in the Ylig River valley, a drowned valley in which limestone occurs as far as 1 to 1.5 miles inland. Along the open coast the 100 ft. elevation terrace reaches to 3000 ft. inland in the Togcha and Camp Dealy re-entrants. In these three situations -- Ylig, Togcha, and Camp Dealy -- there is a good probability of the existence of exploitable fresh basal water.

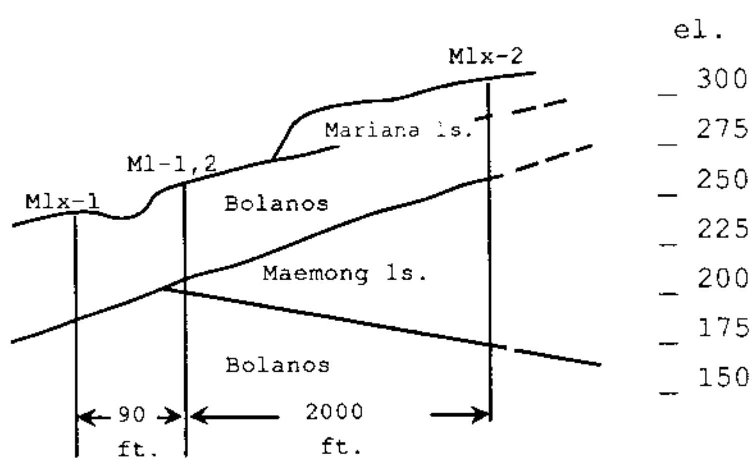
Three test wells have already been drilled in the Ylig valley at the treatment plant in which heads of about 6 ft. and chloride contents of around 60 mg/l were recorded. Driller's logs showed lenses of clean coral in mixed clay-coral sequences. Hydraulic conductivities are characteristic of argillaceous limestone.

In the Togcha re-entrant the basal groundwater, which averages less the 100 mg/l chloride and has a head of 1 to 2 ft., is already being exploited for golf course irrigation. No exploration has been attempted in the Camp Dealy re-entrant, but basal water of acceptable quality is likely to occur there.

Groundwater in Buried High Level Limestones of Southern Guam

In only one location so far has a high level limestone encased in volcanic rocks been discovered and exploited; in another a similar situation may prevail, though not with as clear definition. The successful case is at Malolo where a limestone lens, probably belonging to the Maemong member of the Umatac formation, lies within the Bolanos pyroclastic member. The uncertain case is at Talofofo

At Malolo, the limestone lies below about 30 ft. of volcanics and is wedge-shaped with a known maximum thickness of 80 ft. The following sketch outlines the field relationship as determined after the drilling of 4 wells.



The most accurate log was taken at Mlx-2, now abandoned and lost even though it was the best producer. The log showed the following (values in ft.):

Rock Type	Depth	Elevation	Thickness
Mariana ls.	0-32	315-283	32
Bolanos volc.	32-60	283-255	22
Maemong ls.	60-140	255-175	80
Bolanos volc.	140-275	175-40	

Wells Ml-1 and Ml-2 struck the edge of the limestone wedge but nevertheless produced water which at first flowed under artesian pressure until over-pumping dissipated the pressure. Well Mlx-1 encountered only volcanic rocks. Mlx-3, drilled several years ago on the Dandan road, may have struck the same or another limestone wedge, though no groundwater was encountered in it.

Pumping tests at Mlx-2, using Ml-1 as the observation well, gave a hydraulic conductivity of 37 ft/d. A test at Ml-1 using Ml-2 as the observation well, yielded a conductivity of 60 ft/d. The chloride content of the water is about 30 mg/l.

At Talofofo the limestone extends from the surface to -30 to -40 ft. but at the surface volcanics surround the limestone. Hydraulic conductivity, determined from pump tests, is 30 to 50 ft/d, and the chloride content averages 30 mg/l. Like the limestone at Malolo, that at Talofofo is argillaceous.

High Level Perched Water: Springs

High level springs draining from limestone, with the exception of Mataguac and Janum Springs, are restricted to locations south of the Adelup-Pago contact where masses of limestone overlie impermeable volcanics (see map 1). Most of the springs drain the Alifan limestone cap on the mountains in the headwaters of the Talofofo River basin. These springs include Almagosa, Dobo, and Bona, which drain to the Talofofo basin, and Mao, Anan, Faata, and Santa Rita, which drain to the west coast of the island. Further south at lower elevations springs drain Maemong limestone lenses in the headwaters of streams which traverse the Facpi member of the Umatac formation.

Asan Springs drains an Alifan limestone cap just south of Agana. Appendix A-9 discusses and analyzes Asan Spring in detail.

Geochemistry of the Water Resources

Much data has accumulated on the chemical quality of the ground and surface waters in the past 20 years and especially since 1964 when Layne International set up a water analysis laboratory. In addition to Layne, regular complete analyses are made by the U.S. Navy, and occasional analyses are reported by the USGS and perhaps other government agencies. The Kennedy report of 1964, the Austin, Smith Assoc. report of 1968, and the Ward, et al, report (USGS) of 1965 summarized many analyses. However, only because Layne, International, has diligently carried out routine analyses for the past 10 years, producing hundreds of values for the major dissolved constituents, has a statistical evaluation of water quality been possible.

The natural waters of Guam have not yet been contaminated except in highly localized situations. It is vitally important to know the natural background concentrations of dissolved constituents to show, first of all, that the water meets drinking standards, and then to establish the criteria against which contamination could be measured. A single analysis, or even several if poorly sampled, is an unreliable datum upon which to base decisions, yet this is a common practice. If many analyses are available, as they are on Guam, a firm understanding of the chemistry of the water will follow from application of the simplest statistical measures. In the evaluations which follow the median is used as the central measure rather than the mean because of the distortion extreme values, usually the result of erroneous analysis or improper sampling, impose on the mean. Where too few values are available to produce a reasonable median, either the mode or the mean is used if the range of values appears reasonable.

Tables 8 and 9, Appendix B, summarize the statistics of the water analyses, most of which refer to groundwater in the limestones of the northern plateau. The data in Table 8 are restricted to the major dissolved species, calcium (Ca), chloride (Cl), silica (SiO_2), nitrate, (NO_3), magnesium (Mg), and to total hardness, because these components are included in routine analysis. Heavy metals and trace elements occur in insignificant amounts, judged from the analyses on hand, but few, if any, attempts have been made to ascertain their true concentrations.

Chloride is a critical constituent because it provides a measure of sea water intrusion; calcium and magnesium concentrations, from which total hardness is computed, indicate the utility of the water with regard to industrial and household uses; silica provides an index of the lithology in which the water moves; and nitrate is an indicator of contamination and pollution.

With respect to dissolved mineral species, the ground and surface waters of Guam as delivered to consumers meet the U.S. Public Health Service Standards and the World Health Organization Specifications, except that calcium is somewhat higher than the WHO specifications. Surface waters are very low in dissolved matter. Some wells in the north produce water with a chloride content in excess of normal standards, In particular, wells D-13 and M-11 significantly exceed the suggested limit of 250 mg/l chloride, while A-13 exceeds it by a small amount. Table 2 below lists the USPHS and WHO standards and includes typical analyses of the A, D, and Y series wells, and H-1 and M1-1, for comparison.

Table 2

Water quality standards and typical analyses

of ground water from wells. Values in mg/l, except pH.

Constituent	USPHS Std.(1962)	WHO Spec.	Guam Wells: A series (para-basal)	A-9 (basal)	D series	Y series	H-1	Ml-1
pH		7-8.5	7.0	7.0	7.2	7.3	7.3	7.1
Residue on evap.	500	500	360	600	370	275	450	350
Total Hardness			292	360	226	242	265	380
Ca		75	113	130	78	85	88	98
Mg		50	2	10	6	7	10	8
Cl	250	200	16	140	50	17	95	30
NO_3	45		9	9	9.5	9.3	9	4
SO_4	250	200	2.5	13	8.0	2.0	20	4.5
Fe	0.3	0.3	.01	.01	.02	.02	.02	.03

Aquifer environment

The volcanic flow rocks of Guam are about evenly divided between basalt and andesites (Stark, 1963), and the pyroclastics are chiefly andesitic. Typical concentrations, in percent, of the major constituents of these rocks are as follows:

Constituent	Basalt	Andesite
SiO_2	48 to 52; av. 50	53 to 69; av. 60
CaO	10	7
MgO	8	3
Na_2O	2	3
K_2O	0.5	1.0

During weathering the rocks lose much of the above constituents, leaving a soil residue rich in iron and aluminum oxides but infertile. Ground water in the volcanics reflects, in particular, the high silica content of the original rocks.

The limestones of the island range from argillaceous members containing as low as 50 - 60% calcium carbonate to clean members containing in excess of 98% $CaCO_3$. The clean limestones cover most of the northern plateau, the exception being the region between Barrigada and the Adelup-Pago contact where the Agana argillaceous member is found. Clean Mariana limestone typically contain 98 to 99% $CaCO_3$ and about 1% $MgCO_3$; the Barrigada limestone is nearly 99% $CaCO_3$ with 1% or so of $MgCO_3$; the Alifan limestone, which is somewhat argillaceous, varies from 88 to 99% $CaCO_3$ and 1 to 2% $MgCO_3$; and the Agana argillaceous member of the Mariana formation varies considerably in carbonate content, which generally exceeds 80 to 90%, however. Schlanger (1964) discusses the limestones of Guam in great detail.

Soils on the clean limestones are thin, except where accumulated in sink holes or depressions, but quite fertile. They are composed of the non-carbonate impurities of the original limestone. Where argillaceous limestones occur soils are thicker and even more fertile. As a result of the thick soils, which provide the means and media for water-carbonate chemical reactions, weathering in the argillaceous limestones is more rapid than in the clean limestones, the principal manifestation of which is the highly karstic terrain of areas 1 and 2.

The chemistry of ground water in the limestones is dominated by the $CaCO_3$ - H_2O - CO_2 chemical system, the chief result being high hardness water.

Discussion of dissolved constituents in the water

Chloride (Cl)

In island aquifers chloride concentration is a dominating characteristic of the ground water supply. Where the water occurs in a basal lens there exists the constant danger of intrusion of saline water into the fresh water. Indeed, the slight differential in densities between fresh and sea waters and the horizontal velocity of water in the lens are the sole factors preventing the reduction of the lens to a high chloride transition zone.

All of the chloride in the water originates from the sea, carried either in rainfall or dry salt spray. Neither the limestones nor the volcanic rocks contain enough inherent chlorine to measurably influence the chemistry of the water. Analyses of the chloride content of rainfall have not been made but the probable average concentration is 10 mg/l or less. The combination of chloride in rainfall with that of salt spray rinsed by the rain from ground, plant and other exposed surfaces produces groundwater with an uncontaminated background concentration of 15 to 20 mg/l chloride. If the chloride content is greater than 20 to 30 mg/l in an active flow zone, sea water intrusion is implied. In some instances static ground water will suffer a build-up of chloride from salt spray, and in others fossil sea water may introduce chloride. In the north, however, neither of these processes is significant, and nowhere do they seriously affect the quality of the water.

Ordinarily non-basal ground water contains less than 20 mg/l chloride and normal uncontaminated basal water contains from 20 to

60 mg/l. The higher concentration in the basal water results from hydrodynamic dispersion induced by tidal motions. These movements are greatest nearest the open sea, and consequently the entire lens consists of a zone of mixture within one or two thousand feet of the sea coast. As a general rule a two thousand foot band parallel to the coast may be treated as a zone of mixture containing greater than 250 mg/l chloride, the recommended potable limit. Such a band is obviously an approximation in view of the fact that dispersion depends on aquifer hydraulic conductivity, ground water velocity, and other variables which are not uniform even over short distances.

Table B (Appendix B) lists the median chloride concentrations for uncontaminated wells, springs, and streams, and figure 12 is a bar graph of the same data. The A series wells listed in table 8 develop para-basal water, which is not in contact with underlying sea water. All of the D and M series wells pump basal water; the Y series may be para-basal; F-1 and AG-1 are basal; and T-1 and M1-1 are non-basal.

Stearns (1937) reported that the first drilled well into the basal lens, near Barrigada, encountered 55 mg/l chloride ground water, and noted that ground water from the para-basal region near Chaot had 13 mg/l and that Asan Spring had 18 mg/l. Sundstrom (1948) stated that the ground water in the vicinity of the Naval Air Station originally contained 30 - 70 mg/l chloride but had increased to 460 to 480 mg/l by 1947. This area is still underlain by a tongue of high chloride basal water (map 2), into which well A-16 was drilled within the last year.

Chloride concentrations have increased in many of the basal wells under pumping while in others little change has taken place. No increases have occurred, nor are any expected, in the para-basal and perched aquifers. Figure 13 shows chloride concentration as a function of time for the A series wells. The water from the para-basal aquifer (wells A-1, A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-11, A-12) have remained below 20 mg/l chloride over the years while all the basal water wells have showed sharp increases, with A-13 and A-16 exceeding acceptable potable limits. The high chlorides in the basal wells probably result from poor horizontal permeability in the argillaceous limestone aquifer, exacerbated by well depths which are too great (see table 10, appendix B) and pumping rates which are too high.

Figure 14 is a plot of chlorides versus time for the D series wells, all of which are basal, and for Y-1 and Y-2, which may be either basal or para-basal (see figure 9). All of the wells except D-8, D-9, D-11 and D-13 contain less than 60 mg/l chloride and have been stable since construction, which for some took place nearly 10 years ago. Well D-8, after having reached a peak of 200 mg/l in 1972 has settled back to about 100 mg/l, the same as D-9, and D-11 is approaching 80 mg/l. Well D-13 is an anomaly, yielding water with greater than 500 mg/l chloride, far above the potable limit. It is deeper (bottom elv. -53 feet) than the desired depth (-25 feet) and probably encountered a zone where vertical permeability exceeds horizontal permeability so that deeper water from the transition zone is drawn to the well under pumping stress (see figure 17). In contrast, well D-12, about 1400 feet away, whose bottom elevation is -42 feet produces groundwater with only 20 mg/l at the same pumping rate. At D-12 the normal situation of high horizontal vis a vis vertical permeability probably prevails. It is impossible to predict anomalous aquifer conditions as encountered at D-13; the limestone is so heterogeneous that occasional failures are expectable.

Figure 15 shows changes in chloride concentrations with time for the M series wells, all of which are basal, although MX-9, now an observation well, encountered para-basal water in the vicinity of Barrigada Hill (figure 7). All of the M series, with the exception of M-11, now contain less the 150 mg/l chloride, though M-1 reached a peak of 180 mg/l in 1972. Like D-13, well M-11 is an anomaly, yielding water with more than 650 mg/l chloride. Its bottom elevation is -60 feet, deeper than desirable, and in the near vicinity the vertical permeability probably exceeds the horizontal. This well, and D-13 also, should be disconnected from the water system, just as was A-16.

Chloride concentrations for wells H-1, AG-1, F-1, Tl-1 and Ml-1 are shown on figure 16. Basal water wells, H-1, F-1 and AG-1 are stable at a chloride content of less the 80 mg/l, and Tl-1 and Ml-1, both developing perched water in high level limestone lenses, show 30 mg/l or less chloride.

Anomalously high chloride concentrations in basal water wells result not only from heterogeneities in directional permeabilities of the limestone aquifers but also from improper well depths and well construction, and from pumping rates. The record of restricting well depths where feasible to a bottom elevation of -25 feet as originally specified has been rather erratic over the past several years. The importance of well depth in a thin Ghyben-Herzberg lens, the case in Guam, cannot be over emphasized. Appendix A-7 discusses the limitations on well depth and pumping capacity for given heads in a basal lens. If sustainable yields are the object of development of the basal ground water of northern Guam, then strict controls must be placed on location, design, and construction of wells.

Silica (SiO_2)

In contrast to chloride, the source of which is the sea, silica in the natural waters is derived almost totally from the rocks of the island. Only a negligible quantity of silica accompanies rainfall or occurs in the open sea. About 50% of the volcanic rocks consist of silica. Clean limestones carry trace amounts as impurities, but argillaceous limestones may contain 10% or more in clayey sections.

Silica concentrations are reported as the SiO_2 radical, which, however, actually occurs as part of monomeric ortho silicic acid (H_4SiO_4) in solution, except when pH is greater than 9, a condition not experienced on Guam. The range of solubility of silica in ordinary natural waters at normal temperature and pressure falls between 6 mg/l, the equilibrium concentration in the presence of quartz, and about 120 mg/l, the equilibrium concentration in the presence of amorphous silica. Typical ground water contains less than 50 mg/l silica.

Table 8 (Appendix B) gives the statistics of silica concentrations for ground and surface waters of Guam, and figure 18 is a bar graph of the data. The direct relationship between concentrations and aquifer rock type is clearly evident. Ground water from the cleanest limestone contains less than 1 mg/l SiO_2 (D series) while that from argillaceous limestone (A series) has an average median concentration of 8.4 mg/l and a maximum median of 17 mg/l at well A-11, the well lying closest to the volcanic highlands along the Adelup-Pago demarcation. The M and Y series yield water containing less than 2 mg/l SiO_2. The argillaceous nature of the Maemong limestone encountered by wells Ml-1 and Tl-1 is reflected in ground water silica concentrations of 17 and 14 mg/l, respectively. At these wells some of the SiO_2 is also probably derived from the volcanic rocks in which the limestone lenses are encased. Asan Spring, containing about 9 mg/l SiO_2, drains a mass of somewhat argillaceous Alifan limestone.

Streams draining volcanic rocks reflect basin lithology by their high silica concentrations. Normal stream runoff carries 20 mg/l or more SiO_2. Ground water in the volcanics appears to contain unusually high concentrations of silica, though only two unambiguous analyses could be found. The concentration at the Guam Oil Refinery well, drilled into the Alutom formation, is reported as 92 mg/l and at Mataguac Spring, also in the Alutom, as 71 mg/l.

Silica concentrations may serve as an excellent indicator of the lithology of the aquifer in which the ground water moves. In the limestones concentrations increase with increasing clay content. In all cases ground water in volcanic rocks carry considerably more SiO_2 than in limestones.

Calcium (Ca), Magnesium (Mg), and Hardness

Along with chloride, calcium and to a minor extent magnesium affects the usability of natural waters on Guam, particularly ground water. High chloride concentration affects taste, making water unpalatable, but calcium and magnesium are responsible for hardness, a characteristic which affects industrial and household uses. In the absence of sea water intrusion, calcium and magnesium are derived chiefly from the solution of limestones, both in the monolithologic limestone plateau of the north and in the volcanic formations of the south, in which much marine calcareous material is intercalated. Sea water intrusion into basal water also adds much calcium and magnesium (see figure 19). Rainfall and salt spray contribute these ions but in amounts that are negligible in comparison with those derived from rock solution and sea water encroachment. Hardness, the measure of calcium and magnesium in solution, is notably greater in limestone waters than in volcanic rock waters.

Limestone is composed of calcium carbonate with varying but small amounts of magnesium carbonate, the whole of which originally crystallizes as aragonite, then on aging recrystallizes to calcite. If substantial magnesium either occurs in the original rock or becomes available from an outside source, dolomitization may take place, but this has not yet occurred on Guam (Schlanger, 1964). Calcium is forced into solution by the action of dissolved carbon dioxide (CO_2), which in combination with water forms a weak acid (carbonic), H_2CO_3. The higher the dissolved concentration of carbon dioxide, the lower the pH and the greater the solution of calcium.

Rainfall has a pH of about 5.8 to 6.7, but in infiltrating the soil complex where much CO_2 is produced from the decomposition of organic matter and from plant root respiration the rain water is acidified to a pH of 4 to 6, a solution highly corrosive to limestone. The reactions in their simplest forms are:

$$H_2O + CO_2 = H_2CO_3$$

$$CaCO_3 + H_2CO_3 = Ca^{2+} + 2HCO_3^-$$

These reactions leave a residue predominantly composed of insoluble iron and aluminum oxides and hydroxides, which form the red to yellow bauxitic soils overlying the northern plateau.

As the carbonate rock dissolves, continuous changes take place in the aqueous phase. The pH increases until finally the water is non-reactive. In the saturated zone of the limestone aquifers the pH is 7.0 to 7.8. Although most of the reactivity occurs in the soil complex and in the limestone column just below it, often enough CO_2 remains in solution until the infiltrate reaches the ground water, causing solution of limestone at the water table and thus enhancing permeability there. Once the infiltrate becomes part of the slow moving ground water body it quickly becomes inert. Sometimes the equilibrium of the infiltrate responds to the loss of CO_2 by forcing the deposition of calcite, resulting in recrystallization and cementing, processes which decrease permeability.

Table 8 (Appendix B) and figure 20 summarize the statistics of calcium, magnesium and hardness concentrations for the natural waters of Guam. Where the accompanying chloride concentrations are less than about 30 mg/l, all of the concentrations are from non-seawater intrusion sources and, in effect, practically totally from rock dissolution. Where intrusion occurs every 50 mg/l chloride adds 3.35 mg/l magnesium (14 mg/l hardness) and 1.0 mg/l calcium (2.6 mg/l hardness), for a total hardness of 16.6 mg/l (see figure 19). Thus sea water intrusion degrades the quality of ground water not only by salinizing it with chloride but also by increasing its hardness.

From figure 20 it is clear that ground water in limestone aquifers is much harder than waters draining from volcanic rocks by a factor of two to three. Further, the water in the argillaceous limestones is considerably harder than that in the clean limestones (average median of 293 mg/l in the A series versus 226 mg/l in the D series). Other argillaceous limestones (M1-1, T1-1) show the same higher hardness.

The exceptional high hardness of the waters in the argillaceous limestones apparently results from the greater biological activity in the soil complex overlying these limestones and perhaps from the chemical equilibria in which clay is one of the components in addition to CO_2, H_2O, and $CaCO_3$. Soils over the argillaceous limestones are the thickest and most fertile in the north (U. S. Corps of Engineers, Engineering Intelligence Study n. 257, 1958), producing greater organic growth and decay, prime sources of CO_2. Even the geomorphology of the argillaceous limestone region between the Adelup-Pago demarcation and Barrigada reflects the high solubility of these limestones. The region has a pronounced karstic surface, the most highly developed on the island.

Calcium and hardness are additional indicators of the lithologic type of aquifers in which natural waters occur, the other indicator so far identified being silica. In particular, high concentration of calcium (hardness) and silica imply an aquifer consisting of argillaceous limestone.

Nitrate (NO_3)

Practically all of the nitrogen found in the natural waters of Guam originates in the biosphere. Only a minute amount, much less than 0.1 mg/l to NO_3, falls with the rain, and no more than a trace amount could be expected to derive from the rocks of the island except in those unusual cases, rare or absent in Guam, where fossil biogenic matter, such as guano, were to occur. Sea water intrusion would add negligible amounts to basal water. Because nitrogen originates in the biosphere it can serve as an excellent indicator of pollution if its natural background concentration in ground and surface waters is known.

In the normal oxidizing atmosphere of the soil and rock complex nitrogen converts (nitrifies) to nitrate, NO_3, a stable radical that resists further reactions except under highly reducing conditions, which are uncommon and spatially insignificant in Guam. Little absorption of NO_3 occurs so that essentially all of it which escapes beyond the root zone on the vegetative mantle eventually finds its way to the ground and surface waters.

The natural nitrogen cycle is illustrated in figure 21. The sources of nitrogen are rainfall, a small contributor; organic products, such as plant residue; and legumes, which fix nitrogen from the atmosphere. Ordinarily the nitrate concentration of natural waters is in equilibrium with the growth and decay cycle of biological matter such that the background nitrate content of ground water is about 1.0 mg/l or less, which is typical of the volcanic aquifers of southern Guam.

Figure 21 also illustrates the nitrogen cycle induced by agriculture and urbanization. The nitrogen from organic wastes nitrifies to NO_3, some of which trickles to ground water or to streams, as does the fertilizer nitrate which infiltrates beyond the root zone. If the organic waste load is too heavy for normal aerobic processes in the soil mantle, anaerobic conditions may set in to denitrify nitrogenous decomposition products to gaseous nitrogen, which may then escape to the atmosphere. At present this is a rare occurrence on Guam.

Table 8 (Appendix B) and figure 22 summarize the statistics of background nitrate concentrations in the natural waters of Guam. In waters draining volcanic terraces the background content is quite low, 0.1 to 0.7 mg/l, values characteristic of most natural waters elsewhere. These values reflect a steady state equilibrium among rainfall input, plant growth and plant decay. In the limestone aquifers of the north, however, the background concentration of NO_3 is unusually high, in the neighborhood of 9 mg/l, far greater than normally encountered in all but the most unusual ground waters.

This high background suggests that a source or sources other than rainfall and the steady state growth-decay cycle of plants is contributing nitrate to the hydrologic cycle. The lower background nitrate (3 to 4 mg/l) in the encased limestone lens of southern Guam at Malojloj and Talofofo further suggests that the high concentration in the north has something to do with surface phenomena.

Because nitrate is an indicator of pollution, its high background concentration in the limestone aquifers of northern Guam must be rationalized. Each possible source of nitrogen and the magnitude of its contribution to the ground water may be evaluated as follows:

1. Rainfall -- rain water carries a very small concentration of nitrogen which would not lead to enrichment of nitrate in the ground and surface waters.

2. Organic decay in the natural growth cycle -- where a stable vegetation cover has formed a steady state cycle occurs in which the nitrate produced from organic decay is used in new plant growth. Disruption of the cycle could cause enrichment of NO_3 in the ground water but no evidence of large scale vegetation instability appears in the north.

3. Fertilizer -- nitrogen is the most common component of fertilizer but no large scale use of fertilizer occurs on the island. The fertilizer nitrate which does escape beyond the root zone is so diluted by rainfall infiltration that it hardly affects the composition of the natural waters. In the southern part of the island of Oahu, Hawaii, about 20,000 acres of irrigated sugar cane lands have

been fertilized with 300 lbs. of nitrogen per acre per year for over 60 years, resulting in an equilibrium concentration of approximately 10 mg/l nitrate in the ground water, but on Guam such high rates of application over a sizeable area have never been attempted for an extended period. Because the ground water fluxes per unit area are similar for southern Oahu and northern Guam, it may be inferred that the high background concentration of NO_3 in the limestone ground water is not caused by the leaching of fertilizers.

4. Waste water -- most municipal waste water contains about 125 mg/l nitrate but in northern Guam only a small fraction of the total waste water load is discharged on to the land. Even if the total daily water production of 16 mgd were converted to waste water and allowed to infiltrate, with the added condition that complete mixing with the fresh water of the lens occurred, the resulting nitrate concentration of the mixture would be 9.4 mg/l, derived as follows:

Q_R = rainfall = 200 mgd

C_R = nitrate concentration in rain = 0.1 mg/l

Q_S = waste water = 16 mgd

C_S = nitrate concentration in waste water = 125 mg/l

C_W = nitrate concentration in mixture

$$C_W = \frac{C_R\ Q_R + C_S\ Q_S}{Q_R + Q_S} = 9.4 \text{ mg/l}$$

The value of C_W as computed above is a gross exaggeration because much less than 16 mgd of waste water infiltrates. A more reasonable, but still overstated, daily volume of waste water disposed on the ground would be about 2 mgd, which would result in a ground water mixture containing 1.7 mg/l nitrate. Very likely a portion of the background nitrate content in the aquifers of the north originates from waste water, probably on the order of 1 mg/l, leaving the origin of the remaining 8 mg/l to other sources.

5. Nitrate as part of the composition of the rocks -- Guano or other fossil biogenic matter incorporated in the limestone sediments would yield nitrate to the ground water but such deposits have not been reported except for a localized phosphatic layer noted by Schlanger (1964) near the north coast of the island.

6. Legumes -- up to 400 lbs. of nitrogen (1680 lbs. of nitrate) per acre per year may be fixed by legumes although the average is less than 200 lbs. N (840 lbs. NO_3). The fraction of this nitrogen not consumed by plants eventually drains to the ground water. A common, well known tropical legume which is restricted to the limestone terraces of the island is tangan-tangan (Leucaena glauca), a shrub resembling a small tree. Other legumes nay also be common.

Tangan-tangan, though not endemic to Guam, has grown on the island for a very long time and has become widespread since the war because it quickly fills cleared areas. It will not grow on volcanic soils but thrives on the limestones. As long ago as the middle of the last century Don Felipe De La Cortes (Memoirs) reported that "Tangan-tangan (Leucaena glauca) or Palma Cristi, is found everywhere." The plant is a native of tropical America and probably arrived in Guam by way of the galleons which sailed between Acapulco and Manila in the years 1521 to 1815.

In 1937 an attempt was made to plant tangan-tangan on the volcanic watershed of Fonte Dam (Guam Recorder, July 1940) but the effort failed. Following the destruction of the war similar attempts were made to revegetate the volcanic lands of southern Guam, which also failed, and the limestones of northern Guam, which succeeded. Tangan-tangan is now the most common plant in limestone areas where the original forests have been destroyed.

Tangan-tangan, and other legumes, could be the source of the high nitrate content in ground water of the limestone aquifers. If 200 lbs. of N per acre per year were produced by tangan-tangan, none of which was consumed in plant growth, the ground water would have a concentration of 90 mg/l NO_3. If only 20 lbs. of legume nitrogen per acre per year trickled beyond the root zone, the ground water would carry 9 mg/l NO_3. Because little is known about the areal distribution of legumes in northern Guam or their rate of nitrogen fixation, a categorical statement cannot be made about the actual quantity of nitrogen they add to the natural waters, but there is a strong suggestion that legumes are the major contributor to the nitrate content of the limestone waters.

Temperature of the ground water

The temperature of ground water, in the absence of anomalous heat sources, closely reflects the average annual air temperature over the land surface where recharge originated (Mink, 1964). Surface runoff, on the other hand, is affected by daily solar radiation and its temperature is therefore highly variable.

Few ground water temperatures are reported for Guam, probably because expected variations are small. The best set of data is given in Feltz, et al (1969) and is summarized in table 3 below, along with a few measurements made by Emery (1962).

Table 3

Ground water temperatures in northern Guam

Source	°C	°F	Reference and remarks
Tarague cave	26.3	79.3	Feltz, et al (1969).
Tarague cave	26.1	79.0	Emery (1962).
Well 110	27.5	81.5	Feltz, et al (1969). Water probably static.
Well 85	26.2	79.2	Feltz, et al (1969).
Well 157	27.0	80.6	Feltz, et al (1969).
Well 84	27.0	80.6	Feltz, et al (1969).
Tumon Maui	29.0	84.2	Feltz, et al (1969). Water probably static.
Gognga Beach	26.0	78.8	Emery (1962). Down gradient from Tumon.
Gognga Beach	26.3	79.4	Emery (1962). Down gradient from Tumon.
Well D-4	27.0	80.6	Feltz, et al (1969).
Well 112	27.5	81.5	Feltz, et al (1969). Water probably static.

The above temperatures correspond to the average annual atmospheric temperature of about 80°F in the intake areas. Lower temperatures imply that the principal recharge takes place at somewhat higher elevations. Temperatures greater than 80°F suggest that the ground water at the sampling site is relatively static and is not being flushed away with the normal ground water flux. The higher temperatures are restricted to well bores and the Tumon shaft.

The average annual atmospheric temperature at sea level is 80.9°F (Tracey, et al, 1964), and if temperature decreases with elevation according to the ambient atmospheric lapse rate of 3.3°F per 1000 ft., the coolest recharge water in northern Guam should be about 78°F. To date no evidence of anomalous geothermal heating of ground water in the limestone aquifers has appeared.

Pollution -- waste and storm water disposal

The degradation of the quality of the natural waters of Guam by polluting recharge waters is a matter of constant concern, especially with regard to the ground water in the limestone aquifers of the northern plateau. The principal potential polluting recharge sources would be sewage waste water and, to a lesser degree, urban storm runoff. Other possible pollutants would result from agricultural activities, in which infiltrate containing dissolved fertilizers, pesticides and herbicides would reach the ground water, and from industrial activities, including transportation. At present infiltration from neither agriculture nor industrial practices are voluminous enough to measurably affect the quality of the ground water.

The danger of pollution could be eliminated by diverting all the waste water and urban storm runoff to ocean outfalls, but the consequence would be to disrupt the terrestrial hydrologic cycle to the ultimate detriment of the quantity and quality of fresh ground water which could be produced from the limestone aquifers. The integrity of the basal lens and the para-basal ground water of northern Guam depends on reliable recharge, which would be diminished if the pumped water, which eventually becomes waste water, and storm runoff were removed as recharge components in the hydrologic cycle.

Waste and storm waters could be retained as recharge by spreading them on the land or directing them to injection pits and bore holes. However, in the case of waste water relatively large quantities of some undesirable inorganic constituents, for example NO_3, would reach the ground water to degrade its quality, and in uncontrolled instances organic contaminants, such as bacteria and oxygen demand, would trickle to the saturated zone. Because urban storm runoff is not highly charged with contaminants, its effect on the ground water would be far less than that of waste water.

Waste water could be used in irrigation under controlled conditions without seriously affecting the ground water but this option does not appear to be feasible at this time. Consequently because waste water does pose a contaminating hazard it should be discarded in ocean outfalls except where local hydrogeologic conditions would permit its disposal into the earth. Urban storm runoff, on the other hand, carries a light contaminant load and should be retained within the hydrologic cycle to protect storage and flux in the basal lens.

The lagoonal sediments covering most of the interior of the northern plateau are probably an effective filter of organic wastes, including bacteria. If all urban storm runoff were allowed to infiltrate in properly constructed pits and intake areas, negligible pollution of the basal lens would ensue. Currently most storm runoff is allowed to infiltrate, more as an engineering convenience, however, than as a planned effort to preserve the recharge element of the hydrologic cycle. Injection wells would be less effective than surface spreading in preventing contamination, but they could be designed to minimize potential pollution.

The goal of retaining urban storm runoff for recharge is to maintain the size and quality of the basal lens under development stress. To achieve this goal, the runoff need not be recharged in the interior of the island if the threat of pollution is real. The water could be directed to a 2000 to 3000 ft. wide zone along the coast and either spread on the surface or injected into the limestone via dry wells. Normally in this zone fresh potable ground water cannot be developed because the transition zone of the basal lens extends to the water table. The introduction of storm runoff would have the effect of increasing local head, thereby reducing the landward gradient and velocity of the ground water and enabling fresh ground water storage to build up further inland. This method of protecting the basal lens is successfully used along the coast of southern California.

Surface disposal of urban storm runoff

Disposal of storm runoff by directing it to receiving grounds covered by a permeable mantle and underlain by permeable and porous formations is a traditional and often successful method of recharging ground water aquifers. Surface spreading enhances the quality of the water before it undergoes deep percolation.

Receiving grounds for runoff may consist of the natural soil and vegetative mantle or constructed surfaces such as pits and furrows which are either raw or lined with gravel. Not all soils are efficient acceptors but those of northern Guam normally have high infiltration rates. The utility of soil as an acceptor depends on its sustainable rate of infiltration, which is determined by numerous variables often in delicate equilibrium. Texture, particle size and arrangement, and structure define the initial hydraulic conductivity and porosity of a soil; the physical stability and chemistry determine how these parameters react to and affect an effluent load. The composition of the effluent may initiate chemical and physical changes in the soil and affect its ecology.

Under natural conditions coarse texture soils pass up to 10 ft. of water per day, medium texture 4 ft., and fine texture 1 ft. Clays, however, pass only .02 to 0.2 ft. per day, and silty loams less than 1 ft. per day. In northern Guam infiltration rates probably exceed 1 to 5 ft. per day except where fine silt and mud have settled.

Infiltration rates usually decrease with time of application, although induced biological activity in some cases may improve hydraulic conductivity. To regain high infiltration rates it is necessary to rest the receiving soil periodically and to improve its physical character by drying and mechanical working.

A great many laboratory tests and field trials have been conducted to determine the efficacy of soils and related covers in eliminating pollutants and contaminants from waste water. As a general statement, coliform and other organisms disappear quickly and BOD (biochemical oxygen demand) is satisfied. A sizeable portion of the nitrogen compounds, usually half or more, is removed, and practically all of the phosphorus becomes fixed in iron compounds in the soil. On the other hand most non-plant nutrients, heavy metals, organic salts and ABS (basic detergent compound) are largely unaffected by percolation.

The subsurface formations beneath spreading basins should have a high enough hydraulic conductivity to allow rapid flow laterally. The hydraulic conductivity of the limestones of northern Guam is so great that significant ground water mounds will not form below the area of recharge.

Injection wells and pits for the disposal of urban storm runoff

Throughout the world injection wells are used for a variety of purposes such as the recharge of aquifers with surface water the creation of fresh water barriers against salt water intrusion, and the disposal of fluid wastes. Injection wells rely on either gravity or mechanical pumping to force flow into receiving formations. Gravity flow is obviously cheaper and therefore preferable and would be applicable through northern Guam.

Under ideal aquifer conditions and absolute knowledge of aquifer parameters, injection wells could be designed to guarantee continuous disposal of predetermined volumes of effluent. In an ideal aquifer, one that is isotropic and homogeneous with precisely defined boundaries and for which hydraulic conductivity and porosity are known, the disposition of effluent, identical to the ambient aquifer fluid, could be predicted in time and space by utilizing the equations of flow in porous media (see Appendix A-6 for a mathematical treatment of injection). However, the natural environment may approach but never conforms to the ideal model and therefore the equations of flow are only approximations to real conditions.

Among the critical factors which affect recharge rates are air entrainment in the disposal water, chemical reactions between the effluent, aquifer matrix and ambient aquifer water, rearrangement of loose aquifer material, impaction of debris on the well face, and, in the aquifer, the settling of suspended matter from the effluent and microbial growth near the well bore. The magnitude of each of these factors is variable, time dependent and unpredictable, but in general all injection wells exhibit a decrease in recharge rate with time. The dry drainage wells at Andersen Air Force Base seem to have been unusually successful, however (Feltz, et al 1969).

The construction features of a well which governs injection rates include bore diameter and extent of open or screened hole. In the heterogeneous limestones of Guam, enlarging the surface area of the well face and deepening the open bore enhances the probability of uncovering strata with favorable components of permeability such as fractures, solution channels, and intrinsic structural openings. A well may be a failure if 20 feet in depth but a great success if 21 feet deep.

Appendix A-6 discusses in detail the hydraulics of injection wells in a Ghyben-Herzberg lens. The discussion relates particularly to flow rate and direction of injected water and to its appearance at the sea coast. It is important to recognize that after the initial injected effluent mixes with aquifer water, the volume following travels as a slug toward the coast to discharge there into the sea.

In the appendix a formula is derived for the seepage rate of effluent per unit area at the shore line. This formula, equation 14 of appendix A-6, is:

$$Q/A = 2ak$$

in which Q/A is seepage rate per unit area, a is the density difference between sea and fresh waters divided by the density of fresh water, and k is hydraulic conductivity. For the typical shore line condition of northern Guam, the seepage rate is approximately 0.5 gpm/ft^2.

Summary of water disposal and pollution

Most of the municipal and industrial waste water as a practical matter will have to be discharged to the sea by means of ocean outfalls and will be lost to the hydrologic cycle, but urban storm runoff should be retained as a recharge component in the cycle. Surface spreading could be successfully practiced on the lagoonal sediments in the interior of the island, but if this option is impractical, the storm water could be diverted to recharge pits, dry wells and surface catchments above the brackish water sector of the basal lens within 2000 to 3000 feet of the coast.

Hydrologic Budget

In a finite island environment such as Guam, where the fresh water resources are absolutely limited, estimates of the storage volumes of aquifers and of the flow rates of the components of the hydrologic cycle are necessary to predict the quantity of fresh water which could be produced on a sustainable basis. Estimates of flow are derived by computing a balance sheet, called the hydrologic budget, for the water from the moment is falls as rain to the time it drains from the surface or the subsurface to the sea or is returned to the atmosphere.

The natural water budget in its simplest form is computed by an input-output analysis of flows based on the equation:

$$P = ET + DRO + GW$$

in which P is rainfall, ET is evapo-transpiration, DRO is direct surface runoff, and GW is ground water flow. If P and DRO are known, as often is the case because they are relatively easily measured, then by estimating ET, the GW component of the cycle can be determined. In northern Guam, DRO is very small to negligible, P is measured, and ET may be estimated from records of pan evaporation. If many pumping tests were conducted over the whole of the limestone plateau for the range of aquifer heterogeneities, aquifer parameters might be determined from which GW could be deduced, but test data is scarce and hardly reflects regional aquifer characteristics. Therefore the only obvious approximate solution of the budget equation is that in which ET is estimated from the limited pan evaporation data available and GW is solved for.

A second approximation of the water balance for northern Guam may be computed from an evaluation of the surface runoff in the south where numerous stream gaging stations have provided daily records of flow for as long as 20 years. The surface runoff from the volcanic lands of southern Guam include both DRO and GW, and thus if rainfall were known the true ET could be calculated. Because climatic conditions in the north and south are about the same, the calculated ET for the south could be applied to the north and the budget equation could be solved for GW. This technique was suggested by Ward, et al (1966) and employed by Austin, Smith Associates (1968).

In the following analyses the water balance for northern Guam is calculated by both methods. The one in which ET is estimated from pan data gives conservative values of ground water flow; the one derived from the analysis of stream flow in southern Guam yields the more probable balance.

Rainfall

The meteorological feature most obviously related to ground and surface water resources is rainfall. Ground water in the great limestone aquifers of the north is sustained by rain which frequently falls at intensities high enough to cause infiltration beyond the soil zone. In the volcanic lands of the south base flow of the streams also is sustained by rainfall infiltration while flash flows are caused by direct overland runoff during intense rains.

The island of Guam falls within a single climatological region for which rainfall shows a characteristic seasonal distribution. The spatial distribution of rainfall is slightly influenced by terrain features, but on the average no location receives more that 110 inches per year nor any less than 85 inches per year. More than half the annual rainfall occurs in a four month wet season from mid-July through mid-November. Only about 15% - 20% occurs in the 4 month dry season, January to April. The transient seasons, in which the remaining 30% to 35% of the rain falls, includes the periods May through mid-July and mid-November through December.

The normal rainfall of the dry season is less than 4 in/mos while for the wet months it is greater than 10 inches. Tradewinds, blowing from the northeast off the sub-tropical high pressure area of the western Pacific, occur throughout the year and are accompanied by convective and orographic showers. In the summer and fall months the trades are frequently interrupted by westerly moving storms which often bring intense rain. Some of these storms become typhoons.

The average monthly and yearly rainfalls for several long term stations in northern Guam are given in Table 1, Appendix B. The highest average rainfall at a recording site is found at the U.S. Weather Bureau Station at Taguac on the western side of the island where the annual average is just over 100 inches. At Andersen Air Force Base on the eastern side of the island the annual average is very nearly 90 inches, at the Naval Station in the mid-section of the island it is just under 86 inches, while at Sumay it is about 88 inches. In the south the USGS records show annual means of 94 inches at Ylig and 95 inches at Umatac.

The statistical parameters included in table 1 are means, standard deviations, medians, maximums and minimums for each month and on an annual basis. The close correspondence of the annual mean and median of each station indicates that the annual rainfall follows a normal distribution pattern. The annual mean and the median of each of the four stations differ by no more than 5%; in the perfect normal distribrution the mean and the median are identical.

In the normal distribution, 95% of all values are bounded as follows (let $\overline{P}$ = average rainfall, s = standard deviation):

$\overline{P} + 1.96s$

$\overline{P} - 1.96s$

For example, at Andersen Air Force Base the probability of rainfall being less than 58 in/yr is .025, and of it being greater than 122 in/yr is also .025. Perhaps even more meaningful is the statistic that 99.9% of a all values fall between -3s and +3s, and thus the probability is only one out of a thousand that annual rainfall at the four northern stations would be less than the following

Station	Probability .001	Recorded Minimum
Andersen Air Force Base	41.14 in/yr	62.42 in/yr
Naval Air Station	50.10	64.85
Weather Bureau	55.42	74.46
Sumay	47.62	59.68

The statistics show the improbability of even experiencing a year with less than half the average annual rainfall; in fact, the probability of such an event is vanishingly small. If such an event, the thousand year drought, were to occur, the probability of it being repeated the following year would be one in a million. This statistical exercise has been discussed to put to rest the sometimes expressed fear that Guam could well suffer a disastrous drought which would last for years.

Evaporation and evapotranspiration

Another meteorological feature profoundly influencing the occurrence and volume of fresh water resources is evapotranspiration, which is the combined measure of the water vapor returned to the atmosphere as evaporation from free surfaces and from the transpiration of plants. In the tropics, where the growing season is continuous throughout the year, if free moisture is constantly available to plants, evapotranspiration is approximately equal to evaporation from a free surface. Evapotranspiration, when moisture is constantly available, is called potential evapotranspiration. Thus the standard measurements of pan evaporation commonly collected at weather stations, universities and agricultural stations provide a good estimation of the potential return of moisture to the atmosphere by plant communities. However, for the 1:1 ratio to apply, a continuous replenishment of water to the plants is necessary. For potential evapotranspiration to occur without interruption in the tropics, a minimum rainfall of 5 to 6 inches per month is required

The approximate equivalence of pan evaporation with potential evapotranspiration for tropical conditions has been established by work in Hawaii on consumptive water use by grasses and sugar cane. A paper by Chang, et al (1963) summarized results of extensive experiments which showed that evaporation from a U. S. Weather

Bureau Class A pan is approximately equivalent to potential evapotranspiration from a mature crop of sugar cane. It is not unreasonable to assume that the 1:1 pan to potential evapotranspiration ratio is also applicable to other tropical vegetation under full free moisture sufficiency. If such is the case, then in the absence of surface runoff the difference between rainfall and evaporation, when rainfall is greater than evaporation, will infiltrate beyond the plant root level. The amount of infiltration calculated in this fashion is a conservative estimate of the true quantity because unusual through-flow during intense rainfall may be lost in averaging.

Measurements of pan evaporation at the USWB Station at Taguac in northern Guam were started in 1958, and a short record for the period 1954 through 1957 is available for a pan at Fena Dam. The Taguac data is more representative of northern Guam and will be used in budget computations. Table 2 (appendix B) summarizes the monthly evaporation and rainfall averages at Taguac for nearly equivalent periods of record (1958 - 1972 for evaporation; 1956 - 1972 for rainfall).

It is evident from the table that on an annual basis rainfall exceeds evaporation by a substantial amount and that the entire excess accrues during the wet season months of July, August, September and October, and to a lesser extent the transitional months of November and December. In January rainfall and evaporation are about equal, but for the remaining months of February, March, April, May and June evaporation exceeds rainfall. At Taguac the average annual rain in excess of evaporation amounts to 37.67 inches.

Although no pan data is available for the other standard rain stations in northern Guam at Andersen Air Force Base and the Naval Air Station, the probable monthly evaporation averages can be estimated by assuming that rainfall and evaporation are inversely related, a relationship shown to occur in the wet regions of Hawaii. Using the inverse relationship, evaporation (and therefore evapotranspiration) for Andersen Air Force Base and the Naval Air Station can be obtained from the following expression:

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

where the subscript i refers either to Andersen or the NAS. Table 2 (appendix B) lists the derived monthly evapotranspiration values along with the average monthly rainfalls. Annual rain in excess of evapotranspiration at Andersen is computed as 27.69 inches, and at NAS as 25.62 inches.

The relationship between rainfall and evapotranspiration has been discussed in some detail because it provides an approach, discussed later, to determine the quantity of infiltration to the aquifers of northern Guam.

Hydrologic budget for northern Guam

Practically all of northern Guam is underlain by a heterogeneous, anisotropic limestone aquifer which is essentially continuous from the Adelup-Pago demarcation line to the north coast of the island. Throughout most of this half of the island the fresh water occurs as a basal lens, but near Adelup-Pago and in the north the volcanic basement rises above the theoretical lower limit of the lens, disrupting its continuity.

To simplify the water budget model, northern Guam is divided into 5 sectors for area computations and rainfall-evapotranspiration analysis (see map 3). In the most southerly area, labelled 1, which lies chiefly between Highway 4 and the Adelup-Pago line and has an ares of about 5 mi^2, the elevation of the volcanic basement is higher than the theoretical bottom of the basal lens and therefore fresh water does not physically float on salt water, although it is continuous with the water of the true basal lens of area 2 (see figure 3). In this area the limestones are very argillaceous.

Area 2 contains a basal lens in argillaceous limestone. In a small region in area 3, perhaps 1 to 2 square miles in extent near Mt. Barrigada, the volcanic basement rises above the theoretical lens bottom as determined from the log of test well MX-9. In area 4, which includes Dededo-Yigo, the emergence of Mataguac and Mt. Santa Rosa above the surrounding limestone plain reflects an area of about 15 mi^2 where the volcanic basement rises above sea level, and perhaps a total of 20 mi^2 where it rises above the theoretical lens bottom.

The total area north of the Adelup-Pago line covers 96 mi^2, of which about 70 mi^2 carries a true basal lens. However, practically all of the subsurface drainage, with a few marked exceptions such as in the vicinity of Janum Spring, finds its way to the basal lens before discharging to the sea, which means that the entire limestone plateau is the intake area for recharge to the basal lens. Nevertheless, in calculating sustainable yields, flows through area 1 are treated separately and those of area 5 are arbitrarily left out because this area falls almost entirely within the Andersen Air Force Base Complex and is thus not available for exploitation. Obviously the separation of the areas 4 and 5 is an artificial boundary condition, which results in a calculation of developable groundwater that is somewhat conservative.

Two different approaches to the construction of the water budget of northern Guam have been attempted. The first, called the minimum groundwater budget, utilizes the recorded rainfalls at Taguac, Andersen Air Force Base and the Naval Air Station, the recorded pan evaporation at Taguac and the computed evaporation at Andersen and the NAS, and then solves for the groundwater component. The second, called the probable groundwater budget, utilizes surface water and rainfall records of southern Guam to compute evapotranspiration, which is then applied to the north to derive groundwater flow.

Minimum Groundwater Budget

Table 2 (appendix B) shows the differences between monthly rainfall and pan evaporation for northern Guam when rainfall is greater than evaporation. The assumption that evapotranspiration is equal to pan evaporation yields a minimum value for infiltration below the root zone when infiltration is equated with surplus rain. The meteorological parameters for the Naval Air Station are used to compute the water budget for areas 1, 2 and 3, and those of the Station with the USWB at Taguac for area 4. For area 5 the Andersen Air Force Base values are used. Two minimum budgets have been computed, one assuming no direct overland flow to the sea, and the other a 5% loss of rainfall as surface runoff.

Table 3 (appendix B) summarizes the computations for the minimum ground water budget cases. In addition to infiltration values, computations were made for flux per unit width of coastline (q) and hydraulic conductivity (k) by employing the basic parabolic flow equation for a Ghyben-Herzberg lens (see appendix 2):

$$q = \frac{41\ k\ h^2}{2x}$$

where x is the distance inland for a given head, h.

For the minimum ground water budget, a simple summary of infiltration as abstracted from table 3 (appendix B) is as follows:

Area no.	Area mi^2	I_1 (mgd) Infiltration, no runoff	I_2 (mgd) Infiltration, 5% runoff	Remarks
1	5.2	6.3	5.3	$I_1 = 1.22\ mgd/mi^2$; $I_2 = 1.02\ mgd/mi^2$
2,3	26.4	32.2	26.9	I_1 same as above; exclude Ypao Peninsula from area
4	38.3	57.8	49.4	$I_1 = 1.51\ mgd/mi^2$; $I_2 = 1.29\ mgd/mi^2$
Total 2,3,4	64.7	90.0	76.3	
5	24.8	32.8	27.6	$I_1 = 1.32\ mgd/mi^2$; $I_2 = 1.11\ mgd/mi^2$
Grand Total	94.7	129	109	

The above table indicates that the minimum recharge to the ground water system of northern Guam is greater that 100 mgd; it cannot be less than this unless there is more than 5% direct runoff to the sea. Most investigators, including the geological team of the U.S. Geological Survey (Tracey, et al, 1964) who made the detailed study of the geology of the island, have stated that there is essentially no direct runoff to the sea from the limestones of the north.

Of most direct interest to PUAG is the flux of basal water in areas 2, 3, 4 which amounts to at least 76 mgd, and the 5 mgd passing through area 1. However, it should be clearly understood that only a portion of the infiltration could be safely exploited. The sustainable yield of the basal lens, which is analyzed in appendix 8, lies between 35% and 40% of the infiltration.

Probable ground water budget

The hydrologic budget calculations which more nearly reflect the actual distribution of the rainwater among the output components are based on an evaluation of total runoff from streams draining the volcanic topography of southern Guam. Total stream flow includes direct runoff plus ground water seepage from volcanic formations.

The climatology of southern and northern Guam is similar and the true evapotranspiration values which are determined for the south as the difference between rainfall and stream flow can be applied to the budget equation for the north.

Table 4 (appendix B) outlines the relevant calculations for establishing the budget components. The average rainfall for the south, based on the average rainfall at Ylig of 94.1 in/yr (1957 - 1970) and at Umatac of 95.3 in/yr (1957 - 1970), is 94.7 in/yr, equivalent to 4.51 mgd/mi^2. The average stream flow from the volcanic lithologic basins is 2.78 mgd/mi^2, which is 61.6% of the rainfall, leaving 36.37 inches of the annual rainfall as the evapotranspiration component. Assuming evapotranspiration and rainfall are inversely proportional (see section on Evapotranspiration), the true evapotranspiration for Taguac, Andersen Air Force, and Naval Air Station would be 34.2 in/yr, 38.3 in/yr, and 40.1 in/yr, respectively. The equivalent infiltration rates, assuming no direct runoff, would be 3.17 mgd/mi^2, 2.46 mgd/mi^2, and 2.18 mgd/mi^2. Table 4 (appendix B) lists total infiltration based on the zero direct runoff case and the 5% direct runoff case as well as specific fluxes and hydraulic conductivities.

For the probable ground water budget, a simple summary of table 4 (appendix B) is as follows:

Area no.	Area mi^2	I_1 (mgd) Infiltration, no runoff	I_2 (mgd) Infiltration, 5% runoff	Remarks
1	5.2	11.4	10.3	I_1 = 2.18 mgd/mi^2; I_2 = 1.98 mgd/mi^2
2.3	26.4	57.6	52.3	I_1 same as above. Exclude Ypao Peninsula
4	38.3	102.6	94.2	I_1 = 2.68 mgd/mi^2; I_2 = 2.46 mgd/mi^2
Total 2,3,4	64.7	160.2	146.4	
5	24.8	61.1	55.7	I_1 = 2.46 mgd/mi^2; I_2 = 2.24 mgd/mi^2
Grand Total	94.7	233	212	

The above states that the infiltration of the probable ground water budget exceeds that of the minimum ground water budget by about 100 mgd for the whole of northern Guam. For no direct runoff the minimum budget gives an average infiltration rate of 1.36 mgd/mi^2, while for the probable case it is 2.46 mgd/mi^2; assuming 5% runoff, the respective rates are 1.15 mgd/mi^2 and 2.24 mgd/mi^2.

Table 5 (appendix B) summarizes in matrix form the minimum and probable ground water budgets for northern Guam. The limits on infiltration to the basal lens as abstracted from the table are:

Area 2,3,4,5	Area 2,3,4
$104 \text{ mgd} < I < 221 \text{ mgd}$	$76 \text{ mgd} < I < 168 \text{ mgd}$
$1.12 < \text{mgd/mi}^2 < 2.68$	$1.18 < \text{mgd/mi}^2 < 2.65$

There can be little doubt that the range of infiltration values given above reflects the true magnitude of average recharge to the basal limestone aquifers. The probable ground water budget is the more likely to resemble actual conditions. The mid value of the range of infiltration rates is just about 2 mgd/mi^2, which corresponds to values of 1.9 to 2.3 mgd/mi^2 calculated by Dan Davis, U. S. Geological Survey (in Kennedy Engineers, 1964), and 2.67 mgd/mi^2, computed from data given in Austin, Smith Associates (1970). It should be evident that no precise value is determinable; however, most investigators who have addressed the problem of determining infiltration rates in northern Guam have suggested average values lying within 0.5 mgd/mi^2 of a central value of 2 mgd/mi^2.

Groundwater Development

Investigations of the hydrology of Guam over the past ten years in combination with the experience gained by PUAG and Singer-Layne, International, in developing the island's ground water show that without a doubt there exists a sufficiency of potable ground water in the limestones of central and northern Guam to satisfy demands of at least 50 mgd. The current total ground water production in the north is approximately 16 mgd, less than one third of the conservatively estimated sustainable yield. According to the Austin, Smith and Associates report of 1968 the civil sector water demand in the year 2020 will be 24.5 mgd. Even though this projection is low, it suggests that enough ground water is developable to handle needs considerably beyond the foreseeable future.

The key to the success of supplying potable ground water is intelligent development and management of the subsurface resources, whether they be the large basal water sources in the limestones of the northern half of the island or the smaller sources in the volcanic terrain of the south. The chief considerations in assuring sustainable yields are the proper location of wells and well fields, proper design, construction and outfitting of wells, and proper management of pumping stations. All of these considerations can readily be handled with current knowledge and experience.

The simplest, safest and most economical way to develop a water supply on Guam is by means of drilled wells. Wells can be drilled as the need for water arises and can be put on stream in a relatively short time. The supply from wells is essentially constant and not significantly affected by droughts. Initial capital outlays for wells and well fields are relatively small, an important consideration in view of the reality that the best interest rate in the bond market is already greater than 5 percent. In addition, should long range predictions of growth and demand either drastically increase or fail to materialize or be affected by technological change, the loss on investment for ground water developments would not be excessive. In summary, the major advantages of ground water development by means of wells are minimization of cost, both initial and over time; the maximization of flexibility in planning; and the maximization of reliability of supply.

From the time the first well was drilled in 1937 at Wettengel School, Barrigada, proving the existence of a clean fresh subsurface water supply, the ground water in the limestone aquifers of northern Guam has been exploited with varying degrees of intensity. The year 1937 was one of the most active with respect to drilling activity; 14 wells were bored of which 13 were successful. Between 1937 and the war the main efforts in increasing water supply were directed to transmitting spring water from the Almagosa complex to the military installations near Apra. At the same time, however, Stearns (1937) proposed that Maui wells, the Hawaiian name for infiltration galleries excavated as tunnels approximately at sea level, be used to develop 50 to 100 mgd of ground water in northern Guam. Specifically he recommended that a 300 ft. long tunnel be driven behind Agana Spring into which 50 ft. deep wells spaced 25 ft. apart would be drilled.

Undoubtedly such a construction would have been successful had it been carried out, providing that pumping rates were reasonable.

Upon recapture of Guam by American troops, many wells were drilled throughout the island in an attempt to solve the water supply problem. Experts were invited to Guam to assess the ground water resources and their potential developability. A team from Hawaii (P. Peterman, F. Ohrt, C.K. Wentworth) recommended Maui Shafts (infiltration galleries) because they had proven successful on the islands of Oahu and Maui, Hawaii, though at great cost compared to wells. Piper (1947) of the USGS, like Stearns and Peterman, et al, also recommended Maui Shafts, supplemented by small capacity wells (0.1 mgd, or 70 gpm) located 1000 ft. apart. Sundstrom (1948), also of the USGS, counted 80 wells in northern Guam in 1948, many of which were failures, and subsequently recommended infiltration tunnels and small wells as the best means of developing the ground water, up to a maximum of 20 mgd.

The first Maui well at Tumon (USGS no. 80) was driven at the base of the limestone scarp one half mile inland of the bay. The infiltration tunnel is 1000 ft. long and has an invert of -2.5 ft. Acceptable quality water was pumped and the station is still in use today, helping to supply Air Force requirements. A second Maui well was attempted at Tamuning (ACEORP, USGS no. 79) in 1947 but encountered brackish water and has been abandoned as a water supply point. The tunnel, unfortunately, was sited within the salinized tongue of ground water extending from Ypao Peninsula to Barrigada.

The failure of the ACEORP tunnel and the salinization of many wells discouraged additional groundwater development during the nineteen fifties and it wasn't until the early sixties that the Air Force drilled new wells and PUAG initiated a groundwater program. In the meantime the Navy handled their supply problem by building the Fena Reservoir. In the revitalized program of groundwater development, Maui wells were eliminated from consideration because of high initial cost and constraints on location.

Drilled Wells

The groundwater of Guam is now being developed chiefly by drilled wells, which when expertly located, designed and constructed are economically feasible, dependable producers of potable water. In the last 10 years PUAG has had drilled in the north 59 successful wells, most of which are producing groundwater for the public water system, and about 5 unsuccessful wells, some of which have been converted to observation wells. Also, the U.S. Air Force maintains 8 producing wells and Tumon Shaft, the U.S. Navy NCS maintains 4 wells, and private companies own 6 wells. In all, 77 wells and one shaft exploit the groundwater of the north.

In the limestones of the south, PUAG relies on successful wells at Malolo and Talofofo, and has drilled test wells at these locations and in Ylig valley. A private developer has drilled 10 small wells at Togcha for golf course irrigation. In the volcanic rocks PUAG failed to develop water in Merizo while the Guam Oil Refinery was unexpectedly successful and RCA at Pulantat managed to complete a nearly 400 ft. deep well yielding 20 gpm.

Tables 10, 11, 12, 13, 14 in Appendix B list available basic data on wells drilled over the last decade and on older wells which continue to be used. Table 10 gives the elevation and depth of each well with head at the completion of drilling, the steady pumping level of the water table during the initial tests, water table levels during pumping in 1972 and 1973, and chloride content at the time of drilling and in May of 1974. Table 11 summarizes drillers' logs for many PUAG wells. The descriptions appear to be monotonously similar for most limestone wells and not very indicative of meaningful hydrology except where volcanic basement is noted. Table 12 summarizes the effects of acidizing, that is, the cleansing and enlarging of the well bore with muriatic or other acids which dissolve limestone, on specific capacity in cases where unequivocal records of pump tests are on file. Ordinarily acidizing effectively increases local hydraulic conductivity and specific capacity except where the limestone is moderately to very argillaceous. Table 13 is a summary of relevant data of pumping tests conducted after each well was completed and acidized. From the data it is clearly evident that the specific capacities of argillaceous limestone wells are inferior to those in clean limestone. Table 14 is a summary of pump test analyses by Mink, who employed the standard Theis-Jacob-Hantush methods, and by Sheahan, who used the step-drawdown method. Most of the analyses were made of drawdowns and recoveries on pumping wells and are therefore error-prone because of the complicating effects of turbulent drawdown in the vicinity of the well bore. Also, the application of the step-drawdown method in a basal lens is questionable. Nevertheless, the hydraulic conductivities and transmissivities as computed are of the correct order of magnitude for local aquifer conditions.

In this report the PUAG wells are numbered by geographic location, the Air Force and NCS wells by numbers assigned to them by the appropriate Command, and private wells are designated by owner, Where applicable the USGS numbering system (Ward and Brookhardt, 1962) is also used. The most recent USGS coding system of water point sites is based on their location in one minute squares of latitude and longitude. The new system is fine for data processing but difficult to convert to easy field use. C. Huxel of the USGS has tabulated in a cross-reference format the various designations for each site.

The A series of PUAG wells, which started in the Agana region, extends from the Adelup-Pago contact northward to Barrigada but is restricted to descriptive areas 1 and 2. The M series extends from the Naval Communication Station in Barrigada to Dededo-Yigo. The D series runs north from the town of Dededo, the Y series is restricted to Yigo, and the F and AG series are near Finegayan and Agafa Gumas to the north of Dededo. In the south the wells at Malolo are designated Ml, those at Talofofo Tl, at Ylig Yl, at Togcha Tg, and at Merizo Mr. In the code as it has developed, a single capital letter with a number or a capital letter followed by a lower case letter and a number refer to general geographic location and order of drilling; the lower case letter is added to define a geographical area different from the area which initially preempted the capital letter. When a well is drilled for exploratory purposes, or a producing well which failed has been converted to an observation well, the lower case x is added after the letter designation, before the number (e.g. Mx-9). If possible, no new letter designations should be added to the list.

Well Siting, Design and Construction

The groundwater resources of Guam are large but the aquifers must be exploited carefully if yields are to be sustained indefinitely. This is especially true for a basal lens which is in delicate balance with sea water; equilibrium is easily upset and sea water encroachment can be induced by poor well location, incorrect well design, and improper pumping practices.

Siting a well is the first consideration affecting its success. In the basal lens of northern Guam the groundwater flow path is generally perpendicular to the coastline and flux increases with distance down the flow path as the contributing area of recharge increases. In the ideal model maximum pumpage would be attainable by determining the inland extent of the brackish water zone and locating a line of wells parallel to the coast beyond the limit of this zone. If hydraulic conductivity and specific groundwater flow were known, spacing, depth and size of the wells could be calculated. The ideal production arrangement would maximize the quantity rate of water withdrawable from the lens, but such an ideal development scheme is rarely realizable. Normally wells are located on the basis of short term considerations, for example available land and proximity to transmission and power lines. Sitings become a compromise between the ideal model and real world conditions.

In the past year or two, under the pressure of having to satisfy an ever increasing demand for water, numerous well sitings have been made which are marginal at best and in instances have been responsible for the failure of the wells. Occasional well failures are expectable in a heterogeneous basal aquifer, but even more will fail if the guidance of knowledgeable judgement is ignored.

The design of a well, again especially in regard to a basal lens aquifer, also is of fundamental significance to its success. Permissible well size and depth, and pump type and capacity depend on local hydraulic conductivity and head. A thin basal lens, like that of Guam, is sensitive to well depth and pump rate, a few extra feet of depth or a few extra gpm spelling the difference between failure and success. In 1964 when the PUAG program was started, both administrator and driller alike were conscious of the need to keep wells shallow. Desirable bottom elevation of each well was stipulated at -25 ft. with allowance made for going by increments to -35 ft. or even -50 ft. in order to secure 200 gpm. Table 10 indicates the care exercised until 1968; until that time the D series wells had bottom elevations of -37 ft. or less, except for D-7 at -50 ft., but since 1969 bottom elevations have deepened progressively (D-11 at -37 ft., D-12 at -42 ft., D-13 at -53 ft., and D-14 at -63 ft.). These are dangerous depths for wells in a basal lens and should be avoided. The M series also shows increasing depths over the last few years. The early M wells were drilled to -50 ft. because of experience with poorly permeable limestone at M-1, but M-6 reaches to -80 ft., M-10 to -78 ft., and M-11 to -60 ft. Whether these wells will be able to continuously pump potable water at 200 gpm is questionable.

Appendix A-7 titled, Maximum rate of draft for wells in the basal lens as constrained by local conditions of head, aquifer penetration, and hydraulic conductivity, analyzes the relationships among the variables noted in the title and explains why well depth and pump capacity must be limited if sustainable exploitation of the basal lens is to be successful. Table 7-2 and figure 7-3 of the appendix stipulate the depth-pump rate relationship for wells in argillaceous to clean limestones. The maximum calculated pump rate from a clean limestone (k = 190 ft/d) when head is 4 ft. is 425 gpm, obtained when depth of penetration below sea level is 40 ft; for the most probable limestone (k = 120 ft/d) the maximum rate is 325 gpm at a head of 4 feet, when depth of penetration is 30 ft. These are theoretical maximums, not safely applicable as a general rule.

The thorough analyses given in appendix A-7 had not been done when the initial pump standard of 200 gpm was set in 1964, but the standard turned out to be a practical optimum for the range of aquifer conditions encountered and should be maintained. However, some wells on closer evaluation may be able to accommodate pumps up to 300 gpm while others may require pumps smaller than 200 gpm. Table 7-3 suggests that a pumping rate of 200 gpm in the argillaceous limestone portion of the basal lens (area 2) may be too high, a conclusion supported by the rising chloride content at A-13, A-14, and A-15.

Sustainable yield of the basal lens of northern Guam

Appendix A-8 titled, Derivation of sustainable yields from a Ghyben-Herzberg lens for selected equilibrium heads, thoroughly discusses the concept of sustainable yield, which is defined as the volume rate of water that could be withdrawn from an aquifer continuously without affecting the quality of the water withdrawn. The hydrologic budget and hydraulic flow computations estimate the ground water flux moving through a basal aquifer but do not state what proportion of this flux is developable as sustainable yield. Only a part of the total flux can be safely exploited. It is commonly stated that 75% of the flux in a thick lens (h greater than 10 ft.) is developable while only 25% can be taken from a thin lens (h less than 5 ft.). These are approximations based on the judgement of experience and are more or less applicable as a first approximation. Skillful practices can salvage a greater proportion, as in Israel, while poor planning may lower the proportion.

Appendix A-8 is a quantitative assessment of the total volume of ground water which could be taken from the basal lens at sustainable rates. It assumes that production sites (wells) are designed so not to be affected by sea water intrusion. The sustainable yield depends on the choice of equilibrium head, the level to which the water table is allowed to fall from the initial condition. In the analysis it is assumed that a reduction in head of 1 ft. from the initial 5 ft. isopiestic contour would not threaten the integrity of the basal lens nor compromise the wells now in use. A lower equilibrium head would increase yield but would endanger some currently operating wells and impose more severe restrictions on the design of new wells.

The determination of sustainable yield is really a problem of optimization within an environmental, technological and economic framework. Appendix A-8 deals only with an approximate optimization between environmental and technological variables.

Table 8-1 and fig. 8-1 of the appendix summarize the computations for sustainable yield under the different assumptions of recharge derived from the hydrologic budget. The computations are for half the lens and must be doubled to give the whole lens sustainable yield. The table and graph show that sustainable yield increases greatly with drop in equilibrium head; for example, matrix A of table 8-2 shows that if an initial head of 5 ft. were allowed to decay to 4.5 ft., 19% of the flux would be safely developable whereas if it were allowed to fall to 2.5 ft., 75% would be developable. In the latter instance, however, sea water encroachment would undoubtedly affect a large extent of the lens, thus reducing the developable flux. For the reasonable reduction of the 5 ft. isopiest to 4 ft., 36% of the recharge would be safely developable. If the 2000 ft. zone parallel to the coast were eliminated from consideration as an intake area, 30% of the total recharge computed in the hydrologic budget would provide sustainable yield.

For the selected equilibrium case (initial head of 5 ft. falling to 4 ft.) the probable hydrologic budget, assuming 5% runoff, provides a sustainable yield of 52 mgd for areas 2, 3 and 4 (excludes para-basal water in area 1, and the Andersen Air Force region, area 5), or 44 mgd if the 2000 ft. coastal zone is ignored. These are conservative estimates; there is little doubt that a sustainable yield of at least 50 mgd could be withdrawn from areas 2, 3 and 4 of northern Guam, a value which coincides with the lower limit of the rude approximation made by Stearns in 1937. To date only one third of this amount is being developed.

The current PUAG production of about 12 mgd in northern Guam is insufficient to satisfy demands and has to be increased. But it is not reasonable, and in fact is unrealistic, to believe that the level and manner of groundwater exploitation for the entire future can be determined and planned in one stroke. Water demand is directly subject to the elasticities of population, industry and agriculture, all imponderables. At best a general statement can be made of expected long range development, but definitive plans are a matter for short term goals. In this regard a development goal to be achieved within the next 5 to 10 years should be decided and commitments made on an annual basis to achieve this goal. It would seem reasonable to set a goal of producing an additional 10 mgd in the north before the end of the decade, equivalent to 30 to 35 wells of 200 gpm each. This is the goal toward which the recommendations in the discussions that follow are directed. The planning process must be kept flexible, able to adjust to the uncertainties of economic and demographic conditions.

Area 1: Current development and recommended Additional Development

Area 1, the approximately 5 sq. mi. strip between the Adelup-Pago contact and Highway 4 is being exploited by 6 producing wells whose total draft amounts to about 1.4 mgd. The wells were originally programmed to yield 200 gpm each, but the local permeability of the aquifer, which is composed of argillaceous limestone, is insufficiently high to maintain this rate except in the few wells furthest from the contact. The wells and their yields, as determined from flow measurements made by C. Huxel of the USGS or estimated (e), are as follows:

Producing well	Yield, gpm
A-1	100(e)
A-3	194
A-7	200(e)
A-8	200(e)
A-11	146
A-12	145
Av.	164=1.4 mgd

The volcanic basement, which is the invert of the aquifer, rises above the theoretical sea water interface for heads in the region and consequently the fresh ground water does not rest on sea water, though it is in hydraulic continuity with the basal lens of area 2 into which it spills (see figs. 3, 5, 11 and maps 3, 4). The aquifer limestone is moderately to very argillaceous and poor to moderately permeable, conditions which combined with the shallow basement result in a high water table, reaching to more than 40 feet above sea level toward the volcanic foothills. Heads decrease to 10 ft. at Agana Swamp over a water table gradient of 5.5 ft/1000 ft, ten times greater than that of the basal lens. Area 1 provides a remarkable water resource which was unrecognized until 1964.

The water table is subject to large natural seasonal fluctuations which are exacerbated by pumping withdrawals in the vicinity of wells. Static water levels measured at wells A-1 and A-3 in 1967 showed a maximum change in head of 11 ft. and 14.5 ft., respectively, with the highest head occurring in the middle of the wet season in September and the lowest at the end of the dry season in June. Greater seasonal fluctuations are expectable where the basement is higher and during severe droughts.

In the wet season the volume of recharge undergoing rapid infiltration raises regional head as long as total infiltration exceeds total discharge. In the dry season head decays as ground water flows to the basal lens. The imposition of draft on the system retards the build-up of head and accelerates its decline. Should the draft plus natural leakage exceed infiltration throughout the year, heads will continuously decline until the thickness of the saturated zone is insufficient to sustain well yields. If head decline is permanent, the sea water wedge will advance up the volcanic basement where it lies below sea level at the boundary of para-basal and basal waters (see fig. 11). Ordinary fluctuations of the water table are not harmful to the productivity of the aquifer.

Some of the para-basal water drains to Agana Swamp and is probably responsible for flow at Agana Spring (fig. 5). The water table at the spring fluctuates seasonally around an average of 10 ft. above sea level. The western boundary of the swamp appears to be on the margin of the para-basal and basal sectors. The catchment basin at Agana Spring is an excellent site for measuring head data, a continuous record of which would indicate the short and long term behavior of the regional water table.

Wells in argillaceous limestone are normally deeper than those in clean limestone, tend to be less productive, and suffer greater drawdowns. For area 1 the depth of the wells, their specific capacities (Q/s) and specific capacities per foot of penetration of the saturated aquifer (Q/s/l), taken on completion of each well at a pumping rate of 200 gpm, are given below:

Well	Bottom el. (ft)	Q/s (gpm/ft)	Q/s/l (gpm/ft/ft)
A-1	-152	4.3	.025
A-3	-262	2.0	.007
A-7	-167	10	.167
A-8	-177	5	.026
A-11	-167	1	.005
A-12	-190	7	.032

In a general way, specific capacity and specific capacity per ft. of aquifer penetration increases with distance away from the volcanic contact, a reflection of the reduction of the clay content of the limestone.

Acidizing of wells in argillaceous limestone is not certain to enhance specific capacity, probably because the acid could react with clay to foul the well bore rather than open it. Table 12 (appendix B) shows that at A-1 the specific capacity dropped after acidizing, though it improved slightly at A-12.

Water levels during pumping and shortly after pumps were turned off as measured by C. Huxel of the USGS in 1972 and 1973 at A-3, A-7, A-8 and A-11 indicate that pumping levels were 5 to 40 feet deeper than at the time of well completion (table 10, appendix B). The lower levels could be caused by reduction in the efficiency of each well, local dewatering due to pumping, or a regional fall in the water table because of poor recharge conditions. Such measurements are informative but the regional behavior of the water table will be more clearly ascertained from observation wells located some distance away from the pumped wells. The recently drilled Ax-20, which struck the volcanic basement above sea level, is a good observation well. Another should be located either midway between A-7 and A-8 or in the vicinity of A-7 and A-2 by Highway 4 in Chalan Pago.

Area 1 is reasonably exploited but more ground water could be withdrawn, though it is preferable to obtain a better understanding of aquifer behavior under current conditions of draft, leakage and recharge before initiating a new development program. However, two additional 200 gpm wells should be drilled between A-7 and A-19, the exact locations to be selected when the decision is made to drill additional wells. Also two more 200 gpm wells should be located at the base of the limestone ledge on the western margin of Agana Swamp below Sinajana, one behind Agana Spring, the other approximately 2000 feet toward Agana. The wells should be sited on limestone, not alluvium. The low aquifer hydraulic conductivity in area 1 requires that the wells be placed about 2000 feet apart to minimize the effects of interfering drawdown cones.

Area 2: Current Development and Recommended Additional Development

Area 2 lies between Highway 4, the approximate boundary of the para-basal water of area 1, and the 200 ft. elevation contour where it arcs across the island near Barrigada. It is underlain by an argillaceous limestone aquifer containing a basal lens. The 200 ft. topographic contour appears to mark the approximate northern extent of lagoonal deposition into which much sediment from the volcanic highlands became mixed. All of area 1 and area 2 lies below 200 ft. elevation and is covered by a karstic surface generally falling between elevations 100 and 200 ft. The boundary between the para-basal and basal waters is inferred from a few wells and test holes driven to the volcanic basement. Where the head is less than 7 ft. the region is clearly in basal water; where heads fall between 8 and 10 ft it is transitional to para-basal water (see map 4, and fig. 3, 5, 11).

Eight wells (A-4, A-9, A-10, A-13, A-14, A-17, A-18, and A-21) are definitely located in the basal lens of area 2, three (A-5, A-6, A-2) are at the margin of the para-basal water, the status of one (A-19) is unclear, and three (A-15, A-16, and A-22) lie just beyond the 200 ft. contour but are arbitrarily assigned to area 2. Yields of a few of the wells have been measured and show the following: A-2 @ 179 gpm, A-4 @ 171 gpm, A-5 @ 171 gpm, A-6 @ 211 gpm, and A-13 @ 197 gpm. If an average rate of 190 gpm is applied to the 15 wells, production from the area is 4.1 mgd, which is about equal to or somewhat greater than the sustainable yield of the area.

The basal ground water of area 2 is the most sensitive in all of north Guam to exploitation by wells. It flows in a moderately argillaceous, moderately permeable aquifer and has a maximum head of 6 to 7 ft. (see map 2). To the west it discharges to Agana Swamp, to the east to the open sea. Its northern boundary from Barrigada to Agana is included in the tongue of brackish water which penetrates inland from Ypao Peninsula.

Some places of low aquifer permeability require deeper wells than feasible for withdrawing 200 gpm. Wells for which records have been kept are listed below with bottom elevation, specific capacity, and specific capacity per foot of aquifer penetration. Data for wells drilled in the last several years is either non-existent or so badly recorded as to be incomprehensible.

Well	Bottom el. (ft)	Q/s (gpm/ft)	Q/s/l (gpm/ft/ft)
A-2	- 54	7	.13
A-4	-160	35	.18
A-5	-177	60	.34
A-6	-154	1000	2.3
A-9	- 50	205	3.6
A-10	- 25	400	12.5
A-13	-199	6	.05
A-14	- 60		
A-15	- 52	23	.83
A-16	- 40	27	.64
A-17	- 35	6	.16
A-18	- 45	14	.31
A-19	- 2(?)	10	.34
A-21	- 53	18	.32
A-22	- 40	33	.73

One well, A-13, is extraordinarily deep for being in a basal lens with a head of 6 feet or less. The chloride content of its water has risen from 60 mg/l in 1968 to 276 mg/l in May, 1974. Another, A-14, at -60 ft. is also dangerously deep, and A-21 at -53 ft. and A-17 at -50 ft. may encounter trouble. Well A-16, drilled into the saline water tongue at Barrigada, has had to be abandoned because of high salinity. It should be converted to an observation well. Specific capacity and specific capacity per ft. of aquifer penetration are substantially greater than in the more argillaceous aquifer of area 1.

The six square miles of area 2 already may be suffering from too many wells. However, most of the wells are concentrated on the ground water flow path to the east coast and none (excluding A-5 and A-6) intercept flow moving toward Agana Swamp. Eventually some of the wells in the eastern part of the area will have to be fitted with smaller pumps, perhaps 100 gpm or so. Since over exploitation is skewed to the eastern half of the basin, an opportunity exists to develop additional water on the west along the inland boundary of Agana Swamp between Afami and Chochogo. Two wells, at 200 gpm if possible, should be located on the dirt road connecting Ngachang with Chochogo. Drilling should not be done in the Toto region until a determination is made that it lies outside the Ypao Peninsula brackish water tongue.

In the eastern part of the area a 200 gpm well near Father Duenas School is desirable even though it will add to the already strained sustainable yield. Some of the deeper and poorly located wells unquestionably will become salinized in a few years time and will have to be re-developed or abandoned.

A salient geomorphic and hydrologic feature of area 2 is Agana Swamp, which has proved a challenge to those who believe in reclaiming swamp land through drainage works. Agana Swamp is the expression of para-basal and basal ground water discharging as springs from limestone and as seeps from alluvium. The ground water discharge is in equilibrium with the basal head of area 2; if the swamp is drained, the ground water of area 2 and the para-basal water of area 1 will drain more rapidly than under the present natural balance, reducing the head in area 2 and widening the transition zone so that ground water development by wells would be effectively eliminated. Draining the swamp would result in the loss of a precious resource. If the land must be reclaimed, it should be done by filling.

Agana Spring served for many years as a reliable water source and it is frequently suggested that pumps be re-installed. Before such an action is undertaken, however, wells should be used to capture the ground water and action taken at the spring only to salvage the remaining spillover from the ground water system.

Area 3: Current development and recommended additional development

The 20 sq. mi. of area 3 consists of clean limestone which originated as a lagoonal facies over most of the area and as a barrier reef along the present east coast and perhaps the scarp striking northeast from Tamuning. Within the subsurface a classical Ghyben-Herzberg lens of fresh water is found stretching from coast to coast (see fig. 6). Around Barrigada Hill, however, the basement rises above the theoretical bottom of the fresh water column, creating an unknown but probably limited region of parabasal water. Well Mx-9 struck volcanics at -28 ft. after penetrating a sequence of clean limestone, marl, beach sand, beach rock, and fossil coastal swamp material.

Only 11 producing wells are located in area 3. During and shortly after the war many wells were drilled in the Tamuning-Ypao-Tumon region, but the groundwater is no longer of potable quality between Barrigada and Ypao (see map 2). The PUAG wells in the area are M-1, M-2, M-3, M-4, M-8, and M-9, with Mx-9 as an observation well. Several private wells have also been drilled, two at Hawaiian Rock's quarry on the east coast, one at Island Construction Co., and another at Foremost; E.E. Black, Inc. uses an old well, USGS no. 112.

A check of the flow meters of several wells by C. Huxel showed production as 106 gpm at M-1, 200 gpm at M-2, 157 gpm at M-3, and 183 gpm at M-4. Assuming 200 gpm at all other wells, production from the area is 2.7 mgd, far below its sustainable yield.

The aquifer consists of clean limestone, heterogeneous in its parameters but very permeable on a regional scale. Locally, tight rock sections occur, but in general wells need not be driven very deep below sea level to yield 200 gpm. Trouble was encountered in obtaining 200 gpm at M-1 when it was drilled and so it was extended to -50 ft. and heavily acidized, the results of which were ambiguous. Thereafter all M wells nearby were drilled to -50 ft. or more, except for M-9 at -40 ft. These depths are too great and should not be used as standards. As a rule acidizing is very effective in enhancing local permeability in clean limestone. For example, the specific capacity of M-2 was more than doubled after treatment.

The M series wells in the area for which there is a record are listed below with depth, specific capacity, and specific capacity per foot of aquifer penetration.

Well	Bottom el. (ft)	Q/s (gpm/ft)	Q/s/l (gpm/ft/ft)
M-1	-56	22	.367
M-2	-50	68	1.06
M-3	-52	460	8.07
M-4	-51	1000	17.9
M-8	-52		
M-9	-40		
Mx-9	-77		

Reduction in clay content of the limestones with distance from the Adelup-Pago contact is reflected in the specific capacity per ft. of aquifer penetration of the wells; in area 1, comprised of the most argillaceous limestone, the median Q/s/l is .025, in area 2 it is 0.33, and in area 3 it is 4.57.

Area 3 is under-exploited at present, but a large portion of the area is underlain with poor quality water, and between Barrigada Hill and the scarp to the north of it the volcanic basement may be too high to allow a thick zone of saturation to form. The tongue of brackish water on the west side of the island must be avoided, as well as the near coastal zone on the east. Well Mx-9 has proved the existence of the high volcanic basement (fig. 7), which also must be avoided unless small capacity wells are acceptable. However, for the next stage of development six new 200 gpm wells should be drilled in area 3, four located along the highway north of M-8 at 1500 ft. intervals, one on the highway about 4000 ft. south of M-9, and one on the road about 1500 ft. from the E. E. Black well toward Barrigada Hill in the western part of the area.

Locating wells in area 3 is complicated by the Naval Communication Station which takes up much of the land area and straddles the best production sites. Should arrangements be made with the U.S. Navy for access, many new sites could be selected. Also, it will be desirable to place a monitor well within the boundaries of the Station.

Area 4: Current development and recommended additional development

Area 4, encompassing 38 sq. mi., is bounded on the south by a line extending from Ypao Peninsula on the west along the base of the linear scarp near Barrigada Hill to Pagat Point on the east coast, and on the north by a line arbitrarily drawn from Uruno

Point on the west to Janum Point on the east. The northern boundary differentiates the region presumably available to PUAG for exploitation from the Andersen Air Force Base complex (area 5). Area 4 is covered with clean limestone except in two restricted localities, Mataguac and Mt. Santa Rosa, where Alutom volcanics project above the surface of the ancient emerged lagoon. Area 5 includes about 25 sq. mi. of clean limestone lying between area 4 and the north coast of the island.

A basal lens underlies about 20 to 25 sq. mi. of area 4, but in the remainder of the region the volcanic basement sloping from Mataguac and Mt. Santa Rosa lies above the theoretical thickness of a fresh water column assignable to a Ghyben-Herzberg system governed by the areal heads. Map 2 outlines the sea level position of the volcanic basement. In area 5 approximately 5 sq. mi. of volcanic basement rises above sea level, so that around the Mataguac-Mt. Santa Rosa buried mountain range a total of 15 sq. mi. of volcanic basement lies above sea level and perhaps another 5 to 10 sq. mi. between sea level and the margin of the basal water lens. Eventually an exploratory program should be planned to determine whether an exploitable band of para-basal water surrounds the buried mountains.

The basal lens does not stretch from one coast to the other, except perhaps in a narrow zone near Pagat Point, because of the thinning the limestone thickness caused by the subterranean volcanic hills. In plan section the lens is arcuate around the western rim of the raised volcanic basement and pinches out on the north at

Andersen Air Force Field and on the south toward Janum. The lens carries a large resource of fresh ground water and is maintained by infiltration from overlying limestone and a large volume of sub-surface flow along the limestone-volcanics contact which initially infiltrated the limestone overlying the volcanic basement. Figures 8, 9 and 10 illustrate the complex sub-surface conditions in area 4 and area 5.

Currently 56 wells and Tumon Tunnel (USGS no. 80) exploit the ground water resources of area 4; no producing wells are located in area 5, though AG-1 and AG-2 lie at the arbitrary boundary of the two regions. PUAG has 33 wells, of which about 30 are being used and the others will be on stream soon; the Air Force maintains 8 wells and Tumon Tunnel; NCS has 4 wells; and San Miguel Brewery has 1. If all PUAG, San Miguel, and NCS wells were producing at 200 gpm and the Air Force wells at 350 gpm, the original rating, withdrawals from the area would be 9.5 mgd for PUAG, 3.2 mgd for NCS, 0.3 mgd for San Miguel, and 4.0 mgd for the Air Force, for a total of 15 mgd, about two thirds of the conservative estimate of sustainable yield.

The first PUAG wells were drilled in area 4 near Dededo and were designated the D series. There are now 15 wells in this series between Dededo and a point two miles to the north. All of the wells exploit the basal lens and all yield good quality water except D-13, which apparently draws water from deep in the lens because of locally high vertical permeability (see fig. 17). To the east at Yigo PUAG now has 4 successful wells, 2 of which may tap para-basal water (fig 9, 10). West of the Dededo series PUAG has drilled 3 F wells and 2 AG wells, all successful, and utilizes H-1, an old well (USGS no. 113). Wells of the M series lie between Dededo and Tumon and Dededo and Barrigada Hill. The 8 Air Force wells extend eastward along a line from Dededo to the coast. The NCS wells lie west of the PUAG F series between the coast and the highway, and the San Miguel well is located on the limestone plateau above Tumon Bay.

Except for unusual local aquifer conditions, wells going no deeper than to -35 ft. should provide yields of 200 gpm. This standard was adhered to early in PUAG's development, but recently either poor local conditions have become more frequent or the depth criterion is being ignored. Wells for which there are records of depth and specific capacity are listed below.

Well	Bottom el. (ft)	Q/s (gpm/ft)	Q/s/l (gpm/ft/ft)
M-5	- 57	10	.16
M-6	- 80	7	.08
M-7	- 51	33	.59
M-8	- 78	210	2.5
M-14	- 46	31	.61
Y-1	- 36	29	.70
F-2	- 40	17	.37
F-3	- 55	99	1.7
AG-2	- 77	1000	12
D-1	- 36	290	7.1
D-2	- 36	21	.51
D-3	- 25	13	.42
D-4	- 25	90	3.0
D-5	- 29	6.3	.19
D-6	- 37	45	1.1
D-7	- 50	26	.46
D-8	- 35	11	.28
D-9	- 29	650	.19
D-10	- 25	1000	33
D-11	- 37	40	.95
D-12	- 42	21	.43
D-13	- 53	13	.22
D-14	- 63	16	.23
AF-6	-102	33	.30

The median specific capacity per ft. of aquifer penetration is .55, smaller than the value in area 3 (where, however, the sample was limited) but larger than in areas 1 and 2. Acidizing the well bore enhances local permeability by a large factor, as at D-9 where the specific capacity jumped from 85 to 545 and at D-11 from 42 to 74 (table 12, appendix B).

The density of producing wells in area 4 is greater than elsewhere but production is not yet equal to sustainable yield. In fact, for the next stage of development area 4 provides the easiest opportunities for well sites on government property near pipelines and consuming centers. Along the highway from Wettengel Junction north to Agafo Gumas at least 15 wells could be sited 1000 feet apart, of which 10 would lie between Wettengel Junction and Potts Junction and 5 between the latter junction and Agafo Gumas region.

In the Yigo region two wells (in addition to the recently completed Y-4) could be located between Y-1 and Y-3, and two between Air Force 2 (USGS no. 65) and Air Force 9. Another well of the M series should be located between M-10 and the E. E. Black well. This total of 20 new wells in area 4 will provide another 5.8 to the system if each well is fitted with a 200 gpm pump. It may be possible to use 300 gpm pumps on some wells, but a decision to do so would depend on a careful evaluation of site location and well characteristics.

For the time being area 5 is not treated as a potential supplier of ground water to PUAG. Should the opportunity arise to exploit the resources of that area, however, sites for several wells could be readily selected.

Summary of recommendations for additional ground water development in northern Guam

A total of 33 new wells are recommended in northern Guam for drilling by the end of the decade, 29 to be in the basal water of areas 2, 3, and 4, and 4 in the para-basal water of area 1. The 33 wells will provide 9 mgd, which combines with the present PUAG production of about 12 mgd and expected production of about 1 mgd from completed but still unused wells will give PUAG a total yield of over 20 mgd. If more water than this is needed before 1980, the recommended program should be completed in a shorter time and a supplementary program devised.

Sites for all wells drilled from now on should be carefully selected and the design, construction and operation of each well should be rigidly controlled. The ground water lens of northern Guam is a bountiful resource but sensitive to abusive exploitation and mismanagement. Once degraded, it will not easily recover.

Southern Guam: current development and recommended additional development

The exploitable ground water resources of the southern half of Guam are very small in comparison with those of the limestone plateau of the north but where they occur their utilization is important in satisfying local needs. They are, in addition, unique in their occurrence and are a challenge to the investigator.

Malolo

Wells drilled for PUAG in the Malojloj region south of Talofofo discovered a type of ground water occurrence that had not previously been known on Guam. Wells Ml-1, Ml-2, and Mlx-2 penetrated a small limestone aquifer embedded in the Bolano pyroclastic member of the Umatac formation. Initially the aquifer was artesian, but heavy sustained pumping shortly after its discovery reduced it to water table conditions. A 350 gpm pump was originally installed, and between October 15 and December 13, 1965, an average of 120 gpm was withdrawn from a ground water system which could sustain only a stress of less than 100 gpm. Currently a single producing well (Ml-1) is pumped.

Unfortunately, Mlx-2, a more successful well than Ml-1, located 2000 feet away, has been abandoned and lost. Mlx-2 penetrated a thicker section of the aquifer and would be a more reliable producer than Ml-1. The full extent of the aquifer is not known but it probably extends eastward of Mlx-2 and Ml-1. Two other wells failed to encounter the aquifer, Mlx-1 drilled 200 ft. from Ml-1 and Mlx-3 located on the Dandan road 3000 ft. north of Ml-1.

A small scale exploratory program should be planned to determine whether the aquifer exists to the east of Mlx-2 and Ml-1. If it does, at least one more 50 gpm well could be added to the system.

Talofofo

An old well, USGS no. 214, now designated T-1 (or Tl-1), was reconstructed and yields up to 115 gpm to the local water supply. Pumping tests using observation wells indicate the permeability of the limestone to be about 30 ft/d (see table 14, appendix B). The well reaches to 33 ft. below sea level, the local head is 15 to 20 ft., and the chloride range has been 30 to 250 mg/l, though it is now constant at about 30 mg/l. The extent of the aquifer is limited and it is unlikely that more than 100 gpm can be steadily withdrawn from it. Further exploration is necessary if additional ground water development is desired.

Ylig

Three test wells were drilled in Ylig Valley at the water filtration station but were not developed as producers. The wells were drilled through alluvium into a limestone aquifer and encountered basal water with a head of about 6 feet. The wells were successfully tested and one of them, preferably Yl-3, could be used to supply 50 to 100 gpm should the need arise, but a new analysis of the aquifer should be made before a decision to install a pump is taken.

Togcha and Camp Dealy

At Togcha 10 shallow wells have been drilled in a re-entrant of Mariana limestone to supply golf course irrigation. A small basal lens was struck having a head between 1.5 and 2 ft. and an initial chloride content of 75 mg/l. The wells appear to be successful.

A similar limestone situation occurs at Camp Dealy just south of Togcha. An exploratory well should be drilled on the 100 ft. elevation terrace near the base of the limestone escarpment at the maximum possible distance from the sea. A few producing wells of 50 gpm each could probably be added to the water supply network.

Volcanic rocks

The exploitability of volcanic rocks for ground water supply is grossly inferior to that of limestone. Typical hydraulic conductivity in the pyroclastic volcanics of southern Guam is less than 0.1 ft/d, about 1000 times less than the typical conductivity in limestone, and consequently well capacities are very low. However, the volcanics are saturated with ground water and a degree of exploitation is possible.

The range of measured hydraulic conductivities in the volcanics is from 0.03 ft/d to 2 ft/d. At the lower end of the range a well penetrating 400 ft. of saturated aquifer would yield only about 20 gpm continuously; at the higher end, wells less than 400 ft. deep could yield 100 to 150 gpm. A well would be an unqualified success if it penetrated rocks with an average permeability of about 0.6 ft/d. The success of wells in lower permeability rocks would have to be measured in terms of local situation, that is, remoteness and need. There is no way to predict volcanic rock permeability, and all wells initially would have to be considered exploratory.

In the valley of the Geus River inland of Merizo an attempt was made to develop ground water in the Facpi member of the Umatac formation. A well drilled to -100 ft. was an utter failure; the permeability of the rock was the lowest encountered on Guam.

Surveillance of the behavior of the ground water resources of Guam under development stress

The dynamics of a natural resource as important to Guam as its ground water must be sedulously monitored to make sure the resource will always remain suitable for development. The fresh ground water of Guam is a penultimate phase in a continuum called the hydrologic cycle, and the object of exploitation is to intercept this phase before it completes the cycle by draining to the sea. Interruptions of the preceding phases of the cycle, such as rainfall, evaporation and infiltration, could decrease or enhance the volume and quality of the ground water phase. Excessive interference with the ground water phase itself could cause the resource to diminish in volume or be degraded in quality to the point of uselessness.

A replenishable, dynamic resource such as ground water can be understood and safely developed only if a data base stating its dimensions and changes in them under stress is estahlished. As interference with the natural system intensifies, the required data base must become more and more comprehensive and accurate. Ultimately a degree of sophistication is possible which would allow automatic data collection and real-time analyses to decide the optimal utilization of the resource. Before this level of understanding is attained on Guam, however, much has to be learned about the details of the entire hydrologic cycle and particularly its ground water phase.

A good data base has accumulated for Guam, chiefly as the result of USGS and Singer-Layne activities. The USGS has attempted to meticulously document whatever information on ground and surface waters was recorded (Ward and Brookhardt, 1962; miscellaneous surface and ground water reports; C. Huxel) and presently maintains and is expanding a data collection network. Singer-Layne kept good records for a number of years but since about 1970 the scope and quality of their files has seriously deteriorated. Because Singer-Layne is at the forefront of development, it should be required to maintain standard records and to make them available on a routine basis to PUAG and the USGS.

Singer-Layne's responsibility is directed to drilling and equipping wells so they can be connected to PUAG transmission lines and to monitoring flow of the producing wells. During drilling accurate measurements and reports should be made on site elevation, characteristics and depth of strata encountered, depth of completed well, casing and screen lengths, water levels and quality, acidizing operations, pump tests, and other commonly reported items. Records should be standardized and maintained in accessible form. Flow measurements at wells should be made regularly.

Data collection on the non-groundwater phases of the hydrologic cycle

Rainfall, evapotranspiration and stream flow are the principal components of the non-ground water segment of the hydrologic cycle for which continuous long term records are required. A good data base already exists for rainfall, some records extending back to the turn of the century, but the base can be improved by expanding the network of rain gages and by introducing at least one digital rain recorder to give rainfall intensities on a continuous rather than daily or longer basis. The U.S. Weather Service, the U.S. Navy, and the USGS already maintain gages, to which PUAG should consider adding the following locations:

1. Well A-11 in Ordot (area 1)
2. Well A-13 or A-9 in Mangilao (area 2)
3. Well M-1 (area 3)
4. Well D-1 in Dededo (area 4)
5. Well AG-1(area 4, 5)

The collection of evaporation data requires more care than rainfall. Such data is important in refining hydrologic budget computations and eventually PUAG should become involved in collecting it, but for the present this responsibility is better handled by the University of Guam, Agricultural Departments, the U.S. Weather Service, and perhaps the USGS.

A moderately long record of stream flow, dating to the early 1950s, has been collected by the USGS. Gaging stations on key streams should be continued, the choice of stations being a matter for the USGS to decide in cooperation with PUAG.

The above suggestions deal with basic data and standard methods of collecting it. Costly and difficult to obtain data, such as the chemical composition of rainfall and rates of infiltration in the soils and rocks of the island, though desirable to have, is best left to other agencies equipped to handle the tasks involved.

Data Collection on the Groundwater Phase of the Hydrologic Cycle

The USGS is already involved in collecting relevant groundwater data and in establishing a network of observation points, especially throughout northern Guam. In all cases the data is being obtained from sites of opportunity rather than from sites specifically located and designed to maximize data value. Nevertheless the data being collected is and will be of inestimable aid to understanding the groundwater resources.

Several observation wells with continuous recording devices are maintained by the USGS and spot measurements in other wells are made. The USGS records water levels and occasionally evaluates the behavior of wells during pumping and on its cessation. The program of the USGS should be encouraged and financed when feasible; its scope should be keyed to the goals of PUAG and EPA.

Singer-Layne, Int., should be required to maintain accurate records of drilling and of measurements made before and during pump tests. Close cooperation should be established between Singer-Layne, PUAG, and the USGS. The USGS program of basic data collection and its usefulness to PUAG is frustrated if Singer-Layne activities are conducted independently of outside counsel and cooperation. Whenever opportunities arise to carry out controlled pumping tests, especially if observation wells are nearby, the USGS and PUAG should be advised.

One of the most positive aspects of Singer Layne's stewardship of Guam's ground water resources has been the close attention paid to the quality of water. The company's constant concern with possible quality degradation either by surface pollution or sea water encroachment and the money and effort they have devoted to routinely analyzing samples from each well is commendable.

The USGS program of using existing bore holes as observation wells should be encouraged and eventually supplemented with the construction of specially designed wells at locations chosen to maximize information on the dynamics of the ground water. Two types of data wells could be designed, one a simple observation well outfitted to record water level changes and from which fresh water samples could be collected for analysis, and the other a monitor well to measure variations in quality and hydraulic potential throughout the basal lens and in the sea water below it.

Observation wells

New, or reclaimed abandoned wells, should be located to yield information on the water table, which in area 1 would reflect thickness of the fresh water columns and in areas 2, 3, 4 and 5 the thickness of the Ghyben-Herzberg lens. In area 1, water table levels should be recorded at Ax-20 to determine their relationship to seasonal recharge. This well appears to be sufficiently removed from pumping wells to escape marked effects of drawdown cones. Another observation well drilled to the volcanic basement near Chalan Pago would be desirable. Also, readings of head at Agana Spring should be made on a regular basis.

In area 2 an observation well at Father Duenas School, which has already been activated by the USGS, will provide information on flux changes resulting from heavy pumping of the A series along the groundwater gradient to the east coast. Another observation well to record changes in the gradient to the west should be located at the inland margin of Agana Swamp.

In area 3, Mx-9, which did not strike a basal lens, should be retained as an observation well to measure seasonal changes in recharge. In area 4, Yx-3, also not in the basal lens, could be converted to an observation well, and at least one well in the basal lens could be used to provide a continuous record of head changes.

Monitor Wells

The flexible bottom of a fresh water basal lens and hydrodynamic dispersion induced by movement of the interface create profound problems in predicting total changes taking place in the lens if only water table measurements and pumping or grab water samples are evaluated. A very wide transition zone, ultimately leading to the demise of potable water, could form without ever being expressed in head changes. The most certain way to trace the changes in thicknesses of the fresh water and transition zones is by means of an open bore hole through the entire lens to the underlying sea water.

Figures 23 and 24 illustrate the concept of a monitor well. In figure 23 the well is shown to penetrate to salt water and to be open throughout the fresh water and transition zones. Fig. 24

shows a simple design for a monitor well. The well must be large enough to accommodate measuring devices, in particular a conductivity probe. The standard 8 inch well would be suitable. On Guam monitor wells would be relatively shallow compared to places where the lens is much thicker, such as in Oahu, Hawaii. Depth from surface to salt water would be 500 to 800 ft. on Guam whereas it is nearly 1500 ft. on the coastal plain of Oahu.

The structure of a basal lens is most easily determined on a regular basis by lowering a conductivity sonde into a monitor well and recording changes in conductivity with depth. Conductivity will vary from a few micromhos at the water table to more than 40,000 micromhos in the salt water. Conductivity in micromhos is readily converted to salinity because over most of the concentration range chloride linearly correlates with conductivity. Charts of the correlation are easily prepared.

Conductivity bridges and sondes are commercially available. The technique of measurement is simple and requires no special skills. It is highly recommended for Guam, and in fact, PUAG should purchase one as soon as possible to use in all wells before monitor wells are drilled.

Several monitor wells are justified to record changes in the basal lens of north Guam. In area 2, which is being heavily exploited, a monitor well between A-9 and A-13 is desirable. The well would be less than 500 ft. in depth and in addition to providing critical data on the basal lens in argillaceous limestone might also give a better fix on the position of the volcanic basement.

In area 3 a monitor well on the highway 1000 to 2000 ft. south of M-9 would provide information on fresh water thickness and ground water movement in a lens probably not affected by exploitation. In area 4 a monitor well between the line of D series wells and the highway to the west of it would assist in establishing the allowable pumping stress in a highly exploited basal lens receiving substantial recharge.

Some remarks on geophysical well logging and geophysical surveys

Geophysical well logging refers to the mapping of lithologic units in an open bore hole. It consists of various techniques which measure formation resistivity and self potential, bore hole geometric characteristics, conductivity and water temperature. From the measurements, composition and porosity of the aquifer can be inferred and the salinity of its water determined. Identification of these parameters, however, is by and large a matter of judgement.

Resistivity logging helps to locate water bearing formations; in a saturated rock high resistivity infers low porosity. This type of logging has limited usefulness on Guam where the allowable penetration of the fresh water zone of the basal aquifer is very shallow. Spontaneous potential measurements, caused by electric currents in the earth, also would be of little value on Guam. Somewhat more applicable would be the caliper module which measures boring dimensions and variations in openings at the boring face. Down hole photography and television provide similar data. The only geophysical technique which is categorically justified at this time is measurement of conductivity in the saturated zone. The instrumentation is relatively inexpensive and the data output so valuable that PUAG should invest in a complete unit right away.

Broad geophysical surveys of areal lithology using seismic and electrical resistivity techniques would have application in northern Guam to establish the position of the volcanic basement. This type of information would be especially relevant throughout areas 1 and 2, around Barrigada Hill in area 3, and in the Mataguac-Mt. Santa Rosa region of area 4 and 5. The information would be beneficial though not yet critically needed so that the high cost of the surveys would discourage their use at this time. The surveys would test inferences already made and add details of subsurface configuration. Either method theoretically would work, but the seismic method would be more apt to be successful.

References

Austin, Smith and Associates, Inc., Engineers, 1968, Surface water survey of the island of Guam: Consultant Report.

Austin, Smith and Associates, Inc., Engineers, 1970, A report covering the domestic and agricultural water supplies of the island of Guam which indicates the need for conservation areas: Consultant Report.

Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis: Elsevier.

Chang, J. H., Campbell, P. B., Robinson, F. E., 1963, On the relationship between water and sugar cane yield in Hawaii: Agronomy Journal, V. 55.

Cloud, Preston, 1951, Reconnaissance geology of Guam and problems of water supply and fuel shortage: USGS Manuscript Report.

Cox, I. M., 1904 (revised 1910, 1911, 1916, 1925), The island of Guam, U. S. Government Printing Office (1926).

Don Felipe De La Cortez, in the Guam Recorder, Aug. 1926.

Emery, K. O., 1962, Marine geology of Guam: USGS Prof. Paper 403-B.

Engineer Intelligence Study no. 257, 1958, The vegetation of Micronesia: Dept. of Army, Chief of Engineers E 15 257.

Feltz, H. P., Huxel, C. J., and Jordan, P. R., 1970, Reconnaissance of potential contamination of groundwater from runoff, Andersen Air Force Base, Guam, Mariana Islands: USGS Administrative Report.

Guam Recorder, June 1926, August 1934, May 1937, July 1937, July 1940, August 1940.

Guam Survey Board Report, 1902: U. S. Navy Department.

Hoffard, S. H., 1961, Predicted yield of Fena Reservoir, Guam, M. I.: USGS Manuscript Report.

Huxel, C. J., 1973, Water resources in limestone islands: Seminar on conservation education, South Pacific Commission and Government of Guam, June 7, 1973.

Johnston, E. G., Williams, A. L., 1973, Bibliography relative to the development of water resources Territory of Guam: Micronesian Area Research Center, Univ. of Guam.

Kennedy Report Guam, 1964, Kennedy Engineers, San Francisco, Cal.

Mink, J. F., 1964-1973, Manuscript reports to Layne International.

Mink, J. F., 1964, Groundwater temperatures in a tropical island environment: Jour. Geophys. Res. V. 69, n. 24.

Pacific Island Engineers, 1948, Historical review of the geology of Guam with references: Consultant Report to U. S. Navy.

Piper, A. M., 1947, Water resources of Guam and the ex-Japanese mandated islands in the western Pacific: USGS Manuscript Report.

Reed, E. K., 1952, General report on archeology and history of Guam: U. S. National Park Service Manuscript Report.

Safford, W. E., 1905, The useful plants of Guam: Contribution from the U. S. National Herbarium, vol. IX, U. S. National Museum.

Schlanger, S. O., 1964, Petrology of the limestones of Guam: USGS Prof. Paper, 403-O.

Sheahan, N. T., 1968, Report of groundwater availability and current well development Guam, Mariana Islands: Layne Research Division Report.

Stark, J. T., 1963, Petrology of the volcanic rocks of Guam: USGS Prof. Paper 403-C.

Stearns, H. T., 1937, Geology and water resources of the island of Guam, Mariana Islands: U. S. Navy Manuscript Report.

Sundstrom, P. W., 1948, Water resources of Guam: USGS Manuscript Report.

Taylor, R. C., 1973, An atlas of Pacific Islands rainfall: Hawaii Institute of Geophysics. Data Report no. 25.

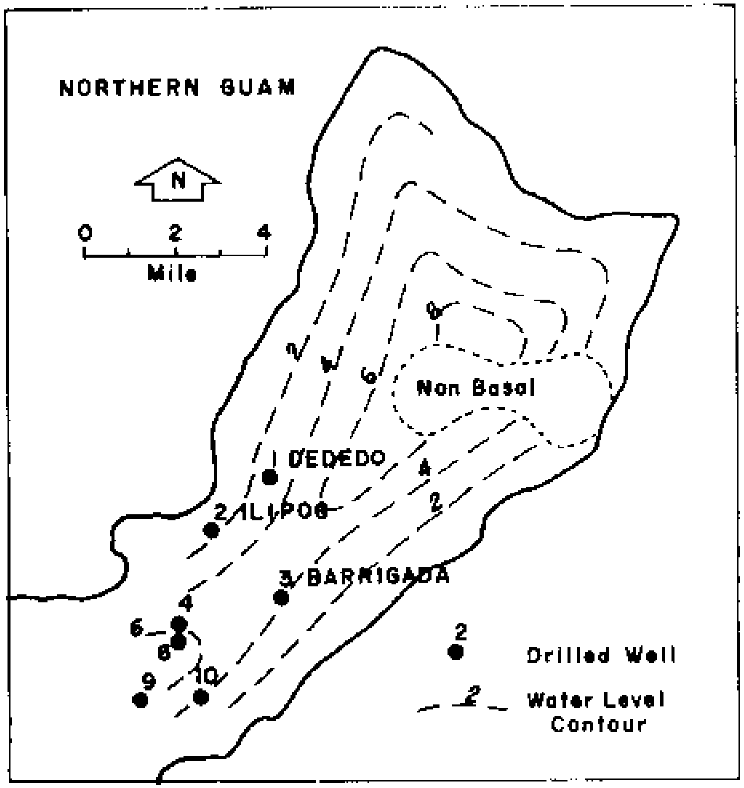
Tracey, J. I., Schlanger, S. O., Stark, J. T., Doan, D. B., and May, H. G., 1964, General geology of Guam: USGS Prof. Paper 403-A.

U. S. Weather Service, 1967, Climatological data Guam.

Ward, P. E., and Brookhardt, J. W., 1962, Military geology of Guam, water resources supplement: USGS and U. S. Army Corps Engineers.

Ward, P. E., Hoffard, S. H., Davis, D. A., 1965, Hydrology of Guam: USGS Prof. Paper 403-H.

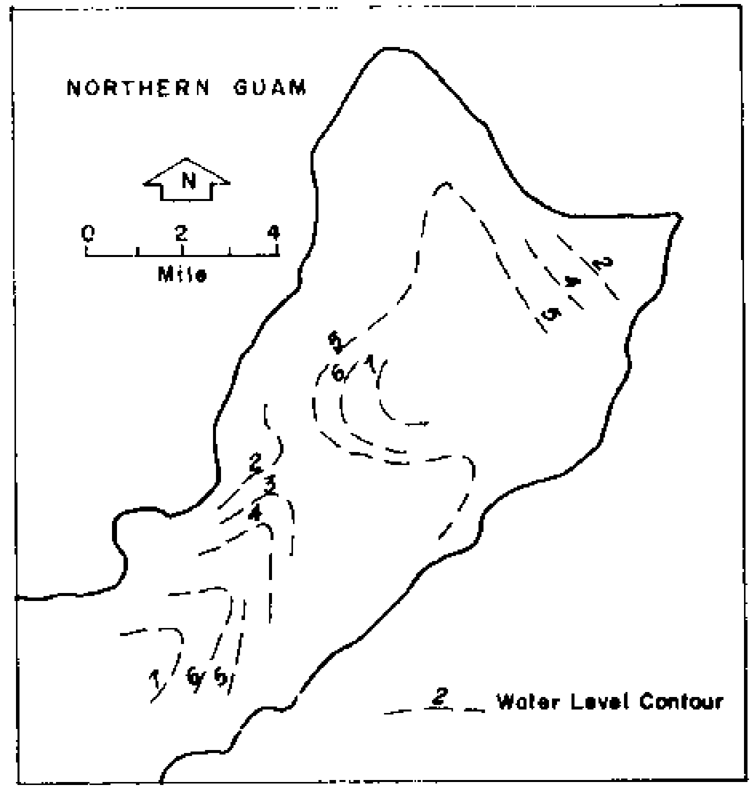
FIG. 1



H.T. Stearns

Geology and Water Resources of the Island of Guam, Marianas Island. 1937

FIG. 2



Piper Report

Map of Basal Water Table 1944-45.

SECTION BB'

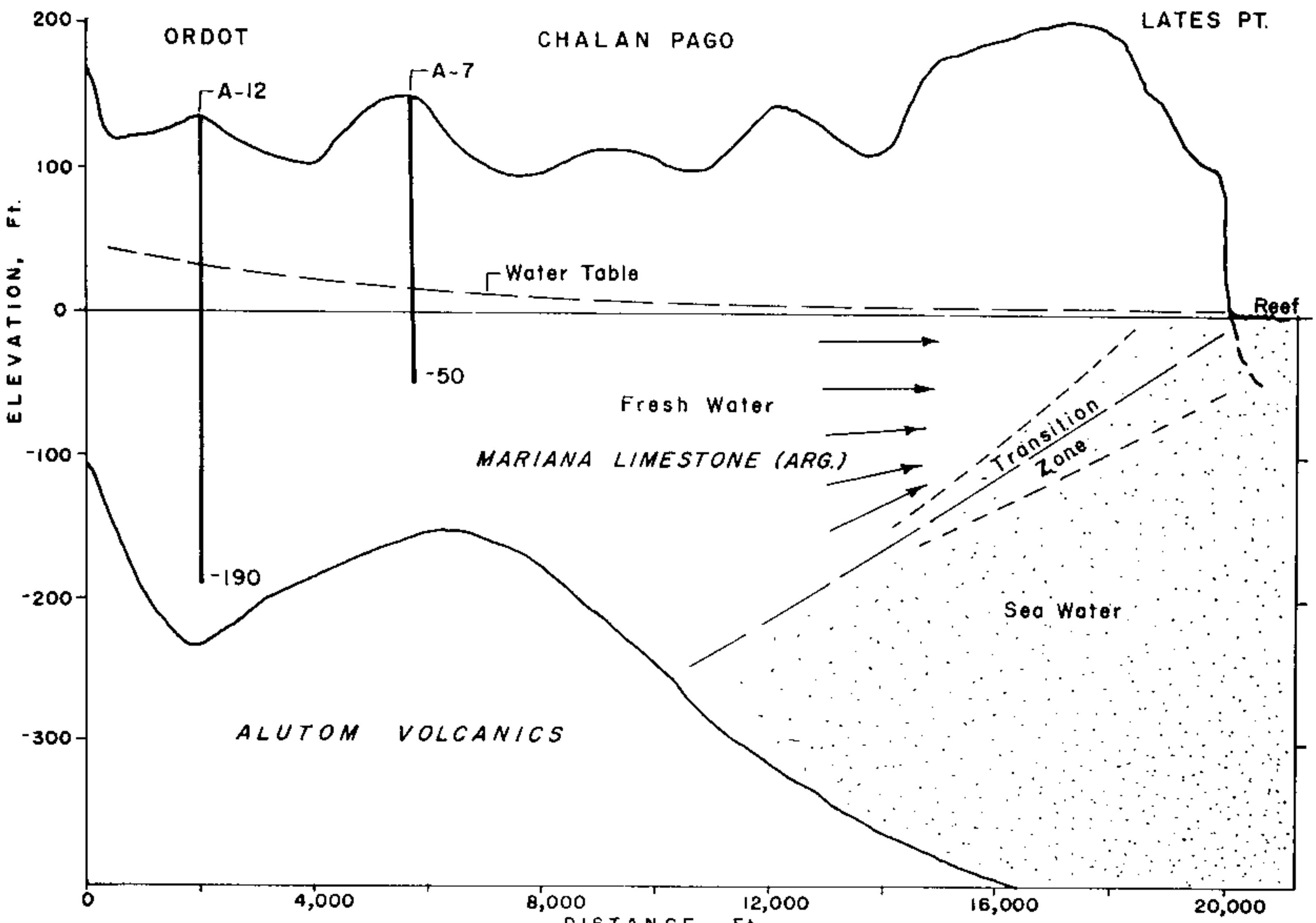


FIG. 3

SECTION CC'

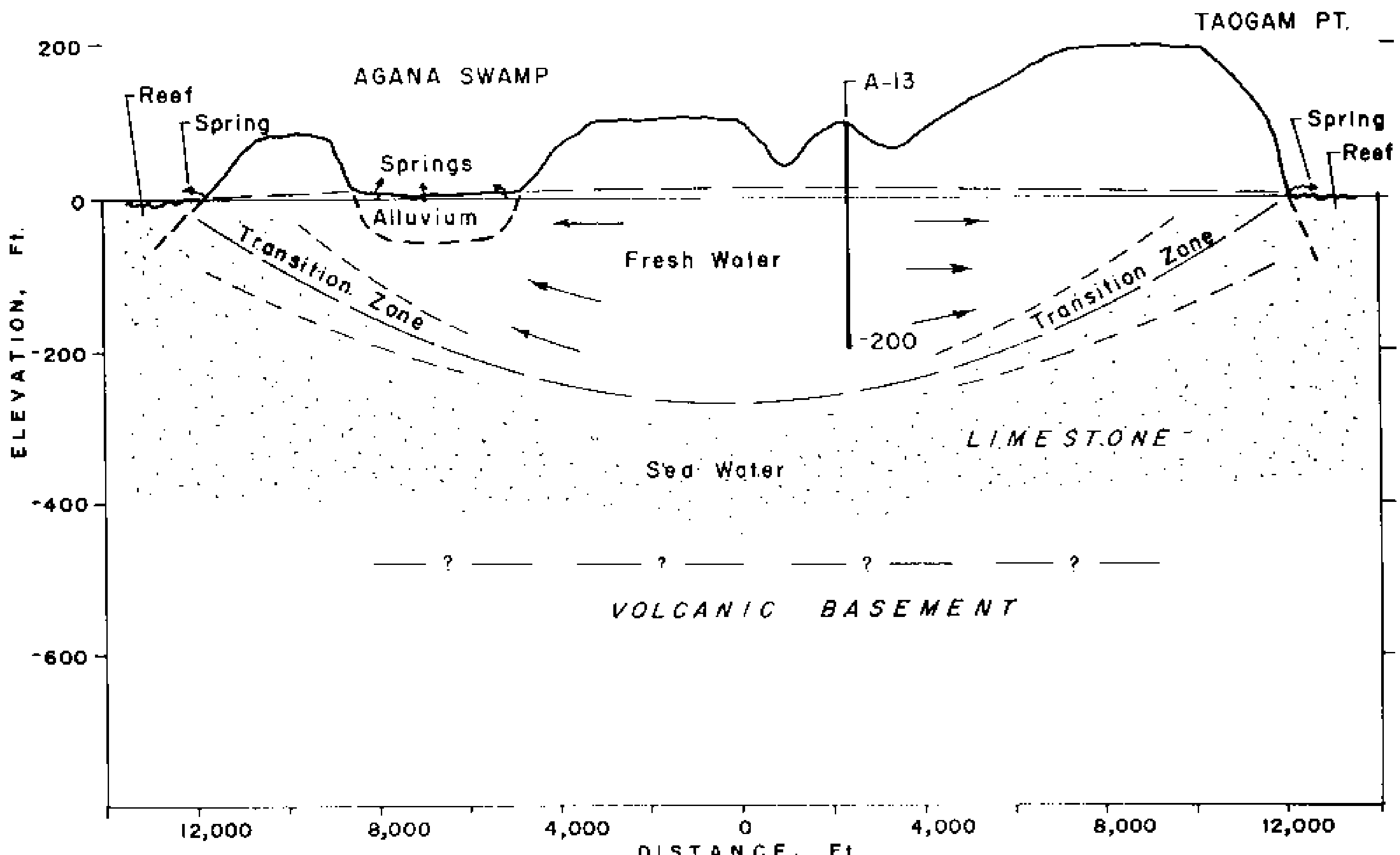
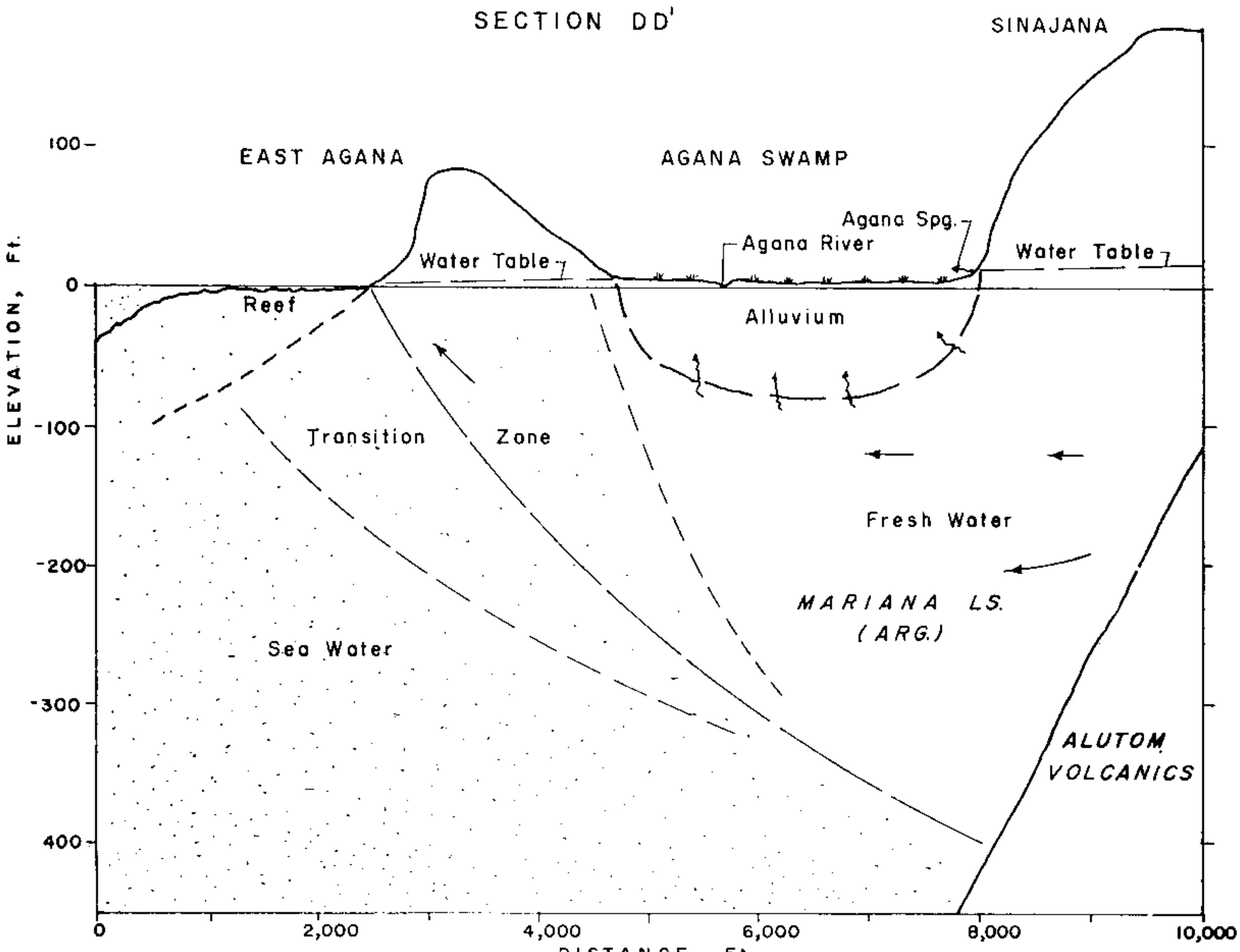


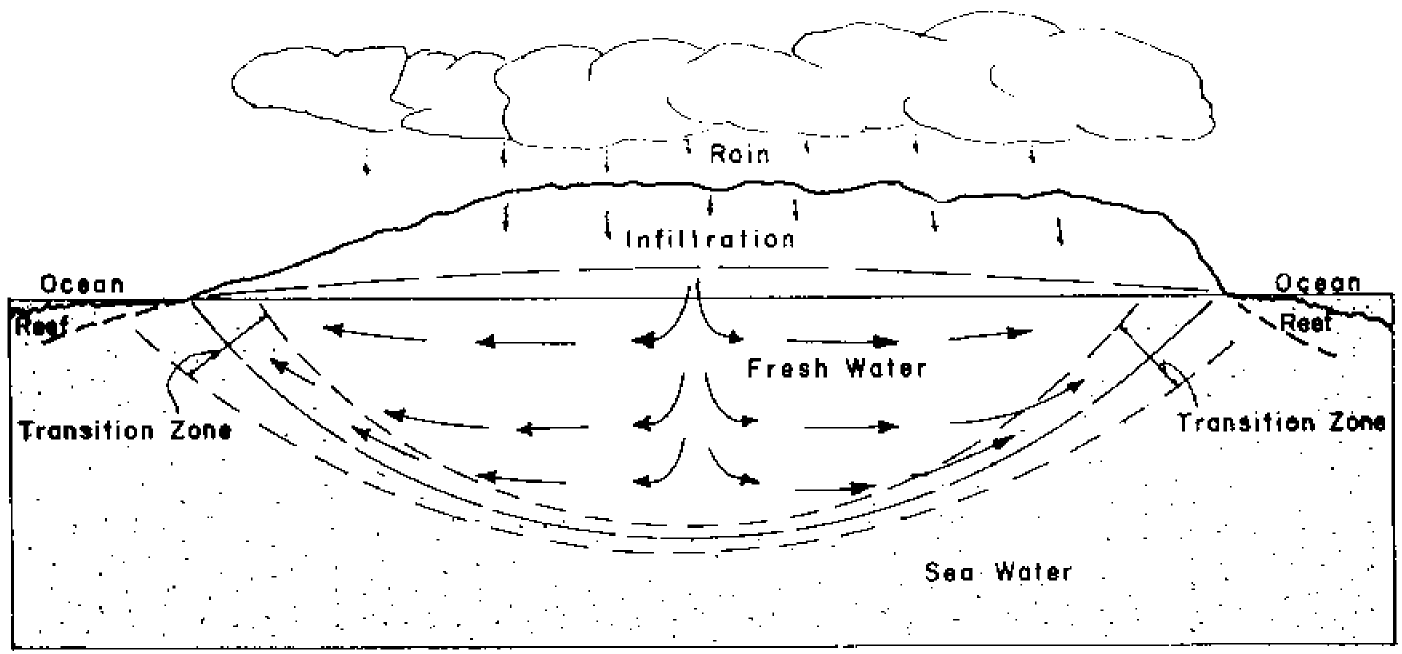
FIG. 4



SECTION DD'
SINAJANA
EAST AGANA
AGANA SWAMP
Agana Spg.
Agana River
Water Table
Water Table
Reef
Alluvium
Transition Zone
Fresh Water
MARIANA LS. (ARG.)
Sea Water
ALUTOM VOLCANICS
ELEVATION, Ft.
100
0
-100
-200
-300
400
0
2,000
4,000
6,000
8,000
10,000
DISTANCE, Ft.

FIG. 5

SECTION EE'



A SCHEMATIC DRAWING SHOWING THE GHYBEN-HERZBERG PRINCIPLE

FIG. 6

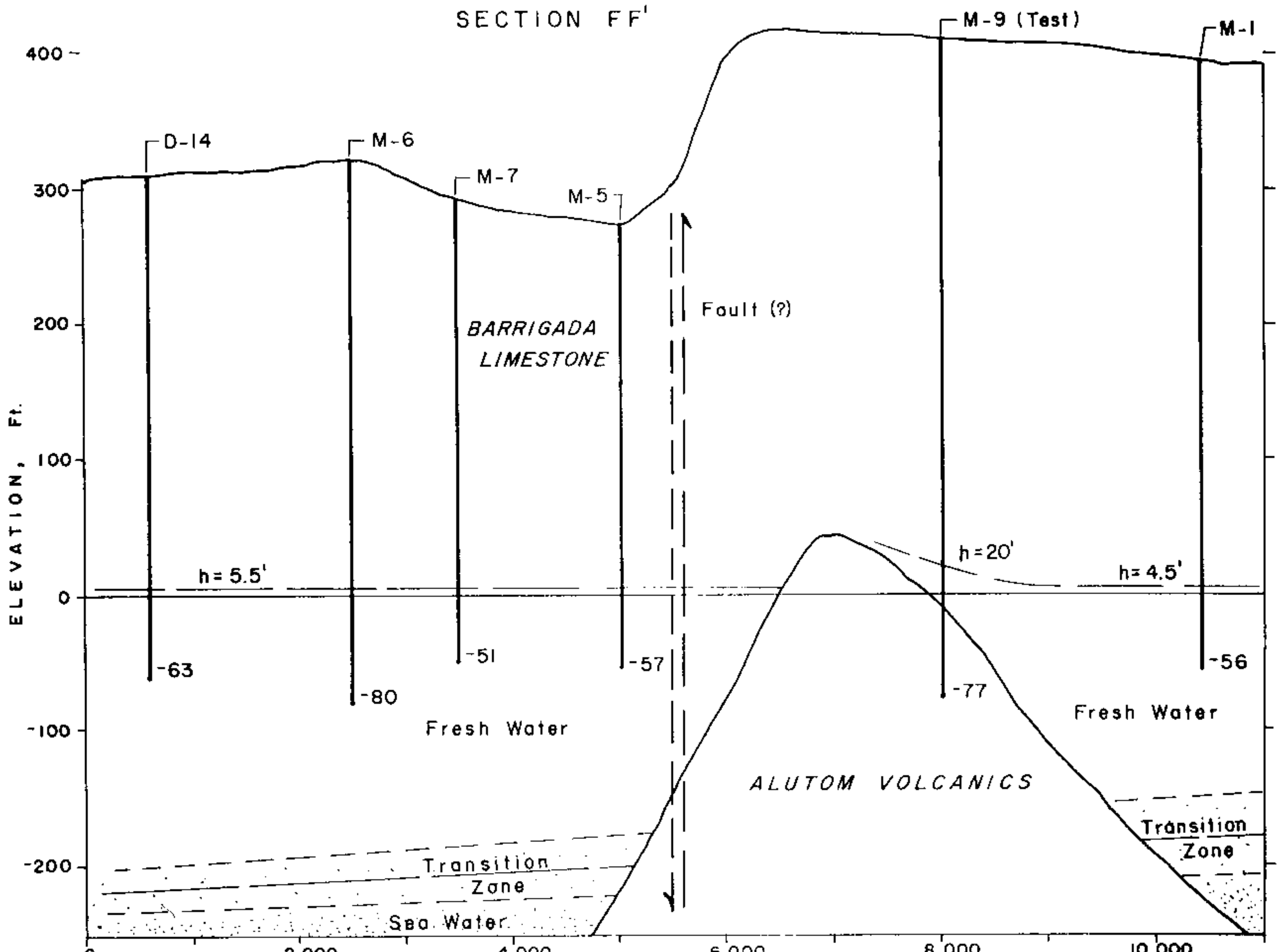

SECTION FF'
D-14
M-6
M-7
M-5
M-9 (Test)
M-1
Fault (?)
BARRIGADA
LIMESTONE
h= 5.5'
h=20'
h= 4.5'
-63
-80
-51
-57
-77
-56
Fresh Water
Fresh Water
ALUTOM VOLCANICS
Transition
Zone
Transition
Zone
Sea Water
400
300
200
100
0
-100
-200
ELEVATION, Ft.
0
2,000
4,000
6,000
8,000
10,000
DISTANCE, Ft.

FIG. 7

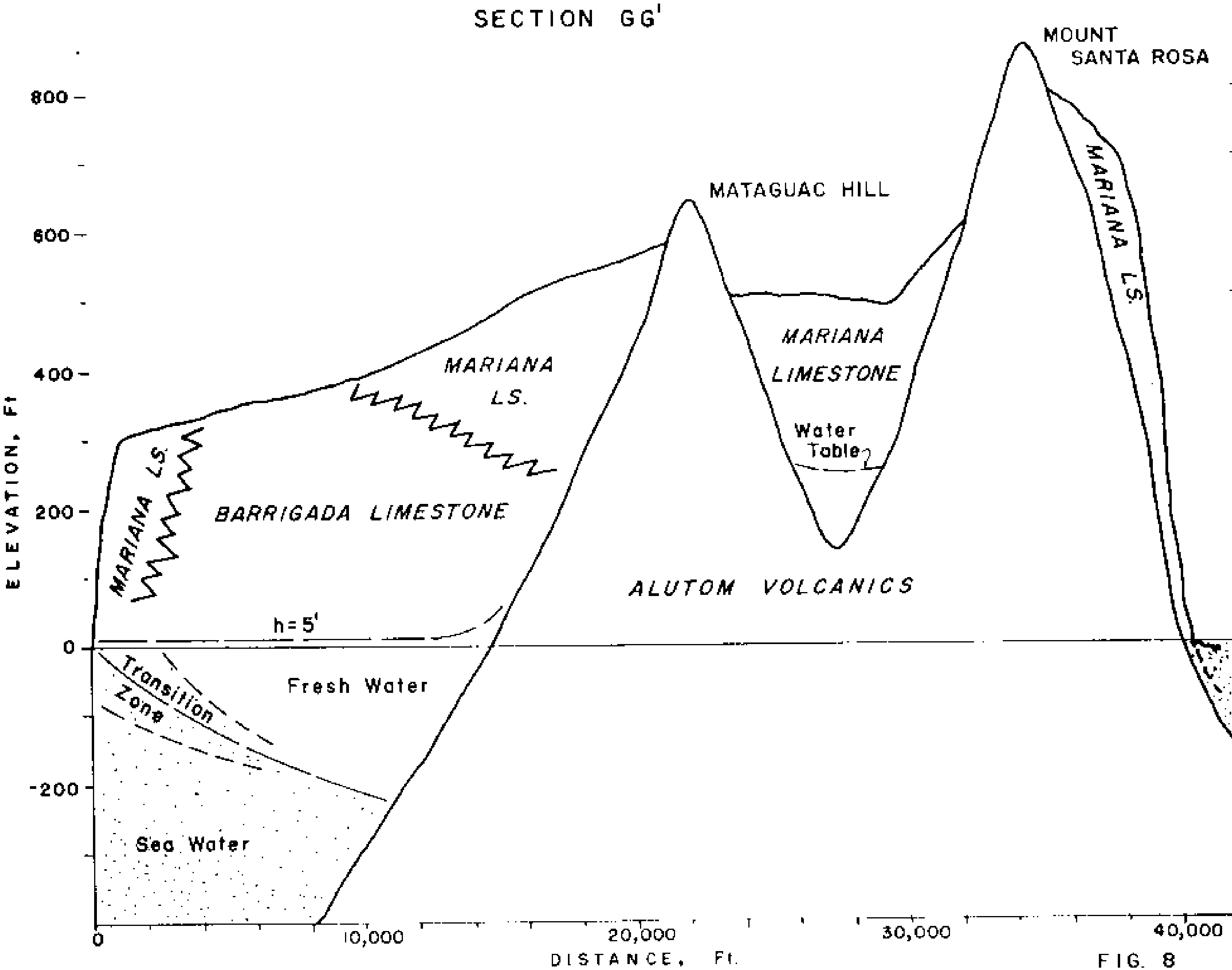

SECTION GG'
MOUNT SANTA ROSA
MATAGUAC HILL
MARIANA LS.
MARIANA LIMESTONE
Water Table
BARRIGADA LIMESTONE
ALUTOM VOLCANICS
h=5'
Fresh Water
Transition Zone
Sea Water
ELEVATION, Ft
800
600
400
200
0
-200
DISTANCE, Ft.
0
10,000
20,000
30,000
40,000

FIG. 8

141

SECTION HH'

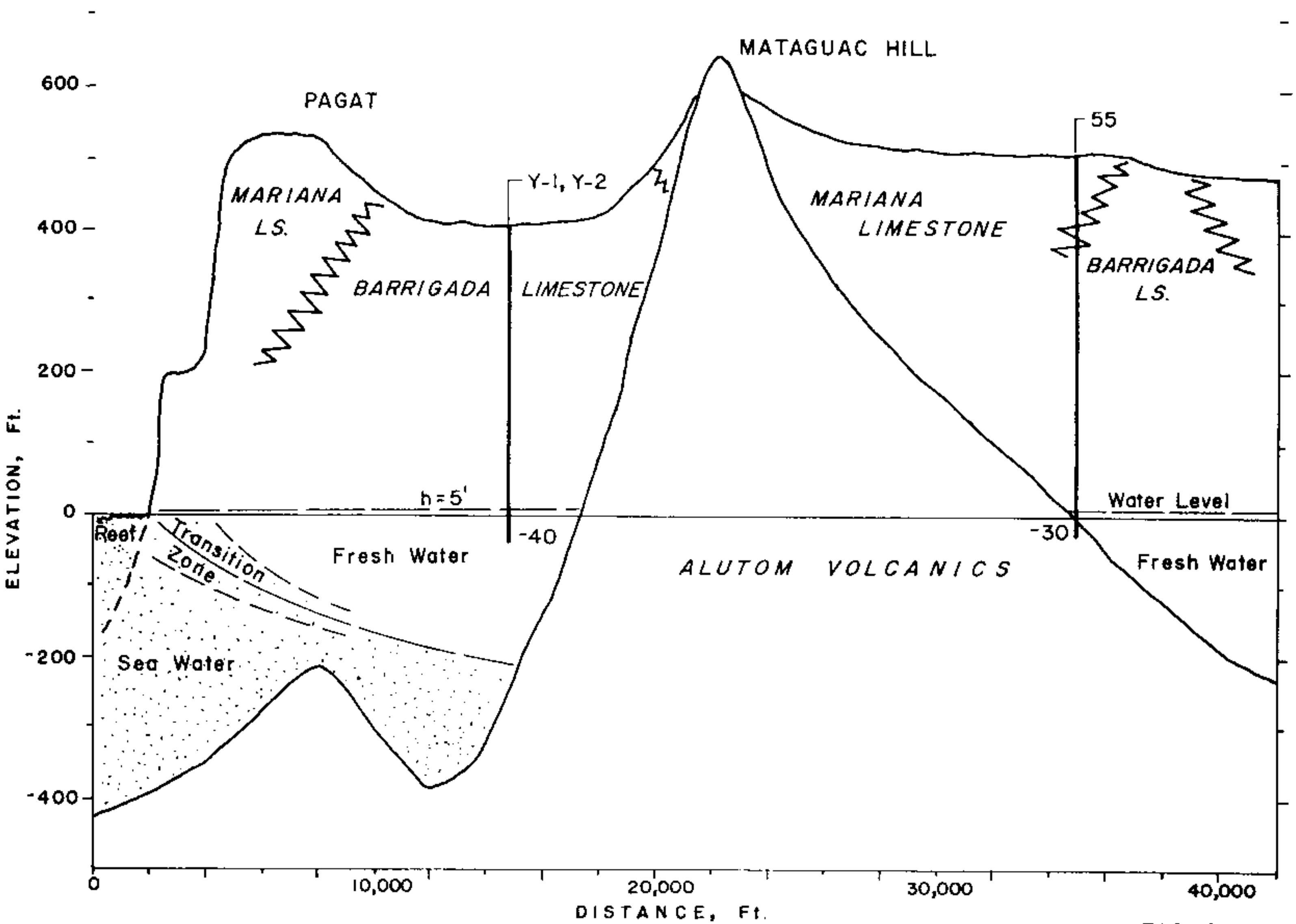


FIG. 9

SECTION II'

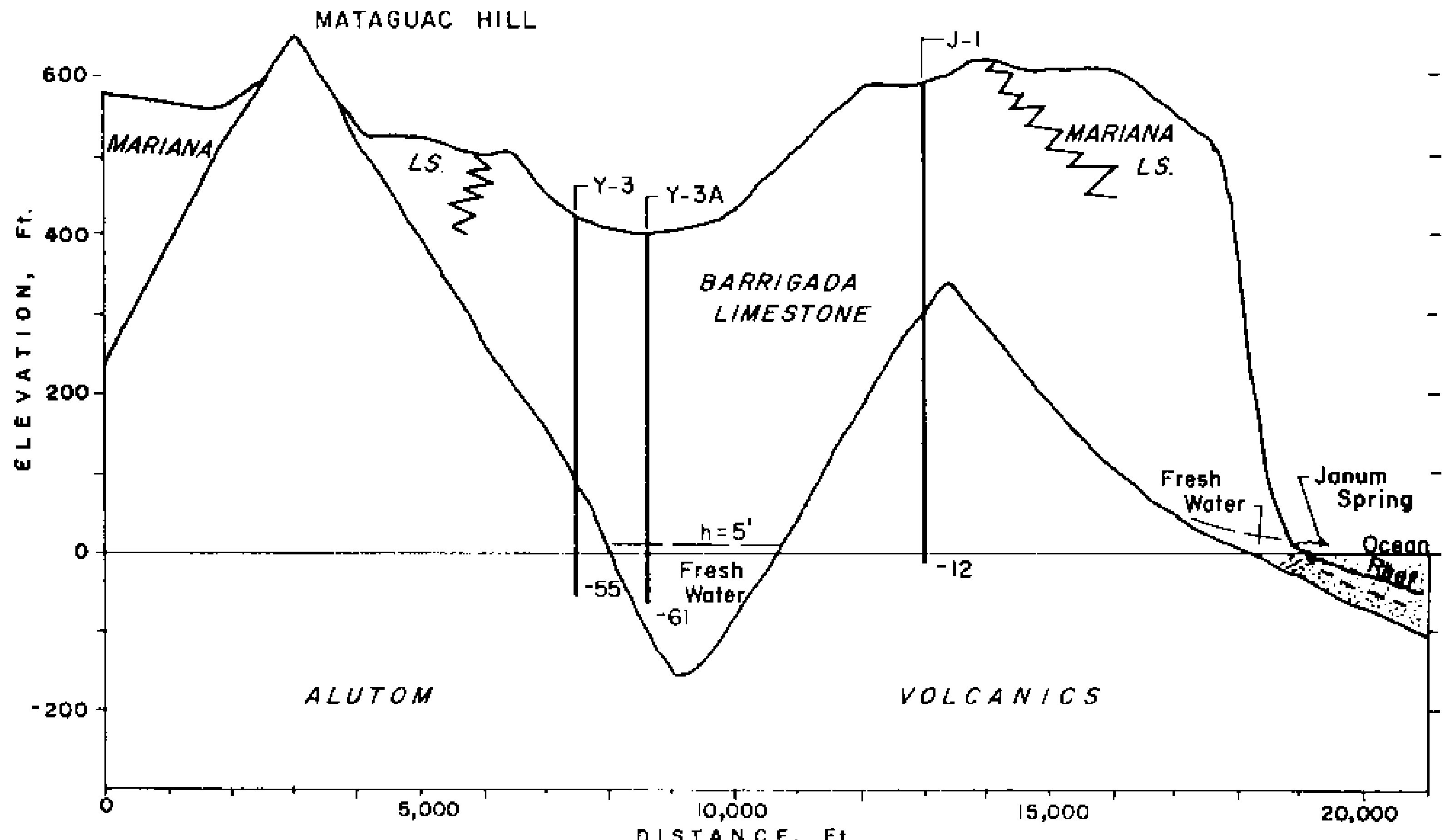


FIG. 10

SECTION AA'

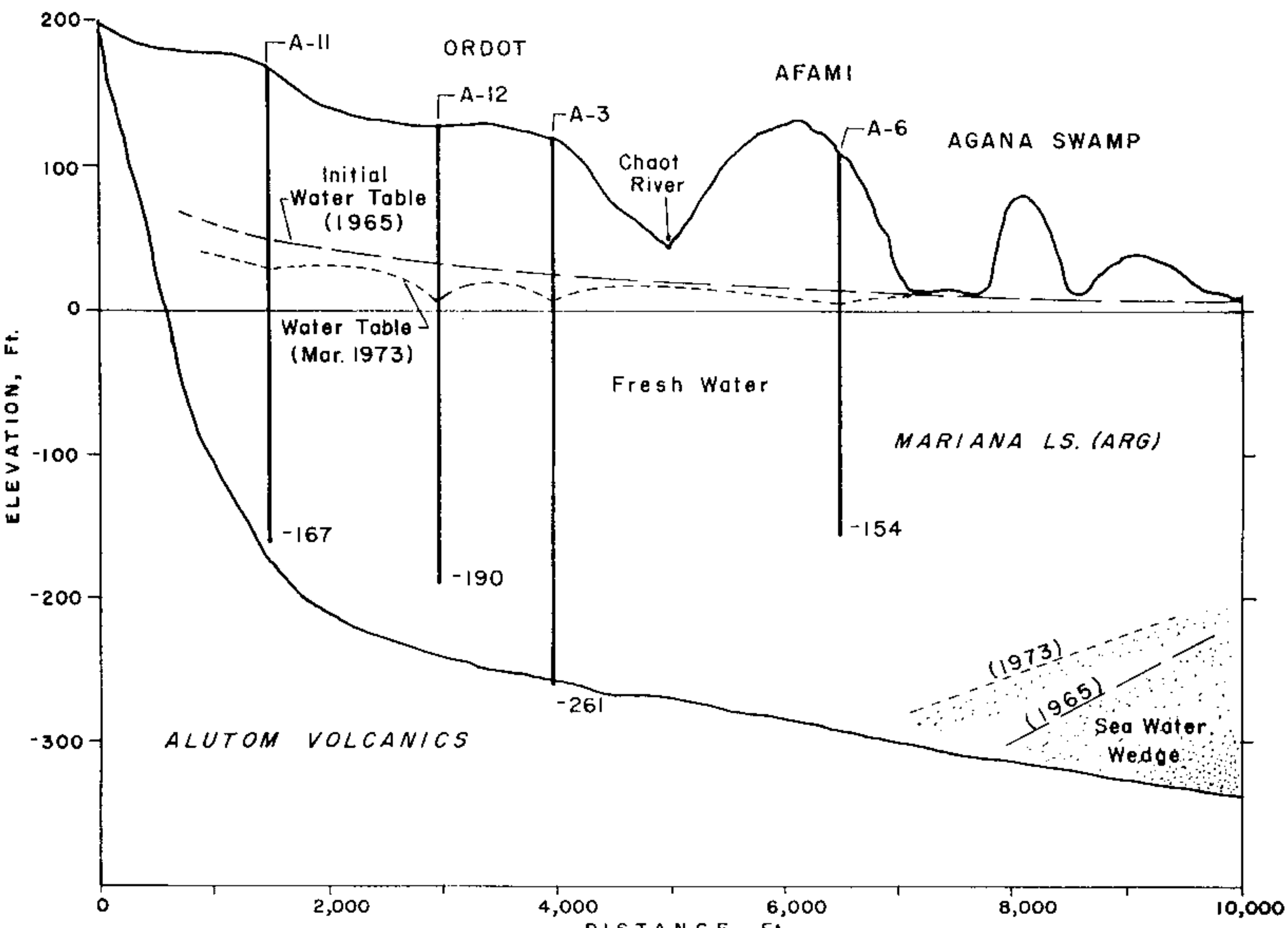


FIG. 11

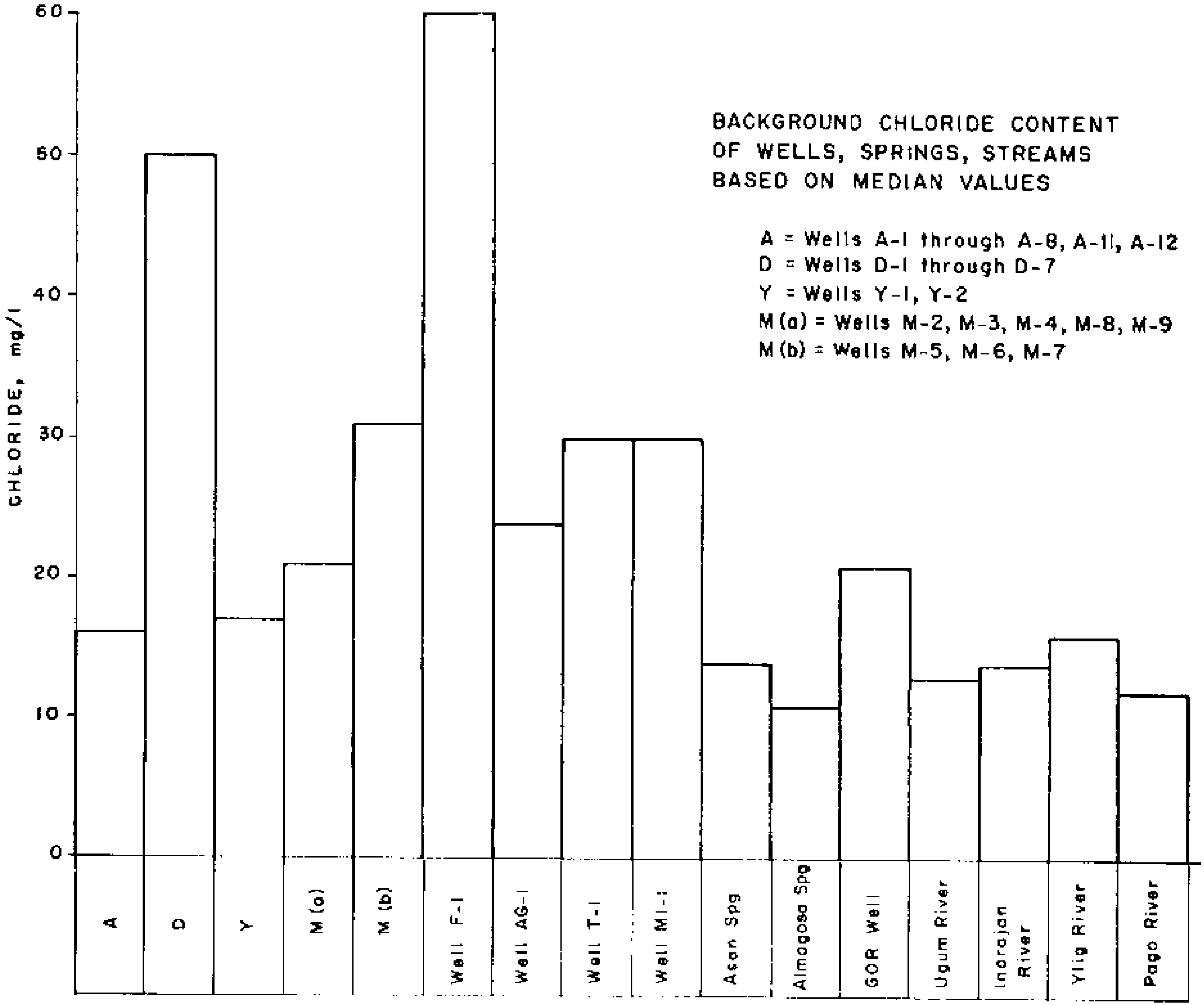
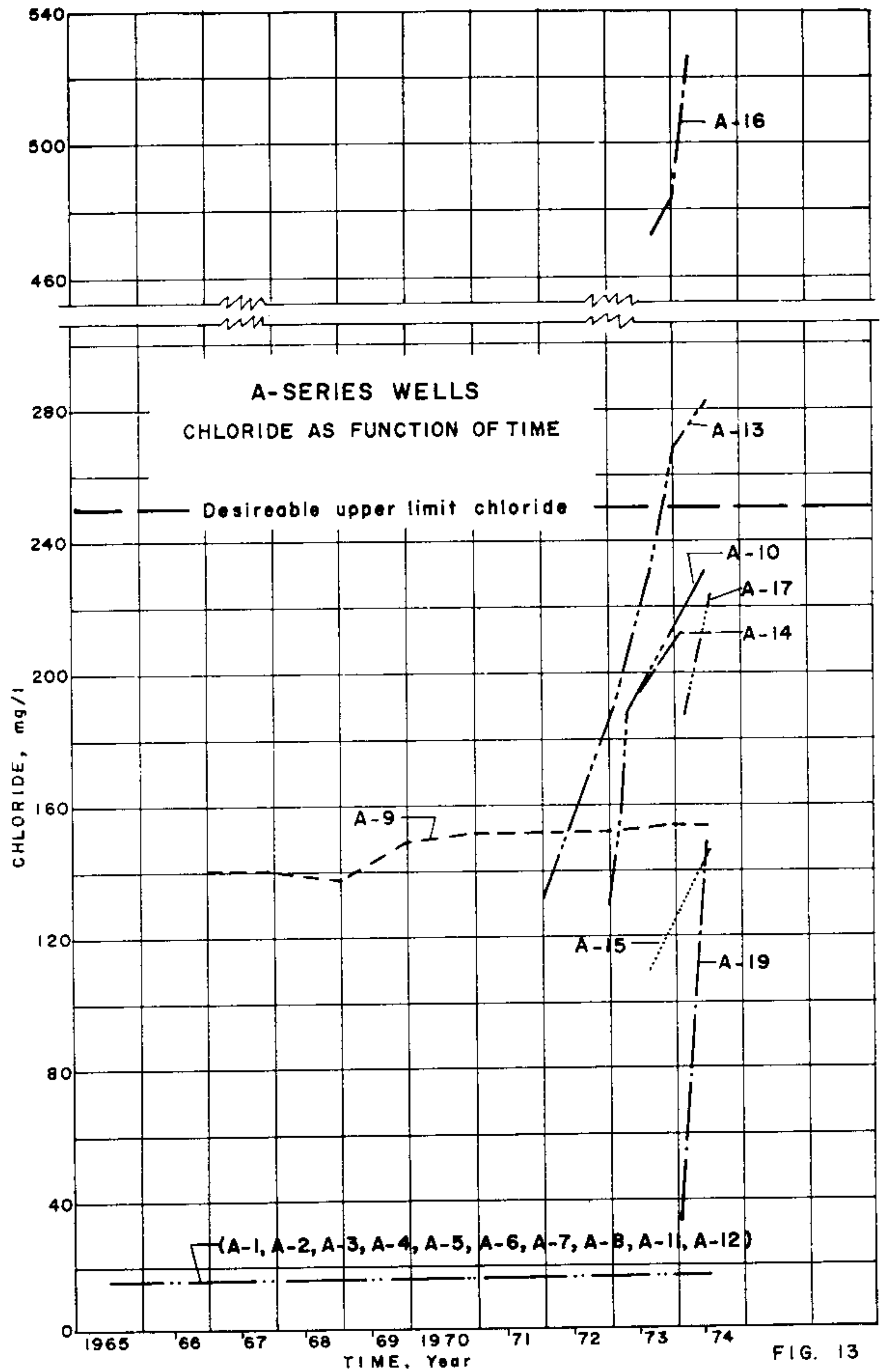

BACKGROUND CHLORIDE CONTENT
OF WELLS, SPRINGS, STREAMS
BASED ON MEDIAN VALUES
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-7
Y = Wells Y-1, Y-2
M (a) = Wells M-2, M-3, M-4, M-8, M-9
M (b) = Wells M-5, M-6, M-7
CHLORIDE, mg/l
60
50
40
30
20
10
0
A
D
Y
M (a)
M (b)
Well F-1
Well AG-1
Well T-1
Well MI-1
Asan Spg
Almagosa Spg
GOR Well
Ugum River
Inarajan River
Ylig River
Pago River

FIG. 12



A-SERIES WELLS
CHLORIDE AS FUNCTION OF TIME
Desireable upper limit chloride
A-16
A-13
A-10
A-17
A-14
A-9
A-15
A-19
(A-1, A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-11, A-12)
CHLORIDE, mg/l
TIME, Year
540
500
460
280
240
200
160
120
80
40
0
1965
'66
'67
'68
'69
1970
'71
'72
'73
'74

FIG. 13

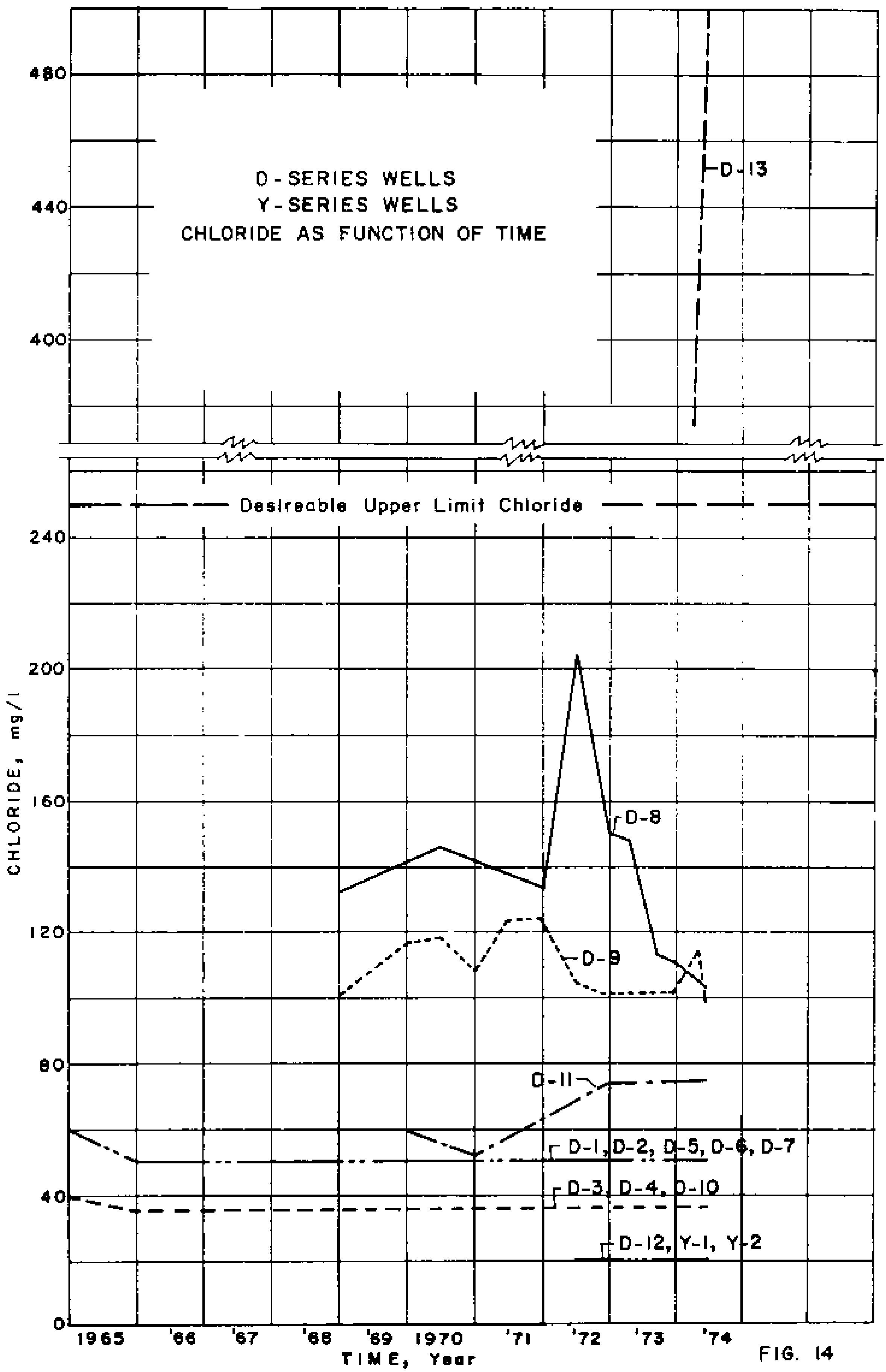

D-SERIES WELLS
Y-SERIES WELLS
CHLORIDE AS FUNCTION OF TIME
480
440
400
240
200
160
120
80
40
0
D-13
Desireable Upper Limit Chloride
D-8
D-9
D-11
D-1, D-2, D-5, D-6, D-7
D-3, D-4, D-10
D-12, Y-1, Y-2
CHLORIDE, mg/l
1965
'66
'67
'68
'69
1970
'71
'72
'73
'74
TIME, Year

FIG. 14

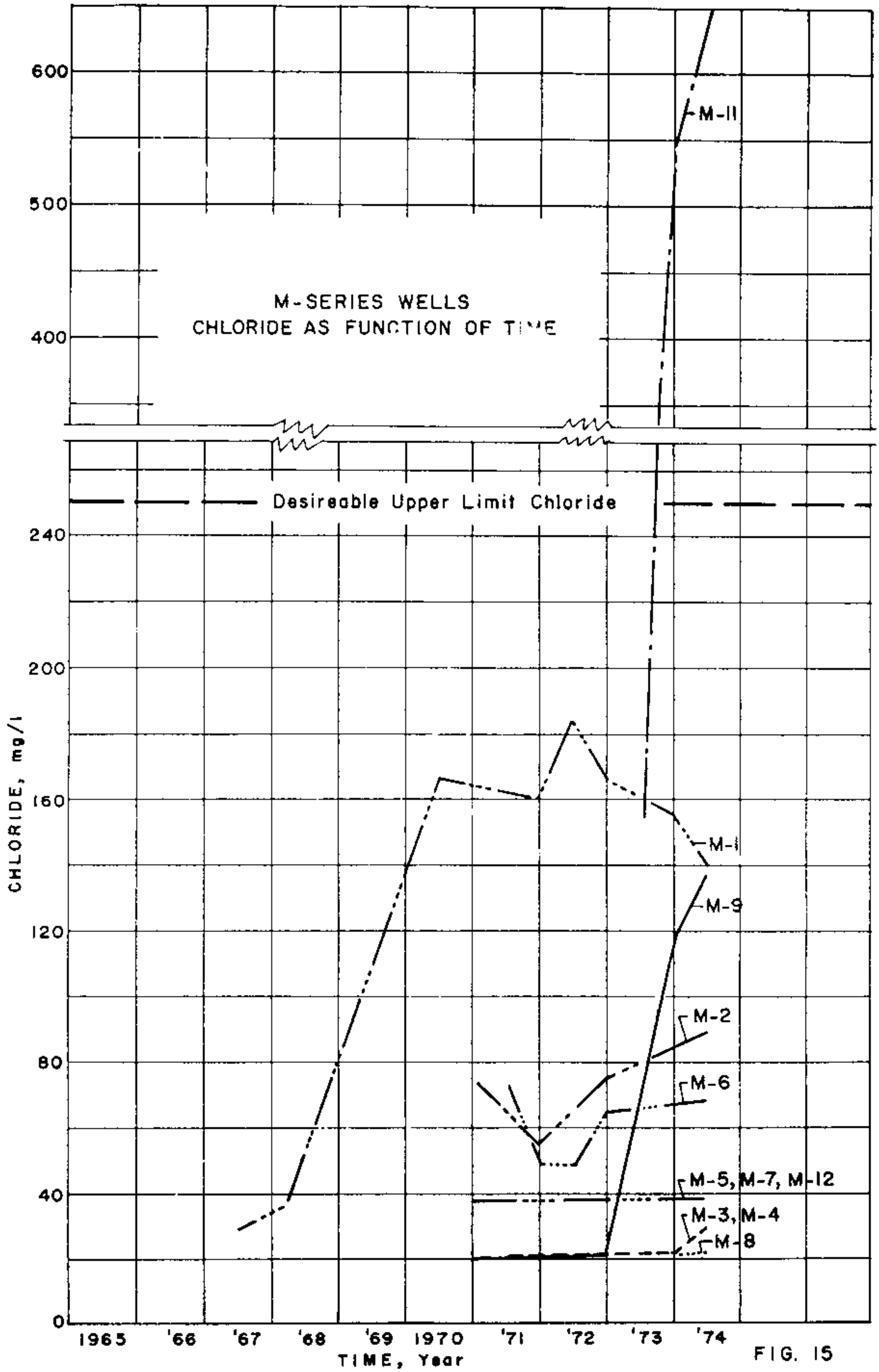
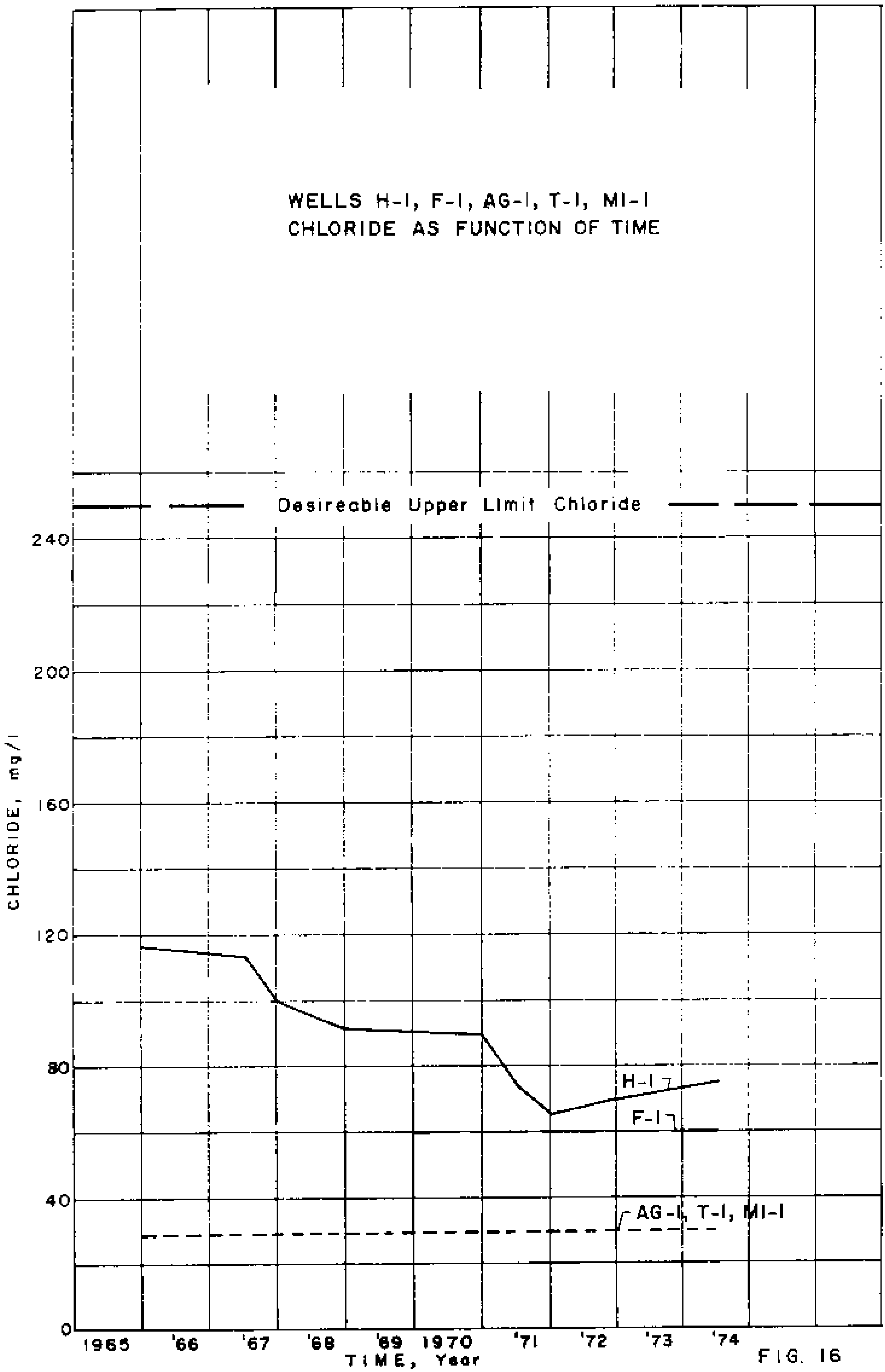
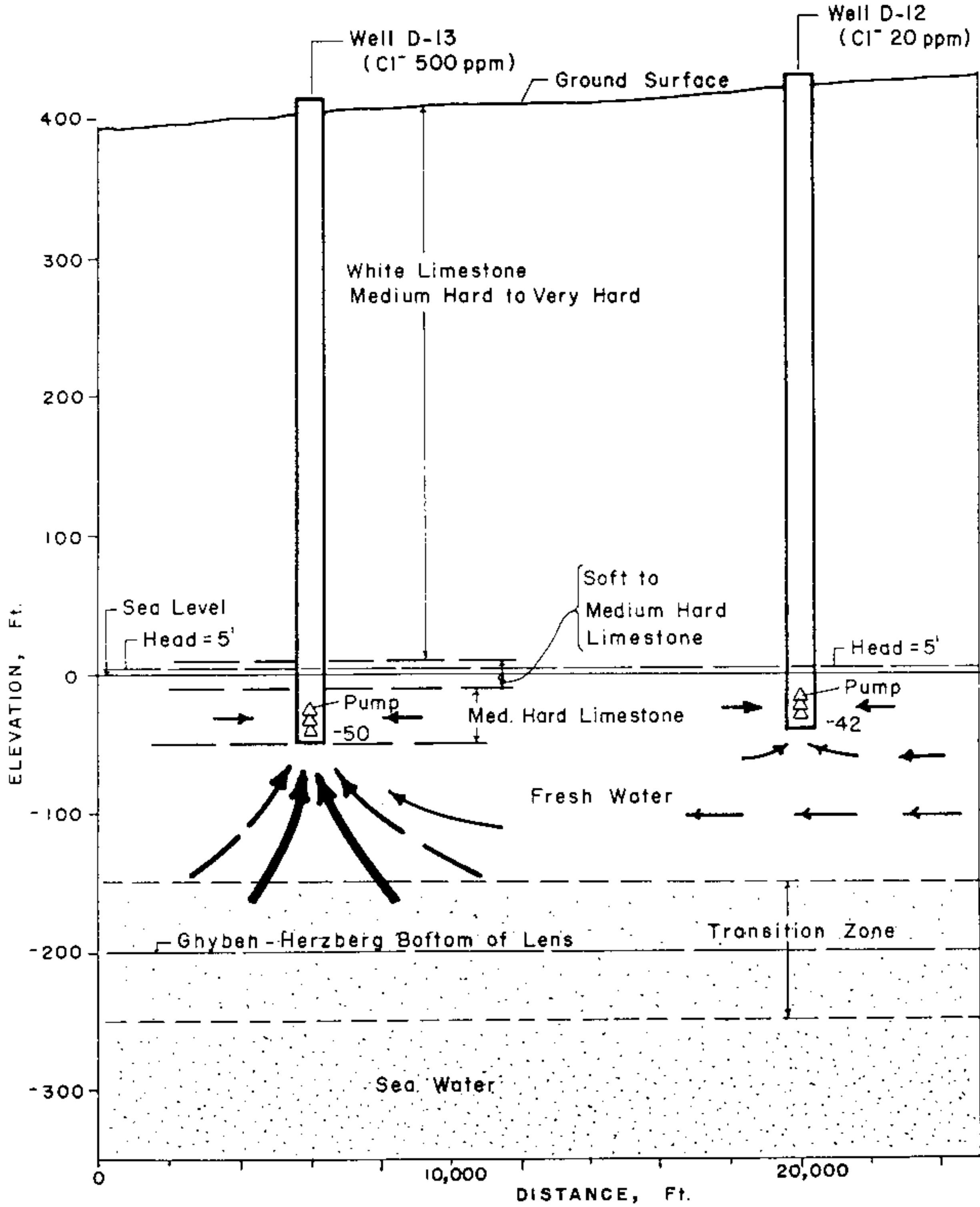

M-SERIES WELLS
CHLORIDE AS FUNCTION OF TIME
Desireable Upper Limit Chloride
CHLORIDE, mg/l
600
500
400
240
200
160
120
80
40
0
M-11
M-1
M-9
M-2
M-6
M-5, M-7, M-12
M-3, M-4
M-8
1965
'66
'67
'68
'69
1970
'71
'72
'73
'74
TIME, Year

FIG. 15



WELLS H-I, F-I, AG-I, T-I, MI-I
CHLORIDE AS FUNCTION OF TIME
Desireable Upper Limit Chloride
240
200
160
120
80
40
0
CHLORIDE, mg/l
H-I
F-I
AG-I, T-I, MI-I
1965
'66
'67
'68
'69
1970
'71
'72
'73
'74
TIME, Year

FIG. 16



Well D-13
(Cl⁻ 500 ppm)
Well D-12
(Cl⁻ 20 ppm)
Ground Surface
White Limestone
Medium Hard to Very Hard
Soft to
Medium Hard
Limestone
Sea Level
Head = 5'
Head = 5'
Pump
-50
Pump
-42
Med. Hard Limestone
Fresh Water
Transition Zone
Ghyben-Herzberg Bottom of Lens
Sea Water
ELEVATION, Ft.
400
300
200
100
0
-100
-200
-300
0
10,000
20,000
DISTANCE, Ft.

FIG. 17

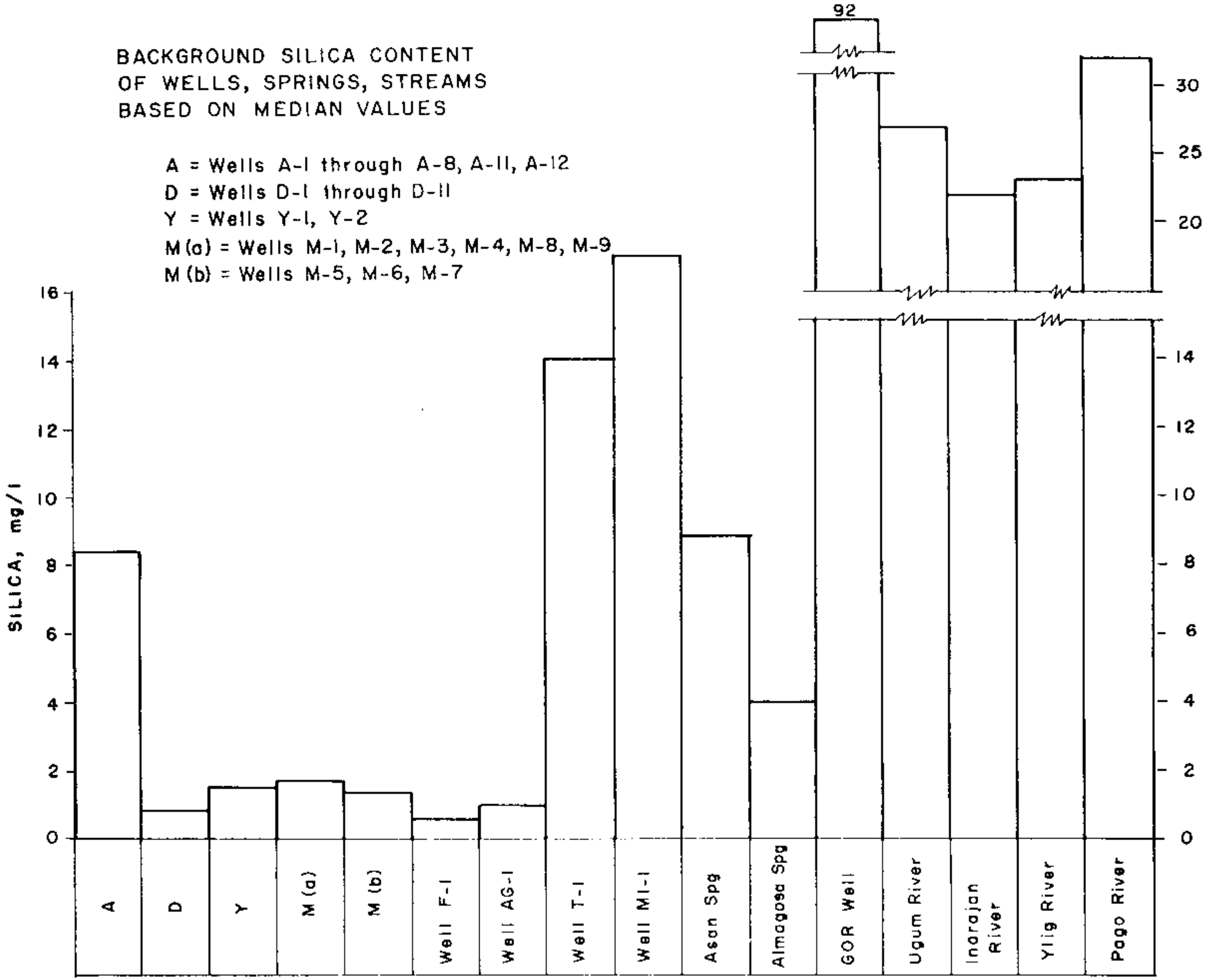

BACKGROUND SILICA CONTENT
OF WELLS, SPRINGS, STREAMS
BASED ON MEDIAN VALUES
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-11
Y = Wells Y-1, Y-2
M (a) = Wells M-1, M-2, M-3, M-4, M-8, M-9
M (b) = Wells M-5, M-6, M-7
SILICA, mg/l
0
2
4
6
8
10
12
14
16
20
25
30
92
A
D
Y
M (a)
M (b)
Well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

FIG. 18

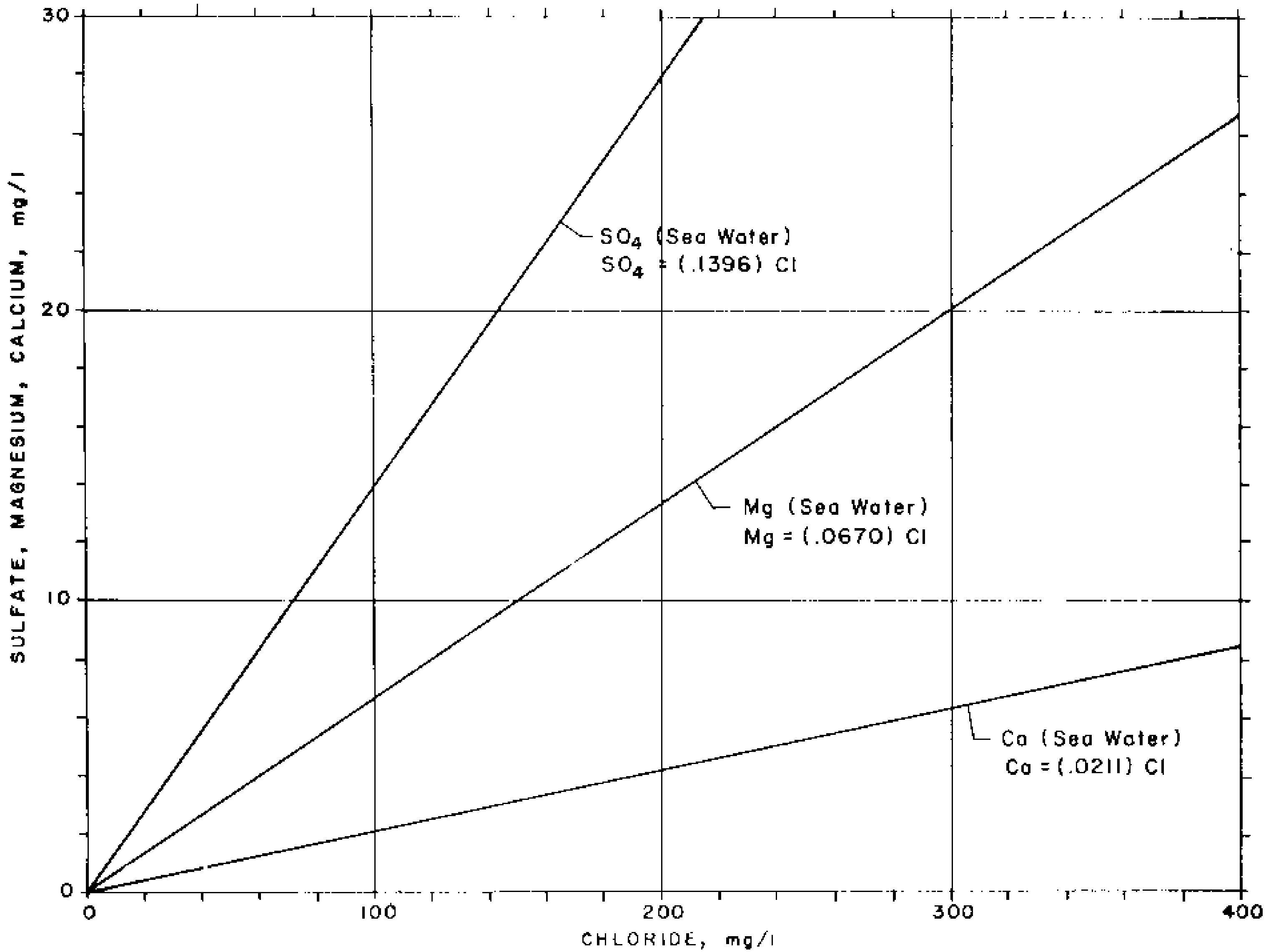

SULFATE, MAGNESIUM, CALCIUM, mg/l
30
20
10
0
0
100
200
300
400
CHLORIDE, mg/l
SO4 (Sea Water)
SO4 = (.1396) Cl
Mg (Sea Water)
Mg = (.0670) Cl
Ca (Sea Water)
Ca = (.0211) Cl

FIG. 19

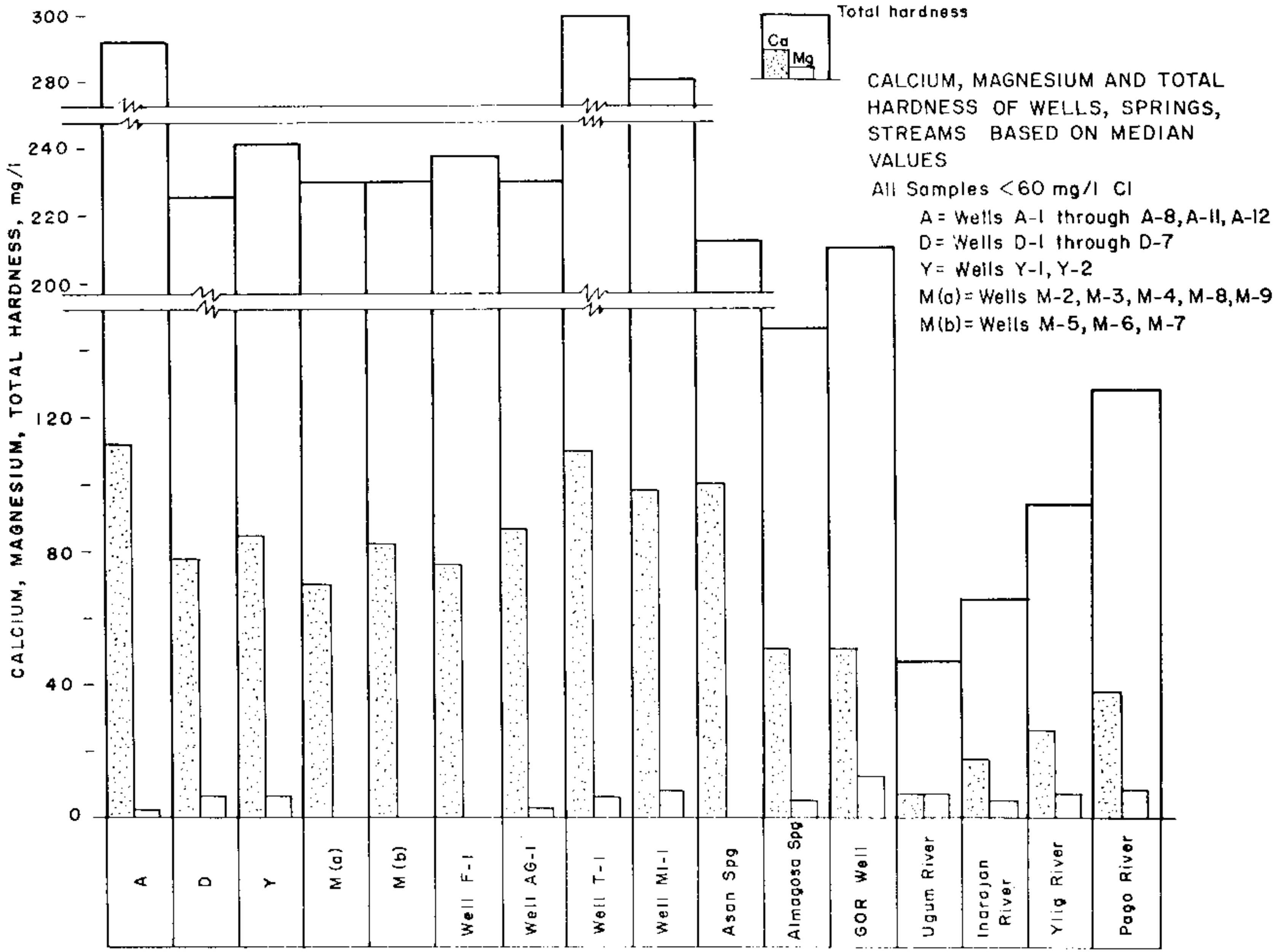

Total hardness
Ca
Mg
CALCIUM, MAGNESIUM AND TOTAL HARDNESS OF WELLS, SPRINGS, STREAMS BASED ON MEDIAN VALUES
All Samples <60 mg/l Cl
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-7
Y = Wells Y-1, Y-2
M(a) = Wells M-2, M-3, M-4, M-8, M-9
M(b) = Wells M-5, M-6, M-7
CALCIUM, MAGNESIUM, TOTAL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

FIG. 20

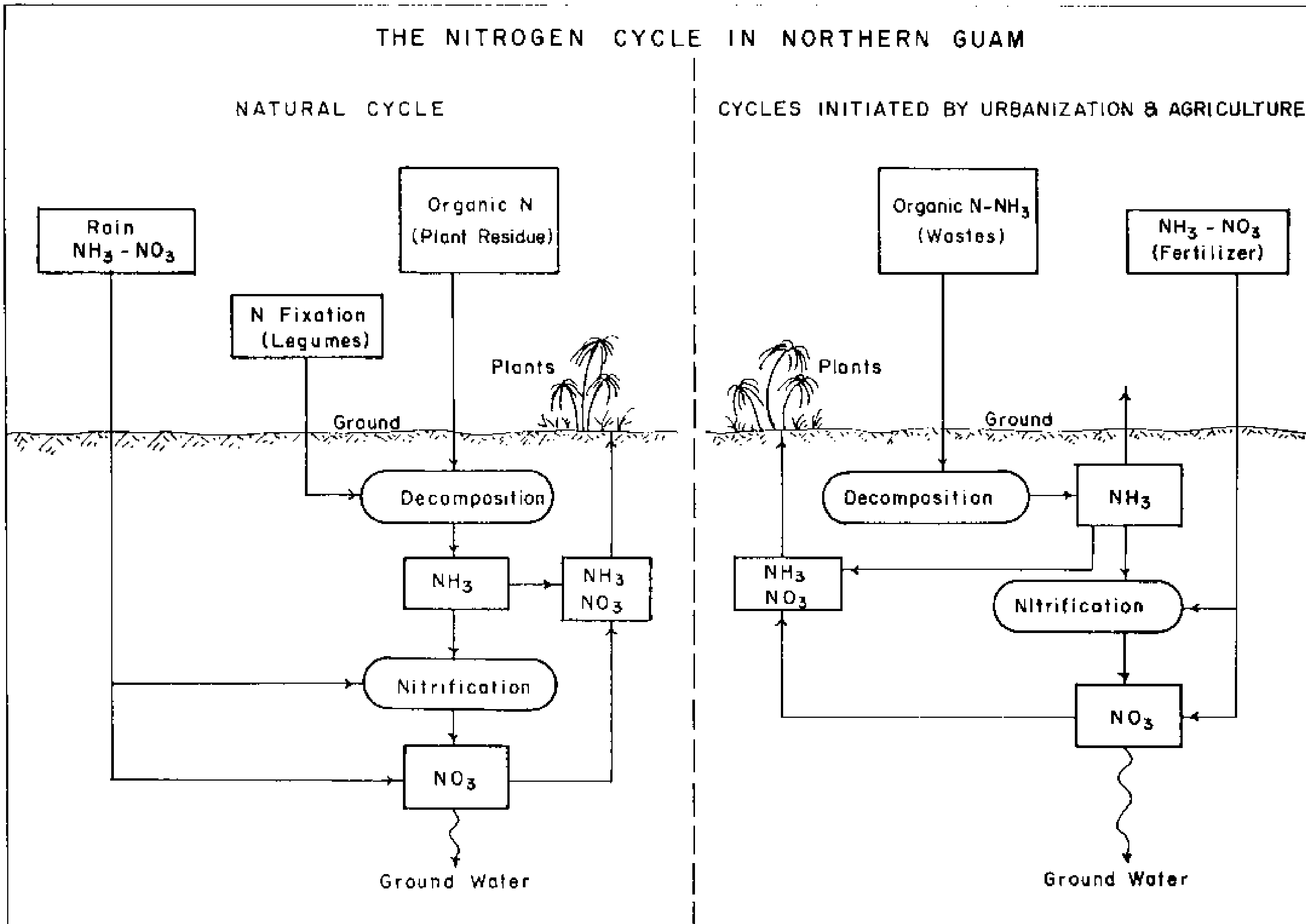

THE NITROGEN CYCLE IN NORTHERN GUAM
NATURAL CYCLE
Rain
NH_3 - NO_3
Organic N
(Plant Residue)
N Fixation
(Legumes)
Plants
Ground
Decomposition
NH_3
NH_3
NO_3
Nitrification
NO_3
Ground Water
CYCLES INITIATED BY URBANIZATION & AGRICULTURE
Organic N-NH_3
(Wastes)
NH_3 - NO_3
(Fertilizer)
Plants
Ground
Decomposition
NH_3
NH_3
NO_3
Nitrification
NO_3
Ground Water

FIG. 21

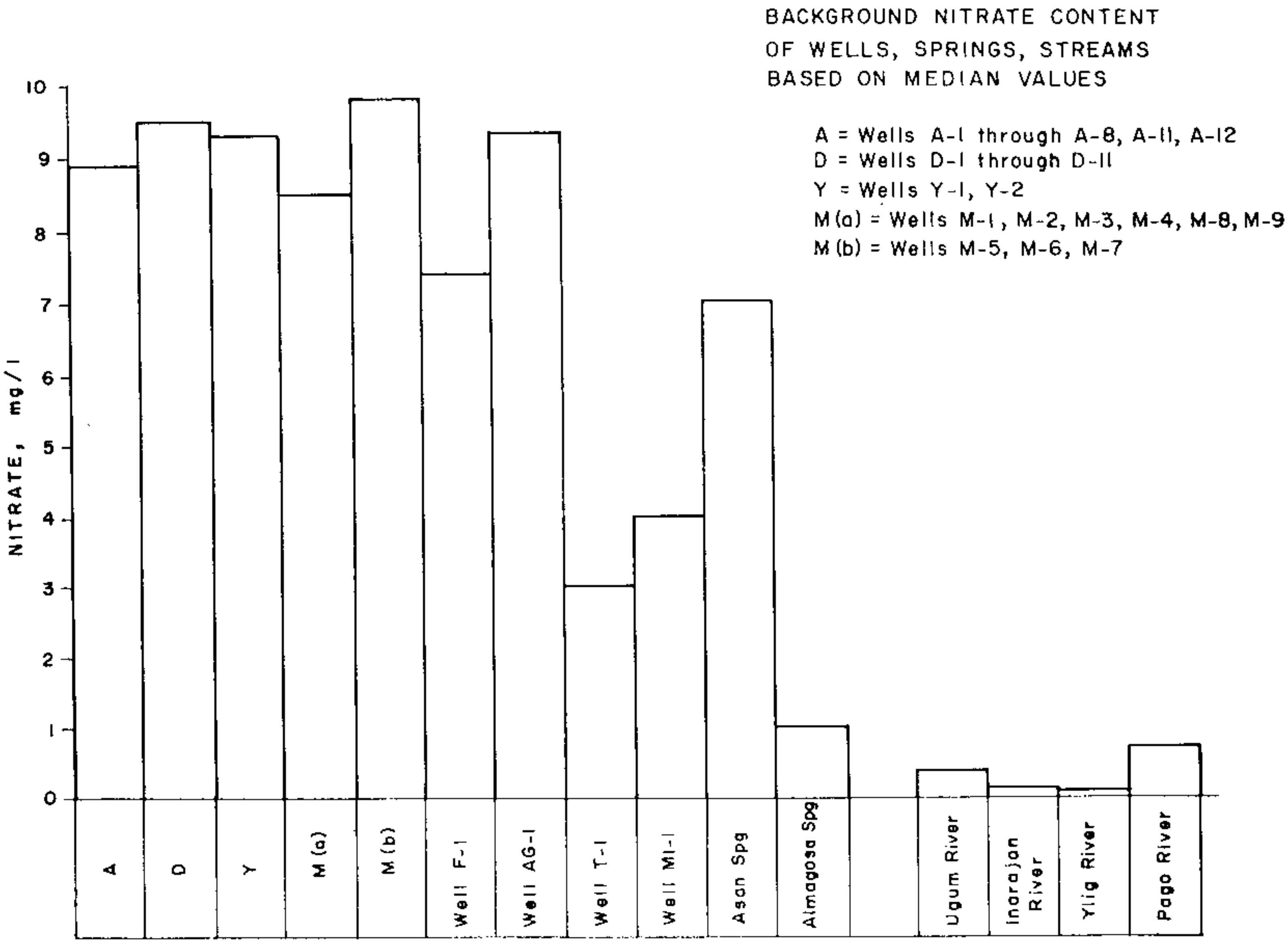
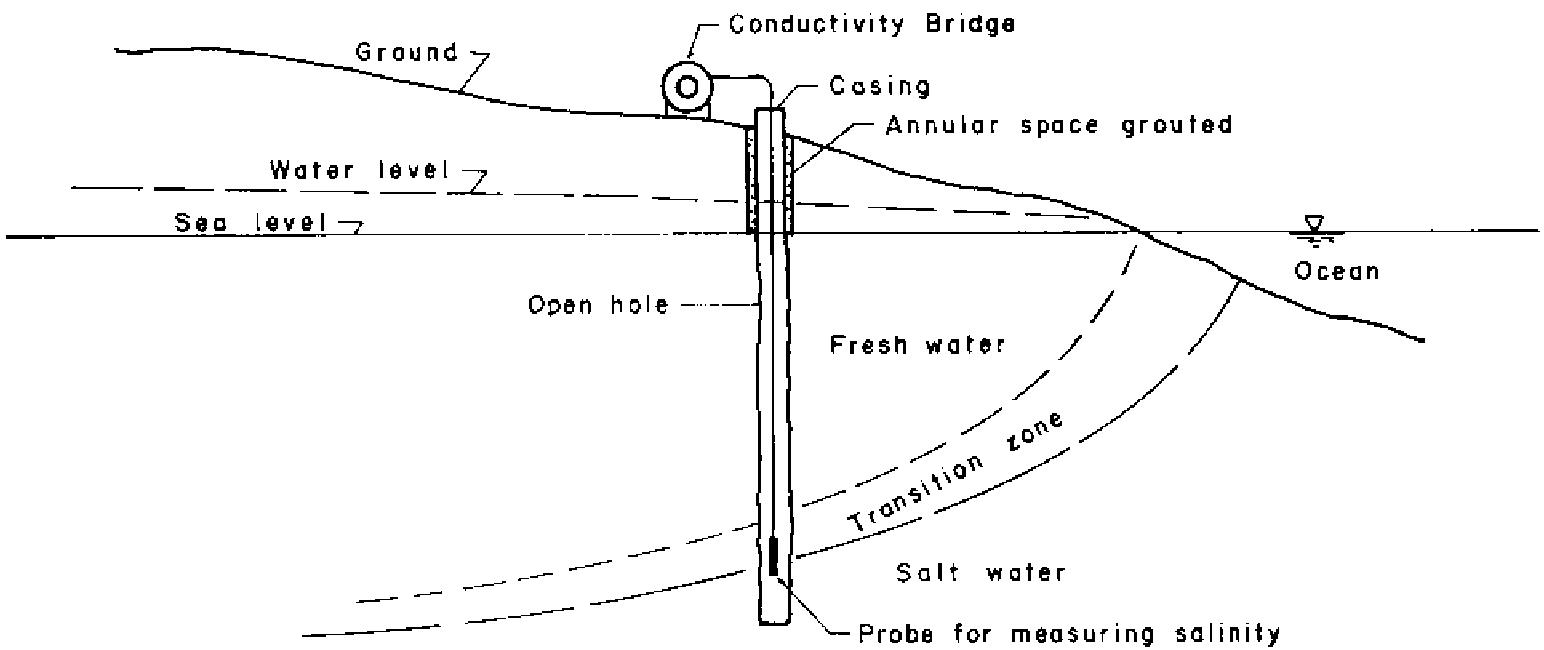

BACKGROUND NITRATE CONTENT
OF WELLS, SPRINGS, STREAMS
BASED ON MEDIAN VALUES
A = Wells A-1 through A-8, A-11, A-12
D = Wells D-1 through D-11
Y = Wells Y-1, Y-2
M(a) = Wells M-1, M-2, M-3, M-4, M-8, M-9
M(b) = Wells M-5, M-6, M-7
NITRATE, mg/l
0
1
2
3
4
5
6
7
8
9
10
A
D
Y
M(a)
M(b)
Well F-1
Well AG-1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

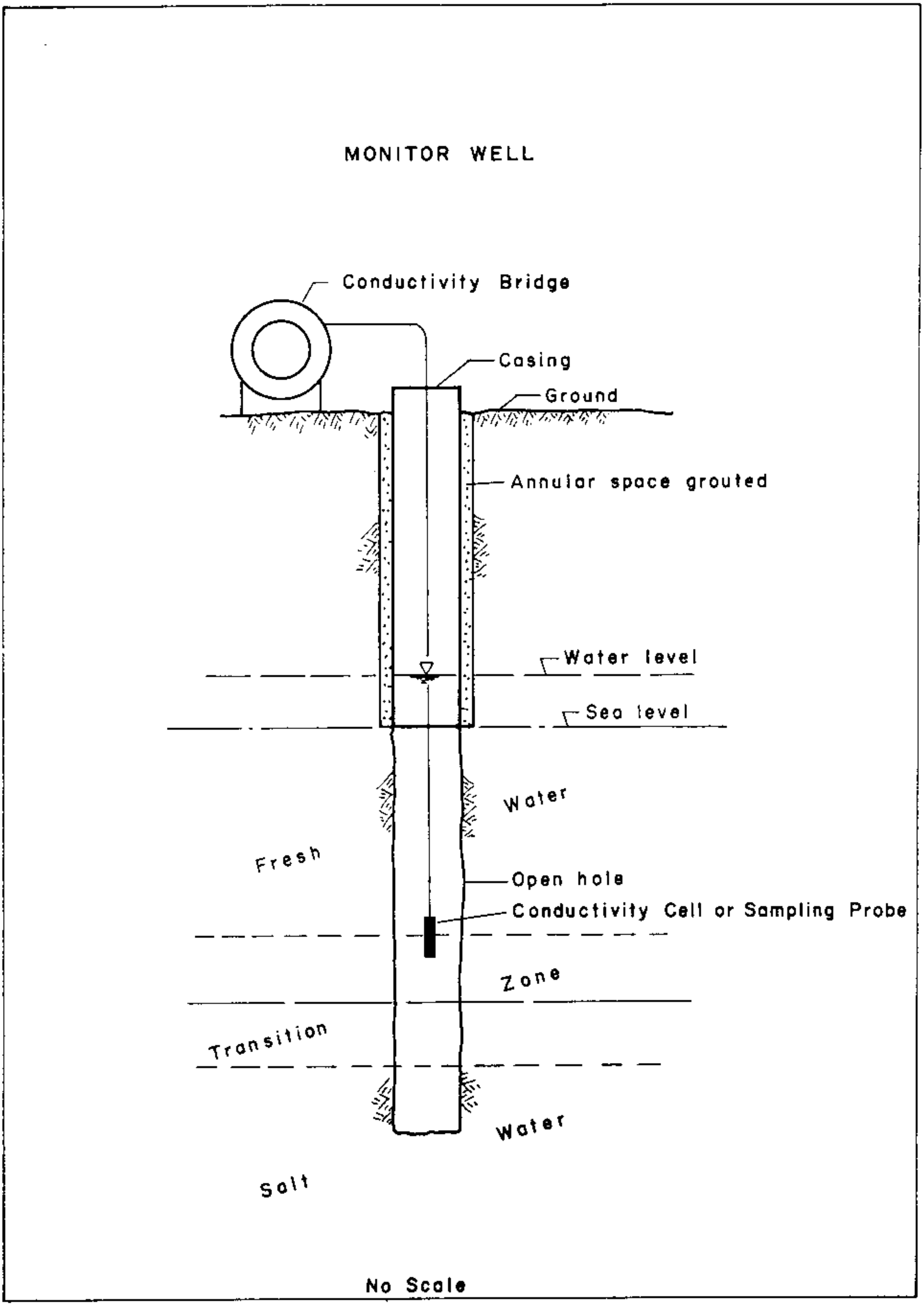
FIG. 22

MONITOR WELL IN GHYBEN-HERZBERG LENS



No Scale

FIG. 23



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

FIG. 24

APPENDIX A-1

Simple derivation of the Ghyben-Herzberg principle

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

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

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

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

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

where:

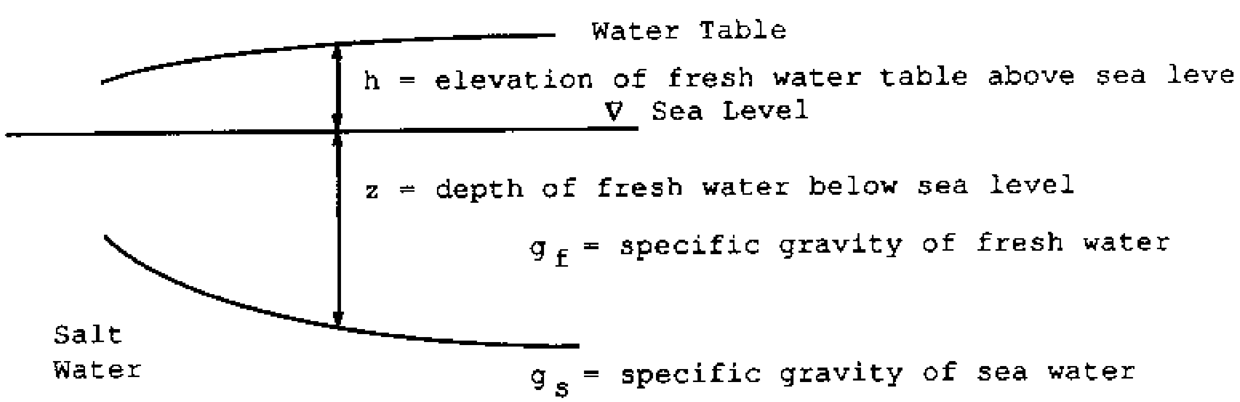


Fig. 1-1

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

(4) $z = 40\ h$

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

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

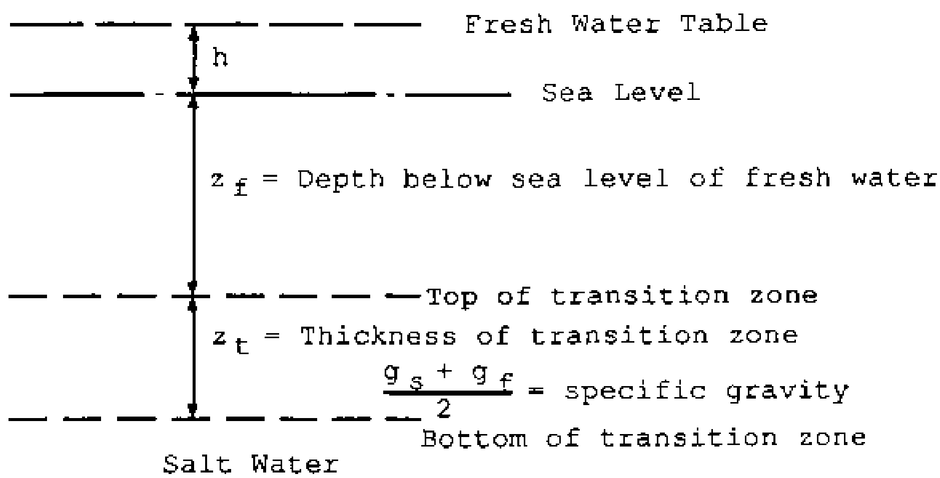


Fig. 1-2

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

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

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

then:

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

and:

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

which is the middle of the transition zone.

APPENDIX A-2

The Shape of the Ghyben-Herzberg Lens

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

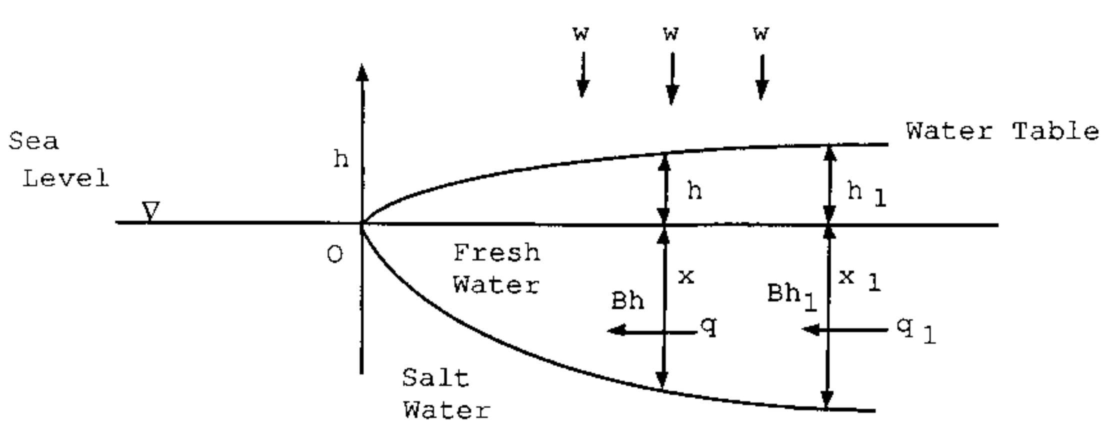


Fig. 2-1

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

Continuity requires that:

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

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

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

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

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

Equating (1) and (3):

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

which in integrable form with approximate limits becomes:

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

and on solution:

(6) $$q_1x + wx_1x - \frac{wx^2}{2} = \frac{41kh^2}{2}$$

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

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

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

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

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

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

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

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

The approximate conditions are:

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

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

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

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

APPENDIX A-3

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

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

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

in which:

h = maximum amplitude of the tide in the aquifer, ft.

h_o = maximum amplitude of the.tide in the sea, ft.

x = distance inland from the sea coast, ft.

s = storage coefficient,or specific yield

T = transmissivity, ft^2/d

t_o = period of tidal cycle (approx. 0.5 days)

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

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

MHHW (mean higher high water) ... 2.3 ft.

MHW (mean higher water) ... 2.2 ft.

MWL (mean water level) ... 1.4 ft.

MLW (mean lower water) ... 0,6 ft.

MLLW (mean lower low water) ... 0.0 ft.

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

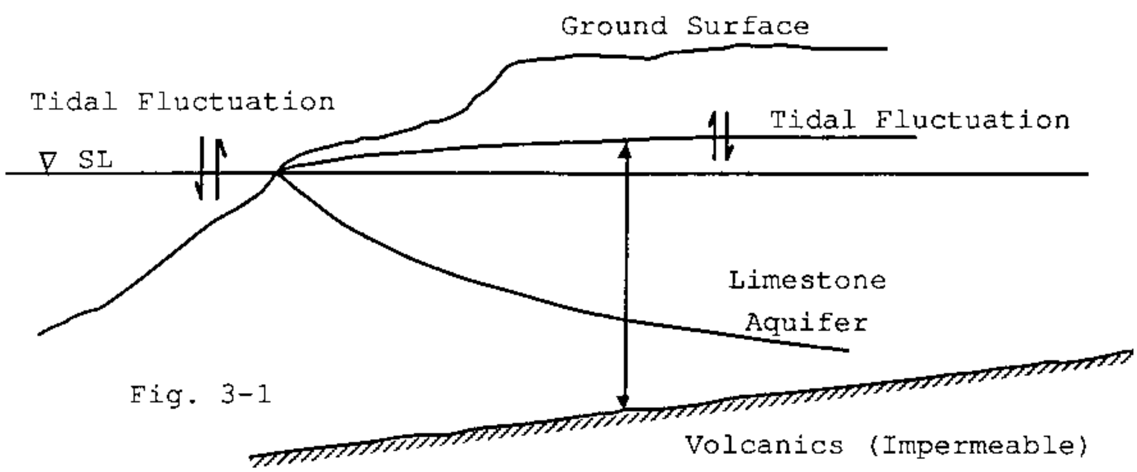


Fig. 3-1

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

Table 3-1

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

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

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

APPXNDIX A-4

<u>Decay of an unconfined Ghyben-Herzberg lens under conditions of no recharge</u>

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

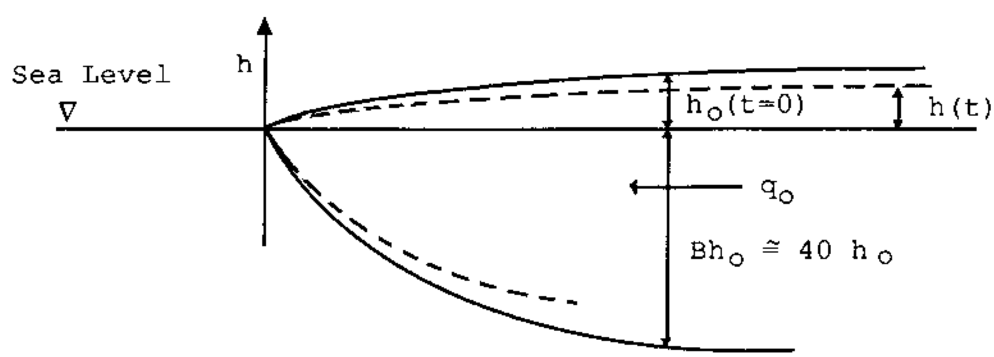


Fig. 4-1

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

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

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

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

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

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

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

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

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

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

from which:

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

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

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

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

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

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

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

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

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

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

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

or:

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

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

$h_o = 5.5$ ft; $x_o = 12{,}000$ ft; $q_o = 103\ ft^3/d$

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

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

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

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

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

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

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

Equating equations (13) and (14):

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

and solving for h_1:

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

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

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

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

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

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

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

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

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

Equation (16) would then become:

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

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

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

APPENDIX A-5

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX A-6

WASTE WATER DISPOSAL BY MEANS OF INJECTION WELLS

HYDRAULICS OF INJECTION WELLS

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

Injection Well in Basal Lens

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

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

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

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

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

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

From Equation 1:

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

and thus:

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

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

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

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

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

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

and:

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

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

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

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

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

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

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

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

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

Discharge at the Sea Coast

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

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

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

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

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

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

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

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

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

and

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

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

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

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

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

Effect of Injection Wells on Pumping Wells

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

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

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

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

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

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

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

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

Injection in Salt Water Below the Lens

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

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

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

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

g_f = density of effluent $\cong$ 1.000

d = depth below sea level to bottom of casing

h_e = head of effluent column above sea level

In terms of effluent head,

$$(17) \quad h_e = \frac{(\rho_s - \rho_f)}{\rho_f} d$$

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

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

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

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

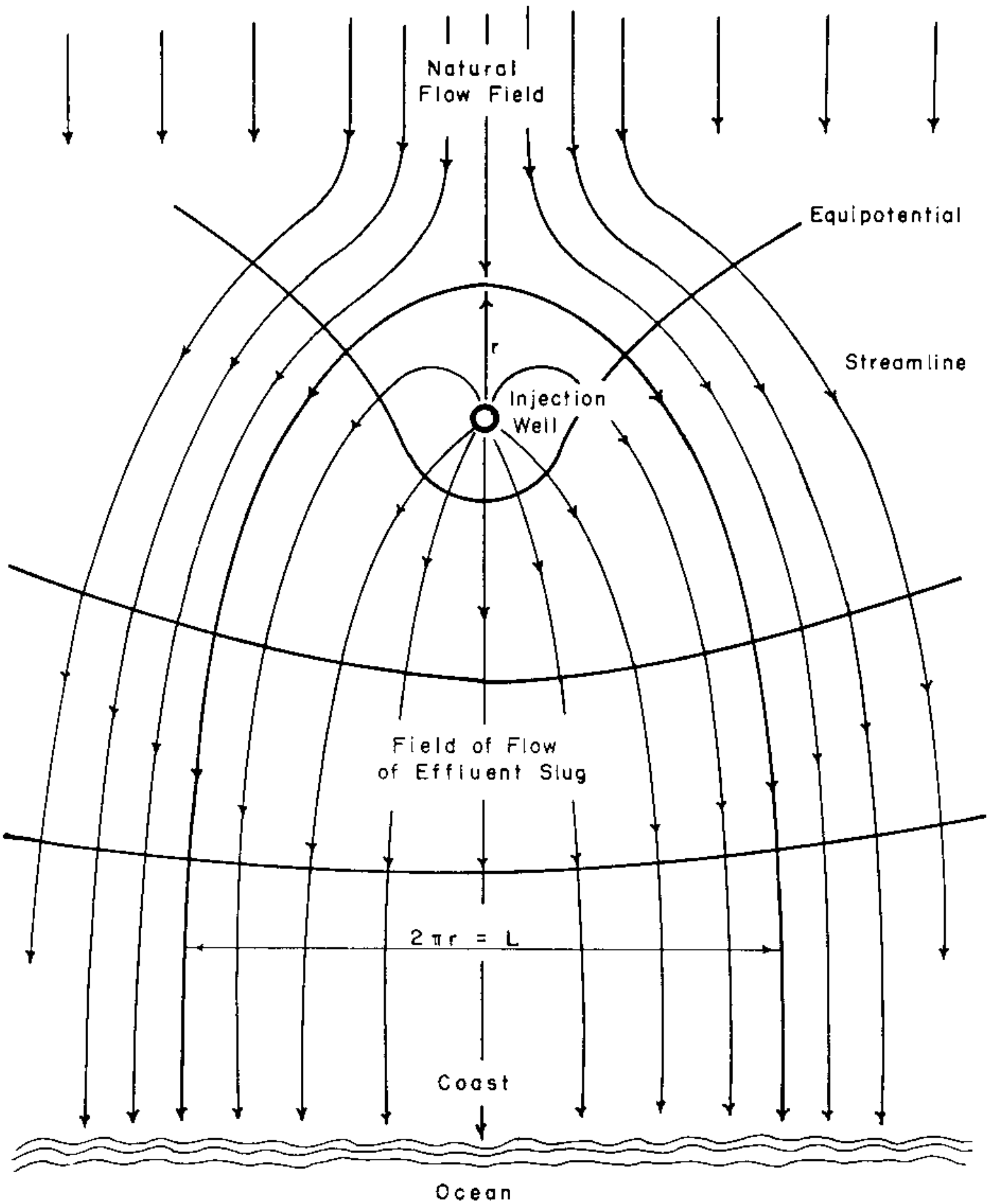


FIGURE 6-1

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

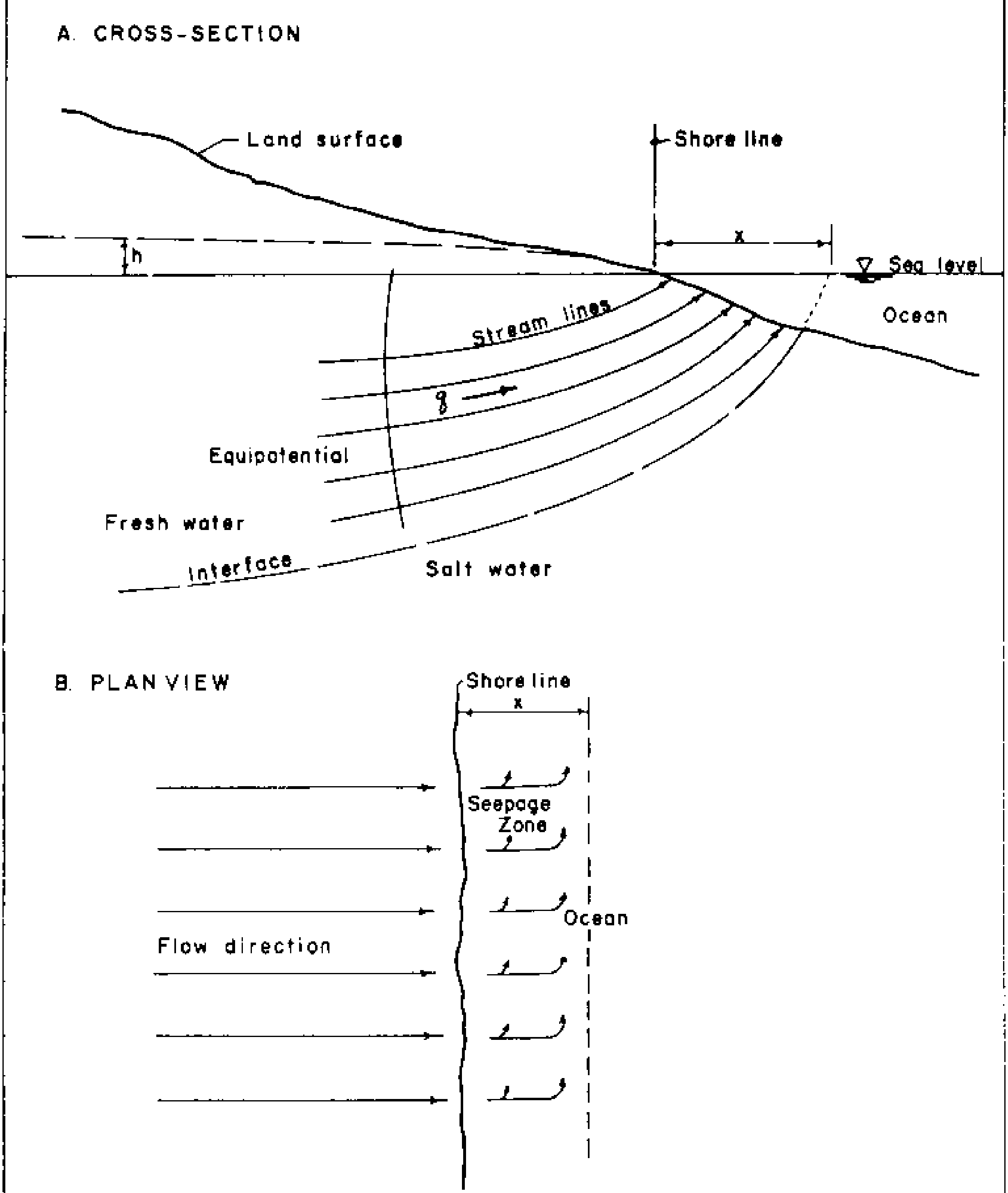


FIGURE 6-2

DISCHARGE FROM A BASAL LENS, IDEAL MODEL

No Scale

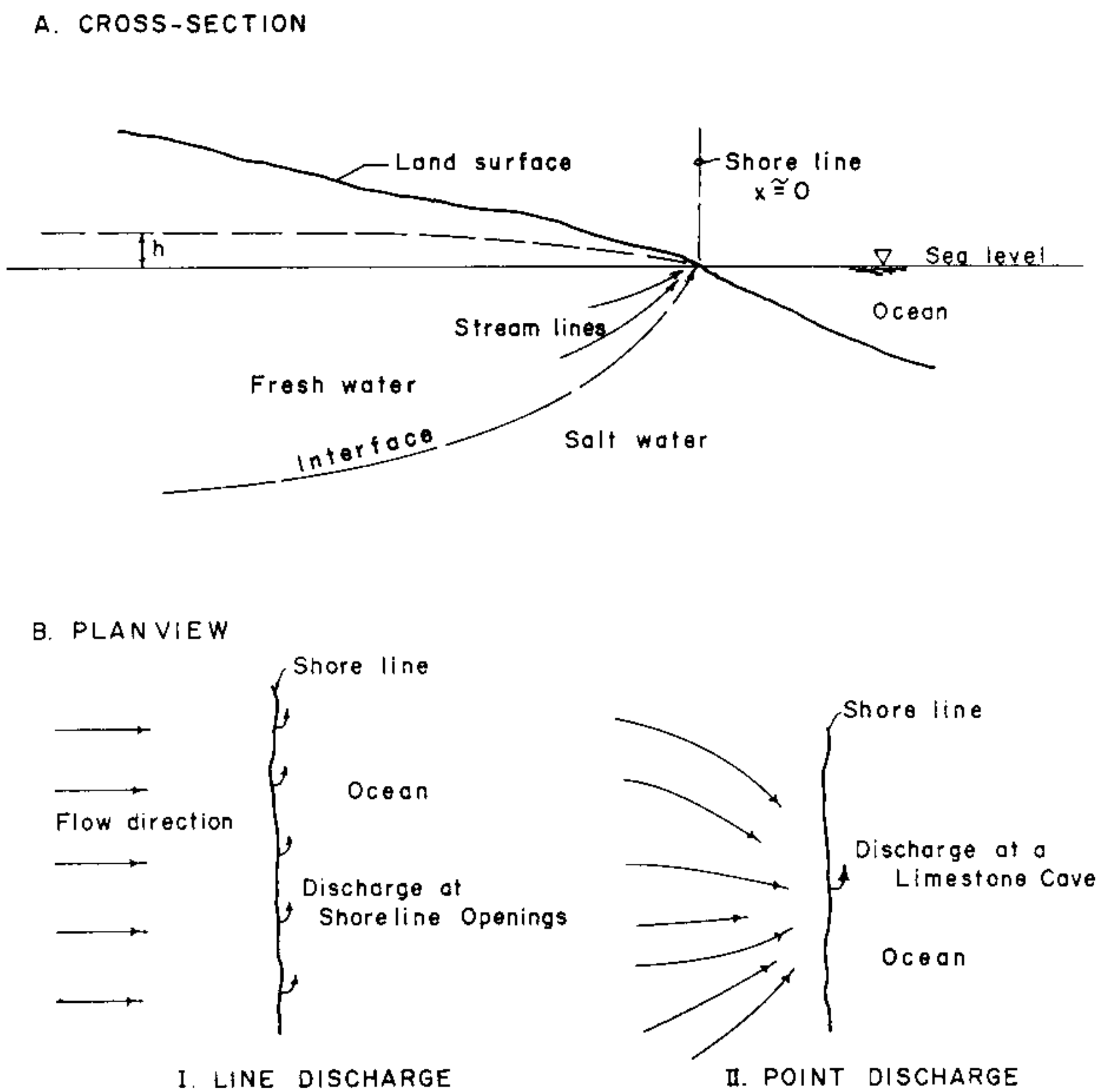


FIGURE 6-3

DISCHARGE FROM A BASAL LENS, HIGH LOCAL PERMEABILITY

No Scale

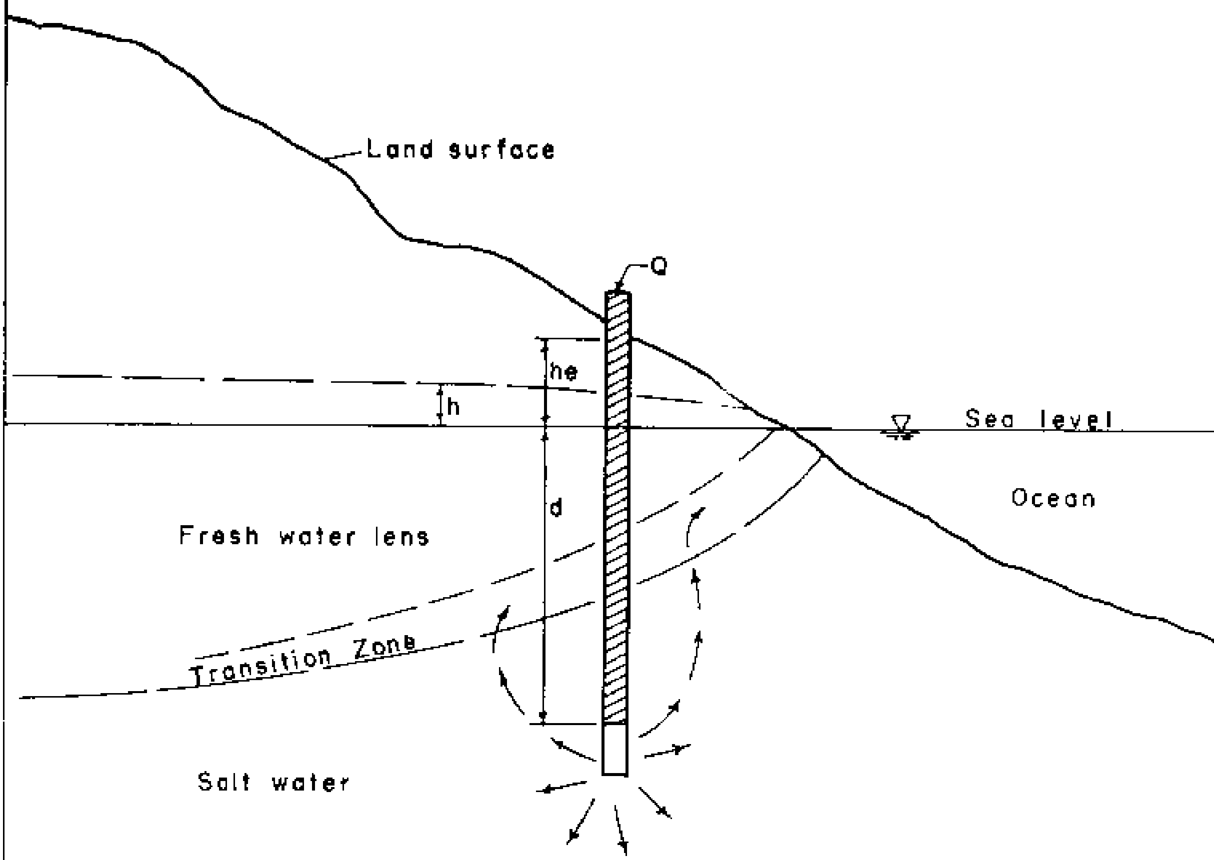


FIGURE 6-4

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

No Scale

APPENDIX A-7

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

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

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

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

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

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

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

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

Table 7-1

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

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

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

These values are obviously approximations but are reasonable for analysis.

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

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

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

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

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

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

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

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

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

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

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

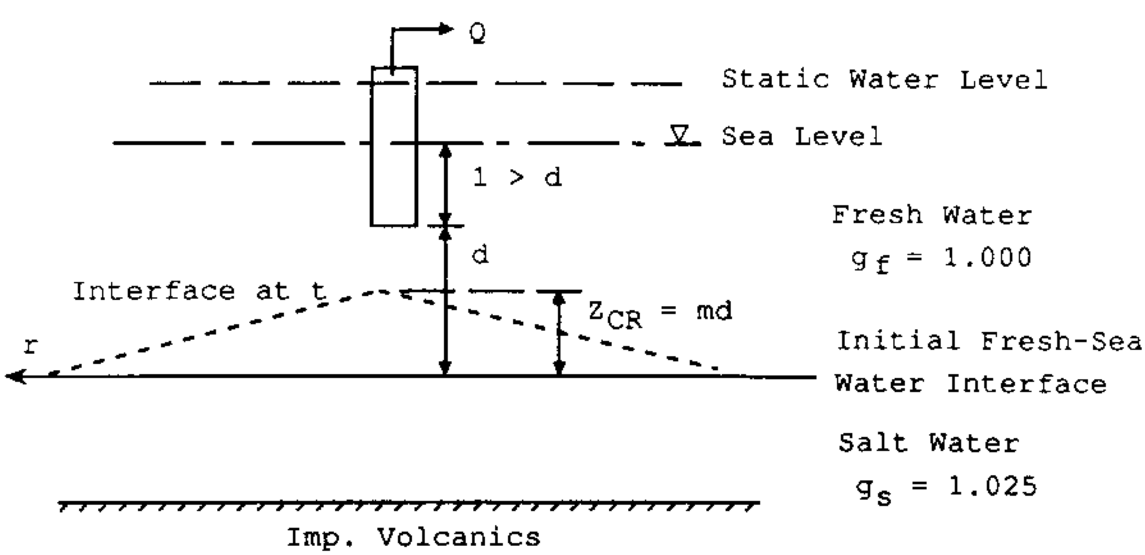


Fig. 7-1

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

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

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

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

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

where k is horizontal conductivity.

The critical rise is:

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

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

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

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

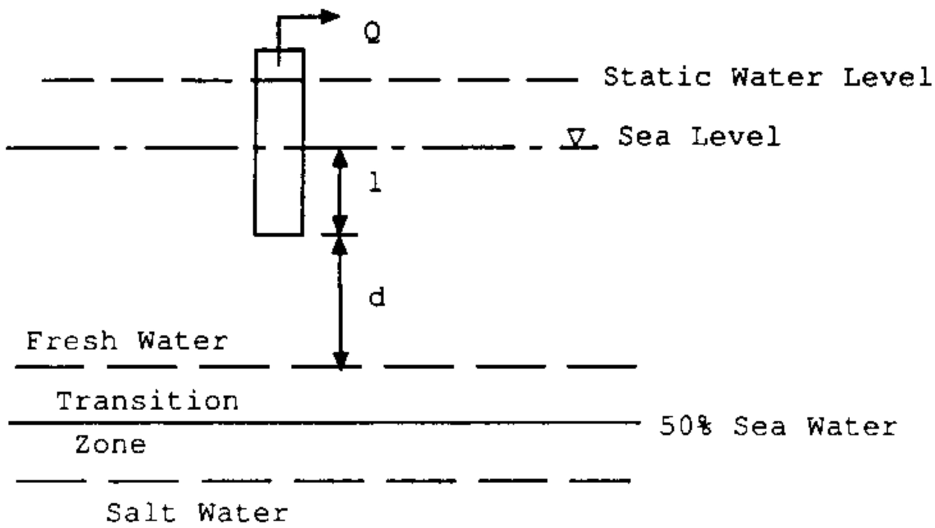


Fig. 7-2

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

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

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

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

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

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

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

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

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

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

TABLE 7-2

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

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

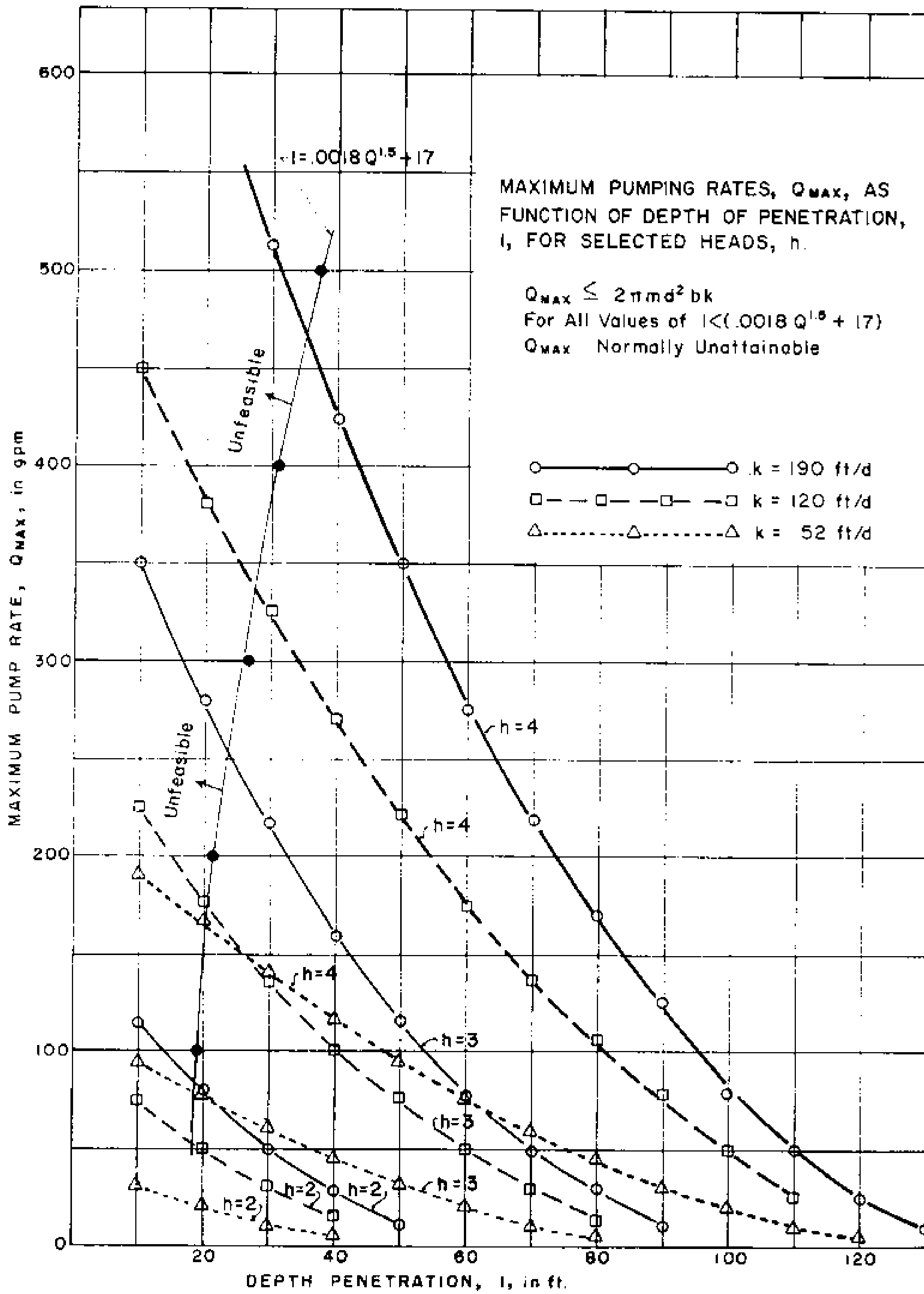

MAXIMUM PUMPING RATES, Q_{MAX}, AS FUNCTION OF DEPTH OF PENETRATION, l, FOR SELECTED HEADS, h.
$Q_{MAX} \leq 2\pi md^2bk$
For All Values of $l < (.0018\,Q^{1.5} + 17)$
Q_{MAX} Normally Unattainable
k = 190 ft/d
k = 120 ft/d
k = 52 ft/d
$l = .0018\,Q^{1.5} + 17$
Unfeasible
Unfeasible
h=4
h=4
h=4
h=3
h=3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

FIG. 7-3

APPENDIX A-8

<u>Derivation of sustainable yields from a Ghyben-Herzberg lens for selected equilibrium heads</u>

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

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

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

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

(2) $I = D + L$

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

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

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

(4) $L = q_1 + wx_1$

also:

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

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

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

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

When $D = 0$,

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

and substituting (8) into (7),

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

which can be expressed as:

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

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

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

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

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

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

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

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

Table 8-1

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

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

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

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

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

$$h_o = 5.5 \rightarrow h_e = 4.4 \text{ ft}$$

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

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

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

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

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

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

TABLE 8-2

SUSTAINABLE YIELD, NORTHERN GUAM

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

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

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

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

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

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

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

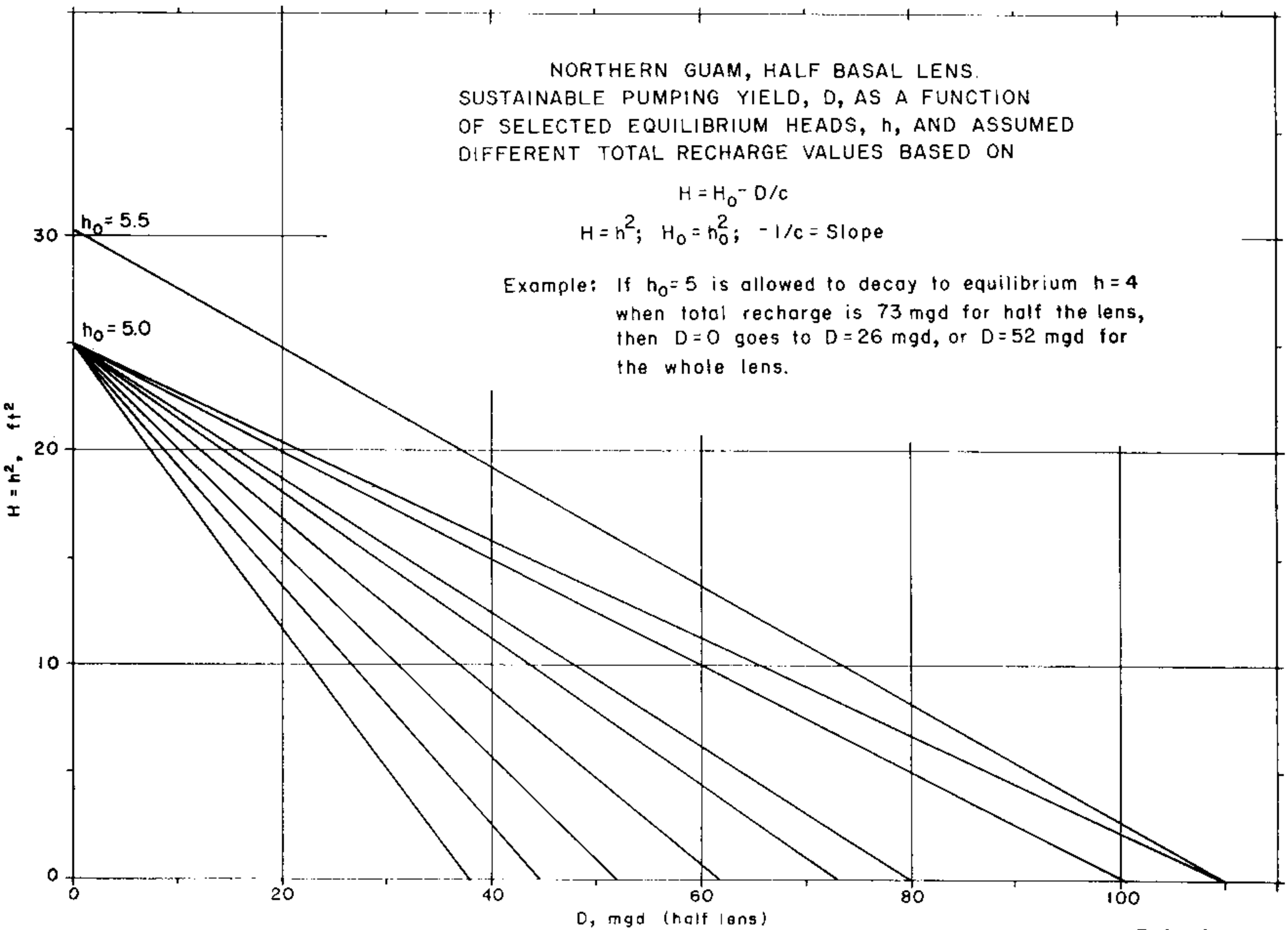

NORTHERN GUAM, HALF BASAL LENS.
SUSTAINABLE PUMPING YIELD, D, AS A FUNCTION OF SELECTED EQUILIBRIUM HEADS, h, AND ASSUMED DIFFERENT TOTAL RECHARGE VALUES BASED ON
$H = H_o - D/c$
$H = h^2$; $H_o = h_o^2$; $-1/c$ = Slope
Example: If $h_o = 5$ is allowed to decay to equilibrium $h = 4$ when total recharge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

FIG. 8-1

APPENDIX A-9

Evaluation of flow from Asan Spring

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

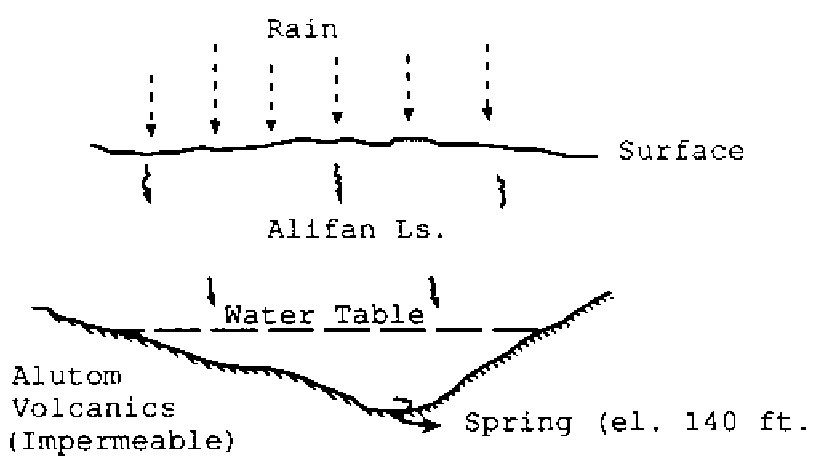


Fig. 9-1

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

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

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

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

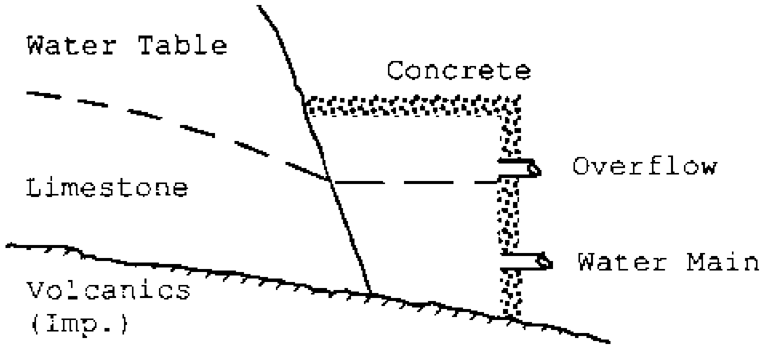


Fig. 9-3

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

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

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

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

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

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

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

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

(3) $V_o = Q_o/a = 124$ mg

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

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

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

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

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

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

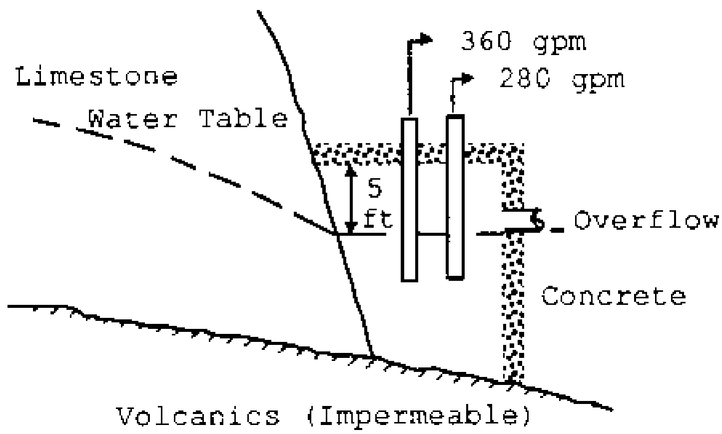


Fig. 9-4

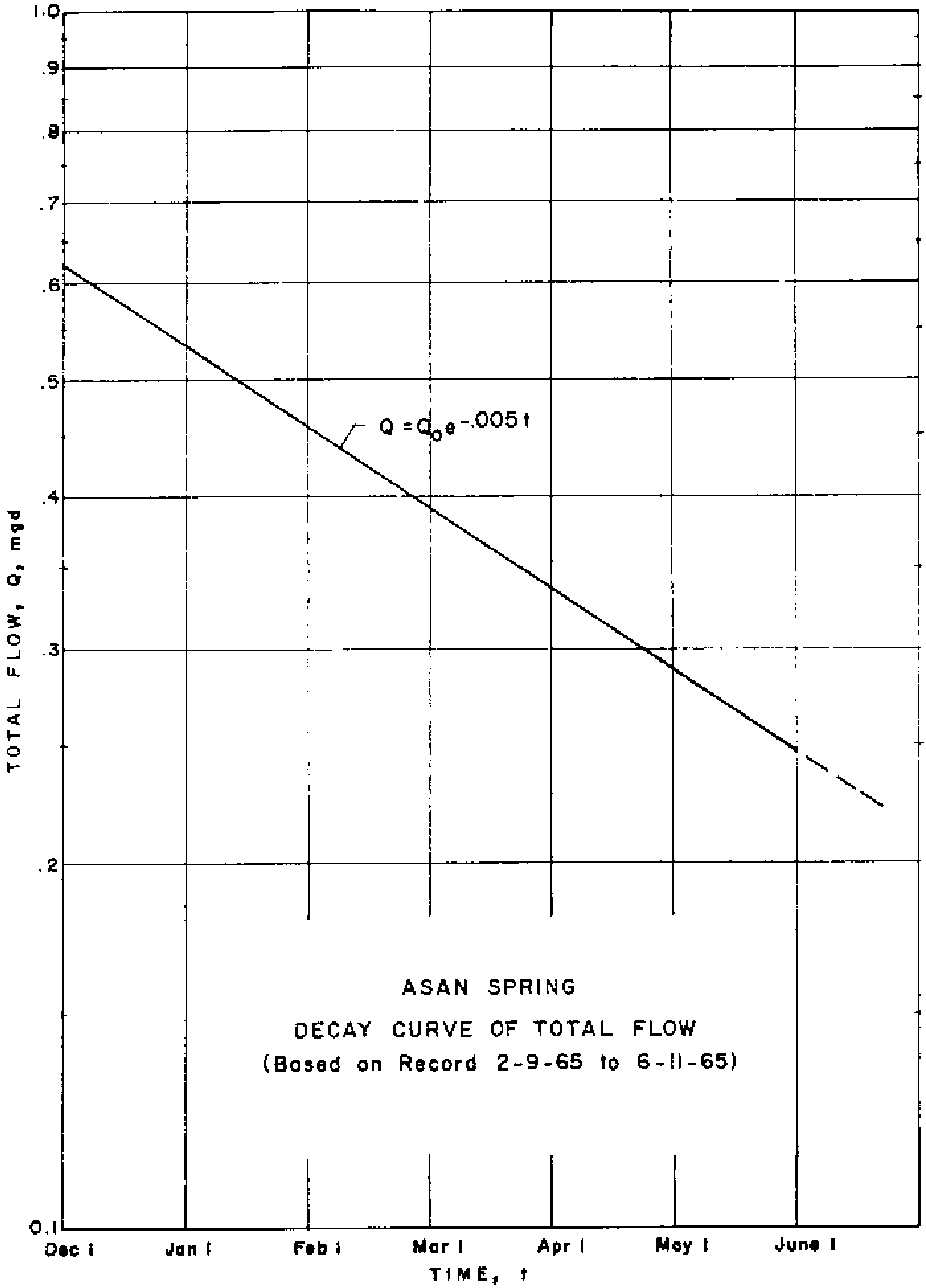
The pumps run as long as depth to water is less than 5 ft. Overflow no longer occurs: all water is used.

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

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

and V_o = 482 mg

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



1.0
.9
.8
.7
.6
.5
.4
.3
.2
0.1
TOTAL FLOW, Q, mgd
$Q = Q_0 e^{-.005t}$
ASAN SPRING
DECAY CURVE OF TOTAL FLOW
(Based on Record 2-9-65 to 6-11-65)
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
June 1
TIME, t

FIG. 9-2

TABLE 1

RAINFALL RECORDS

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

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

Data in inches.

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

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

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

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

TABLE 1

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

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

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

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

TABLE 2

AVERAGE RAINFALL AND EVAPORATION

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

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

Data in inches.

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

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

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

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

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

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

TABLE 3

HYDROLOGIC BUDGET, NORTHERN GUAM

1. Minimum budget case, by sectors.

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

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

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

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

TABLE 3

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

Column explanation

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

TABLE 3

Column explanation (cont.):

10. k_1 = computed regional hydraulic conductivity assuming no surface runoff.

11. k_2 = computed hydraulic conductivity assuming that 5% of the rainfall is lost as direct surface runoff to the sea.

TABLE 4

HYDROLOGIC BUDGET, NORTHERN GUAM

2. Probable budget case.

Based on evaluation of rainfall and streamflow in southern Guam.

<u>Conditions</u>

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

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

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

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

   Assume this average occurs throughout southern Guam.

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

Streams (gaged portions)

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

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

TABLE 4

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

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

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

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

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

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

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

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

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

TABLE 4

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

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

TABLE 4

HYDROLOGIC BUDGET, NORTHERN GUAM

2. Probable budget case, by sectors.

Based on evaluation of rainfall and streamflow in southern Guam

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

TABLE 4

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

Column explanation

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

TABLE 5

HYDROLOGIC BUDGET SUMMARY

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

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

TABLE 6

FLOW CHARACTERISTICS OF STREAMS DRAINING VOLCANIC ROCK FORMATIONS OF SOUTHERN GUAM. DATA FROM U. S. G. S. RECORDS

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

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

TABLE 6

FLOW CHARACTERISTICS OF STREAMS DRAINING VOLCANIC ROCK

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

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

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

Q_6 = minimum flow from storage, June 1.

TABLE 7

SUMMARY OF FLOW CHARACTERISTICS OF STREAMS DRAINING

VOLCANIC ROCK FORMATIONS OF SOUTHERN GUAM

(Flow rates in mgd; volume in mg)

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

Column explanation:

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

TABLE 8

GEOCHEMISTRY

MEDIAN[(1)] VALUES IN mg/l

(n) = number of samples

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

TABLE 8

GEOCHEMISTRY

MEDIAN[1] VALUES, mg/l

(n) = number of samples

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

TABLE 8

GEOCHEMISTRY

MEDIAN[1] VALUES, mg/l

(n) = number of samples

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

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

TABLE 9

GEOCHEMISTRY

TYPICAL ANALYSIS

MEDIAN VALUES, mg/l

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

TABLE 9

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

TABLE 9

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

Footnotes

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

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

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

TABLE 10

SUMMARY OF PUMPING DATA FOR ACTIVE WELLS

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

1	2	3	4	5	6	7	8	9	10
Well	Approx. el. (ft)	Bottom el. (ft)	h_0(ft) (yr)	Original Pumping Water Level (Q gpm)	1972 Pumping Water Level (Q gpm)	1973 Pumping Water Level (Q gpm)	$(Cl)_0$ mg/l	$(Cl)_{74}$ mg/l	Remarks
Togcha									
Tg-1	79	- 32	1.5				31	53	
Tg-2	105	- 25	2.6				31	52	
Tg-3							29	34	
Tg-4							79	51	
Tg-5							77	66	
Tg-6							75	85	
Tg-7							76	92	
Tg-8							75	82	
Tg-9							75	123	
Tg-10							306		
Volcanic Wells									
RCA (Pulantat)	362	+ 2	342	200(20)			20		Alutom fm.
Guam Oil	134	- 66	135				20		Alutom fm.

TABLE 10

Column explanations:

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

TABLE 11

DRILLER LOGS

NORTH GUAM WELLS

Code to driller logs:

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

Logs

Well A-1 Approx. el. 67 ft.

Drilled Feb. 1965

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

Well A-2 Approx. el. 118 ft.

Drilled Feb. 1965

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

Logs

Well A-3 Approx. el. 128 ft.

Drilled April 1966

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

Logs

Well A-4 Approx. el. 140 ft.

Drilled July 1966

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

Backfill to 300 ft.

Well A-5 Approx. el. 147 ft.

Drilled Aug. 1966

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

Well A-5, (cont.)

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

Well A-6 Approx. el. 152 ft.

Drilled Aug. 1967

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

Logs

Well A-7 Approx. el. 136 ft.

Drilled April 1967

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

Well A-8 Approx. el. 124 ft.

Drilled June 1967

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

Well A-8 (cont.)

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

Well A-9 Approx. el. 187 ft.

Drilled March 1967

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

Logs

Well A-10 Approx. el. 191 ft.

Drilled May 1967

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

Well A-11 Approx. el. 178 ft.

Drilled June 1968

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

Well A-11 (cont.)

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

Well A-12 Approx. el. 138 ft.

Drilled July 1968

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

Well A-12 (cont.)

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

Well A-13 Approx. el. 131 ft.

Drilled Nov. 1968

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

Logs

Well A-13 (cont.)

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

Logs

Well D-5 Approx. el. 381 ft.

Drilled Nov. 1965

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

Well D-9 Approx. el. 388 ft.

Drilled Dec. 1967

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

Logs

Well D-10 Approx. el. 389 ft.

Drilled Feb. 1968

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

Well D-11 Approx. el. 393 ft.

Drilled March 1969

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

Well D-11 (cont.)

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

Well D-13 Approx. el. 404 ft.

Drilled Nov. 1970

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

Logs

Well M-1 Approx. el. 394 ft.

Drilled March 1965

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

Logs

Well M-2 Approx. el. 401 ft.

Drilled March 1968

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

Logs

Well M-3 Approx. el. 423 ft.

Drilled Nov. 1967

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

Logs

Well M-4 Approx. el. 421 ft.

Drilled Oct. 1967

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

Well M-5 Approx. el. 273 ft.

Drilled Dec. 1968

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

(backfill to 330)

Logs

Well M-6 Approx. el. 326 ft.

Drilled May 1969

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

Well M-7 Approx. el. 289 ft.

Drilled June 1969

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

Logs

Well M-8 Approx. el. 443 ft.

Drilled 1969

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

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

Drilled Aug. 1969

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

Logs

Well J-1 Approx. el. 583 ft.

Drilled Sept. 1968

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

Logs

Well AG-2 Approx. el. 503 ft.

Drilled April 1968

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

Logs

Well F-1 Approx. el. 423 ft.

Drilled Feb. 1969

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

TABLE 12

EFFECTS OF ACIDIZING ON PUMP TESTS

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

TABLE 13

SUMMARY OF PUMPING TESTS AT TIME OF WELL COMPLETION

NORTH GUAM

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

TABLE 13

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

TABLE 13

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

TABLE 13

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

TABLE 14

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

Column explanations:

1. Well number used by PUAG.

2. l = depth of penetration into saturated aquifer.

3. T = transmissivity.

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

TABLE 14

Column explanations (cont.):

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

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

7. Investigator who analyzed data.

TABLE 14

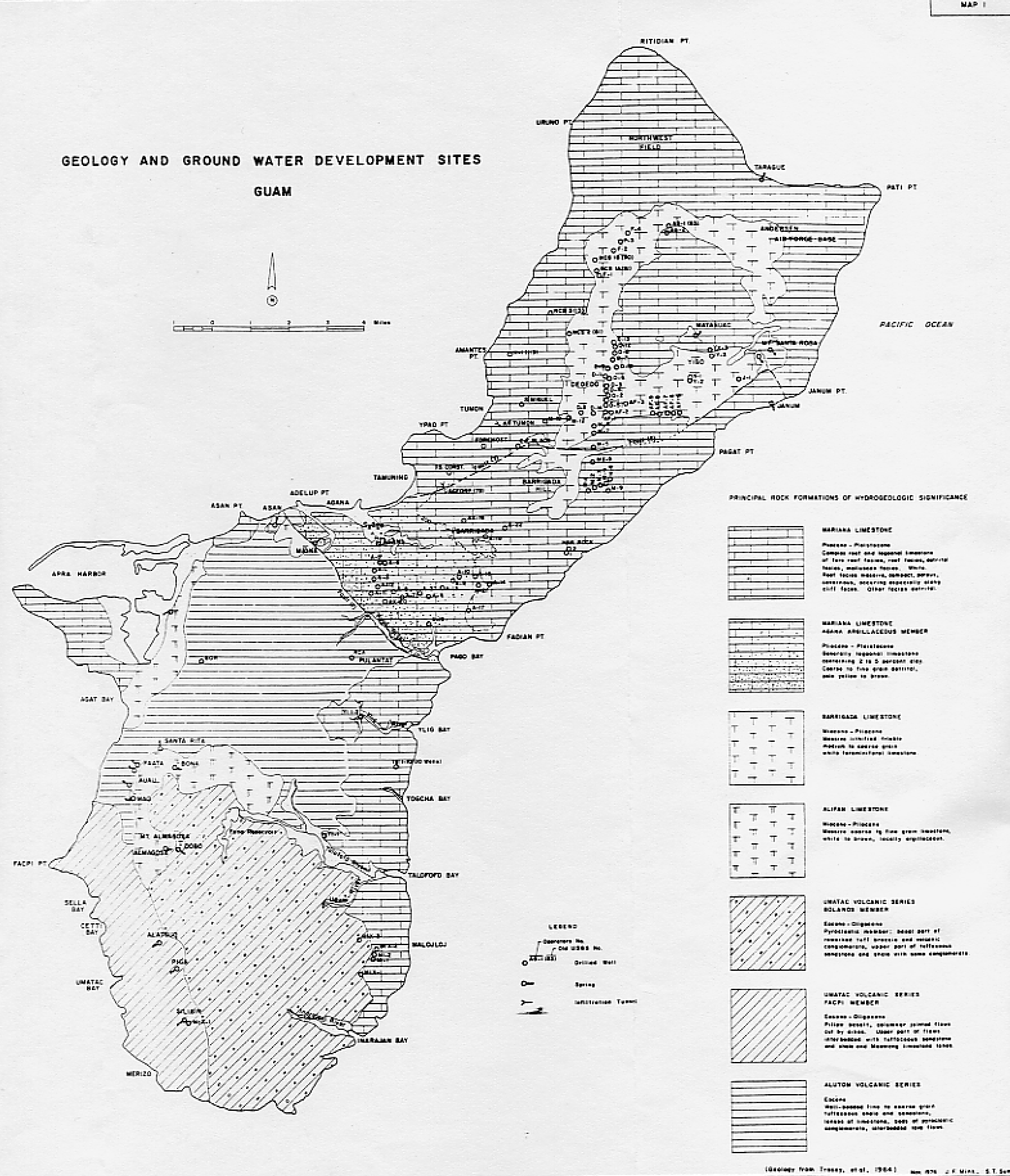
SUMMARY OF PUMPING TEST ANALYSIS

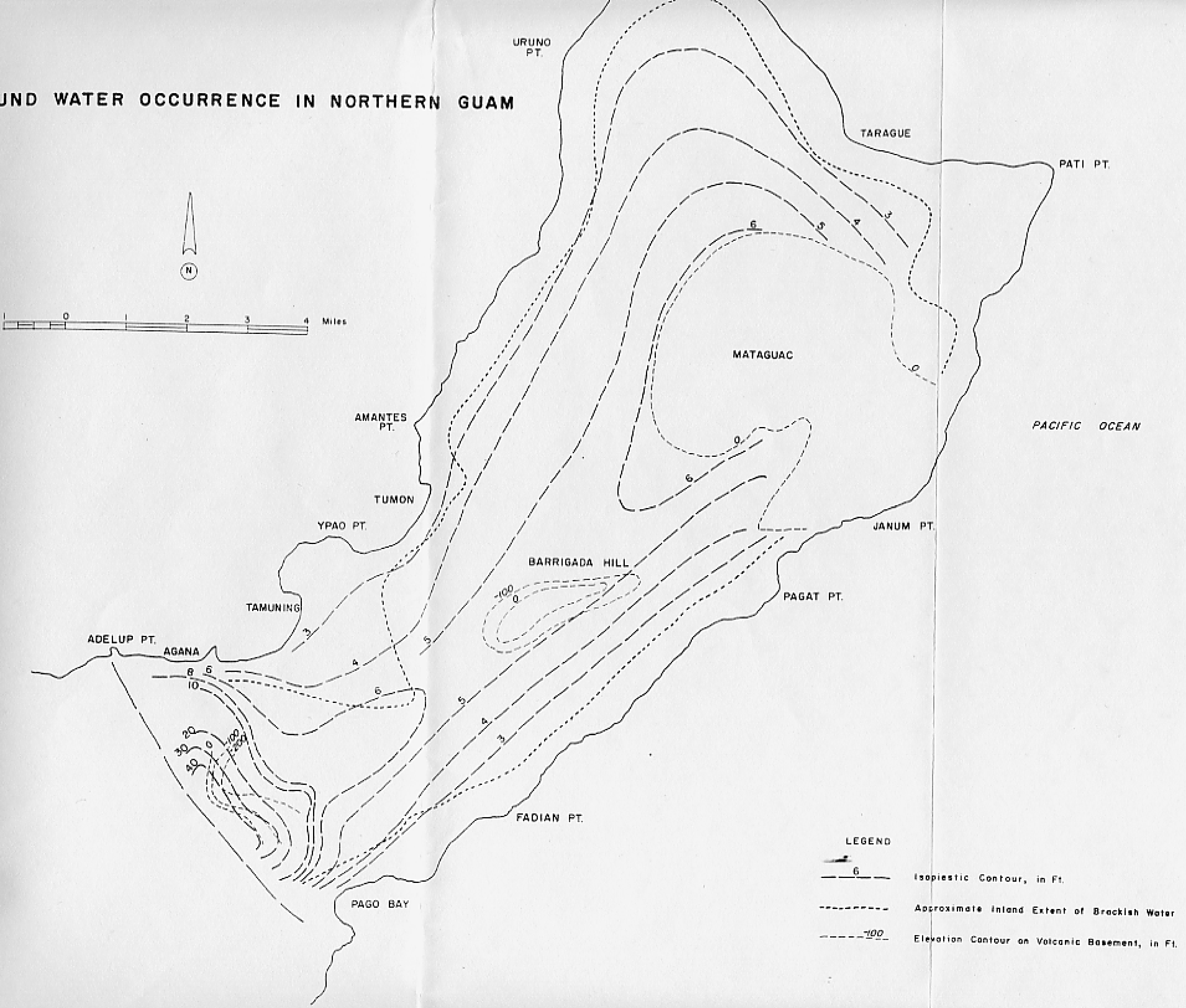
(See column numbers at end of table for column explanations)

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

GEOLOGY AND GROUND WATER DEVELOPMENT SITES

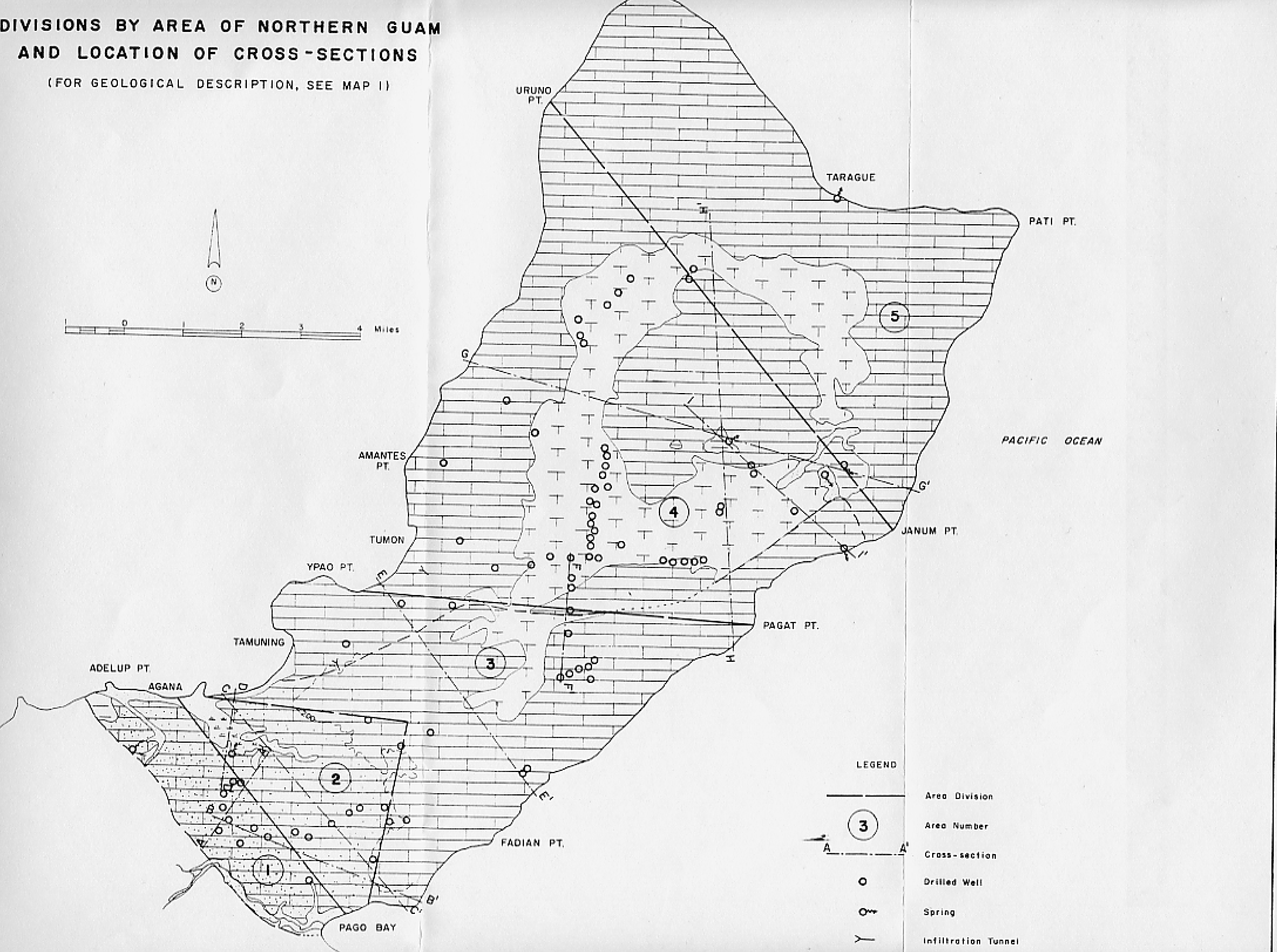
GUAM




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

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

(FOR GEOLOGICAL DESCRIPTION, SEE MAP I)



HYDROGEOLOGY OF THE AGANA-BARRIGADA REGION