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ASSESSMENT OF VIABILITY OF GROUNDWATER AND SURFACE WATER RESOURCES FOR THE GUAM WATER AUTHORITY WATER RESOURCES MASTER PLAN

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INTRODUCTION AND BRIEF REVIEW OF PREVIOUS STUDIES

In an island such as Guam the water resources play a fundamental role in the evolution of indigenous cultures and the development of subsequent societies. Some islands in spite of their small size are fortunate to be endowed with a plentitude of accessible fresh water, others without water resources remain barren. Guam, like the islands of Hawaii, enjoys copious and dependable supplies of fresh water. Although only about 200 square miles in size, Guam already sustains a population of about 160,000 people, and with careful management of its fresh water resources can accommodate many more.

The principal set of water resources on which the population and activities of the island depends is groundwater in the 100 square miles of limestone aquifers of Northern Guam. The island is divided into nearly equal halves by a downthrown fault extending across its width from Adelup on the Philippine Sea to Pago on the Pacific Ocean. The geology on the northern half on the downthrown side of the fault is dominated by fossil lagoonal limestones that in most areas reach far below sea level, while that of the southern half on the upthrown side of the fault principally comprises volcanic rocks that were deposited in a submarine environment. The limestones of the north constitute voluminous, permeable aquifers; in the south the dominant volcanic formations have very low permeability and tend to reject infiltration of recharge from rainfall, giving rise to numerous streams and rivers. The geology of the island was first comprehensively described by the U.S. Geological Survey (Tracey, et al, 1964), and thereafter numerous studies by a variety of investigators have related the occurrence of water resources to the geology.

Although interest in the occurrence and development of water resources started with the earliest Chammoro society, not until after World War II did the necessity to understand the behavior of the resources in response to exploitation become apparent. A brief history of the attention given to water supply in the era before World War II is given Technical Report 1 (TR 1) of WERI (Water and Energy Research Institute of the Western Pacific, University of Guam). Subsequent to the Tracey, et al, study several other U.S. Geological Survey (USGS) reports were devoted to an evaluation of the water resources, and since then numerous studies have been performed by consultants, in particular the Northern Guam Lens Study (NGLS).

This report that follows derived most of its information and conclusions from virtually the entire spectrum of studies but especially from the sources listed below.

1. General Geology of Guam, J.I. Tracey, et al, 1964, USGS.
2. Groundwater Resources of Guam: Occurrence and Development, J.F. Mink, 1976, WERI TR 1.
3. Northern Guam Lens Study, Barrett Harris and Associates with Camp Dresser McKee, 1982, Guam Environmental Protection Agency.
4. Groundwater in Northern Guam: Sustainable Yield and Groundwater Development, Barrett Consulting with J.F. Mink, 1991, Public Utility Agency of Guam.
5. Surface Water Development Study, Barrett Consulting Group, 1994, Public Utility Agency of Guam.

6. Chloride History and Trends of Water Production Wells in the Northern Guam Lens Aquifer, M.Q. McDonald and J.W. Jenson, 2003, WERI TR 98.
7. Numerous WERI Technical Reports.

The above are the most fundamental references. Information has also been extracted from less comprehensive reports, which are referred to in the text when appropriate. In addition, data has been obtained from the Guam Environmental Protection Agency (GEPA) management reports and from the Guam Water Authority (GWA) files. Other sources of data include EarthTech and a variety of golf course developments.

HYDROLOGIC BUDGETS

The Barrett Consulting Group – J.F. Mink 1991 study (Groundwater in Northern Guam, Sustainable Yield and Groundwater Development) revisited previous efforts to arrive at a satisfactory hydrologic budget for Northern Guam and offered somewhat different and higher values than had been stated in the NGLS. Much of the following text and analyses is taken from the 1991 study, and additional analyses are given in an Appendix. Also, WERI (Water and Energy Research Institute of the Western Pacific: University of Guam) composed a budget for Northern Guam in 1999 (Technical Report TR 88), a discussion of which is included in the following.

Northern Guam

The goal of hydrologic budgeting is to determine a mass balance among input and output variables in the hydrologic cycle. Input variables include rainfall (P) along with other atmospheric moisture sources, and fluxes across boundaries in the region of interest. These fluxes are surface water and groundwater. Output variables consist of direct surface runoff (DRO), evapotranspiration (ET), deep percolation (I) and boundary fluxes. Total runoff, R, which includes DRO and groundwater seepage, and rainfall are often known to some degree of accuracy as a result of measurements. Evapotranspiration is approximated from theoretical and empirical models, in particular equating it to measured pan evaporation, and infiltration is normally solved for as the unknown variable that closes the balance equation.

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

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

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

Hydrological mass balances for Northern Guam have been proposed by numerous investigators employing a variety of methods. The balances were attempted in order to calculate the infiltration component because in the north the only developable water resource is groundwater. In 1937 H.T. Stearns, who was the first scientist-engineer to attempt a hydrologic budget, suggested that 50 to 100 mgd of groundwater could be safely extracted from the north (H.T. Stearns, 1937, Geology and Water Resources of the Island of Guam, Mariana Islands: Manuscript Report to the U.S. Navy). Shortly after World War II a U.S. Geological Survey report concluded that 15 mgd was safely developable (P.E. Ward, S,H. Hoffard, and D.A. Davis, 1965, Hydrology of Guam: U.S. Geological Survey Professional Paper 403-H). On the other hand, Kennedy Engineers (1964, Water Supply for the Government of Guam, Mariana Islands) suggested that just 8 mgd of groundwater should be developed in the north from wells and proposed exploitation of surface water in the south as the principal supply for the island.

In a study completed for the Public Utility Agency Guam (PUAG), now titled GWA, two hydrologic budgets were calculated, one employing evaporation as the equivalent of evapotranspiration, and the other deducing evapotranspiration from the water budget for Southern Guam (J.F. Mink, 1976, Groundwater Resources of Guam: Occurrence and Development: University of Guam Water Resources Research Center Technical Report 1 (hereafter referred to as TR-1). In the 1984 Northern Guam Lens Study (NGLS) a budget was derived based on a theoretical determination of evapotranspiration, and as part of the study WERI produced a partial budget in which infiltration was computed by relating the gain in salinity in groundwater compared to salinity in rainfall and attributing the difference to the effects of evapotranspiration.

Each method is an approximation based on assumptions combined with a body of measured data for rainfall, pan evaporation and stream flow. The unknowns in every case are evapotranspiration and infiltration. Runoff from the northern limestones is likely to be trivial and is either ignored or assigned a small value. Recent studies by WERI (TR 104) of the surfaces of the limestone affirm this conclusion. Because groundwater is the sole resource of interest in North Guam the equations are solved to yield infiltration.

The fundamental water budget balance equation is:

$$P = R + ET + I$$

In which P is average rainfall, the only input variable; R is runoff, which in North Guam is zero; ET is evapotranspiration, or loss of moisture to the atmosphere due to ordinary evaporation and plant transpiration; and I is infiltration to groundwater. This equation is for the steady state in which input is equal to output. The change in volume of groundwater does not enter the equation until groundwater withdrawals by artificial means take place.

In Northern Guam rainfall is known from rain gage records, runoff is ignored, and evapotranspiration is estimated by various methods. The solution for infiltration is singularly dependent on the value assigned to evapotranspiration. The differences in computed values of I among different investigators are a result of the value given to ET by each.

Table 1 is a summary of attempts to create a global hydrologic budget for Northern Guam. The budget taken from TR-1 (1976) is based on a total limestone area of 94.6 square miles, which is virtually the entire northern half of the island. The NGLS (1984) budget refers to only 67.92 square miles, which is the area inland of a 4,000 feet wide buffer zone, which assumes that groundwater in the buffer zone is non-potable. This restriction of total area understates total input. The alternate balances were recomputed from the TR-1 budgets by altering some parameters and employing the total area of North Guam (100.3 square miles), or the area inland of a zone 0.5 miles in width from the coast, leaving an input area of 80.1 square miles. The most recent attempt at budgeting was performed by WERI (Jocson, Jenson and Contractor, 2002, Recharge and Aquifer Response: Northern Guam Lens Aquifer, Guam, Mariana Islands, Journal of Hydrology, 260, pp.231-254; also TR 88) in which the probable recharge to groundwater is calculated as 67 percent of the rainfall, and for which the authors noted that this value is consistent with the most probable estimate given in TR 1.

The TR-1 budgets are developed and explained in detail in that report. The minimum budget assumes the most conservative conditions wherein evapotranspiration is equated to measured pan evaporation. This, of course, is not realistic because moisture is not constantly available to plants. Much of the wet season rainfall quickly transits the thin soil to infiltrate rapidly while in the dry season insufficient rain falls to support potential evapotranspiration.

The "probable" budgets in TR 1 are a considerable improvement on the minimum budgets and are the most reliable of the postulated budgets in that report because of the straightforward methodology employed. The balance takes advantage of the excellent U.S. Geological Survey stream gage data for Southern Guam where about 60 percent of rainfall leaves the land as stream flow. The stream flow is predominantly direct overland flow (about 90 to 95 percent) with the remainder derived from groundwater seepage. It is a fair assumption to equate the ratio of runoff to rainfall in the south to infiltration to rainfall in the north, leaving the balance of rain for evapotranspiration. This assumption is reasonable because the small quantity of groundwater that escapes from the low permeability volcanic aquifers is likely matched by the fraction of rainfall that infiltrates. Otherwise all of the output from the volcanic drainage basins is known because stream flow is accurately measured and evapotranspiration is the difference between rainfall and runoff.

The calculated evapotranspiration in the probable budget is 42.79 in./yr. This amount is consistent with values commonly assigned to humid tropical areas where average rainfall exceeds 60 inches (L.A. Bruijnzeel, 1990, Hydrology of Moist Tropical Forests and Effects of conversion: A state of Knowledge Review: UNESCO Hydrology Program). WERI (Jocson, et al) computed ET as 31 inches per year. Since TR-1 was published, additional stream flow and rainfall data for southern Guam have accumulated. Re-working the basic premise that evapotranspiration is the difference between rainfall and runoff in Southern Guam the up-dated values for recharge in the North are not greatly different from the original estimates (Appendix). Infiltration in northern Guam for the probable budget is 232 mgd when no allowance is made for loss by surface runoff, and 212 mgd when runoff is taken as 5 percent of the rain. These values refer to a total area of 94.6 square miles.

The NGLS budget limits the infiltration intake area to 67 square miles, only two thirds of the total area of northern Guam, and assigns an evapotranspiration rate of 59 inches per year, leaving 32.97 inches for recharge. The evapotranspiration rate was calculated by the Blaney-Criddle method. Estimated recharge was 112 mgd. Adjusted for the entire area of north Guam the comparable infiltration rate would be 167 mgd. However, the entire area of intake must be considered when deriving estimates of sustainable yield based on groundwater flow hydraulics. The aquifers are hydraulically continuous from the coast inland to their termination by the volcanic basement, and the allowable rate of groundwater withdrawal depends on an equilibrium head which preserves the integrity of the resource. Head is governed by input over the entire area of the aquifers, not just the area declared suitable for potable water development.

The evapotranspiration value used in the NGLS budget is high, 16 inches greater than the annual average used in the TR-1 probable budget, 22 inches higher than the probable budget recalculated in Appendix, and 28 inches higher than in the WERI report. The NGLS budget was supported by the calculation for infiltration based on salinity of rain water and groundwater, but this calculation ignores the dry salt deposited on the surface of the ground which becomes entrained in the water that percolates through the soil to add another increment of salt to the groundwater.

In the budgets discussed above, calculated infiltration rates range from 1.67 to 3.00 mgd/sq.mi. for Northern Guam. The 1.67 mgd/sq.mi. rate is given in the NGLS report, which is unreasonably low. More reasonable values approach or exceed 2.3 mgd/sq.mi.

Southern Guam

In Southern Guam recharge to groundwater is small while direct surface runoff is high because of the low permeability of the predominant volcanic geology. Where limestone occurs along stretches of the coast and in the highlands of Mt. Alifan, Mt. Almagosa and Mt. Lamlam, as well as in the upper reaches of the Talofofo River valley, infiltration may be as high as in Northern Guam, but the area covered by limestone is small in comparison with the volcanic terrain and most of the groundwater that accumulates eventually percolates as springs that flow to rivers. In the Appendix on hydrologic budgets the balance for Southern Guam is explained.

Assuming an average rainfall of 88.9 inches per year (based on rainfall measurements at Inrajan) and an evapotranspiration total of 38 inches per year (see Appendix for derivation), the combination of infiltration plus direct surface runoff is 50 inches. Conversion of the Inarajan River data results in total overland flow of 52.3 inches per year (average flow is 11 mgd), and by subtracting average flow during the dry season of 6.2 inches per year yields an average direct surface runoff of 48.5 inches per year. Because the volcanic rock mass is saturated virtually to the ground surface at low places in the volcanic topography, not much infiltration to groundwater can accumulate as storage. The 6.2 inches per year flow during the dry season may be considered as the probable infiltration during the wet season.

Table 1

Source	Area (sq.mi.)	P (in/yr)	ET (in/yr)	R (in/yr)	I (mgd/sq.mi.)
Mink, TR 1	94.6	94.7	42.8	0	2.45
NGLS	67.2	94.0	59	0	1.67
WERI TR 88	100	94.0	31	0	3.00

WATER RESOURCES OCCURRENCE AND BEHAVIOR

The Adelup-Pago fault which geologically and topographically divides the island also is the boundary between two distinct suites of water resources. To the north the occurrence of fresh water is limited to groundwater in permeable limestone aquifers; there are no streams, although a few small springs exist. In the south surface runoff as springs, streams and rivers are the dominant sources of fresh water, although small areas of limestone contain groundwater but in trivial amounts in comparison with the aquifers of the north. The cost of developing the groundwater of the north and distributing it to consumers, the greatest number of whom live in the north, is far less than would be the cost of storing, treating and distributing the surface waters of the south. The groundwater of the north supplies the public demand except for parts of the sparsely populated regions of the south.

Northern Guam

Groundwater occurs in two ways, basal and parabasal. In basal groundwater a lens of fresh to brackish floats on salt water because of the difference in density between the heavier salt water and the lighter fresh-brackish water. Parabasal groundwater is hydraulically continuous with basal groundwater but rests on the virtually impermeable volcanic basement rather than on salt water. Basal groundwater constitutes most of the fresh water resources but is subject to degradation by salt water if developed improperly. Parabasal groundwater resources are less voluminous but resist mixture with salt water until or unless overall groundwater extraction exceeds a safe limit.

The hydrologic budget for Northern Guam states that the rate of recharge to groundwater averages 2 to 3 mgd/sq.mi., or a total of 200 to 300 mgd for the 100 square miles of the north. Not all of this amount is safely developable, however. A fraction, perhaps as little as 30 percent, may be extracted without deteriorating either the quality or quantity of the water extracted. The rate of removal that meets this constraint is called the "sustainable yield". Assuming an average recharge rate of 2.5 mgd/sq.mi., at a 30 percent extraction rate over the 100 square miles the sustainable yield may be as high as 75 mgd. The most recent attempt to deduce sustainable yield for the north resulted in an average value of 70 mgd (Barrett Consulting – J.F. Mink, 1991).

The above estimates of sustainable yield have been determined by regarding the entirety of the groundwater resources in the north. More accurate determinations on regional scales can be derived through methods such as numerical modeling. WERI has and continues to create numerical models describing the behavior of groundwater in the north, especially in the Yigo – Tumon and Finegayan regions.

Sustainable yield never equals recharge. Under average steady state conditions recharge that accumulates in the aquifers is balanced by discharges from the aquifers. Discharge is a combination of draft (pumpage) and seepage to the sea in the vicinity of the coast line. If draft were to equal recharge, seepage would deplete storage until the lens vanished.

Recharge as infiltration first passes through the "vadose" zone, which is unsaturated, then accumulates in the "phreatic" zone, in which the rock matrix is saturated. Investigations conducted at WERI (Jocson, et al, TR 88) suggests that not all of the infiltration reaches the saturated zone because a fraction may be diverted in the vadose zone to escape as `fast flow'. This concept is hypothetical and continues to be studied at WERI.

The most comprehensive investigation of the behavior of groundwater in limestones of the north on a regional scale was made in 1995 by consultants for the Air Force to determine the potential effect of seepage from landfills on groundwater quality. The results of the study proved that the groundwater behavior is consistent with laminar flow implicit in the Darcy equation,

$$q = -k\ dh/dx$$

in which q is specific flow (cu.ft./day/sq.ft.), k is hydraulic conductivity (ft./day), and dh/dx is groundwater gradient (dimensionless). The occurrence of groundwater as a basal lens conforms to this model. Even though the groundwater flux is very high, heads (elevation of the water table above sea level) and groundwater gradients are low because of high hydraulic conductivity. No evidence of non-laminar channel flow typical of continental karstic terrains has been identified. Cavities and voids in the limestones occur, but flow in the saturated zone is governed by the aquifer matrix of porous coralline detritus. On a local scale water accumulates in the voids as it does in the general porosity, but velocity of movement in the voids is no greater than in the matrix porosity. Near the coast some channeling in the limestone may occur, but these channels are truncated inland and are not continuous drains on the aquifer over long distances and wide areas.

In spite of the high recharge rate in Northern Guam, heads in the clean limestone north of Barrigada are less than 4 feet. The low heads result from regional hydraulic conductivities on the order of 20,000 ft./day. There are no geological deposits or structures to impede the flow of groundwater and consequently the hydraulic gradient is low, averaging about .00025.

Regional groundwater velocities in the Andersen Air Base area have been determined to be about 25 ft./day from rhodamine dye tests conducted by Kaiser Engineers (consultants), which is very high for typical groundwaters. Actual groundwater velocity in laminar flow is expressed as,

$$v = (k/m)\, dh/dx$$

in which m is effective porosity. The porosity parameter is difficult to assess because of the heterogeneity of the limestones, but a value of 13 percent was calculated for the NGLS from a gravity traverse made between Yigo and Andersen. Employing this value with a gradient of .00025 and velocity of 25 ft./day, hydraulic conductivity is calculated as 13,000 ft./day. This is consistent with the average of 19,000 ft./day derived from a WERI numerical model (Jocson, et al, TR 88).

In a basal lens the depth of fresh water below sea level is governed by the densities of the fresh and salt waters. Typically the depth is considered to be 40 feet below sea level for every foot of the water table above sea level. The 40:1 Ghyben Herzberg ratio assumes the density of fresh water is standard at 1.000 and that of sea water at 1.025. However, in

Guam the temperature of the fresh groundwater and underlying sea water results in densities that yield a somewhat different Ghyben Herzberg ratio.

The average temperature of groundwater in Guam is 80.4 F (data from TR 1), about the same as the average atmospheric temperature. At this temperature fresh water has a specific gravity of .99648 while sea water has a specific gravity of 1.02204 (data from DeMarsily). The ratio is therefore,

$$\gamma_f / (\gamma_s - \gamma_f) = .99648 / (1.02204 - .99648) = 38.98 = 39.0$$

The above applies only for a sharp interface between the fresh and salt waters and when the salt water head is zero. A sharp interface is impossible, however, because of dispersion, the intrusion of salt water into the fresh water. A transition zone of a mixture of fresh and salt waters form, and the thickness of the zone depends on the velocity of the fresh water in the lens. Employing the realistic assumption that the salt water is static, the Ghyben Herzberg ratio applies to the middle of the transition zone (50 percent sea water isochlor). Chloride content as the measure of sea water mixture increases symmetrically as an S shape curve with depth below the start of the transition zone with the 50 percent isochlor as the mid point. If the transition zone is narrow, as it is in the clean limestones of Northern Guam, the true depth of fresh water in the lens approaches that determined by the Ghyben Herzberg ratio.

The thickness of the transition zone can be measured by geophysical logging of monitor wells drilled through the lens to the sea water below. When the EX series of exploratory wells were drilled in 1981 – 1982, conductivity logs yielded the following transition zone information. The half width of the transition zone is the distance from the 250 mg/l chloride level to the 50 percent isochlor (9,500 mg/l chloride).

Well	Half Width (ft)	Aquifer Geology
EX 1	100	Argillaceous Limestone
EX 4	50	Limestone
EX 7	20	Clean Limestone
EX 8	15	Clean Limestone
EX 9	15	Clean Limestone
EX 10	15	Clean Limestone
GHURA	30	Clean Limestone

In the clean limestone the transition zone is narrow because of the high velocity of the fresh groundwater, which is a function of the very high hydraulic conductivity, while in the less permeable argillaceous limestone the transition zone is comparatively thick.

The clean limestone occurs north of Barrigada through Yigo-Tumon to the coast along Andersen Air Base. In the Agana-Chaot-Ordot region south of Barrigada argillaceous limestone dominates. A consequence of the geology is that in the clean limestone region the water table elevations (heads) in the basal lens are relatively low, less than about 4 feet above sea level, but fresh water is readily extractable, whereas in the argillaceous sector the heads reach as high as 8 feet or so but extracting low chloride water is less certain.

Parabasal groundwater is restricted to where the volcanic basement rises above the theoretical Ghyben Herzberg depth of the lens. Substantial parabasal resources occur in the Yigo area where the Mataguac Hill volcanics surface above the limestone terrain and in the Ordot-Chaot region near Agana where the basement rises toward the Adelup-Pago fault.

Aquifer Classification

The most comprehensive review of Northern Guam's water resources was made about 25 years ago and is commonly referred to as the NGLS. The NGLS organized and evaluated existing hydrogeologic data, made analyses relevant to groundwater production, and subdivided all of Northern Guam into Sub-Basins and Management Zones. This classification formed the basis for the Guam Environmental Protection Agency management decisions about the expansion of groundwater development.

In the NGLS only 67 square miles of the total of 100 square miles in Northern Guam were considered favorable for the production of potable water. This production area was divided into 47 Management Zones, each having an average area of somewhat more than one square mile. The outlines of the zones reflect hyrogeological and topographic features but each is too small to be uniquely identified by these parameters. Strict adherence to a Zone as a management unit inhibits flexibility in taking advantage of groundwater conditions.

To allow managers more latitude in initiating new groundwater development and in revising existing ones, an aquifer classification scheme similar to but less restrictive than that in the NGLS was proposed in the Barrett Consulting – J.F. Mink report, 1991. The same classification arrangement is recommended for future determinations. The proposed divisions are congruent with those of the NGLS but are fewer in number.

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

An Aquifer Sector is a region within which exist similar hydrologic and geologic features and in which direction of groundwater flow is to the same general discharge line (i.e., Pacific Ocean; Philippine Sea). A Sector incorporates one or more Aquifer Systems. In an Aquifer System hydraulic continuity exists among all groundwater components (e.g., parabasal; basal). The Aquifer Type is defined by specific hydrogeological conditions within an Aquifer System.

In all instances the Aquifer Sectors correspond to the Sub-Basins of the NGLS, but the Agana Sub-Basin is further divided into the Agana and Fadian Aquifer Sectors to reflect the direction of groundwater flow (Agana Sector to the Philippine Sea; Fadian Sector to the Pacific Ocean). Aquifer Systems embrace a group of Management Zones. A System is a more flexible division for allocating water development than the much smaller

Management Zones. System boundaries depend on geology (e.g., argillaceous versus clean limestone), basement configuration, groundwater accumulation and groundwater flow direction. Figure 1 is a map showing Sectors and Systems.

Correspondence between the NGLS divisions and the proposed classification is presented in Table 2.

Southern Guam: Groundwater

Groundwater is not as dominating a fresh water resource south of the Adelup-Pago fault as it is to the north. Nevertheless, virtually the whole of Southern Guam is saturated with fresh groundwater and a small quantity has been successfully exploited. The groundwater occurs in the limited areas of limestone as well as in the far larger areas of volcanics.

The principal limestone deposits in the south consist of a band along the eastern coast having a maximum width of 2.5 miles at Yona but elsewhere reaching less than a mile inland. The continuity of the coastal zone of limestone ends at Inarajan. A smaller area of a different limestone formation drapes the highlands from Mt. Lamlam to Mt. Alifan and extends into the upper Talofofo River valley. In addition to the exposed areas of limestone at least two instances of limestone formations buried in the volcanics have been identified. One of the subsurface limestones was encountered in Malojloj and the other in the lower Talofofo valley. The Malojloj limestone aquifer originally contained artesian water, the only recognized occurrence in the island.

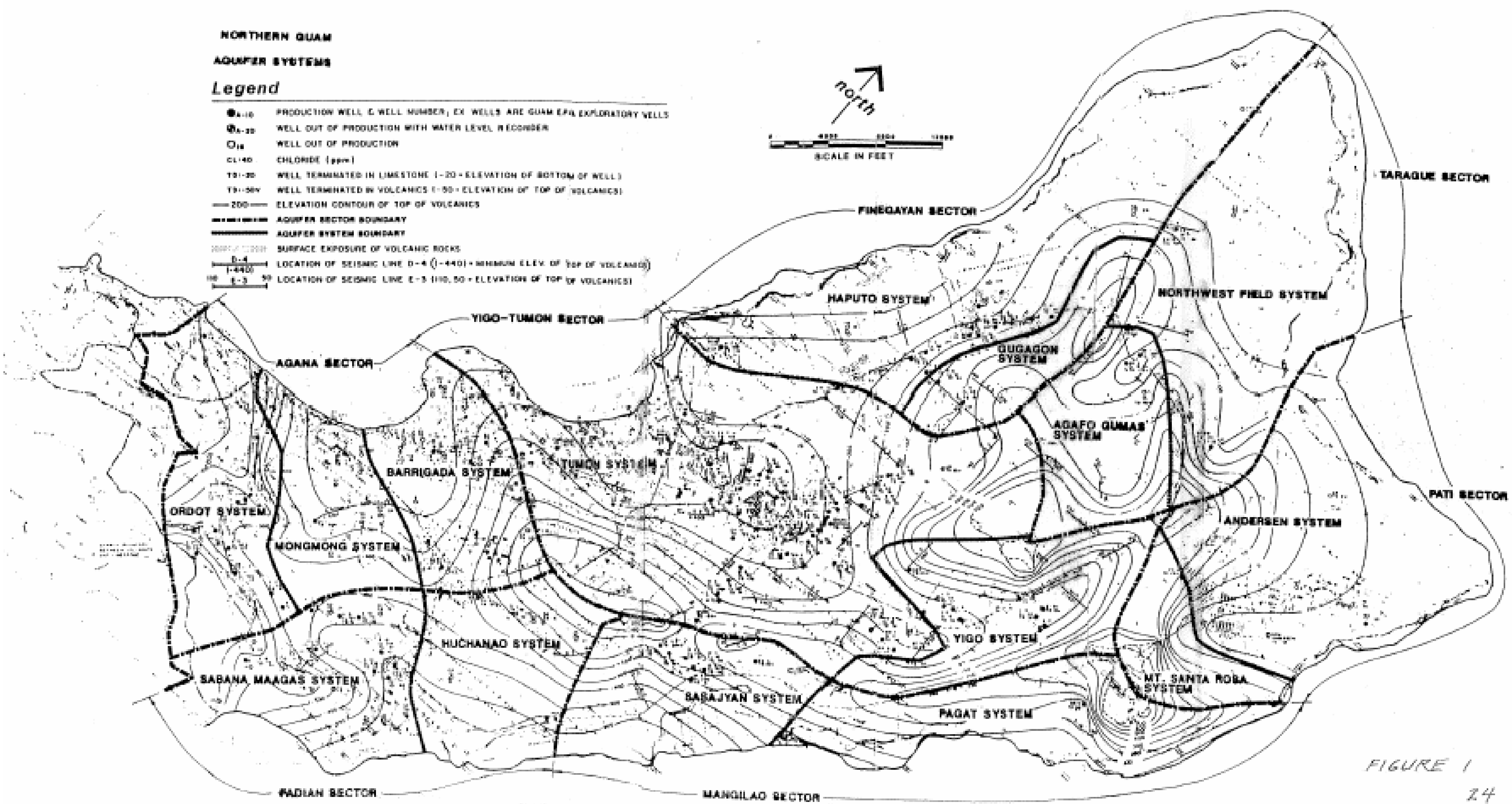
NORTHERN GUAM
AQUIFER SYSTEMS
Legend
PRODUCTION WELL & WELL NUMBER; EX WELLS ARE GUAM EPA EXPLORATORY WELLS
WELL OUT OF PRODUCTION WITH WATER LEVEL RECORDER
WELL OUT OF PRODUCTION
CHLORIDE (ppm)
WELL TERMINATED IN LIMESTONE (-20 = ELEVATION OF BOTTOM OF WELL)
WELL TERMINATED IN VOLCANICS (-50 = ELEVATION OF TOP OF VOLCANICS)
ELEVATION CONTOUR OF TOP OF VOLCANICS
AQUIFER SECTOR BOUNDARY
AQUIFER SYSTEM BOUNDARY
SURFACE EXPOSURE OF VOLCANIC ROCKS
LOCATION OF SEISMIC LINE D-4 (-440) = MINIMUM ELEV. OF TOP OF VOLCANICS)
LOCATION OF SEISMIC LINE E-5 (110, 50 = ELEVATION OF TOP OF VOLCANICS)
north
SCALE IN FEET
TARAGUE SECTOR
FINEGAYAN SECTOR
HAPUTO SYSTEM
NORTHWEST FIELD SYSTEM
YIGO-TUMON SECTOR
AGANA SECTOR
GUGAGON SYSTEM
AGAFO GUMAS SYSTEM
BARRIGADA SYSTEM
TUMON SYSTEM
PATI SECTOR
ORDOT SYSTEM
ANDERSEN SYSTEM
MONGMONG SYSTEM
HUCHANAO SYSTEM
YIGO SYSTEM
SABANA MAAGAS SYSTEM
MT. SANTA ROSA SYSTEM
SABAJYAN SYSTEM
PAGAT SYSTEM
PADIAN SECTOR
MANGILAO SECTOR

FIGURE 1
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TABLE 2

NGLS AND PROPOSED AQUIFER CLASSIFICATIONS

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

The low lying Mariana limestone shelf along the east coast carries basal groundwater and perhaps a narrow zone of parabasal groundwater. The higher Mariana shelf is underlain by volcanic rock at elevations above sea level, a condition which normally pre-empts the accumulation of groundwater.

The limestones of the south do not compare in aquifer volume with those of the north. Nevertheless, a number of successful small capacity wells have been drilled. Eventually more small capacity wells could be located to serve local water needs.

The volcanic aquifers of the south are comprised of irregularly layered submarine deposits of pyroclastics and lavas. In general the upper 15 to 50 feet of the sequence have been softened by weathering, but at depth the volcanics retain their original lithology which consists chiefly of breccia, tuff, vocanic sandstone and shale, and layered lavas. Secondary hydrothermal mineralization of the original rocks is common. The combination of compact layering and secondary mineralization has imparted to the rock mass very low permeability. Groundwater saturates the formations, but it moves very slowly and its residence time at depth must be very long. In regions of gentle topography the water table lies at shallow depth, mostly less than 15 feet below the ground surface, and may be exposed at the surface in low areas to create wetlands.

Throughout Southern Guam the entire volcanic rock mass to an unknown but substantial depth is saturated with groundwater. Although of low permeability, the volcanics constitute a nearly continuous aquifer. A few attempts to exploit the aquifers by drilled wells have succeeded in yielding low rates of production in the range of 25 to 60 gpm. On the other hand, some attempts have failed to yield even a few gpm from very deep borings.

Southern Guam: Surface Water

A comprehensive study of potential surface water development in the south was made by Barrett Consulting Group for PUAG in 1994. Eighteen of more than 40 rivers and streams were evaluated as potential sources of fresh water. The remainder were considered too small to be worth considering.

Development of surface water would be by means of storage reservoirs or simple diversions, such as currently is in place on the Ugum River. The construction of storage reservoirs would be very destructive of the environment as well as extraordinarily costly for the reliable amount of water that could be captured for potable use. Diversions, on the other hand, would be far less costly and would require a minimum of construction that would not severely impact the environment. The report concluded that diversions would be preferable to storage reservoirs although the amount of water gained would be small. Nevertheless, in the report both storage reservoirs and diversions are fully analyzed.

The only storage reservoir in Southern Guam is the U.S. Navy Fena Reservoir which collects drainage from three rivers – Almagosa, Imong and Maulap. Fena can sustain a draft of 11.5 mgd. About 4 mgd is provided to GWA and the remainder serves Navy demand.

Numerous studies have been performed relating to the construction of a dam and reservoir on the Ugum River that would yield available draft of 11 mgd. Studies have also been made for a dam-reservoir on the Inarajan River that would allow for available draft of about 6 mgd. The cost of construction and the environmental degradation that would accompany these projects have relegated them to a low priority on the list of water development schemes.

Diversion of stream flow is more acceptable from both a cost and environmental perspective, but the potential quantity of water captureable is far less than for dam-storage reservoirs. Numerous diversion structures have been installed in the past. Some are still active, others have been abandoned. The most productive diversion is on the Ugum River which was designed to reliably yield 2 mgd. Diversions on small streams serve the Umatac and Merizo areas. At one time the Tinago River was diverted to serve the Malojloj region, but it has been abandoned and the supply now comes from the Ugum. A well in Malojloj also contributed to the supply but is not active at the moment. .

Should all of the potential reservoirs listed in the Barrett study be constructed the total available draft would be 64 mgd. This total does not include the current available draft of the Fena system but does include yield made available by improving that system. For all of the potential diversions, excluding the present yield from the Ugum, the available draft would be 10.3 mgd. With the 2 mgd from Ugum included, the total would be 12.3 mgd.

These total available drafts are fractions of total surface runoff. Average surface runoff is estimated at 2.5 mgd/sq.mi. (see section on Hydrologic Budgets), which over the approximately 100 square miles of the south totals 250 mgd. The available draft of 64 mgd if all the reservoirs were constructed and Fena improved would amount to 26 percent of total runoff; adding the current Fena yield of 11 mgd raises the fraction to 30 percent. If all of the diversions were implemented, the fraction of average runoff would be approximately 5 percent.

Surface water in the south is a substantial resource that may have to be exploited more intensively should population demand in the future exceed the sustainable yield of the northern aquifers.

WATER DEVELOPMENT

Guam with a population of 155,000 (2000 Census) should consume about 20 mgd, assuming a per capita usage of 125 gpdc (gallons per day per capita). Allowing for an additional 5 to 10 mgd for miscellaneous purposes, total consumption should be 25 to 30 mgd. If typical water system leakage of 15 percent of production is allowed, the gross demand should be approximately 29 to 35 mgd. Total current production, however, approaches 60 to 65 mgd, which includes pumpage from the Northern aquifers (approximately 47 mgd), the Ugum diversion (2 mgd), Fena Reservoir (yield 11 mgd), and miscellaneous springs. Evidently the water distribution systems lose a substantial share of the water developed.

Of greatest concern is pumpage from the Northern Guam limestone aquifers. The GWA depends on production from about 110 wells under its control and purchases water from 10 wells managed by Earth Tech corporation. It also obtains a small quantity from Air Force wells. According to the GWA production data report dated July 10, 2003, Agency wells account for approximately 39 mgd, and Earth Tech supplies an additional 3.3 mgd (Tables 3 and 4), for a total of 42.3 mgd. The Air force also pumps for its own use about 2.5 mgd, the US Navy pumps about 2 mgd, and private users pump about 2 mgd, resulting in total groundwater production of approximately 47 mgd. Although this figure can’t be treated as truly accurate because of the approximations made in assigning yield values to each well, it suggests that even if the entire population of Guam was served by Northern groundwater, per capita consumption would be 292 gpdc as based on a linearly

TABLE 3

GUAM WATERWORKS AUTHORITY DEEPWELLS DATA

July 10, 2003

B. ISLAND WIDE DEEPWELLS

No. of Deepwells: 110

Item No.	Well No.	Location	Well Depth	Ground Elev. (Top of conc. Slab)	Well Bottom Elev.	Gen.	Motor				GPM				Pump		TDH Feet	Date Completed	Service Are
						KW	HP	Volts 3 PH	RPM	Brand	Design Actual	S/Water Level	Current	S/Water Level	Stages	Brand			Reservoir
1	A-1	Ordot-After Chaot Bridge	221	63	-153		50	460	3450		216	76.57	70					Feb-65	CHOAT
2	A-2	Dairy Rd next to Santurary	170	119	-52		40	460	3450		241	106.11	200					Sep-65	CHOAT
3	A-3	Ordot RT4	390	-263	172		40	460	3450		180	105.8	190					Apr-66	CHOAT
4	A-4	Da iry. Evangelista St.	301	141	-160		50	460	3450		244	133.9	280					Jun-66	CHOAT
5	A-5	Afame St. Sinajana	323	146	-177		50	460	3450		269	137	250					Aug-66	CHOAT
6	A-6	Afame St. Sinajana	306	153	-154		40	460	3450		241	142	280					May-67	CHOAT
7	A-7	Ch Pago Across Super MKT	188	139	-50		40	460	3450		113	126	200					May-67	Pago brg.
8	A-8	Ch pago Across Gas Station	305	128	-177		50	460	3450		206	109	220					Jul-67	Pago brg.
9	A-9	Dairy Rd Back Entrance	237	186	-50		50	460	3450		280	180.5	230					Apr-67	ABIS
10	A-10	Dairy Rd Corner White St.	216	190	-25		40	460	3450		233	184.5	255					May-67	
11	A-12	Ordot Acrss Bautista Church	340	138	-200		50	460	3450		176		170					Oct-73	CHOAT
12	A-13	Dariy Rd Before DOC Ent	325	130	-194		40	460	3450		237		237					Oct-73	ASBP
13	A-14	Corner Rt . 10 Rt. 15	260	210			50	460	3450		147	206	190					May-73	mangilao
14	A-15	Rt. 10 Untalan Elem . School	250	199	-52		50	460	3450		231	194	270					Jun-73	RT.10 ;8
15	A-17	Rt. 10 Public Health	235	194	-39		50	460	3450		180	192.9	240					Aug-73	Mangilao
16	A-18	Dairy Rd.Dept of Agriculture	250	195	-45		50	460	3450		229	193.5	100					Oct-73	ASBP
17	A-19	Ch Pago After Stop Light	160	136	-24		50	460	3450		138	133.3	160					Oct-73	Pago brg.
18	A-21	Mangilao (Near Mayor Office)	234	183	-51		50	460	3450		213	182.2	205					Feb-74	Mangilao
19	A-23	Rt. 4 Agana After Mc Donald	82	35	-45		50	460	3450		317	29	340					May-83	CHOAT
20	A-25	Rt 4 Agana After Town Hse	166	58	-11		50	460	3450		245	50.11	250					Oct-83	CHOAT
21	A-26	Mongmong Toto s- ball Field	204	157	-47		40	460	3450		50	148.5	70					May-83	Toto Chur
22	A-28	Corner Leyang Manebusan	247	199	-47		50	460	3450		223	195.1	320					May-83	Leyang ba
23	A-29	Agana Spring	120	51	-34		50	460	3450										
24	A-30	Agana Spring	145	119	-26		100	460	3450		755		760						CHOAT
25	A-31	Before Cliff Hotel Agana Hgts	310	195	-50		40	460	3450		293		280						Agana Hts
26	A-32	Aga. Hghts Across N Hospital	170	148	-47		15	460	3450		225		173						Agana Hts
27	MJ-1	Malojloj Subdivision	300	257	-43		15	460	3450		56								Malolo

B. ISLAND WIDE DEEPWELLS

No. of Deepwells: 110

Item No.	Well No.	Location	Well Depth	Ground Elev. (Top of conc. Slab)	Well Bottom Elev.	Generator	Motor				GPM				Pump		TDH Feet	Date Completed	Service Area
						KW	HP	Volts 3 PH	RPM	Brand	Design Actual	S/Water Level	Current	S/Water Level	Stages	Brand			Reservoir
28	MJ-5	Malojloj Subdivision					40	460	3450		58								Malolo
29	NAS-1	Behind Post Office Tiyan						460	3450				58						
30	D-1	Dededo Golf Course	418	382	-36		50	460	3450		250	379.25	210					Feb-65	Kaiser
31	D-2	Dededo Golf Course	417	382	-35		50	460	3450		187	377.77	187					Feb-65	Kaiser
32	D-3	Dededo Golf Course	407	384	-23		40	460	3450		149	383	180					Jun-65	Kaiser
33	D-4	Dededo Golf Course	408	384	-24		50	460	3450		172	383	240					May-65	Kaiser
34	D-5	Dededo Golf Course	412	378	-34		50	460	3450		166	381	180					Dec-65	Kaiser
35	D-6	Dededo Golf Course	422	397	-35		50	460	3450		187	3969	280					Feb-66	Kaiser
36	D-7	Y- Seng Song Road	437	379	-50		50	460	3450		198	382						Nov-96	Kaiser
37	D-8	Y- Seng Song Road	450	414	-35		50	460	3450		185	110.5	230					Sep-96	Astumbo
38	D-9	Dededo Golf Course	417	388	-29		50	460	3450		196	383	220					Jan-96	Kaiser
39	D-10	Butullo Street, Dededo	415	391	-25		50	460	3540		351	384.58	170					Mar-68	Kaiser
40	D-11	Dededo Golf Course	430	393	-37		50	460	3540		226	389						Apr-69	Kaiser
41	D-12	Y- Seng Song Road	460	421	-42		50	460	3540		188	417.42	190					Oct-71	Astumbo
42	D-13	Swamp Road Dededo	455	395	-20		50	460	3540		172	397						Jan-71	Astumbo
43	D-14	Bio Path Dededo	372	319	-60		50	460	3450		200	315.25						Aug-73	Kaiser
44	D-15	Benavente Middle School	452	363	-49		50	460	3540		202	363						Nov-74	Kaiser
45	D-16	Sta. Monica Public Heath	387	329	-37		50	460	3540		161	320.1	170					Oct-79	Kaiser
45	D-17	Sta .Monica Pipe Line	350	301	-45		50	460	3450		199	297.5	170					Oct-79	Kaiser
47	D-18	Sta. Monica Public Heath	360	310	-50		50	460	3450		180	308.7						Nov-79	Kaiser
48	D-19	Swamp Road Dededo	438	391	-47		50	460	3450		227		150						Astumbo
49	D-20	Swamp Road Dededo	421	372	-47		50	460	3450		207		190						Astumbo
50	D-21	Swamp Road Dededo	420	373	-47		50	460	3450		157		190						Astumbo
51	D-22	Y- Seng Song Road	435	450	-5		50	460	3540		200	40.74	200						Astumbo
52	D-23	Y- Seng Song Road	434	434	-1		50	460	3450		150	40.05						Dec-96	Astumbo
53	D-24	Y- Seng Song Road	498	436	-51		50	460	3450		205	3.3	170						Astumbo
54	EX-5	Dededo Golf Course	424	386	-39		50	460	3450		254		240						Kaiser

B. ISLAND WIDE DEEPWELLS

No. of Deepwells: 110

Item No.	Well No.	Location	Well Depth	Ground Elev. (Top of conc. Slab)	Well Bottom Elev.	Generator KW	Motor HP	Volts 3 PH	RPM	Brand	GPM Design Actual	S/Water Level	Current	S/Water Level	Pump Stages	Brand	TDH Feet	Date Completed	Service A Reservoir
55	G-501	GHURA 501 Playground	460	410	-50		50	460	3450		183		190						Kaiser
56	F-1	Fenegayan POL RT. 3	460	425	-37		50	460	3450		140		180						YIGO
57	F-2	Fenegayan POL RT. 3	490	450	-43		50	460	3450		121		180						YIGO
58	F-3	Fenegayan POL RT. 3	492	455	-37		50	460	3450		142		150						YIGO
59	F-4	Fenegayan POL RT. 3	495	457	-35		50	460	3450		137		130						YIGO
60	F-5	Near Astumbo Comm'ty. Ctr.	425	391	-35		50	460	3450		145		214						Astumbo
61	F-6	Intersection Rte. 3, Y-sengsong	370	347	-26		50	460	3450		151		190						Astumbo
62	F-7	NCS Pipe Rt.3	388	391	-35		50	460	3450		170		140						YIGO
63	F-8	Y -Seng Song \ Balaku	358	439	-81		50	460	3450		149		140						Astumbo
64	F-9	Y- Seng Song Magic Store	445	394	-50		50	460	3450		140		200						Astumbo
65	F-10	NCS POL Rt.3	483	437	-50		50	460	3450		142		200						YIGO
66	F-11	NCS POL Rt. 3	487	441	-50		50	460	3450		113		158						YIGO
67	F-12	Machanao To Piga	496	471	-25		50	460	3450		148								Astumbo
68	F-13	Bong Bong Machanao	515	433	-38		50	460	3450		200	2.34	150				720	Dec-96	Astumbo
69	F-15	Corazon Machanao	485	466	-50		75	460	3450		350	4.36					670	Dec-96	Astumbo
70	F-16	Corazon Machanao	520	472	-45		75	460	3450		350	3.88	330				725	Dec-96	Astumbo
71	F-17	Corazon Machanao	525	480	-45		75	460	3450		240	4.79	240				813	Dec-95	Astumbo
72	F-18	Corazon Machanao	523	479	-44		75	460	3450		240	3.2	240				813	Dec-95	Astumbo
73	HG-2	Santa Ana Subdivision	583	506	-77		125	460	3450		447		470						YIGO
74	H-1	Harmon 2 Lovers Pt.	44.95	440	-50		50	460	3450		288		265						YIGO
75	AG-1	Machananao USAF	496	469.98	-27		50	460	3450		250		120						YIGO
76	AG-2A	Machananao Paintball	583	506	-70		150	460	3450		500	500.78	500				747	May-00	YIGO
77	M-1	Latte Heights Plantation	450	395	-54		50	460	3450		109	391.8	140					Apr-65	MAN
78	M-2	Latte Heights Plantation	451	403	-48		50	460	3450		184	396	220					Apr-68	MAN
79	M-3	Latte Heights Plantation	474	422	-50		50	460	3450		177	418.3	45					Dec-67	BAR

GUAM WATERWORKS AUTHORITY DEEPWELLS DATA

July 10, 2003

B. ISLAND WIDE DEEPWELLS

No. of Deepwells: 110

Item No.	Well No.	Location	Well Depth	Ground Elev. (Top of conc. Slab)	Well Bottom Elev.	Generator KW	Motor HP	Motor Volts 3 PH	Motor RPM	Motor Brand	GPM Design Actual	GPM S/Water Level	GPM Current	S/Water Level	Pump Stages	Pump Brand	TDH Feet	Date Completed	Service A Reservoir
80	M-4	Latte Heights Plantation	472	442	-51		50	460	3450		138	418.3	160					Mar-68	BAR
81	M-5	Lemon China St. Latte Hts,	405	273	-132		50	460	3450		176	267.3	160					Feb-69	BAR
82	M-6	Villa Rosario Condo	406	326	-80		50	460	3450		168	320.6	160					Aug-69	BAR
83	M-7	Butter Cup Street, Macheche	340	489	-51		50	460	3450		175	284.2	175					Jun-70	BAR
84	M-8	Carnation Rd Latte Hts.	538	486	-52		50	460	3450		158		170					Jun-70	MAN
85	M-9	Mangilao Rt. 15	489	449	-40		50	460	3450		162		160					Sep-70	MAN
86	M-12	Harmon Loop Road	380	272	-109		50	460	3450		114							Oct-73	TUMON
87	M-14	Liguan Terrace B-ball	315	274	-46		50	460	3450		239	269.6	220					Oct-74	TUMON
88	M-15	Lemon China St.Latte Hgts	347	296	-54		50	460	3450		172	292.09	190					May-82	BAR
89	M-17A	Back of Price Mart	476	431	-45		75	460	3450		200		210						Hyndai
90	M-17B	Back of Price Mart	521	480	-41		75	460	3450		354		160						Hyndai
91	M-18	Rt.15 Iglesia ni Cristo	245	208	-42		50	460	3450		325		220				460	Jun-97	TUMON
92	M-20A	Back of Price Mart	528	487	-38		75	460	3450		400	2.34	400				858	Dec-95	Hyndai
93	M-21	Airport Rd Next to Gas Sta.	395	355	-40		60	460	3450		250	5.25	180				670	Jul-99	Air-BAR
94	M-23	Carnation Lane Latte Hgts.	451	401	-50		60	460	3450		225	394.6	220				801	May-00	MAN
95	EX-11	Latte Heights,					50	460	3450		210		200						MAN
96	Y-1	Asardas Drive, Yigo	461	415	-46		50	460	3450		141		150						YIGO
97	Y-2	Asardas Drive, Yigo	465	415	-50		50	460	3450		161		161						YIGO
98	Y-3	Beside Mayor Office, Yigo	469	416	-53		50	460	3450		138								YIGO
99	Y-4A	Back of Ace Hardware	450	399	-52		50	460	3450				220						YIGO
100	Y-5	Simon Sanchez High School	483	433	-50		50	460	3450		143		160						YIGO
101	Y-6	Simon Sanchez High School	478	428	-50		50	460	3450		136		180						YIGO
102	Y-7	Gaynero Rd. Yigo Elem Sch.	476	412	-64		125	460	3450		514	409.5	550						YIGO
103	Y-9	Gaynero Rd. Yigo Elem Sch	455	402	-53		125	460	3450		472		472						YIGO
104	Y-10	Aga Blvd Ypaopao Est.	447	390	-56		50	460	3450		200	4.19	200				730	Jul-97	YIGO
105	Y-12	Batulo Street Dededo	430	406	-23		60	460	3450		235	8.59	235				718		Kaiser
106	Y-14	Back of Ace Hardware,Yigo	447	409	-39		100	460	3450		350	4.1	350				730	Jul-97	YIGO

GUAM WATERWORKS AUTHORITY DEEPWELLS DATA

July 10, 2003

B. ISLAND WIDE DEEPWELLS

No. of Deepwells: 110

107	Y-15	Rte. 15 UPI Elem School, Yigo	445	466	-50		125	460	3450		650		650				770	May-93	Sta.Rosa
108	Y-16	Before Ace Hardware,Yigo.	445	404	-41		75	460	3450		200	403.2	200				738	Aug-00	YIGO
109	Y-17	Evangelista Rd.,Yigo	335	502	167		40	460	3450		300	183.6	300				674	May-00	YIGO
110	Y-21A	Before Ace Hardware,Yigo.	425	381	-41	-33.25	100	460	3450		350	379.32	350				718	Aug-00	YIGO
111	Y-23	Chalan Paharu, Yigo	416	517	102	261.82	40	460	3450		300	170.57	300				661	Feb-00	YIGO

TABLE 4

Earth Tech Water System

Name of System: Earth Tech Public Water Supply System

Owner: Earth Tech

Responsible Person: Bill Chang (1999-2001); Mark Whitney (2001-2003); Mark Schmidt (2003-2020) General Manager

Mailing Address: P.O. Box 12346, Tamuning, Guam 96931

PWS Type: Community Public Water Supply System

Type of Water Source: Groundwater

Water Sources: (See Below)

Well Name	Location	Coordinates, ft.	Elevation, ft. (Top of Conc. Pedestal)	Pumping Rate, gpm (Maximum)	Date of Activation	Permit Expiration	Next Renewal Date
ETF-19 (Formerly ETF-1)	Lot 10123-R2, CLTP Route 3, Dededo	N 676424.52 E 360071.39	369.66	200	November 24,1998	November 24, 2003	**Nov. 24 2008**
ETF-20 (Formerly ETF-2)	Lot 10123-R2, CLTP Route 3, Dededo	N 674548.92 E 359014.47	381.51	200	December 18,1998	November 24, 2003	**Nov. 24 2008**
ETD-25 (Formerly ETD-7)	Tract 1022, CLTP Swamp Road, Dededo	N 672582.75 E 364297.08	407.40	400	March 4, 1999	March 2, 2004	**March 2, 2009**
ETD-26 (Formerly ETD-9)	Lot 10125-11-R1, CLTP Swamp Road, Dededo	N 672808.89 E 363109.60	368.43	250	March 4, 1999	March 2, 2004	**March 2, 2009**
ETD-27 (Formerly ETD-4)	Lot 10122-R18, CLTP Stampa Road, Dededo	N 671022.00 E 365679.11	416.38	400	August 25, 1999	**August 19, 2004**	AUGUST 26, 20[illegible]
ETD-28 (Formerly ETD-6A)	Lot 10120-R19, CLTP Swamp Road, Dededo	N 670225.06 E 362874.95	396.67	200	August 25, 1999	**August 19, 2004**	August 26, 20[illegible]
ETY-18 (Formerly ETY-1)	Lot Marbo Base Command "B"-4, Yigo	N 180526.06 E 209485.95	398.41	250	April 28, 1999	April 26, 2004	**April 26, 2009**
ETY-19 (Formerly ETY-2)	Lot Marbo Base Command "B"-4, Yigo	N 180200.47 E 208487.71	376.09	500	April 28, 1999	April 26, 2004	**April 26, 2009**
ETY-20 (Formerly ETY-3)	Lot Marbo Base Command "B"-4, Yigo	N 179527.75 E 209552.60	398.06	500	April 28, 1999	April 26, 2004	**April 26, 2009**
ETY-22 (Formerly ETY-27)	Ypapao, Dededo	N665922.9839 E368668.1549	416.00	300	March 8, 2002	February 4, 2007	

extrapolated population of 161,000 in 2003. The difference between 292 gpdc and the expected average consumption of 125 gpdc implies a system loss of greater than 55 percent, which is far in excess of the 15 percent suffered by most systems in good order.

Northern Guam

The groundwater of Northern Guam is the most voluminous supply source for the island's population and its activities. Pumpage has steadily increased since large scale exploitation started in the 1960s. Since 1990 total pumpage has risen from about 31 mgd (data from Barrett Consulting Group – J.F. Mink, 1991) when the island's population was 133,000 to about 47 mgd in 2003. The common statement that just 25 to 30 mgd is pumped must be erroneous because it is likely based on just GWA production. The data sources for the higher estimate of 47 mgd are the compilation of records included in a University of Guam – WERI Masters Thesis of M.Q. McDonald (2001), the GWA Deep Well data printout of July, 2003, and Earth Tech records.

Comparison of the GWA and McDonald data sets by Aquifer Sectors and Aquifer Systems are listed below. All pumpage as mgd is included. The Earth Tech and Navy data are summed with the original McDonald and GWA data.

Agana Aquifer Sector

AquiferSystem		McDonald	GWA
Ordot		4.95	4.84
Mongmong		1.50	1.12
Barrigada		0.83	0.82
	Total	7.28	6.78

Fadian Aquifer Sector

Aquifer System		McDonald	GWA
Sabana Maagas		2.97	2.79
Huchunao		1.22	1.23
	Total	4.19	4.01

Mangilao Aquifer Sector

Aquifer System		McDonald	GWA
Sasajayan		1.54	1.57
Pagat		0	0
	Total	1.54	1.57

Pati Aquifer Sector

Aquifer System		McDonald	GWA
Mt. Santa Rosa		0	0
Andersen		0.81	0.94
	Total	0.81	0.94

Tarague Aquifer Sector

Aquifer System		McDonald	GWA
Agafo Gumas		1.94	2.07
Northwest Field		0	0
	Total	1.94	2.07

Finagayan Aquifer Sector

Aquifer System		McDonald	GWA
Guagon		2.75	3.07
Haputo		4.74	4.65
	Total	7.49	7.72

Yigo-Tumon Aquifer Sector

Aquifer System		McDonald	GWA
Yigo		4.51	5.12
Tumon		15.04	14.13
	Total	19.55	19.25
	TOTAL	42.8	42.3
Air Force		2.5	2.5
Private		1.0	1.0
	TOTAL	47.3	46.8

Groundwater withdrawals in the Northern aquifers already surpass the early estimates of sustainable yield and are approaching the most recent estimates of about 70 mgd. Not all of this total estimate is available to GWA, however, because a significant portion is in Federal land, in particular the Andersen Air Base complex. In the NGLS sustainable yield available to GWA was estimated at 60 mgd.

The total average draft of nearly 50 mgd satisfies a demand which is, at most, 35 mgd. The difference is lost in the distribution network by leakage, most of which presumably returns to the aquifers. If so, the net loss to the aquifers by pumping may be closer to 35 mgd than to 50 mgd. Nevertheless, a prime goal for GWA is to reduce system leakage. Pumping costs would be reduced and mismanagement of the aquifers would be avoided.

The sustainable yield given in the NGLS for each Management Zone was adjusted in the Barrett Consulting – J.F. Mink study (1991) for each Aquifer System. The NGLS estimate of 60 mgd for Northern Guam was increased to 75 mgd, but 15 mgd of this amount was assigned to Federal property and thus considered not available to GWA, leaving an accessible sustainable yield of 60 mgd, the same as proposed in the NGLS. Table summarizes the revised sustainable yields and the portions available to GWA along with the current draft and the unused sustainable yield for each Aquifer System (all values in mgd).

Table 5

Agana Aquifer Sector	Total SY	Non-Fed SY	Draft	Unused Non-Fed SY
Ordot System	7.5	7.5	4.84	2.7
Mongmong System	2.8	2.8	1.12	1.7
Barrigada System	3.0	3.0	0.82	2.2
Total	13.3	13.3	6.78	6.5
Fadian Aquifer Sector				
Sabana Maagas System	3.0	3.0	2.79	0.2
Huchunao System	4.2	4.2	1.23	3.0
Total	7.2	7.2	4.02	3.2

Mangilao Aquifer Sector				
Sasajyan System	3.3	3.3	1.57	1.7
Pagat System	3.3	0	0	0
Total	6.6	3.3	1.57	1.7
Pati Aquifer Sector				
Mt. Santa Rosa System	2.3	2.3	0.94	1.4
Andersen System	7.5	0	0	0
Total	9.8	2.3	0.94	1.4
Tarague Aquifer Sector				
Agafo Gumas System	5.0	5.0	2.07	2.9
Northwest Field System	7.0	0	0	0
Total	12.0	5.0	2.07	2.9
Finegayan Aquifer Sector				
Gugagon System	5.0	5.0	3.07	1.9
Haputo System	6.6	4.0	4.65	(-0.65)
Total	11.6	9.0	7.72	1.3
Yigo-Tumon Aquifer Sector				
Yigo System	6.4	6.4	5.12	1.3
Tumon System	13.6	13.6	14.13	(-0.59)
Total	20.0	20.0	19.25	0.8
TOTAL	80	60	42.4	17.8
Miscellaneous Draft (Air Force + USN + Private)			4.5	
TOTAL			46.9	13.1

The unused sustainable yield accessible by GWA totals about 13 mgd. This value should be treated as a simple estimate which probably underestimates the remaining sustainable yield developable by optimal means. Not all of the remaining sustainable yield will be easy to access, however. A portion may elude cost effectiveness and its capture may never come about.

The premium remaining sustainable yield is in the Agana Aquifer Sector, especially in the Ordot Aquifer System in which the aquifers are parabasal. The production wells are A1 through A8, A12, A23, A25, A31, A32, NRMC-1, NRMC-2 and NRMC-3. Another 2.7 mgd can be taken from the System. The Mongmong Aquifer System, in which the Agana Swamp (Springs) is located can provide an additional 1.7 mgd. Two wells, A29 and A30, both located near the old Navy sump, yield about 1.5 mgd. In the GWA printout A29 is listed as NO (not operating). Although the residual sustainable yield in the Barrigada Aquifer System is 2.2 mgd, the groundwater is basal and pumpage of high chloride water is common. The active wells are A15, NCS-3 and NCS-8. A new approach to developing this supply is needed to reduce the tendency toward unacceptable salinity.

The Agana Swamp (Springs) is a prolific source of fresh water which is derived from both parabasal and basal sources. Undoubtedly in pre-historic times and the Spanish era it was the main fresh water source for the Hagatna region. At first ignored by the Navy upon occupation of the island in 1898, it later became the principal source of supply with the construction of a concrete-lined sump and the installation of pumps in 1914. Over the years pumpage ranged from 1.5 to 4.9 mgd. The water table elevation in the swamp varied between a low of 8.5 feet and a high greater than 10 feet. The sump overflowed when the water table exceeded 10.3 feet. Pumpage from the sump was always of low salinity but often it contained contaminants that originated from seepage from nearby cesspools. In 1957 the Navy abandoned the source when treated water became available from Fena.

In the Fadian Aquifer Sector the Sabana Maagas System is almost fully developed by wells A9, A10, A13, A14, A17, A18, A19, A21 and A28. Very little sustainable yield (approximately 0.2 mgd) remains. In the Huchunao Aquifer System, however, an additional 3.0 mgd can be developed. Only two wells, HRP-1 and HRP-2, currently exploit the System.

The Mangilao Aquifer Sector has a surplus sustainable yield of 1.7 mgd, all of it in the Sasajyan Aquifer System. Parabasal wells M3, M4, M8, and basal wells EX11, M1, M2 and M16B are in the System. Wells serving a golf course, which are not included in the compilation of draft, reduces the residual sustainable yield to perhaps 1 mgd or so. In the Pagat System the total sustainable yield of 3.3 mgd is restricted to Federal property.

In the Mt. Santa Rosa System of the Pati Aquifer Sector a residual sustainable yield of 1.4 mgd remains. Only well Y-15 draws from the System. The total sustainable yield of 7.5 mgd in the Andersen System is in the Air Base complex and not accessible by GWA.

The Northwest Field Aquifer System of the Tarague Sector is also in U.S. Government land, and its sustainable yield of 7.0 mgd may be developed by the Air Force to replace the Marbo wells, which now are the source of supply. The Agafo Gumas System is exploited by GWA (wells AG-1, AG-2A, HGC-2) and a golf course (HGC-2) but still has an unused sustainable yield of 2.9 mgd. The groundwater is parabasal and can handle larger than normal well capacities.

In the Finegayan Aquifer Sector the Gugagon System has a sustainable yield surplus of 1.9 mgd, but the Haputo System sustainable yield is overdrawn by 0.65 mgd. Parabasal wells in the Gugagon System include D22A, D24, F15, F16, F17 and F18. Basal wells are F8, F9, F12 and F13. The Haputo System contains basal groundwater which is developed by wells F1 – F7, F10, F11, F19 (Earth Tech), F20 (Earth Tech), and US Navy wells NCSA, NCSB, NCS4, NCS5, NCS6, NCS7 and NCS9A.

The Yigo-Tumon Aquifer Sector embraces the greatest sustainable yield (20 mgd) of any Sector but is also the most heavily exploited. A residual sustainable yield of just 0.8 mgd remains. A surplus of 1.3 mgd in the Yigo Aquifer System can be developed, but the Tumon System may be overdrawn by 0.6 mgd. In the Yigo System GWA pumps from 13 Y series wells, several of which are parabasal. The Tumon System contains more wells than any other System or Sector. Among the total are 7 Y series wells, 4 of which belong to Earth Tech; 25 D series wells, 4 of which also belong to Earth Tech; 14 M series wells; and wells H1 and GH501. Also in the System are 9 Air Force wells which pump an average of about 2 to 3 mgd. Of the total pumpage of 47 mgd in Northern Guam, 22 mgd is withdrawn from the Yigo-Tumon Sector

The first well drilled for the Civil Government of Guam in 1965 was D1 in the Tumon Aquifer System. Drilling was concentrated on the D series over the next several decades. The first well was simple in design and fitted with a pump to provide 200 gpm (Figure 2). It became the standard throughout Northern Guam. Recognition that parabasal groundwater could sustain higher pump rates led to the installation of pump capacities as high as 755 gpm (well A30, Agana Swamp, Mongmong Aquifer System). Most of the wells pump an average of 150 to 200 gpm, and the parabasal wells 200 to 700 gpm. Tables and list the GWA wells as of July, 2003 and the Earth Tech wells, respectively.

Southern Guam

Both groundwater and surface water are developed in Southern Guam, but surface water offers the most voluminous source of supply. Surface water is already extensively exploited in the Fena Reservoir System and to a lesser extent as a diversion from the Ugum River. Numerous wells have been drilled but only one at the old GORCO Refinery can be pumped at a rate similar to the typical Northern Guam well at 150 to 200 gpm. The importance of the surface water opportunities in Southern Guam will rise as population of the island continues to grow. Groundwater development will always be limited but may play an important role in supplying local demands.

Surface Water

The surface water resources of Southern Guam and proposals for developing them are thoroughly discussed in the Barrett Consulting Group 1994 report to PUAG titled, ”Surface Water Development Study”. The study concluded that although a dam-reservoir

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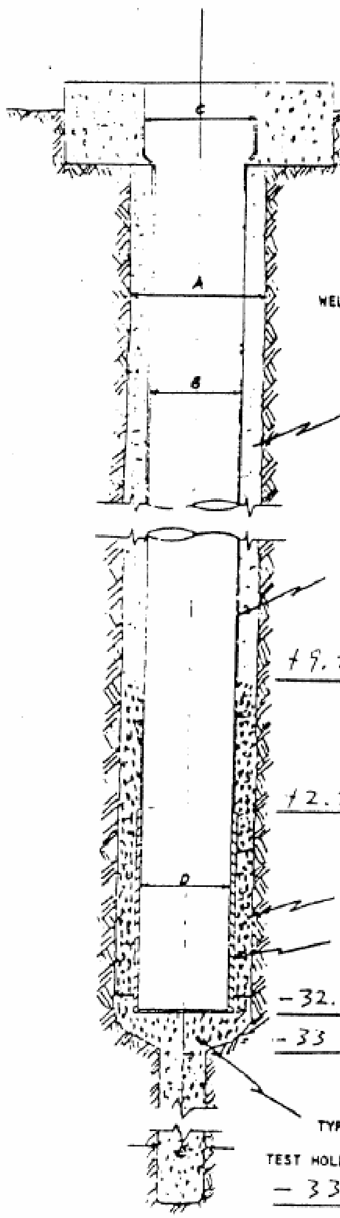
FIGURE 2

WELL CONSTRUCTION DIAGRAM

WELL NUMBER D-1



DATE STARTED ____________

DATE COMPLETED ____________

COORDINATES (1000 METER GRID) N ________ E ________

SPECIFIC CAPACITY AT 200 GPM ____________ GPM/FT.

DESIGN CAPACITY ____________ GPM

46

WELL NUMBER D-1

on several rivers would provide the greatest reliable yield, the most practical way to capture stream flow for use is by means of diversions. Tables 6 and 7, taken from the Barrett report, summarizes the expectation of reliable draft for potential reservoir sites and for diversion works. Figures 3 and 4, also from the Barrett report, shows the locations of the potential reservoirs and diversions.

At present one large scale dam-reservoir, a moderate river diversion, and several springs constitute water development in the south. The dam-reservoir is the US Navy Fena system. Average yield is about 11.5 mgd, of which about 4 mgd is sold to GWA. The Fena Reservoir is large, having a surface area of 196 acres, a length of 1.9 miles, a maximum width of 0.4 miles, and maximum depth of 66 feet near the spillway (Kennedy Engineers, 1973). The dam is 125 feet high and 1,500 feet long. Surface runoff plus some spring flow from a watershed area of 6 square miles drains to the reservoir whose storage volume is approximately 7,500 acre feet. The dam-reservoir was completed in 1952. The water is treated before it is distributed for potable use.

The Ugum River diversion, a GWA project, was put on line in 1993 to supply about 2 mgd for the Malojloj-Inarajan region. The water is treated then delivered to a 1 mg steel reservoir for distribution. The Ugum project has been a success and is a model for future diversions.

Several springs provide water for communities in the south. Asan Spring south of Hagatna has an estimated reliable flow of 298 gpm. Santa Rita Spring near Agat yields

TABLE 6

SUMMARY OF POTENTIAL RESERVOIR SITES

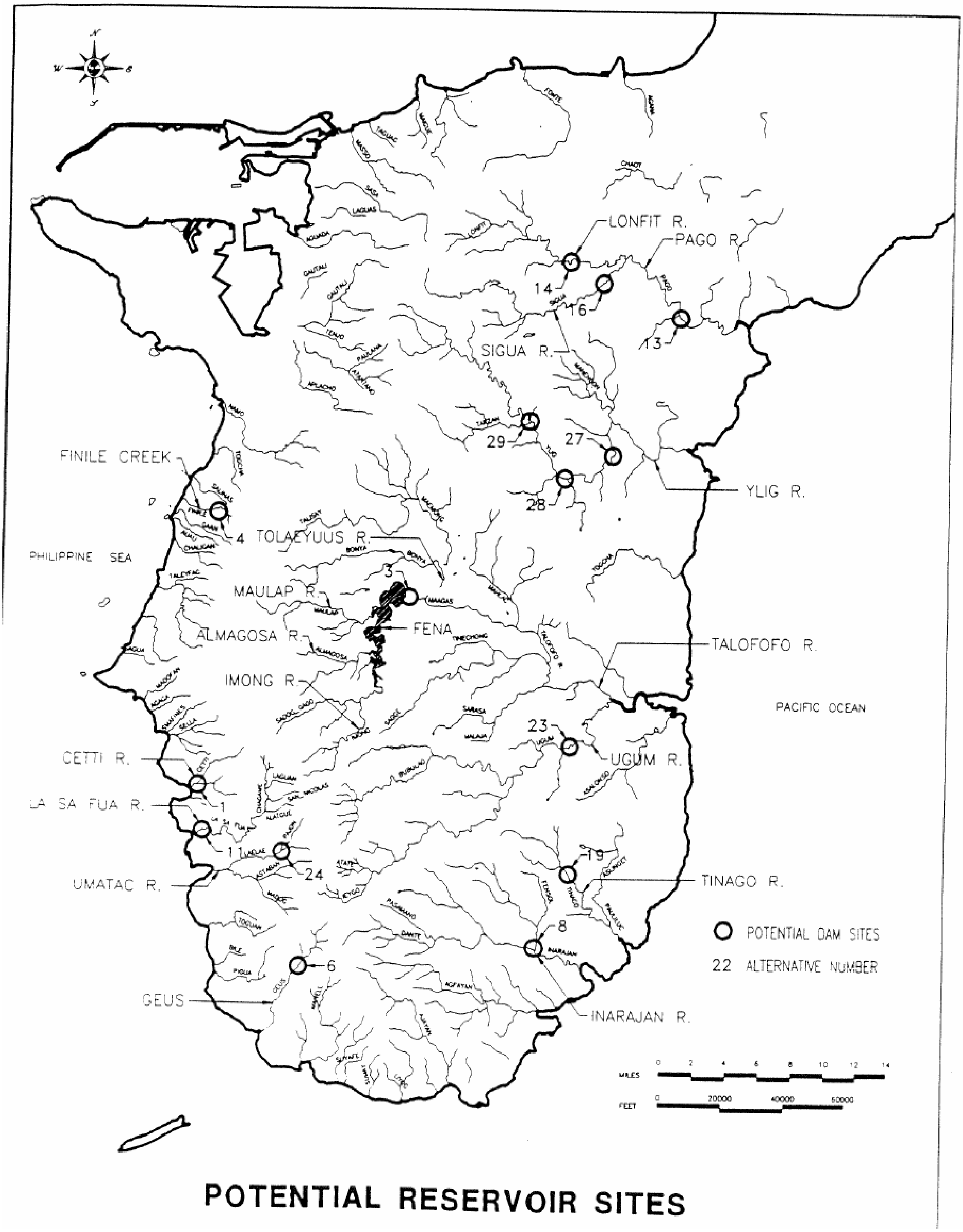
Reservoir	Available Draft (MGD)	Reservoir Volume (AF)	Reservoir [1] Depth at Dam (FT)	Minimum Downstream Base Flow (CFS)	Shortage Index	Remarks
Cetti	1.0	854	46	0.50	0.04	
Fena[2]	4.0	10,740	20	0.00	0.03	Raise existing dam
Finile	0.15	88	50	0.23	NF[3]	
Geus	0.15	90	60	0.13	NF	Replace existing dam
Inarajan	5.9	4,090	72	2.37	0.17	
La Sa Fua	0.5	96	35	0.74	NF	
Lonfit	3.3	2,270	78	0.31	0.00	
Pago	9.6	7,010	50	0.93	NF	
Sigua	5.4	5,200	78	0.45	0.02	
Tarzan	7.5	4,915	76	0.83	0.02	
Tinago	1.8	2,350	42	0.19	0.02	
Ugum	11.0	5,010	68	5.17	0.02	
Umatac	0.15	101	40	0.2	NF	Supplemented by La Sa Fua River
Windward Hills	2.1	1,215	60	1.11	0.02	Supplemented by Ylig River
Ylig	11.4	7,720	70	1.26	0.02	

(1) Does not include sediment or storm flow volume.
(2) Values show increase above existing conditions.
(3) Determined not feasible. See discussions of each alternative in Section II.

TABLE 7

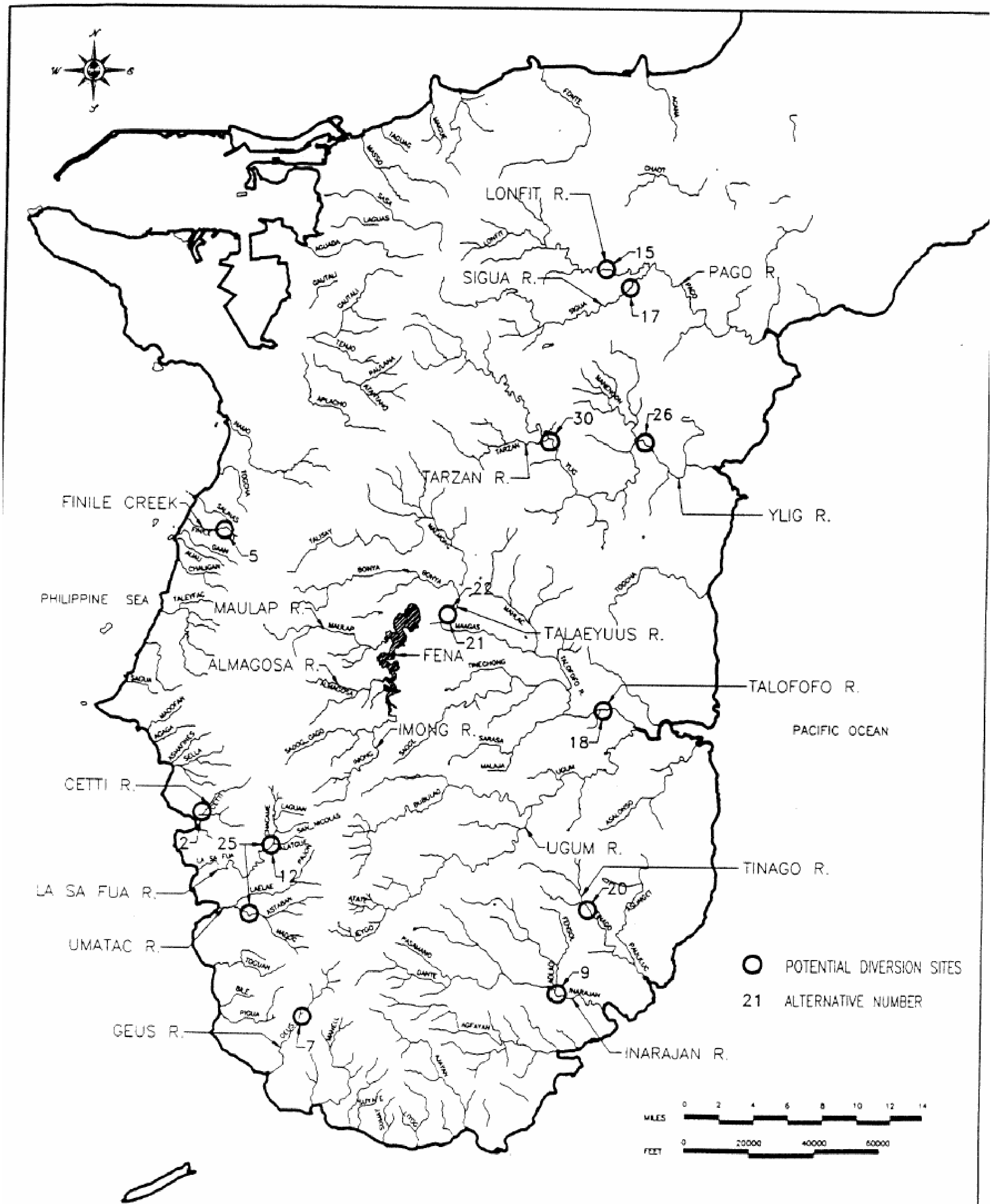
SUMMARY OF POTENTIAL DIVERSION SITES				
DIVERSION	AVAILABLE DRAFT (MGD)	MINIMUM DOWNSTREAM BASE FLOW (CFS)	SHORTAGE INDEX	REMARKS
Cetti	0.15	0.50	4.74	
Finile	0.15	0.23	7.86	
Geus	0.15	0.13	6.16	Rehabilitate existing facility
Inarajan	2.00	2.37	9.68	
La Sa Fua	0.15	0.2	0.39	
Lonfit	0.15	0.31	4.82	
Sigua	0.15	0.45	3.66	
Talofofo	2.00	2.95	4.71	
Tarzan	1.0	0.83	5.57	
Tinago	0.15	10.19	4.81	
Tolaeyuus	1.0	1.10	3.52	
Tolaeyuus/Fena	0.9	1.10	0.05	Supplement existing Fena Reservoir
Umatac/La Sa Fua	0.30	0.20	2.96	Supplement existing Umatac Facility
Ylig	2.0	1.48	5.24	Rehabilitate abandoned plant
Janum	1.00	0.00		Maui type tunnel intercept

FIGURE 3



POTENTIAL RESERVOIR SITES

FIGURE 4



POTENTIAL DIVERSION SITES

about 165 gpm. Further south the village of Merizo is supplied by flow in the Geus River (about 53 gpm) and Siligin Spring (about 10 gpm). Umatac depends on Laelae, or Piga, Spring with a flow of about 37 gpm.

The role of surface water as a supply source will undoubtedly increase in the future as the population demand approaches the sustainable yield of the Northern Guam aquifers.

Groundwater

Numerous attempts have been made to extract groundwater from both the limestone and volcanic aquifers in the south. By and large the efforts have not been successful in yielding sufficient water to justify extensive development of the resources. Table 8 is an inventory of wells drilled in Southern Guam since 1965. Approximately 50 test wells were drilled, only one of which (GORCO) exceeded a pump rate of 100 gpm for more than several hours. Table 9 lists wells drilled in limestone aquifers, and Table 10 lists those drilled in volcanic aquifers since 1965.

Not any of the southern wells currently serves potable demand. Before the installation of the Ugum diversion a limestone well in Malojloj was a source of supply, and tests of at least one other well in the area suggests that a reliable groundwater resource exists. The unusually productive well in the volcanics at the former GORCO refinery was never connected to a distribution system. It may be a source of potable water for local demand in the future. Many of the other volcanic wells were drilled to supply water for irrigation of golf courses. Some were successful, others abandoned as failures.

Test wells were drilled for PUAG (the predecessor of GWA) in Ylig valley, the Asalonso coastal plain, Malojloj and Ipan. Several of the Ylig wells were proved to be potential sources, as were the Asalonso wells and two of the Malojloj wells. The Ipan wells yielded high chloride water.

TABLE 8

Inventory of wells drilled in Southern Guam since 1965. Includes both successes and failures.

Location	Sponsor	Number	Aquifer	Pump Rate	Comments
Ylig	GovGuam	5	Limestone	55-105 gpm	Abandoned
Togcha	Private	10	Limestone	25	Inactive
Talofofo	GovGuam	1	Limestone	115	Inactive
Asalonso	GovGuam	2	Limestone	60-80	Inactive
Ipan	GovGuam	1	Limestone	60	Failure
Malojloj	GovGuam	7	Volc/Lime.	68-170	3 Fail. Inactive
Lonfit	Private	3	Volcanics	10-55	Failures
Pulantat	Private	5	Volcanics	35-65	Abandoned
RCA	Private	1	Volcanics	20	In use
Leo Palace	Private	1	Volcanics	30	?
Cascada	Private	4	Volcanics	30-60	Abandoned
Talofofo	Private	4	Volcanics	25-90	Golf course use
Gorco	Private	1	Volc/Lime	218	Inactive
Windward Hills	Private	3	Volcanics		Failure
Dandan	GovGuam	1	Volcanics		Failure
Geus River	GovGuam	1	Volcanics		Failure

Table 9

Wells Drilled in the Limestones of Southern Guam Since 1965

Location	Name	Ground Elev.(ft)	Depth(ft)	Head Elev.(ft)	Chloride mg/l	Pump gpm	Draw down(ft)	Hyd.Con. ft/day	Note
Ylig	YL-1	21	105	8.5		55	12	23	
(GovGuam)	YL-2	32	150	6.0	<100	55	17		
	YL-3	24	140	6.0	<100	55	10	15	(1)
	YL-4	20	94	9	206	95	16		
	YL-5	22	130	9		105	14		
Togcha (Golf Course)	TG1-10	100	154	~3	100	25			(2)
Talofofo (GovGuam)	T-1			18	<250	115		60	(3)
Asalonso (GovGuam)	AL-1	43	70	4.3	30	60	12		
	AL-2	38	70	4.5	141	82	14		
Ipan (GovGuam)	Ip-1	105	117	1	625	60	2		
Malojloj	ML-1	257			35			60	(4)
(GovGuam)	ML-2	257			35			70	
	ML-3	315				170		37	
	ML-4	340	365	77		<5	98		
	ML-5	320	267	215		68	65		
	ML-6	280	220	83					
	ML-7								

Column Headings

Location: general area of drilling. Sponsoring entity in parentheses.
Name: Identification of well at time of drilling.
Ground Elev.(ft): ground elevation above mean sea level.
Depth(ft): depth of drilling.
Head Elev.(ft): elevation of water table above sea level.
Chloride mg/l: chloride content in milligrams per liter.
Pump gpm: Test pumping rate in gallons per minute.
Drawdown (ft): water table drawdown during pumping.
Hyd.Con. ft/day: Local hydraulic conductivity derived from pump test data.

Notes

(1) YL-3 was completed for production but is now lost.
(2) For the golf course at Togcha 10 successful wells were drilled. They are now inactive because the golf course now uses GWA water.

(3) This well was drilled post World War II, used by the Military, abandoned, then reclaimed by PUAG and provided water for several tears. It is now inactive.
(4) ML-1, ML-2, ML-3 and ML-5 were successful. The others were failures.

Table 10

Wells Drilled in the Volcanics of Southern Guam Since 1965

Location	Name	Ground Elev.(ft)	Depth(ft)	Head Elev.(ft)	Chloride mg/l	Pump gpm	Draw down(ft)	Hyd.Con. ft/day	Note
Lonfit	1	270	270	245		55	163	.022	(1)
(Private)	2	280	385	218		10	139		
	3	330	380	284		23	170	.05	
Pulantat	W-1	236	305	210	25	67	32	.55	(2)
(Private)	W-2	232	310	99	20	60	33	.54	
	W-3	223	300	205	25	60	34	.57	
	W-4	225	285	206	48	35	6.3		
	Y-1	225	300	110	22				
(RCA)		362	360	342		20	250	.04	
Leo Palace	1	427	585	367	23	30	100		
(Private)									
Cascada	1				2475	30	100	.27	(3)
(Private)	2	410		Dry					
	3	112		69	14	60	19	1.6	
	4			86		40	50	1.6	
Talofofo	E-1					90	100		(4)
(Private)	E-2					48	161	.61	
	W-1					25	100		
	W-2							.15	
Gorco		134	200			218	118	2.6	(5)
(Private)									
Windward Hills(private)	Y-1,Y-2,Y-3								(6)
Dandan		242						.034	
(GovGuam)									
Geus River		169	375			Bail dry			
(GovGuam)									

Column Headings

Location: general area of drilling. Sponsoring entity in parentheses.
Name: Identification of well at time of drilling.
Ground Elev.(ft): ground elevation above mean sea level.
Depth(ft): depth of drilling.
Head Elev.(ft): elevation of water table above sea level.

Chloride mg/l: chloride content in milligrams per liter.
Pump gpm: Test pumping rate in gallons per minute.
Drawdown (ft): water table drawdown during pumping.
Hyd.Con. ft/day: Local hydraulic conductivity derived from pump test data.

Notes

(1) Drilled for Lonfit New Town, but project not undertaken.
(2) Drilled for First Green Golf Course, which was not developed.
(3) Test wells for a golf course, which was not developed. Water from Well 1 is unusually warm and saline.
(4) Active wells for Talofofo Golf Course.
(5) The GORCO well may derive some of its water from limestone. The well served the refinery for several years, but is now inactive.
(6) Test borings for a golf course, which was not developed.

STATUS OF THE WATER RESOURCES

By and large, development has not caused irreversible detrimental impacts to either the groundwater of Northern Guam or the surface water of Southern Guam. However, in Northern Guam increases in salinity in some wells imply salt water intrusion. A number of wells have had to be abandoned and others may have to be re-configured. Permanent loss of head over time is not evident, even in the Tumon Aquifer System which has been especially heavily exploited. In the south the only water development of consequence besides the Fena Reservoir complex is the Ugum River diversion of GWA. As the population and the demand on the Northern Guam aquifers increase, additional surface water development opportunities in the south will have to be explored.

Northern Guam

McDonald (2001) examined and commented on the changes in salinity, expressed as chloride (Cl) content in mg/l, of 128 wells in Northern Guam since the 1970s. The chloride content had increased in 64 wells, in 21 of which it now exceeds 150 mg/l, and in 8 it exceeds the suggested maximum concentration limit of 250 mg/l. McDonald categorizes salinities as follows:

1. Acceptable at less than 150 mg/l with no upward trend.
2. Acceptable but suspect, upward trend.
3. Unacceptable but remediable, greater than 150 mg/l.
4. Unacceptable and unremediable, greater than 150 mg/l.

The analyses of the change in salinity by McDonald affirms that salinity of basal groundwater is primarily a function of well depth and rate of draft. As a general rule, which is consistent with expectations, the deeper the well boring and the higher the rate of draft, the greater will be salinity as a result of sea water intrusion caused by upcoming. A derivation given in TR 1 based on upcoming theory of Mercado (1968) suggested that the maximum allowable pumping rate from a single well depends on head, thickness of the transition zone above the 50 percent isochlor (middle of the transition zone), depth of penetration of the boring below sea level, and hydraulic conductivity. Stated as the maximum allowable rate in gpm, the empirical relationship is,

$$Q(max) < .000204\ d^2\ k$$

in which Q is in gpm, k is local hydraulic conductivity in ft/day, and d = (40h – utz – l) where h = head, utz is the thickness of the transition zone between the 250 mg/l isochlor and the 50 percent (9,500 mg/l) isochlor, and l is depth of penetration of the well below sea level. Applying the formula in conjunction with data given in Table 14, page 274 of TR 1 for wells D2, D3, D6, D7, D8 and D11 in the Tumon Aquifer System, the only wells on which standard pumping tests were conducted, for which the average local hydraulic conductivity is 240 ft/day, the average depth of penetration is 42 feet BSL, utz is 17 feet (obtained from exploratory wells EX6, EX7, EX10 and EXGH), and average head is 3.5 feet gives an allowable maximum pump rate of 321 gpm. Although this a greater rate than has generally proven practical, the empirical relationship suggests the highest allowable rate.

The thickness of the upper limb of the transition zone (utz) was obtained from data in McDonald. Data for the EX series of exploratory wells is as follows.

Well	Depth(250Cl)	Depth(9,500 Cl)	utz	Head
EX1	66 ft.	250 ft.	184 ft.	6.4 ft.
EX4	69	225	156	5.8
EX6	133	139	6	3.5
EX7	127	137	10	3.5
EX10	84	117	33	3.0
EX GH	116	136	20	3.5

Applying the same type of analysis to the A series of wells in the basal lens with data from EX1 and EX4 indicates that pumping of low salinity groundwater is virtually impossible because of the thickness of the upper limb of the transition zone. Except in unusual cases (e.g., well A26) the basal A series will produce water with salinity exceeding 150 mg/l.

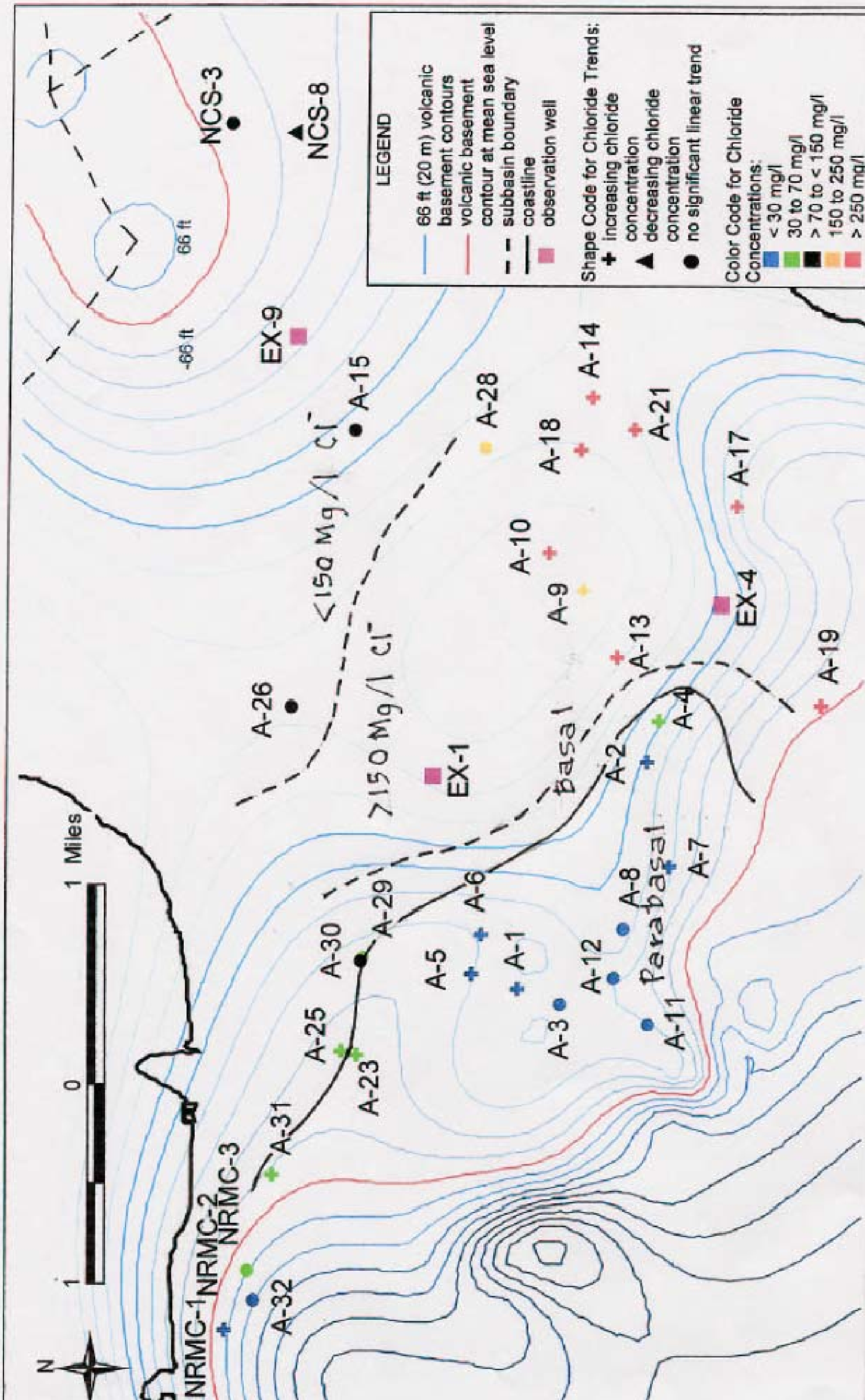
The McDonald Master of Science Thesis contains a comprehensive array of data relating to development of groundwater in the Northern Guam aquifers. In addition to tabulating new data since the NGLS, it summarizes data given in that report and also in TR 1. The Thesis brings together in a single volume data that appear in a variety of separate reports such as those of Guam EPA, the U.S.G.S., and consultants.

The discussions about the status of groundwater in the Aquifer Sectors that follow incorporate much of McDonald's work. The salinity benchmarks listed in McDonald are basically the same as those previously employed. They are: parabasal, < 30 mg/l; boundary between parabasal and basal, 30 to 70 mg/l; normal basal not seriously impacted by sea water intrusion, 70 to 150 mg/l; and basal affected by upcoming, greater than 150 mg/l. Heads associated with the limestone aquifer types as given in the NGLS are: parabasal, > 5 feet; basal (clean limestone), < 4 feet; and basal (argillaceous limestone), <8 feet.

<u>Groundwater Status by Aquifer Sectors</u>

Three Aquifer Sectors yield most of the groundwater for GWA. The most important is the Yigo-Tumon Sector, followed by the Finegayan and Agana Sectors. Each of these Sectors is already heavily exploited.

The Agana Sector serves much of the southern half of Northern Guam. Its Ordot Aquifer System is especially important because the resource is parabasal and thus free of sea water intrusion. The basal groundwater has already been impacted by sea water intrusion, and many A series wells produce water with greater than 150 mg/l and some exceed 250 mg/l. The probability of successfully withdrawing additional potable water from the basal wells is poor at best, but production from the parabasal resource can be expanded. Figure (from McDonald, amended) depicts the parabasal and basal portions of the Sector. The wells near the old Navy pumping station at Agana Springs are on the boundary between basal and parabasal conditions.

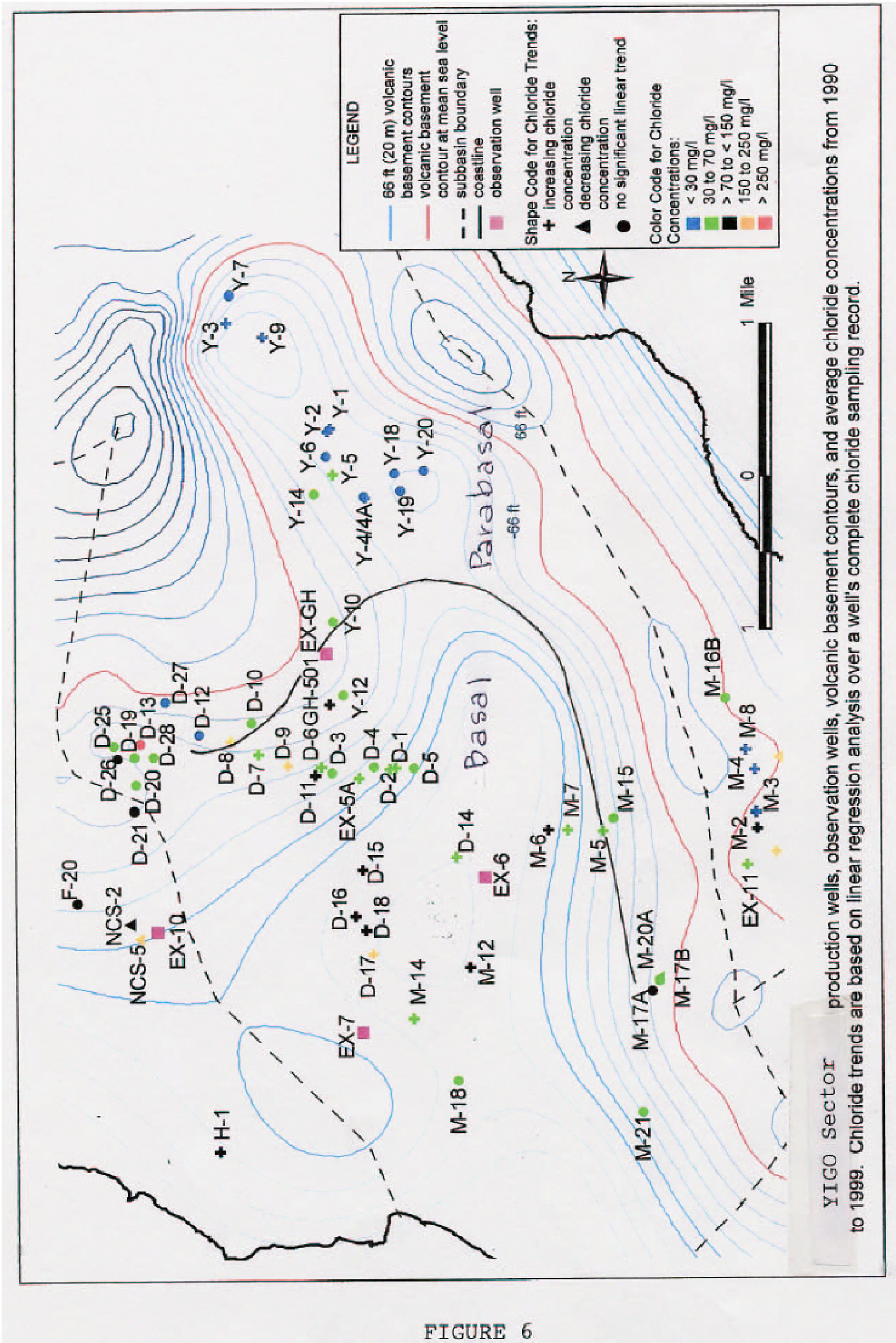


AGANA Sector production wells, observation wells, volcanic basement contours, and average chloride concentrations from 1990 to 1999. Chloride trends are based on regression analysis over a well's complete chloride sampling record.

FIGURE 5

The Yigo-Tumon Aquifer Sector is the most productive potable groundwater provider in the island. Although exploited to the limit of its putative sustainable yield, its basic hydrologic parameters have remained essentially constant since pumping started about 40 years ago. Average head at 3.5 feet has not varied significantly, depth to the 50 percent isochlor has been virtually invariant, and in most wells the salinity of the water has not risen significantly. Among all the Sectors of the north, Yigo-Tumon is the most ideally configured to accumulate and concentrate the flow of groundwater. A large region, the Yigo Aquifer System, contains parabasal aquifers, and downgradient toward Tumon where basal conditions prevail the flow of groundwater is very high. Figure (from McDonald, amended) illustrates the trough-like subsurface topography in which the groundwater flows toward Tumon Bay. The transition zone in the basal region is thin, averaging less than 20 to 30 feet from the 250 mg/l isochlor to the 50 percent isochlor. Fresh water occurs over the top 120 feet depth of the lens. Most wells in the basal region that are less than 50 feet below sea level can yield at least 200 gpm of water containing less than 150 mg/l chloride. In the parabasal region and the boundary between the parabasal and basal regions wells of greater than 200 gpm capacity successfully yield low salinity water.

The Yigo-Tumon Aquifer Sector, because of its productivity and its reasonably well defined boundaries, has been numerically modeled by WERI and will be the subject of more advanced models. Its importance for the supply of potable water to Northern Guam can't be overemphasized. Although a robust hydrogeological system, it may be at the point of excessive development. The WERI models should signal whether or not



YIGO Sector production wells, observation wells, volcanic basement contours, and average chloride concentrations from 1990 to 1999. Chloride trends are based on linear regression analysis over a well's complete chloride sampling record.

FIGURE 6

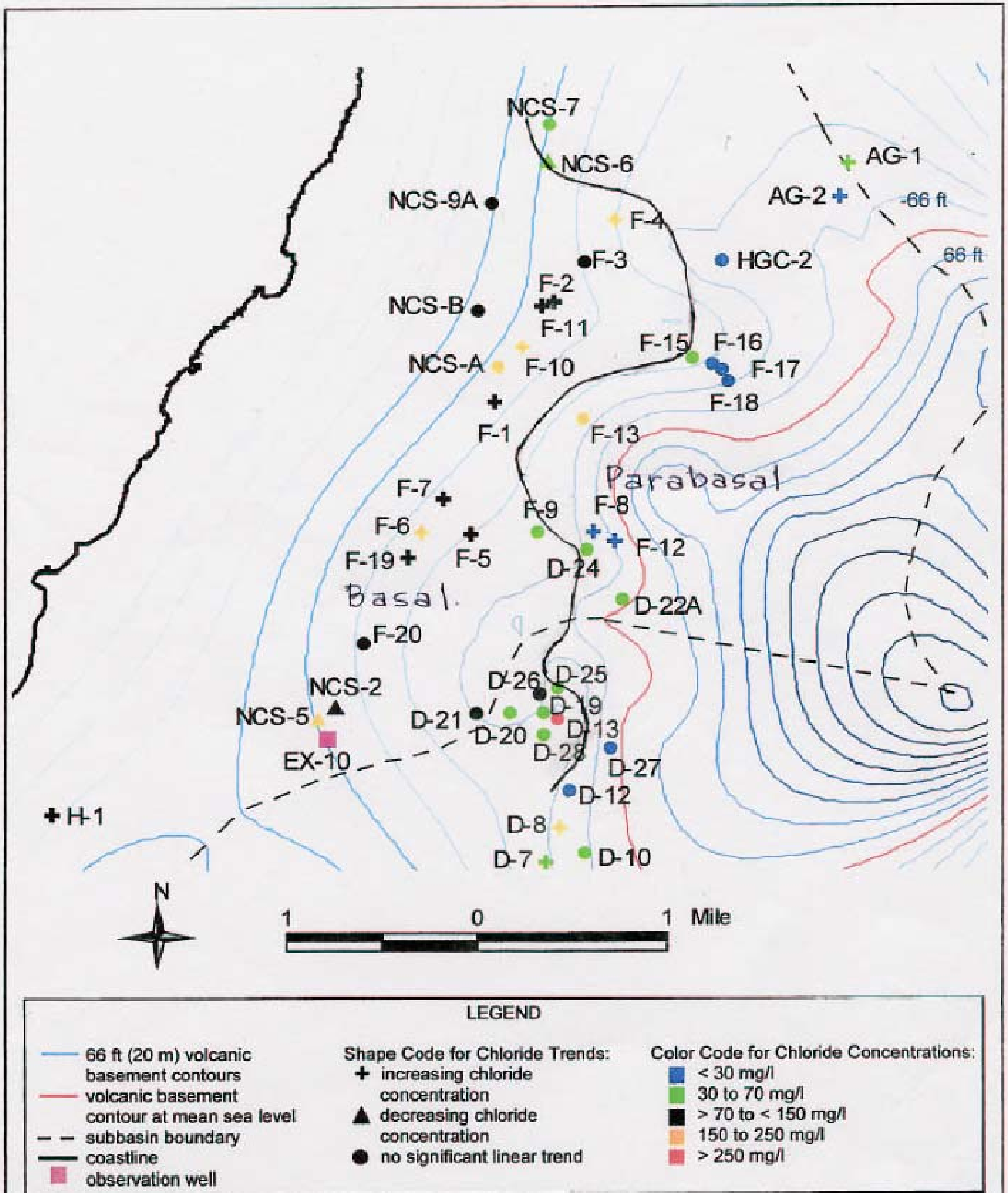
additional groundwater can be withdrawn without affecting either the quality or quantity of water pumped.

The Finegayan Aquifer Sector is also crucial to the water supply of Guam. The parabasal and transitional basal to parabasal regions include 13 wells yielding water of less than 70 mg/l chloride (Figure , from McDonald, amended). Thirteen basal wells have retained their low salinity, while six have risen above 150 mg/l.

In the Mangilao Aquifer Sector three parabasal and two near-parabasal wells contribute potable water to GWA. Several basal wells also are active (Figure , McDonald, amended). Additional water having less than 150 mg/l chloride will be difficult to extract from the Sector.

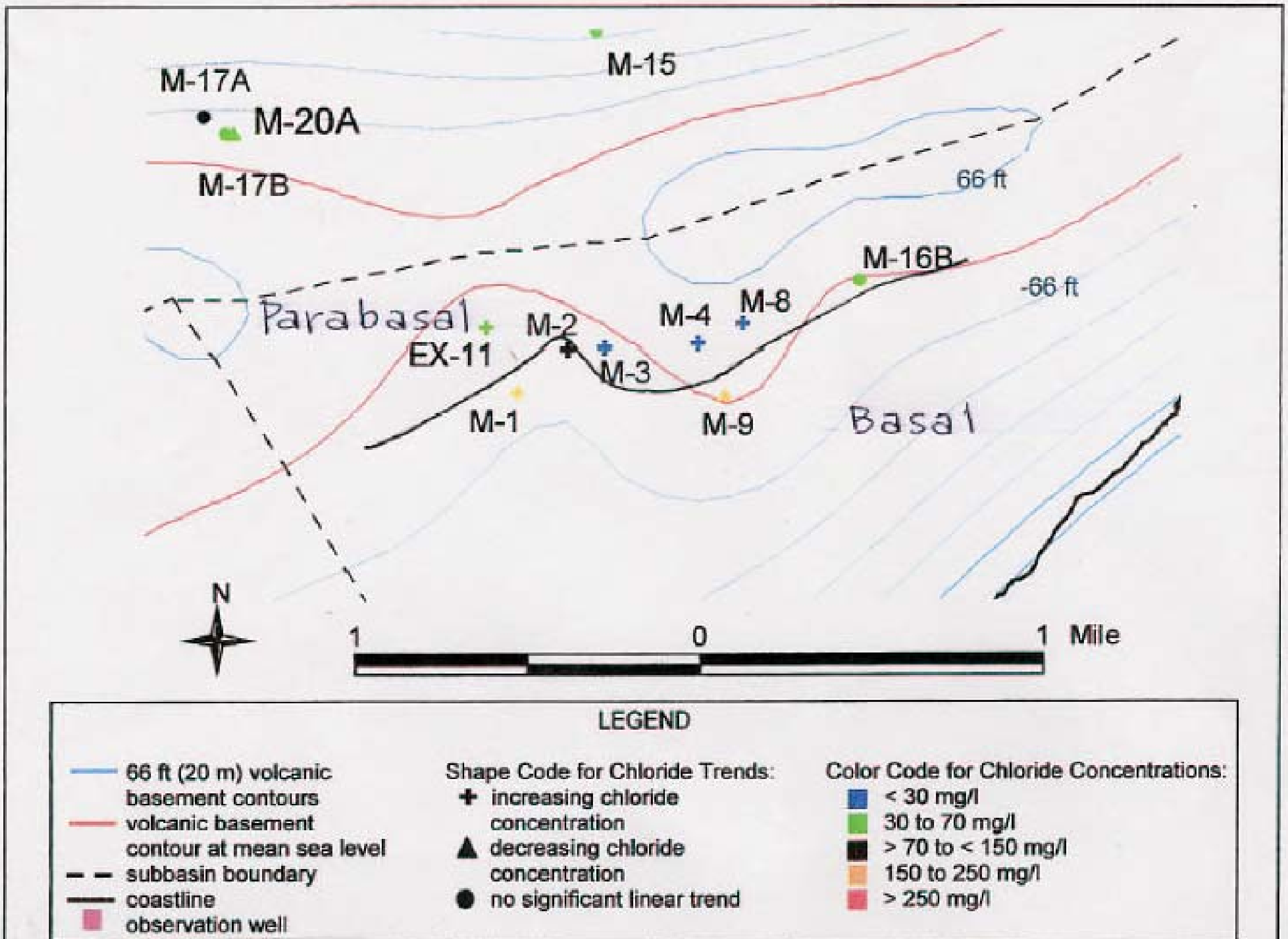
In the Mt. Santa Rosa or Andersen Aquifer Sector one parabasal well produces water for GWA. One parabasal well in the Agafo Gumas Sector also contributes low salinity water. In both Sectors additional low salinity water can be developed.

The tendency to drill more wells to increase water supply, especially in the Yigo-Tumon Aquifer Sector, can be curbed once improvements in the distribution system are undertaken. In a nearly ideal production-distribution system that supplies water at a rate of 125 gpcd accompanied by 20 percent leakage for a total of 150 gpcd, the current dtafr on the Northern Guam aquifers should be able to supply the needs of about 300,000



FINEGAYAN Sector production wells, observation wells, volcanic basement contours, and average chloride concentrations from 1990 to 1999. Chloride trends are based on linear regression analysis over a well's complete chloride sampling record.

FIGURE 7



MANGILAO Sector production wells, volcanic basement contours, and average chloride concentrations from 1990 to 1999. Chloride trends are based on linear regression analysis over a well's complete chloride sampling record.

FIGURE 8

people. Current island population is approximately 161,000. It is clear that emphasis on improving the system should focus on repairs and reconfiguration.

New wells that may have to be added should preferentially exploit the parabasal resources of the Ordot Aquifer System of the Agana Aquifer Sector, the Agafo Gumas Aquifer Sector, and the Mt. Santa Rosa – Andersen Aquifers Sectors. The sustainable yield of the Yigo-Tumon Aquifer Sector needs to be more accurately determined before additional development takes place. The WERI numerical models are necessary to establish a proper sustainable yield.

Southern Guam

The final (1995) Annual Data Management Report of the Guam Environmental Protection Agency listed the average total groundwater pumpage from wells in Southern Guam as 0.4 mgd from a total of 20 wells. Many of the wells are no longer active. Only two GWA wells were included, MJ 1 and MJ 2 at Malojloj, but these wells are no longer used. Their production has been replaced by the Ugum River diversion. The remaining active wells serve golf course irrigation needs. Total current pumpage averages no more than about 0.2 mgd.

The economically exploitable groundwater resources of Southern Guam are not nearly as voluminous as those of the north but nevertheless may be adequate to supply remote localities.

The major surface water development in the south is the Fena catchment, storage and treatment complex of the U.S. Navy. The system has a reliable yield of 11 to 11.5 mgd, which is approximately equivalent to 15 percent of the sustainable yield of the Northern Guam aquifers. About 4 mgd is diverted to GWA. The next most productive GWA source is the Ugum River diversion, which has a capacity of 2 mgd. The communities of Merizo and Umatac are served by springs and stream flow. The Geus River supplies about 51 gpm and Siligin Spring another 10 gpm to Merizo. Umatac receives water from Piga Spring at a rate of about 37 gpm. The most productive spring in Southern Guam available to GWA is Asan, which has an average flow of about 298 gpm. Santa Rita Spring, the next most productive, averages about 165 gpm. Both of these springs drain limestone; the others drain volcanics. Spring yields are already maximized, so as population grows in the south additional water resources will be required.

Appendix

Hydrologic Budget

The steady state water balance equation for southern Guam may be expressed as,

$$R=P-ET+GW-I$$

In which R is stream runoff, P is rainfall, ET is evapotranspiration, GW is groundwater contribution to the runoff, and I is infiltration to groundwater. Runoff and rainfall have been measured for some drainage basins while groundwater can be estimated by analysis of the stream flow records during the dry months of the year, January through June. Pan evaporation has been measured at WMSO and in one approach to the budget is put equal to evapotranspiration. Infiltration is likely to be small and transitory because the water table in the volcanic aquifers is either exposed at the ground surface or normally less than 15 feet below.

Assuming that GW and I cancel each other, the balance equation reduces to,

$$P=R+ET$$

from which ET is determined from the two known values, ET=P-R.

Employing the Inarajan drainage basin as representative of hydrologic conditions in southern Guam, ET can be calculated from the excellent measurements of stream flow and rainfall in the basin. Average annual rainfall in Inarajan has been 88.92 inches, and average stream flow at the USGS gage (16835000) for the 30 year period of record (1952-1983) was 11 mgd from an area of 4.42 square miles. The table below is structured to derive an estimate of ET.

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. Rain,in.	3.40	4.06	2.60	3.52	4.59	7.66	10.55	14.42	13.51	11.79	9.30	5.37
Av.Rain mgd	8.4	11.3	6.4	9.0	11.4	19.6	26.1	35.7	34.6	29.2	23.8	13.3
Av.Flowmgd	7.1	6.2	3.5	3.8	6.5	4.3	9.0	19.4	24.6	23.3	16.8	9.7
P-R=ET mgd	1.3	5.1	2.9	5.2	4.9	15.3	17.1	16.3	10.0	5.9	7.0	3.6
ET, in.	0.53	1.83	1.18	2.03	1.97	5.98	6.91	6.58	3.91	2.38	2.74	1.45

In the above, the annual ET totals 37.5 inches, which subtracted from the rainfall (88.92 inches) gives 51.4 inches. Assuming that ET in the north is the same as ET in the south and that no runoff occurs in the north, recharge in the north is 51.4 inches per year, equivalent to 2.45 mgd/sq.mi.

The minimum infiltration rate is calculated as the difference between rainfall and pan evaporation, which is assumed equal to evapotranspiration. For the WMSO at Taguac the rainfall and evaporation rates with the difference between them assumed equal to infiltration are as follows (these values are from TR-1).

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av.Rain, in	5.54	4.19	4.44	4.65	6.26	6.18	11.25	13.41	15.78	13.19	9.48	6.48
Av.Evap,in	5.49	5.93	7.23	7.64	7.68	6.52	5.84	5.15	4.85	5.12	5.22	5.74
Rain-Evap	0	0	0	0	0	0	5.41	8.26	10.93	8.07	4.26	0.74

The average annual difference between rain and evaporation is 37.67 inches, equal to 1.79 mgd/sq.mi., which is about 73% of the value determined by solving for ET.

Still another way to estimate recharge in the North by the balance equation in the South is to decompose the recorded runoff values into direct surface runoff, the immediate response to rainfall, and the groundwater contribution. Once again employing the Inarajan River stream flow record coupled with rainfall data, and estimating the groundwater contribution to runoff from low flows in the record, the balance equation reduces to,

$$DRO=R-GW$$

in which DRO is runoff responding to rainfall. Total runoff, R, is known, and the groundwater contribution is estimated from low stream flows during the dry period of the year, January through June. For Inarajan the average of the monthly minimum flows for the 30 year record was 1.31 mgd, equivalent to 6.2 in./yr. The average flow was 11 mgd, equivalent to 52.3 in./yr., and thus the DRO is 46.1 in./yr. Because in the North there is no direct surface runoff, DRO calculated for the South is equal to recharge in the North. Runoff of 46.1 in./yr. Converts to 2.19 mgd/sq.mi.

The same method applied to the Ugum River above Talofofo Falls (USGS Gage 16854500) results in an estimate for the groundwater contribution to stream flow of 3.5 mgd of the average total of 16.8 mgd. Direct surface runoff is calculated as 48.5 in./yr., equivalent to 2.31 mgd/sq.mi.

In a report relating infiltration, recharge and discharge in the NGLA (J. Jocson, J. Jenson, and D. Contractor, 1999, Numerical Modeling and Field Investigation of Infiltration, Recharge and Discharge in the Northern Guam Limestone Aquifer: Univ. Guam WERI, TR 88), infiltration was estimated to amount to 67% of rainfall. For an average rainfall of 94 in./yr. in Northern Guam, the infiltration rate is 3.0 mgd/sq.mi. The authors speculate on the fate of infiltration, whether all of it recharges the lens or some escapes by traveling complicated pathways. They conclude the rate of 3.0 mgd/sq.mi. is a maximum.

The WERI budget was meticulously calculated by using daily pan evaporation as an estimate of daily potential evapotranspiration, then calculating daily minimum recharge estimates as measured daily rainfall minus daily pan evaporation. The daily data were then converted to monthly totals and a relationship between estimated recharge and monthly rainfall established. The relationship is statistically linear for which the equation is (values in cm.),

$$I = 0.87\ P - 4.24$$

In which I is monthly recharge and P is monthly rainfall. The equation applies only when monthly rainfall is greater than about 5 cm. For lesser monthly rainfall no recharge takes place. It is from the above analysis that the investigators concluded that recharge in Northern Guam is 67 percent of rainfall.

The global approach to estimating recharge discussed above suggests that actual recharge in the north falls in the range 2 mgd/sq.mi. to 3 mgd/sq.mi.

Water Budget for Northern Guam.

The water budget for Northern Guam is derived by employing the following variables.

1. P = rainfall; measured.
2. E = pan evaporation, measured.
3. ET = evapotranspiration; unknown.
4. R = stream runoff; measured in South.
5. GW = groundwater contribution to R in South.
6. I = Infiltration to groundwater; unknown.
7. DRO = direct surface runoff, derived from R.

Source	Pin/yr	Ein/yr	ETin/yr	Iin/yr	Imgd/sq.mi.	Asq.mi.	Imgd
WERI TR-1	95	70	36.4	58.6	2.78	94.6	263
NGLS	92	82	59.0	33.0	1.65	67.9	112
WERI TR-88	95	32	32	63	3.00	94.6	284
Current	89	72	37.5	51.4	2.45	94.6	232
Current	90	72	43.9	46.1	2.19	94.6	207

Method of computation

WERI TR-1: Equate runoff (R) in Southern Guam with recharge (I) in North Guam.
NGLS: Compute ET by Blaney-Criddle method. $I = P - ET$.
WERI TR-88: Compute recharge as difference between measured daily rainfall and measured daily pan evaporation.
Current I: Compute ET for river of Southern Guam by $P - R = ET$; then, $P - ET = I$.
Current II: Compute DRO by $DRO = R - GW$, estimate GW from Inarajan River flow record (30 years). Equate DRO to recharge in North.