RECONNAISSANCE GEOLOGY OF A PROPOSED DAM/RESERVOIR SITE IN SOUTHERN GUAM

by

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ABSTRACT

This report describes the rationale, methodologies, results, and conclusions drawn from a six-week long class exercise project. The study was undertaken to train Environmental Science graduate students with no prior geologic experience to undertake a reconnaissance level field geology project. They were given the task of conceptualizing an environmental-geology problem and carrying out certain simple but fundamental field procedures required of a geologist who might be called on to investigate that problem.

The class of six graduate students investigated the feasibility, solely on geologic grounds, of constructing and maintaining a relatively large water supply dam and reservoir on the Inarajan River in southern Guam. Although the study focused on field geology, students were required to know and integrate results of related studies, especially those involving hydrology, and to have studied air photos. Field assignments were roughly grouped into three broad overlapping categories: a) bedrock geology, b) surficial processes, and c) water resources, with two students assigned to each group.

This study showed that a rigorous, short-term reconnaissance geologic field study can be structured as a training module to provide a wealth of information that would be useful in judging the feasibility of constructing a significant water storage dam and reservoir. The study demonstrated that small groups of relatively inexperienced science graduate students can be trained on the job to assemble critical field observations and measurements on which planning decisions could be reasonable based. The study further demonstrated that such reconnaissance efforts are a cost-effective way to identify potential geologic impacts on large built structures in Guam.

Positive geologic aspects for locating the proposed dam on the Inarajan River were determined to be the need for water in the south, favorable topography, and completeness of available hydrologic data. *Negative* aspects include obvious and widespread slope instability that could lead to unacceptable sedimentation in the reservoir for many years; vulnerability of dam and spillway to episodic sedimentation from badlands; potential for high levels of imported iron and manganese from both groundwater seepage and surface water runoff; possible reservoir leakage along bedrock fractures; high seismicity of Guam in general and abundance of possible fault-related lineaments; and planned housing construction on the slopes adjacent to the southern side of the proposed reservoir.

Notwithstanding the real and potential drawbacks of the site, the need for future potable water in southern Guam may demand that this site be developed. If that situation comes to pass we recommend, for this site and any other dam site under consideration, the following:

Geology: Undertake a seismic refraction profiling and deep rock coring program covering the entire extent of the proposed reservoir and surrounding slopes. Construct and digitize a 5 foot contour-interval topographic base map of the entire watershed.

Construct by computer accurate cross-sections of impacted valleys. Remap and digitize the bedrock and saprolite geology on the new topographic base map at least a 1:1000 scale.

Hydrogeology & Geomorphology: Develop accurate estimates of soil loss and sediment movement in the watershed. Develop and implement a badlands restoration program. Remobilize disused stream gaging station(s) on the main river and install temporary (5-10 year) stations along with rain and evaporation gages on important tributaries. Reverify previous studies that estimate base flow on the Inarajan River.

Geochemistry: Undertake exhaustive chemical profiling of all tributary streams and seeps to develop more accurate concentration estimates of natural pollutants, and define point source problems.

Computer Modeling: Purchase, modify, and/or develop computer packages that forecast dam and reservoir behavior based on watershed characteristics, hydrology, climate, seismicity, bedrock geology, geomorphology, etc.

Legal Steps: Develop and publicize a set of enforceable land use ordinances restricting slope and stream channel modifications and waste handling and removal within the watershed.

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INTRODUCTION

BACKGROUND

Guam has recurring environmental concerns tied to one or more aspects of its basic geologic makeup. Addressing those concerns in a meaningful way requires experienced geoscience professionals, hitherto a rare commodity on Guam. The Environmental Science Graduate Program at the University of Guam was, in part, designed to help meet this deficiency. Most of the students that enroll in this program have no geologic experience beyond an introductory course in college. Nevertheless, we are attempting through field and laboratory units in several courses to develop a level of confidence and expertise that will enable future M.S. graduates to serve productively when working with professional environmental geologists and engineers.

Among the many potential environmental situations on Guam where geologic training at some level is usually required, is in screening alternative locations for the construction of large built structures, specifically in the present case, a large water storage dam and reservoir, (but not the related infrastructure, that would include a water treatment plant and pump station). To be sure, the decision to locate a dam of specific design on a given river involves many diverse and interrelated economic, ecologic, and sociologic factors, but it also requires rigorous engineering and hydrologic expertise. Both of these depend on sound geologic information, much of it attainable from reconnaissance level studies such as the current effort.

In southern Guam, the need for cooperation between engineers, hydrologists, and geologists is underscored by obvious instability of the volcanic terrain. This condition arises from a) Guam's location in the Mariana Island Arc, a zone of intense seismicity, regional uplift, and major active fault systems; b) a dominant bedrock that is highly vulnerable to slope failure and stream erosion; c) steep slopes; and d) several centuries of sub-optimal land use that have left extensive tracts (badlands) with almost no vegetative cover.

STORAGE DAM

Barrett Consulting Group (1994) evaluated a possible storage dam and reservoir site for the Public Utility Agency of Guam (PUAG) on the fall line of the Inarajan River, immediately downstream from its confluence with the Laolao River (Figure 1). The projected dam would be of clay core and outer rock shell construction and would crest at an elevation of +34 meters (+112 ft) with a spillway elevation at +29 meters (+ 95 feet). The storage reservoir would back up a lake with an approximate volume of 5 million cubic meters (4,090 acre-feet), that would be about 22 meters (72 feet) deep at the dam. When completed and filled the reservoir would provide a daily draw of about 23,300 cubic meters per day (5.9 million gallons per day (MGD).

Location of Proposed Dam and Reservoir on Inarajan River in Southern Guam

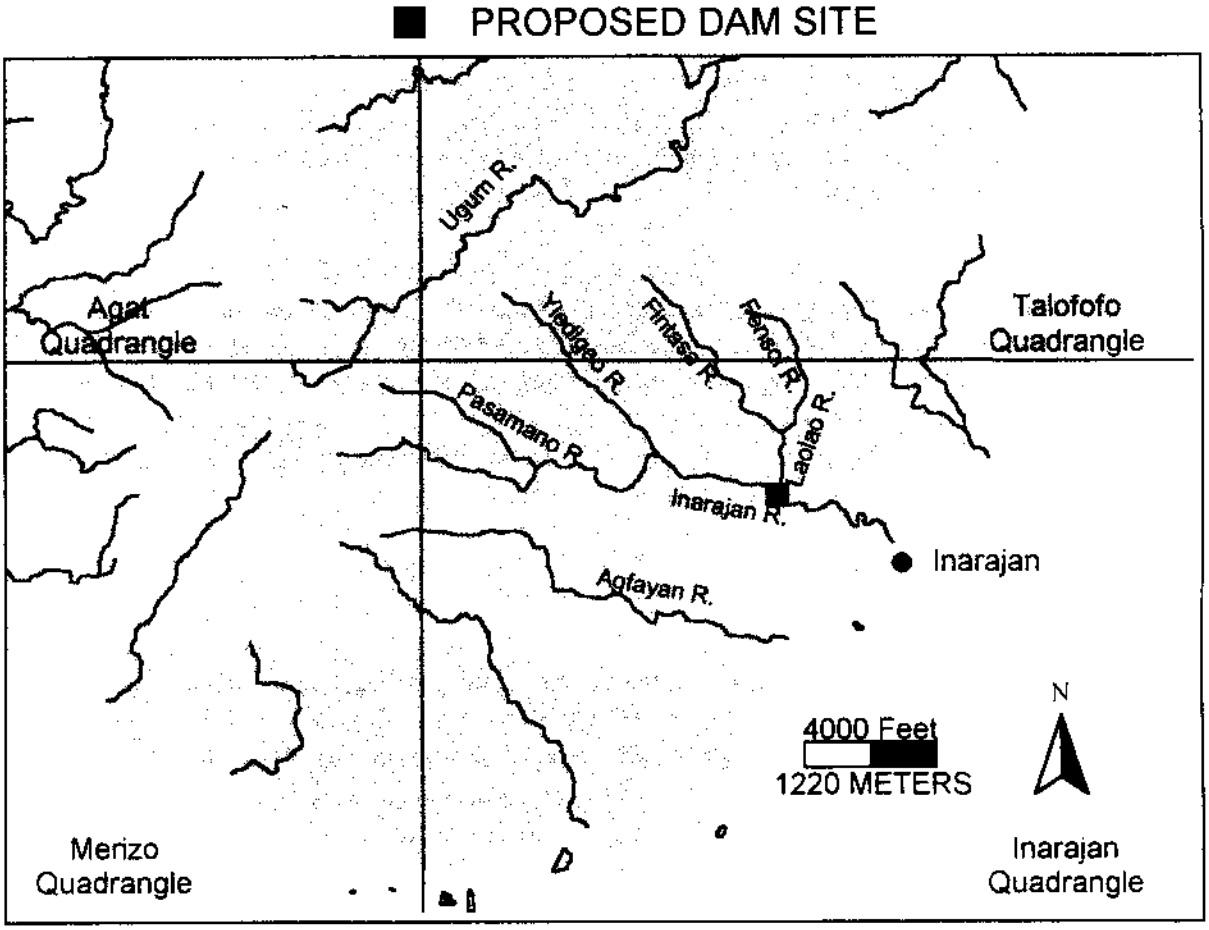


Figure 1

The 1994 study evaluated the overall site and watershed, primarily on the bases of archaeological, ecologic, and demographic information; it evaluated the immediate dam site on the basis of geophysics and trenching; and it suggested the size and design of a potential dam on the basis of topography, hydrology, and availability of construction-grade clay and rock. In the end, the report of 1994 neither recommended nor seriously condemned the site on the Inarajan, but favored alternative locations in southern Guam. The present study takes off from the 1994 report, adding information on slope stability, structural geology, groundwater movement, and water chemistry in a major feeder stream of the proposed reservoir.

GOALS AND OBJECTIVES

Goals

The overall goals of this study were to a) design and implement a 4-6-week long geology tutorial adaptable to Environmental Science graduate students who have had minimal previous geologic training; b) focus their efforts on studying at the reconnaissance level a visible environmental problem that has a major geologic component; and c) publish results and recommendations from the study together with procedures that could be useful for conducting related research.

Objectives:

The specific objective was to complete a thorough screening analysis of the bedrock and surficial geology relevant to the design, construction, and management of a major water supply impoundment on the Inarajan River in southern Guam (Figure 1). This objective required that students first familiarize themselves with findings of earlier studies of the Inarajan River area, especially hydrologic research, and to examine current and older sets of aerial photographs. It then required that they locate, identify, and interpret prominent geologic and geomorphic features, including formations and bedrock structures, to take field observations and measurements, collect and analyze rock and sediment samples, examine earlier efforts at developing water resources in the watershed, and even to interview farmers and hunters familiar with recent upland, channel, and floodplain modifications.

SCOPE

The study on the Inarajan River was a four-week long field exercise for six students in *EV 511, Environmental Science: Geology/Engineering,* with two weeks of follow up discussions, seminars, and class reports. The study concentrates on field observations, measurements, and deductions at a suggested dam and reservoir site on the Inarajan River.

Results and recommendations are not intended for extrapolation to other potential dams and reservoirs on Guam; study methods and protocols, however, are general and can be applied to any number of environmental concerns on Guam. This report summarizes background, methodologies, results, and recommendations.

METHODS

Field methodologies were drawn from published texts and references that detail basic outcrop procedures, specifically Compton (1985) and Lehee (1952), well-tested by thousands of field geologists through many published editions. Three teams of two students each were selected and assigned specific field tasks. The course instructor acted as a field partner/mentor for each group.

Teams first reviewed aerial photographs and geologic reports in conjunction with a one-day geologic field trip to the watershed and dam site with the course instructor. The tasks of each group were outlined and discussed during the field trip. Key transects and bedrock sections were located and discussed, field note taking and data collecting, rock and soil sampling, and Brunton Compass™ techniques were reviewed.

The final report from each group focused on its specific field assignment, although each included general background information. The three groups and their specific assignments were as follows.

JOCSON & MORAN: Bedrock Geology: Volcanic Stratigraphy, Structural Geology, and Macroscopic Petrography.

Involved defining and characterizing geologic formations and smaller units, including describing sections, mapping, and detailing macroscopic physical properties. Added key tasks included locating, tracing, verifying, and describing lineaments, notably large fractures and scarp lines, but also other linear features such as anomalous drainage, topographic offsets, alignment of springs, etc.

GUZMAN & LEWIS: Slope Processes, Weathering & and Sedimentation:

Included locating, photographing, and plotting on base maps indications and extent of earlier, ongoing and incipient slope failures such as landslides, debris slides, rockfalls, rotational slumps, continuous and discontinuous soil slips, etc. This pair also described typical soil and saprolite sections, and secondary mineralization along zones of bedrock permeability.

DUMALAING & SALAS: Water Resources and Hydrogeology:

Involved analyzing and integrating historic stream gauging and water planning and management data for the Inarajan River Watershed. They were also responsible for locating and describing groundwater seeps and springs that directly feed into the projected reservoir or near the base of the dam.

Site Map and Plan View of Proposed Dam and Reservoir on Inarajan River

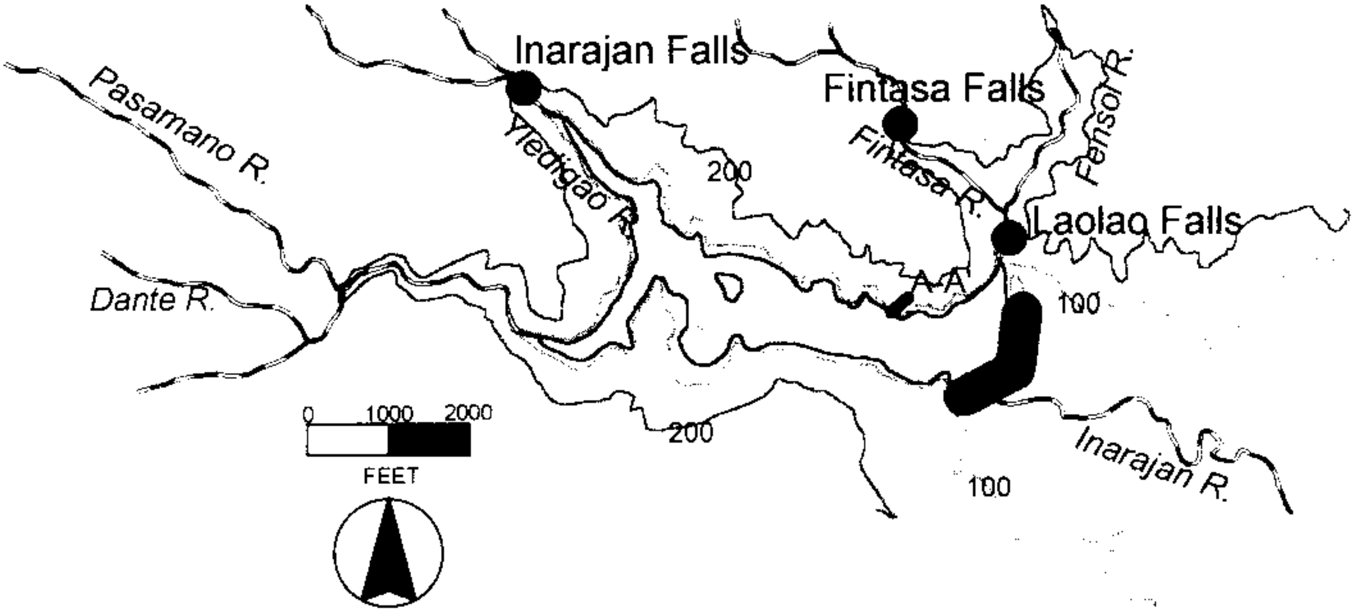


Figure 2

RESULTS AND DISCUSSIONS

The following section records the observations, findings, and interpretations of the three working field parties synthesized within a background context which they developed from published information and airphotos.

REGIONAL GEOGRAPHY AND GEOMORPHOLOGY

The proposed dam site lies in the Inarajan River watershed, at the confluence of the Inarajan River and a small tributary stream, the Laolao River, about 2.2 kilometers upstream from the Route 4 highway bridge in the Village of Inarajan, in the U.S. Geological Survey 7.5-minute Inarajan Quadrangle (Figure 2). The watershed includes an area of 11.39 square-kilometers with a main trunk stream, the Inarajan River, flowing predominantly from west-to east. The extreme western portion of the watershed lies in the 7.5 minute Merizo and Agat Quadrangles, and the northern extreme in the 7.5 minute Talofofo Quadrangle. The overall watershed relief is approximately 100 meters.

Inarajan River Valley

Upstream from Proposed Dam Site: Two main branches, the Yledigao (northern) and Pasamano Rivers (southern) merge to form the Inarajan River about 0.8 kilometer upstream and west of the proposed dam site. Along this reach the Inarajan River flows with an average gradient about 10-15 meters/kilometer, and is tightly constrained by steep valley slopes that variously support savanna grasslands, thick ravine forests, and denuded badlands (Plate 1). Valley slopes generally range from 2:1 to 3:1 throughout the entire upper Inarajan Valley and are frequently disrupted from slides and other types of failures (Plate 2).

Scenic Inarajan Waterfalls occurs on the Yledigao River at an elevation of approximately +53 meters (+175 feet), about one kilometer upstream from the merger of the Yledigao and Pasamano Rivers. The falls is about 7 meters high and is formed by a resistant ledge of well-cemented flow breccia. Downstream from the Inarajan Waterfalls, at least 15 sets of white-water rapids and low falls separate deeper, more laminar flow intervals before reaching the site of the proposed dam. All of those rapids and low falls will be destroyed by the water storage reservoir.

Downstream from Proposed Dam Site: Beginning immediately downstream from the dam site the Inarajan River valley walls recede away from the river, replaced by an extensive alluvial floodplain (Plate 3) that widens to a maximum of 0.75 kilometers and merges 1.2 kilometers downstream, in the upper estuary, with a seaward prograding river delta. The floodplain surface is composed of sediment deposited during overbank flooding modified on the perimeter by prograding alluvial fans from the local valley slopes. Ayres and Clayshulte (1983) indicate from shallow drilling and geophysical studies that these upper layers, averaging 4 meters in thickness, cover an older unit of marine sediment of approximately the same thickness. The latter deposits were probably deposited when the Inarajan Valley was reflooded with marine waters following the last low stand of the ocean (17-20,000 years ago).

The Inarajan River has incised 1-2 meters down into its floodplain for about 400 meters downstream from the dam site, but over the remaining distance to the estuary, the river meanders more or less randomly over the surface of the floodplain. Stream incising generally occurs either as a result of uplift of the watershed or lowering of sea level. In this case, it may have been brought about by the well-documented 1-2 meter emergence of the coastal area of Guam that occurred about 3,700 years ago (Randall & Siegrist, 1996).

Laolao River Valley

The Laolao River is a short perennial stream formed by the confluence of the Fintasa and Fensol Rivers. The Laolao River watershed drains about 3.5 million square meters (350) hectares of badlands and savanna immediately west (Fintasa River) and north (Fensol River) of Inarajan High School, and north of the main Inarajan River Valley (Figure 2), Below the confluence of the Fintasa and Fensol Rivers, the Laolao River turns south cascading through a narrow valley that drops approximately 35 meters over a total distance of only about 0.65 kilometers (54 meters/km) to its juncture with the Inarajan River at the proposed dam site

Two significant waterfalls and numerous smaller rapids exist in the dam site area. On the Laolao River, the 9-10 meter high Laolao Waterfalls occurs at elevation +32 meters (+105 feet) midway between the confluence of the Fintasa and Fensol Rivers and the suggested dam site (Plate 4). Further up the Fintasa River, the 8.5-10 meter high Fintasa Waterfalls occurs at elevation +62.4 meters (+205 feet) (Plate 5). Both waterfalls are slowly retreating upstream with a massive 1-3 meter thick breccia flow rock acting as the resistant caprock layer. The Laolao River has no floodplain and never meanders as it flows on bedrock for its entire length. It is an excellent example of a vertically eroding or ungraded stream, one that has not yet achieved a smooth longitudinal profile.

Proposed Dam Site

At the dam site, the pronounced alignment of valley slopes along the north side of the Inarajan River is abruptly interrupted by a north-south trending spur composed of a pair of low (20-30 meters relief) grassy bedrock knolls and a separating saddle (Figure 2, Plate 6) This feature prevents eastward shifting of the channel of the lower Laolao River. The knolls together with the valley slope on the southern side of the Inarajan River constitute the foundation of the proposed dam. The saddle between the knolls is the projected site for the dam spillway.

BEDROCK GEOLOGY

Geologic Formations

The bedrock under the entire region of the study is part of the Bolanos Member of the Umatac Formation, a product of explosive shallow submarine and subaerial eruptions

(Tracey et al, 1964). The formation is comprised of smaller units of well-bedded tuffaceous mudstones and sandstones, tuffaceous flow breccias, and agglomerates. Coarse clasts are identifiable as red to tan andesite or dark gray basalt porphyry; many are either amygdaloidal or scoriaceous. Reef limestone xenoliths up to about 15 centimeters diameter are common and distinctive clasts in some sections of the Bolanos Formation (Plate 7).

The underlying Alutom Formation and overlying Maemong Limestone do not crop out in the study area. Near the top of the Bolanos Formation occur concentrations of huge (max. > 1-meter diameter) spheroidal boulders of a dense fine- to coarse-grained porphyritic basalt, separately mapped as the Dandan Flow Member of the Umatac Formation (Tracey et al, 1964). This distinctive unit appears in the upper Fintasa and Inarajan River watersheds as badlands littered with scores of scattered, decomposing boulders. A few boulders from the Dandan Flow Member eventually work their way into river channels through slope processes, but they are not a major concern to the dam and reservoir project.

Bedding planes have a general regional dip of between 3 and 10 degrees to the east, although slumped beds and other, almost random dip directions were observed frequently along the trace of several presumed faults. Tracey et al (1964) state that the southeast dipping beds of the Bolanos Formation are the original eastern flank of the early Miocene cone centered southwest of Facpi Point.

Geologic Structures

Tracey et al (1964) mapped from airphotos several large normal faults and fracture zones in the Inarajan Quadrangle, and commented on the presence of numerous joints. Siegrist and Lewis (1996) field verified most of those structures, and mapped additional lineaments in the vicinity of the dam site and reservoir. The major lineaments are indicated on Figure 3, and described in Table 1. They were mapped from airphotos and field verified on the basis of topographic and geologic continuity (and discontinuity) and drainage patterns. That they all represent faults can not be determined unequivocally without expensive subsurface investigation. Nevertheless they are sufficiently defined as to be a cause for concern in constructing any large structure in this area.

Three lineaments that are almost certainly faults are the Fintasa Valley, Fensol-Laolao Valley, and the Yledigao Valley Lineament. Along each trend, bedrock outcrops display a very high density of joints, crumpled and thrust faulted beds (Plate 8), mineralized zones, seeps, slickensides, and breccia zones that are discordant to bedding. The exact fault plane and fault mechanisms are not resolvable from outcrop but the Fintasa Valley Fault appears to be a vertically or possibly southwest dipping normal fault with the upthrown side to the northeast. The Fensol-Laolao Valley fault appears to be an eastward dipping high angle normal fault. The Yledigao Valley lineament can not be resolved as to fault plane movement; in fact the sense of movement appears to change along its strike.

Map of Geologic Lineaments Crossing Inarajan River Watershed

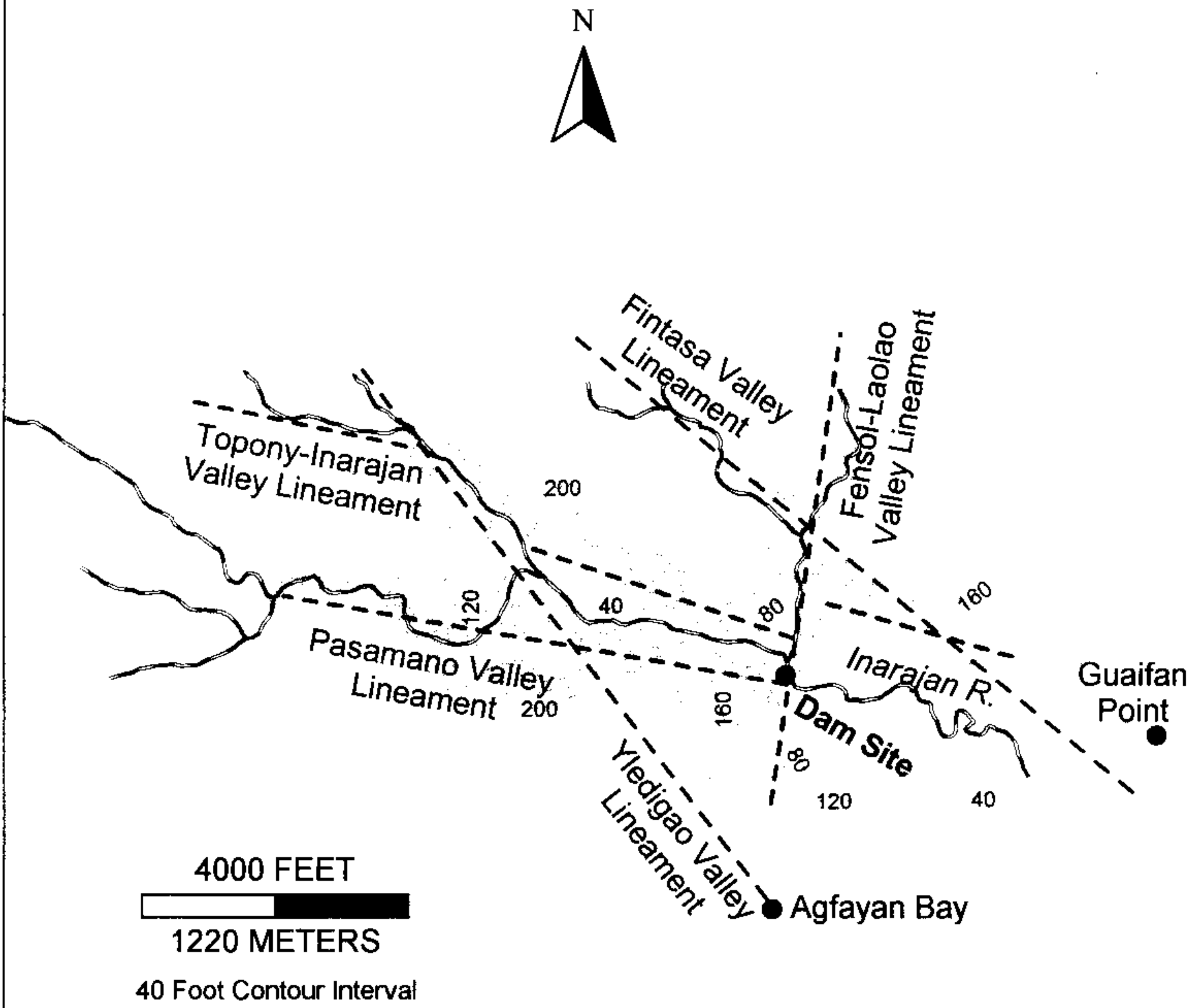


Figure 3

Table 1: Major Geologic Lineaments Crossing the Inarajan River Watershed

Trend	Name of Lineament	Description (Figure 3)
N55°W	Fintasa Valley	Follows Fintasa River, extending northwestward to the sharp (90°) double bend in the Ugum River, and southeastward to Guaifan Point on the north coast of Inarajan Bay. Coincides with normal fault trace mapped by Tracey et al (1964)
N80°W	Topony-Inarajan Valley	Follows along Topony River, southeast to Inarajan Falls; offset by Yledigao Valley Lineament, follows northern valley wall of Inarajan River, offset to the north by Fensol-Laolao Valley Lineament.
N44°W	Yledigao Valley	Follows the Yledigao River southeast to Asdonao Hill and to the coast at Agfayan Bay.
N85°W	Pasamano Valley	Follows Pasamano River extending to dam site
N5°E	Fensol-Laolao Valley	Follows the almost north-south trend of the Fensol and Laolao Rivers through the dam site.

About 15 percent of the small faults and joints in the watershed are partially mineralized with manganese and/or iron oxides (Plate 9), about 3-5 percent with chalcedony (SiO_2), and about 8 percent are seasonal groundwater seeps. Precipitation of fibrous chalcedony and manganese oxide minerals within fractures and other pore spaces, and as replacements, is a fairly widespread feature in volcanics throughout Guam, but is especially concentrated along the fracture zones. We suspect that the highly mineralized zones signal concentrated groundwater flow and chemical transfer in fractured bedrock zones. While we did not analyze groundwater in this project, earlier studies (Stark and Tracey, 1963; Barnard, 1988)) of bedrock and soil chemistry of volcanic rocks on Guam imply the existence of a wide spectrum of potentially toxic levels of heavy metals in bedrock and weathered residuum (Ni, Cr, Mn, etc.), that could be mobilized in groundwater and be imported into the reservoir via fracture zones, if not from overland runoff.

It is thus apparent that the water chemistry of any reservoir in the Inarajan watershed could be influenced to some degree by zones of high bedrock permeability. Fracture zones can also have the effect of causing water loss from a reservoir. The trends of the Yledigao Valley and Fensol-Laolao Valley fault lines cross the projected reservoir and are potential drains on reservoir capacity.

WEATHERING, SOILS, AND SLOPE PROCESSES

Outcrops weather deeply and rapidly to a spongy sandy-clay saprolitic residuum, variously pigmented in reds, purples, oranges, yellows, and grays from iron oxides and hydroxides. The dominant clay minerals in the residuum are a varying combination of gibbsite, kaolinite, and smectite (Siegrist, unpublished analyses, 1984, 1990). Black manganese oxides fill small joints and slickensides in the saprolite and soils and often occur as dendrites on bedding planes of sandstones and mudstones. Original bedding planes of fine-grained volcaniclastics are usually well preserved despite the rock body having been transformed to saprolite. Agglomerate and breccia clasts in flow members of the Bolanos Member tend to exfoliate and produce spheroidal boulders with oxidized rinds and less weathered cores. These litter by the hundreds several badlands tracts in the upper Inarajan watershed (Plate 10). Where badlands have not developed the saprolite residuum supports a gravely to sandy clay-loam soil Young (1989).

No studies have been reported on sediment yield from the Inarajan River watershed. Based on superficial similarities with the Ugum River, Barrett Consulting Group (1994) estimated a yield of about 4.236×10^5 kg/yr/km^2 (1,210 tons/yr/mi^2) (DeMeo, 1994).

The high degree of chemical weathering has exacerbated slope instability and badland development. Steepened bare slopes display many forms of instability ranging from rock-falls to massive debris flows (Plate 11) to huge (hectare-scale) rotational slumps (Plate 12 (Siegrist et al, 1992, Siegrist 1996). Toes of such slopes commonly contain large accumulations of chaotically deposited sediment which further downslope evolve into alluvial fans and wetlands (Siegrist, 1992). Although slopes movements are common features in the volcanic terrain of southern Guam, no relationship between them and deep crustal movements has yet been established.

SUBSURFACE STUDIES

Geophysical (seismic refraction) and trenching studies were run at the proposed dam site as part of a comprehensive study of southern Guam surface water resources (Barrett Consulting group, 1994). Depending upon slope and proximity to valley floor they reveal variable thickness (0-10 meters) of saprolite/soil resting on relatively impervious andesitic pyroclastic basalt. The geophysical profile (Figure 4) for the northern side of the reservoir reported by Barrett Consulting Group (1994) indicates a significant downslope thickening and upslope thinning of the soil-saprolite layer, a condition that is frequently associated with mass slope movements.

WATER RESOURCES

Abandoned Surface Water Structures in the Laolao River Valley

The Inarajan River watershed has seen several ambitious water resource management efforts fail. These attempts are evidenced by abandoned structures. On the Fintasa River immediately upstream from Fintasa Waterfalls (Plate) are concrete ruins and rusted pipes of the Fintasa Diversion (Plate 13), a small dam and water transmission line leading downstream to a small disused water treatment facility. Downstream, on the Laolao River are similar ruins of the so-called Laolao Diversion (Barrett Consulting Group, 1994), that re-instituted the earlier Fintasa River water treatment facility, but later was used exclusively for irrigation (Plate 14).

Gaging Station on the Inarajan River

A U. S. Geological Survey stream gaging station (# 8350) formerly operated about 0.5 kilometers downstream from the proposed dam site and about +3.5 meters elevation on the Inarajan River. The station recorded continuous stage and flow from 1953 through 1988. Data from that station were incorporated in the preliminary hydrologic evaluation of the proposed dam-reservoir by Barrett Consulting Group (1994, vol II, p II-7.1 through II-7.7).

The hydrologic evaluation included deriving the flow-duration curve for the Inarajan River (Figure 5). Plotted on log probability paper, the flow-duration curve shows the percentage of time a given stream flow will be exceeded ("exceedence value"). For most streams on Guam, the flow-duration curve is steep, indicating that the flow is heavily influenced by direct runoff (flashy flow), and that it is not significantly affected by groundwater (i.e. they are non-gaining streams) . On the Inarajan River, however, the lower end of the flow-duration curve (<2.0 MGD) flattens out, implying that groundwater is being imported into the rivers, and during low flows, accounts for a significant portion of the stream flow.

The flow-duration curve is useful in defining the "base flow", the minimum flow which must be maintained to prevent damage to aquatic habitats. This minimum flow is often set at the 90% exceedence value. For the Inarajan River, 1.5 MGD is the 90% exceedence value or base flow (Barrett Consulting Group, 1994).

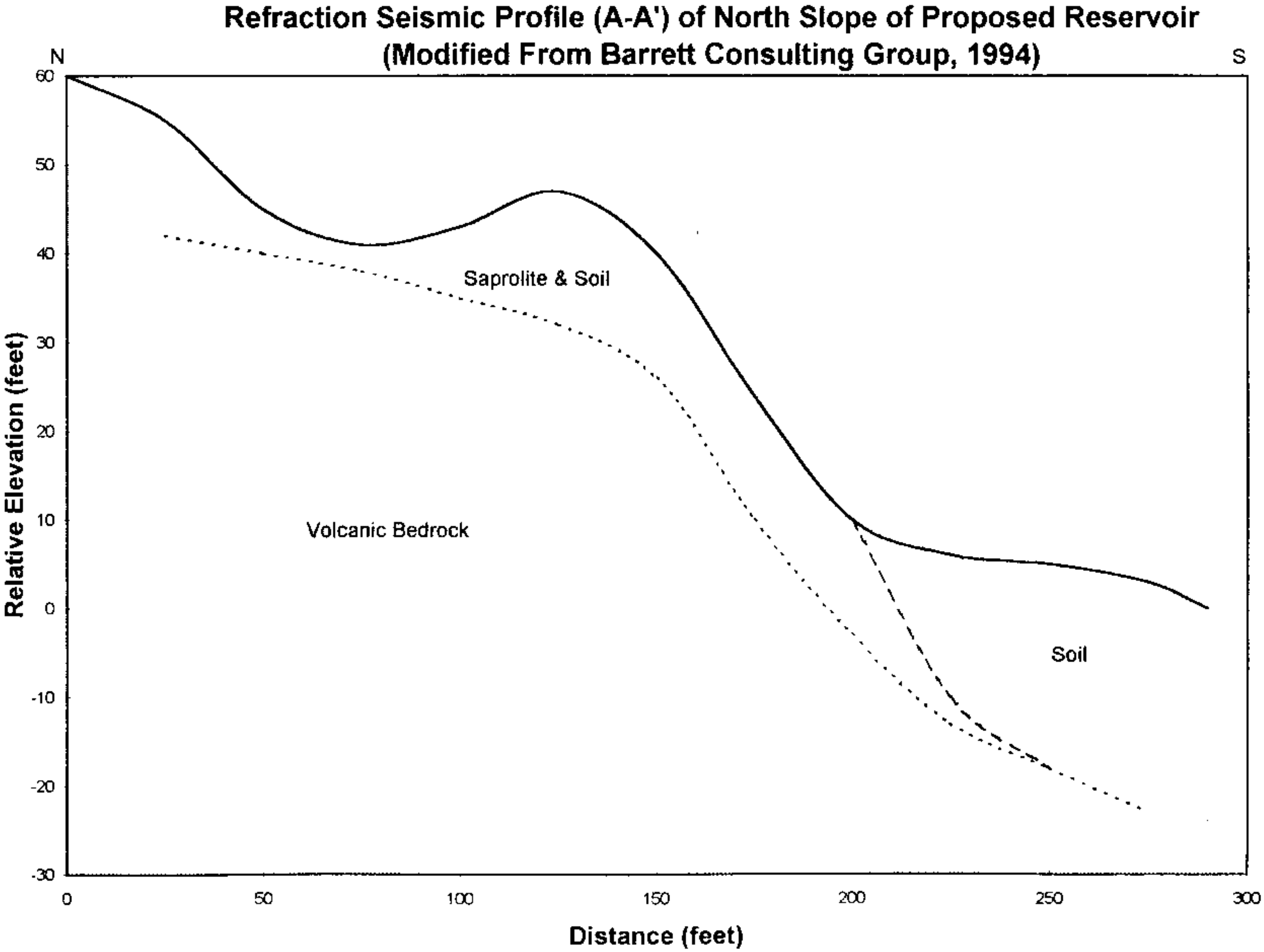
Shallow Groundwater in the Lower Inarajan River Floodplain

Ayres and Clayshulte (1984) showed that the buried alluvial sands and gravels within the floodplain of the lower Inarajan River valley, downstream from the proposed dam site, could provide a limited volume of potable water for irrigation purposes. They identified two systems that could be exploited: In the alluvial fans along the perimeter of the floodplain, especially on the southern side of the valley, a perennial seepage zone could be intercepted with a horizontal perforated pipe below the water table. This pipe would lead to a storage sump that they estimate could be pumped to yield between 1,500 and 3,000 gallons per day. However, nearer the channel, where recharge of the aquifer came from the river, they recommend shallow wells be sunk, which they estimated could yield about 3,000 gallons potable water per day.

Deep Groundwater in the Inarajan River Watershed.

No record exists of successful groundwater development of volcanic bedrock aquifers within the Inarajan River watershed. This absence does not indicate a lack of subsurface water, but points to the economic realities of exploring and developing probable low yield aquifers in rugged terrain when cheaper and more productive alternatives exist.

The high density of bedrock fractures, including those associated with water seepage, along the Fintasa Valley and Yledigao Valley Fault traces may offer an opportunity and strategy for successful groundwater exploration in the Bolanos volcanics. Should these fractures persist at depth, they could act as high permeability zones. Drilling along a fault



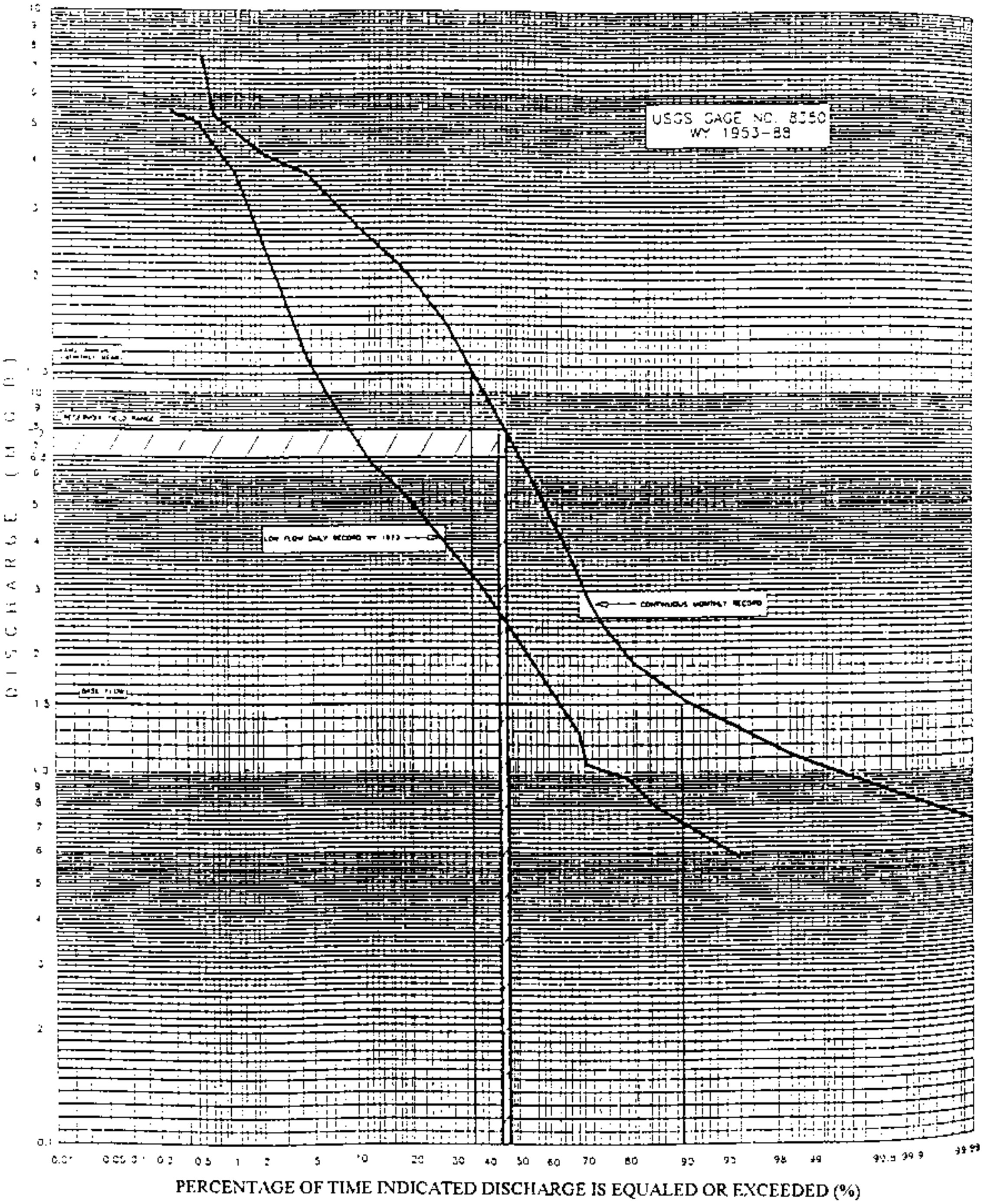


FIGURE 5
INARAJAN RIVER FLOW-DURATION CURVE

(From Barrett Consulting Group, 1994)

trace, or an intersection of two fault traces would increase the probability of tapping into a high permeability zone and locating significant groundwater.

Drainage Patterns

Streams in southeastern Guam generally flow in a dendritic or modified rectangular pattern, indicative respectively, of random and fracture controlled drainage. Both styles are evidenced in the Inarajan River watershed but modified rectangular (rhombic) drainage is dominant. A frequency distribution of channel azimuths of all permanent streams in the Inarajan River watershed, taken every 300-meters, is indicated in Figure 6. The representation indicates two maxima, corresponding approximately to N75°W and N50°W, and a lesser maxima of almost N-S. The structural relationship and implication of these maxima will be discussed later in this report.

Dynamics of Proposed Reservoir

The full 5 million cubic meter reservoir of impounded water is plotted on the map in Figure 2. If and when completed, the reservoir will drown the Inarajan Valley beyond the confluence of the Yledigao and Pasamano Rivers, encroaching up the Yledigao River Valley to within 150 meters of the Inarajan Waterfalls. It is anticipated that a deltaic wetland will quickly become organized and prograde into the upper shallows of the reservoir, downstream from the new terminus of the Pasamano and Yledigao branches.

The reservoir will contain one prominent island that will rise about 15.2 meters (50 feet) above the lake surface, approximately 1.1 kilometers upstream from the dam site. That site was not visited in this study, but as viewed from adjacent valley slopes it appears to be made up of basalt flow rock. The island should be scenic and its shoreline should be relatively stable.

The Laolao River will be drowned to within a few meters or tens of meters of the Laolao Waterfalls. Because of the large percentage of badlands in the Fintasa River, it is conceivable that typhoon rains will liberate enormous quantities of eroded sediment that will be imported into the reservoir at rapid rates, only 300 meters from the spillway. Such a huge, fast-moving volume of sediment will have the potential of forming a surface water plume of clay and/or a subsurface turbidity current of clay, silt, and sand, both of which could easily reach the spillway or base of the dam.

The shoreline around much of a newly filled reservoir is unstable for years owing to the rapid erosion at base of the valley slopes. Eventually a shoreline equilibrates, but in the case of this reservoir, the problem will be compounded by an already destabilized upper slope. The slumping and other forms of mass movement, and the badlands erosional processes will surely impact negatively the reservoir for many years.

Water Quality

Groundwater: Barrett Consulting Group (1994) reported on the water quality from a single sample from a shallow-(2-4 meters) observation well (Well #AH-4 from Ayres and Clayshulte, 1983), augered in alluvium downstream from the projected dam site. This analysis lists many potentially important metals and nutrients, but lacked information on pesticides, other organics, and microbials. Most constituents fell below the upper limits for drinking water as defined by the both Federal and Territorial legislation, exceptions included nitrate-nitrogen, dissolved iron and dissolved manganese. The elevated nitrogen is doubtless a function of agricultural animal wastes. High manganese and iron levels may reflect high levels of those metals in basaltic source rocks and soils and the importance of the REDOX driven reactions in mobilizing these metals in the pore waters of the floodplain.

Surface Water: The Inarajan River is not among those rivers periodically monitored for water quality by the Guam Environmental Protection Agency. Water samples from the Laolao River and its principal tributary stream, the Fintasa River, were analyzed in 1993 (Table 2) in connection with water quality studies of springs, rivers, and wetlands by the Water and Energy Research Institute of the Western Pacific. Samples were collected at 50-150 meter intervals in the channel along the entire course of these rivers and at mouths of several feeder seeps. Samples were collected in glass vials containing a few milliliters

Table 2: Iron and Manganese Concentrations (µ/l) in Stream Waters from the Fintasa River in upper Laolao River Watershed

WERI Number	River & Date in 1993	General Location Channel Samples	Fe (µ/l) filt/unfilt	Mn (µ/l) filt/unfilt
L3/L4	Laolao, 11/10	5m sth of Laolao Waterfalls	40/570	180/210
F5/F6	Fintasa, 11/23	15m upstr fr. abandon. weir	150/760	260/260
F7/F8	Fintasa, 11/23	70m upstr fr. abandon. weir	50/1100	1210/1200
F9/F10	Fintasa, 11/23	100m upstr. abandon. weir	260/800	230/270
F13/F14	Fintasa, 11/23	150m upstr. abandon. weir	140/440	130/140
F15/F16	Fintasa, 11/23	200m upstr. abandon. weir	220/820	260/270
F17/F18	Fintasa, 11/23	250m upstr. abandon weir	310/680	170/150
F19/F20	Fintasa, 11/23	285m upstr. abandon. weir	210/900	150/170
F21/F22	Fintasa, 11/23	325m upstr. abandon. weir	260/880	150/160
F23/F24	Fintasa, 11/23	400m upstr. abandon. weir	880/1320	170/180
F29/30	Fintasa, 11/17	300m dwnstr Nelansa R. confluen.	60/140	50/50
F31/32	Fintasa, 11/17	250m dwnstr Nelansa R. confluen.	320/460	70/70
F33/F34	Fintasa, 11/17	Seep, 215 m downstr. Nelansa R.	10210/11160	390/400
F35/F36	Fintasa, 11/17	100m dwnstr Nelansa R. confluen.	2550/3600	190/30
F37/F38	Fintasa, 11/17	50m dwnstr Nelansa R. confluen.	3340/3720	170/170
F39/F40	Nelansa 11/17	5m above Fintasa R. confluen.	20/80	<10/<10
F43/F44	Fintasa 11/17	50m above Nelansa R. confluen.	1220/1600	40/40
F45/46	Fintasa, 11/17	150m above Nelansa R. confluen.	1160/1220	130/130

of nitric acid by injecting 10-20 ml of stream waters thorough a syringe that was mounted with a 0.3 micron filter. Filterable (filt) and unfilterable (unfilt) iron and manganese are reported in µ/l (parts per billion).

Average levels of total and filterable iron and manganese in the Fintasa River, even excluding the extraordinary levels in the one seep, are elevated well beyond the average of other streams in southern Guam, as reported elsewhere (Barrett Consulting Group, 1944). Statistically, the probability that the average of the above analyses of either Fe or Mn does not exceed average Guam river water values in less than 1 in a 1,000 (written $P< .001$). Only the Talaeyag River along the western coast near Agat has comparable values with the Fintasa River (Siegrist et al, 1992). Levels of total iron are consistently greater by 10-30 percent than levels of filterable iron; filterable and total manganese do not have the same relationship.

If we assume that all the iron and manganese in the Fintasa River arrives in the proposed reservoir, and taking conservative estimates of 1 MGD water discharge from that small stream (or ca. 3.04 billion lb./water/yr), an average total iron concentration of 1500(µ/l), and an average total manganese level of 230(µ/l), the future impoundment will import from the Fintasa River alone over two tons of iron and about 700 lb. of manganese per year. The potential for local buildups of toxic levels of these metals cannot be dismissed if the metals are allowed to concentrate in anoxic bottom waters in the reservoir.

Human Impact on Reservoir Water Quality.

The southern valley slopes above the reservoir drain an upland area that is currently being subdivided for development under the former GovGuam "Land for the Landless" program. Several fast moving ephemeral streams flow off the area under development and would empty into the proposed reservoir. Their headwaters are the loci for intensified erosion as well as potential sites for domestic waste dumping. (Plate 15). Furthermore, there are many signs below the housing tracts of landslides and other forms of hillside movements implying a general condition of oversteepened slopes. Seepage from those slides and from the plateau above is visible most of the year indicating some water storage in the colluvium, frequently a factor in slope failures. Further west, the Yledigao Valley lineament crosses the southern slope of the reservoir and trends directly across the future housing tract. The possibility exists for seepage originating from the housing development to move through the fracture zone into the reservoir.

In summary, severe negative impacts from the housing development on any future water supply impoundment below Land managers and planners should be wary of the potential vulnerability of any reservoir below this area to seepage, stream runoff, sediment; and slope instability.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study shows that a rigorous, short-term reconnaissance geologic field study can be structured as a training module and, at the same time, provide a wealth of information that could prove effective in judging the feasibility of constructing a significant water storage dam and reservoir complex. The study demonstrated that small groups of relatively inexperienced science graduate students can be trained on the job to assemble critical field observations and measurements on which planning decisions could be reasonable based. The study further demonstrates that such reconnaissance efforts are a cost-effective way to identify potential geologic impacts on large built structures in Guam.

In regard to the specific site, earlier published studies provided students with invaluable background information. This information can be classified into positive and negative factors relative to constructing a dam and reservoir at the Inarajan-Laolao confluence. We believe that the negative factors outnumber, but may not necessarily outweigh, those that are positive. The most significant points are listed below, omitting those, such as historic impacts, agriculture, etc. that are clearly beyond the scope of a reconnaissance geologic report.

Favorable Observations on Dam Installation

- **Real Need:** The projected dam will create a large impoundment that is much needed in an area of Guam that traditionally has had serious water shortages, and which will only have more protracted shortages in the future.

- **Long Record:** A reasonable hydrologic record exists for the Inarajan River. Therefore, there is a fairly firm basis for predicting storm- and draught-related behavior of the river systems feeding and draining the reservoir.

- **Favorable Valley Profile**: The confluence of the Inarajan and Laolao Rivers is a major valley profile constriction and appears to maximize the volume of any impoundment.

Unfavorable Observations on Dam Installation

- **Slopes and Shoreline Instability**: The upper watershed of the Inarajan river valley has enormous slope mass wastage problems. Sedimentation into the reservoir and along the edges of the reservoir will be a major problem for many years following its initial creation.

- **Storm Related Sedimentation**: In tropical storm-typhoon events, the Laolao River may import sediment into the dam near the spillway and base at unacceptable rates and volumes.

- **Chemical Loading from Rivers:** The Laolao-Fintasa River carries high levels of dissolved manganese and sediment containing particulate manganese. Chemical and bacterial reduction of particulate manganese in deep anoxic reservoir waters could boost dissolved Mn concentrations well beyond safe drinking water levels.

- **Reservoir Leakage**: The reservoir is crossed by at least one fault zone that is the locus of fractured, crushed, and otherwise deformed rock. This condition could signal high bedrock permeability and potential water losses, especially when rock pore pressures rise as the reservoir fills.

- **Groundwater Contamination**: The same fracture zones that could serve as zones of leakage under the reservoir could also act as conduits for importing groundwater and dissolved chemicals leached from the volcanic bedrock into the reservoir. Such a situation could require expensive additions to a normal water treatment plant.

- **Seismicity and Fault Movements**: The dam site is on a topographic saddle that may coincide with a fault zone. Notwithstanding the geophysical data indicating sold dense bedrock below the site, field data suggest significant crustal movement in the past

- **Solid Waste and Waste Water from Nearby Housing**: Acreage on the upper slopes on the southern side of the reservoir is slated for fairly intense residential development under the old Land for the Landless Program. Reservoir pollution problems from sewage and other household waste will be highly probable.

RECOMMENDATIONS

Any plans to develop the Inarajan-Laolao River confluence as a site for a water supply dam should be tempered by the number of negative conclusions postulated above. Notwithstanding these real and potential drawbacks, the need for future potable water in southern Guam may demand that this site be developed. If that situation comes to pass we recommend:

Geology:

Undertake a seismic refraction profiling and deep rock coring program covering the entire extent of the proposed reservoir and surrounding slopes. Remap the topography of the entire watershed at a 5 ft contour interval. Remap the bedrock and saprolite geology on the new topographic base at an appx. 1:5000 scale.

Hydrogeology & Geomorphology

Develop accurate estimates of soil loss and sediment movement in the watershed. Develop and put in place a badlands restoration program.

Remobilize the disused stream gaging station and install temporary (5-10 year) stations on key tributaries, and put in place rainfall/evaporation measurement stations.

Geochemistry
Undertake exhaustive chemical profiling of all tributary streams and seeps to develop more accurate concentration estimates of natural pollutants, and define point-source problems.

Computer Modeling
There are computer models and software packages that forecast dam and reservoir behavior based on watershed characteristics, hydrology, climate, bedrock geology, geomorphology, etc. Software can be modified for Guam, and be on-line for evaluating this and other sites.

Legal Steps
Develop enforceable ordinances restricting slope and stream channel modifications and regulating waste handling and removal within the watershed.

PLATES 1 & 2

Plate 1: Inarajan River Valley Upstream from Proposed Dam Site. Photo taken looking southeast toward Inarajan village. Dark area to right foreground is riverine and lower valley forest. Note erosion and slope instability on upper slopes.

Plate 2: Slope Failures in Inarajan River Upstream from Proposed Dam Site. Same slope failures as shown in Plate 1. Note area in left center (arrow) is a mud slide moving between spurs of ridge.

PLATES 3 & 4

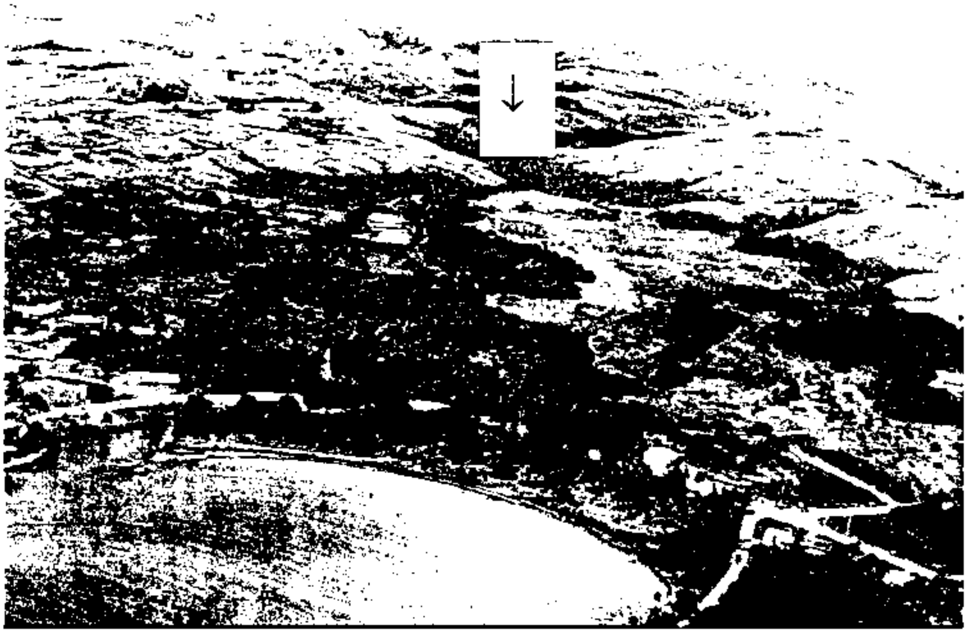


PLATE 3: Floodplain of Lower Inarajan River Valley. Photo looks west-northwest up the axis of the broad lower Inarajan River floodplain, below the location of proposed dam (arrow).

Plate 4: Laolao Waterfalls. Photo looks northwest from one of two grassy knolls that would anchor proposed dam. Dry season (April, 1996) low flow. Resistant caprock consists of volcanic breccia.

PLATES 5 & 6

Plate 5: Fintasa Waterfalls. Approximately one kilometer upstream from juncture of Fintasa and Fensol Rivers. Photo taken during April low flow conditions.

Plate 6: Grassy Knoll Intended for Support of Dam Structure. Photo looks south toward grassy knoll (right middleground) and was taken from a second grassy knoll that is intended to anchor north end of spillway.

PLATES 7 & 8

Plate 7: Reef Limestone Xenolith Clasts in Bolanos Formation: Fintasa Valley. Large residual boulders from the Bolanos Formation are slowly working down slope into valleys within the Inarajan River watershed.

Plate 8: Tectonically Deformed Strata along the Fensol-Laolao Lineament. Slumped or folded agglomerate beds (right center and upper left) in multiple fault contact with tuffaceous sandstones (left, below, and far right).

PLATES 9 & 10

Plate 9: Mn and Fe Oxide Mineralization of Bedrock Fractures: Fintasa River Valley. Black lines indicate pyrolusite- and goethite fracture filling in Bolanos Formation along the Fintasa Valley Lineament. Chert is also a common fracture filling. This outcrop contains about five hundred mineralized fractures, some of which are seeping water.

Plate 10: Saprolitized Basalt Boulder Field: Dandan Flow Member: Fintasa Valley. Decomposing and exfoliating boulders of scoriaceous basalt litter many hectares in the Inarajan River watershed.

PLATES 11 & 12

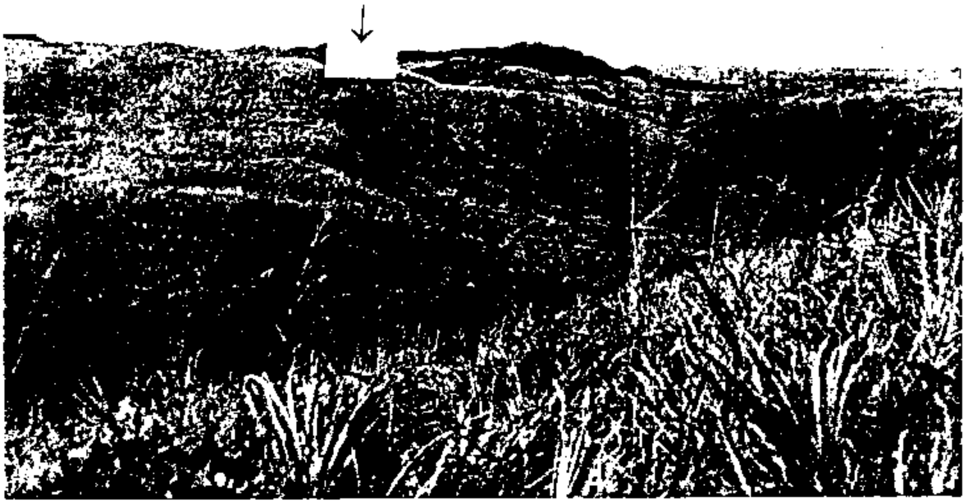


Plate 11: Modern Rotational Slump on Upper Slopes above Fintasa River. Fresh scars (arrow), concave or "hollowed out" slope, and lower bulging are indicative of rotational slope movement. Fintasa River below slump is littered with huge residual large boulders.

Plate 12: Abandoned Fintasa River Water Diversion, Upstream from Fintasa Waterfalls.

PLATES 13 & 14

Plate 13: Abandoned Laolao River Diversion, Upstream from Laolao Waterfalls.

Plate 14 (right): "Land for the Landless" Tracts. Slopes and ridge on right are now open to homesteading. The area overlooks and drains (both surface and groundwater) into potential reservoir (dark vegetated area on left) of inundated Inarajan River valley. Photo looks ESE toward village.

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