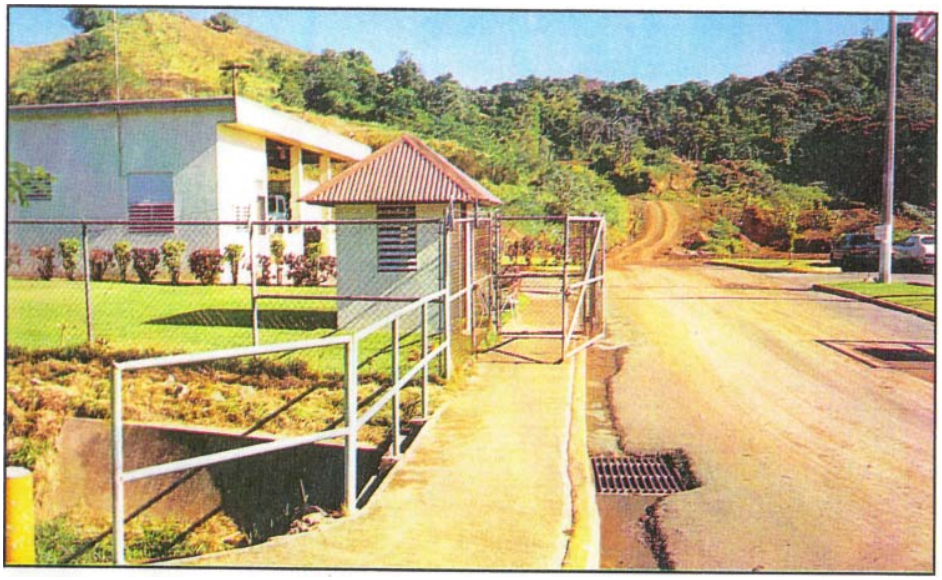
# REPORT OF A RECONNAISSANCE OF THE GEOLOGIC AND THE SURFACE AND GROUND WATER INCLUDING HYDROLOGIC CHARACTERIZATION AT THE HORMIGUEROS MUNICIPAL LANDFILL JAGÜITAS WARD, HORMIGUEROS, PUERTO RICO

## Municipal of Hormigueros



**Prepared By:**

*Sondeos Inc.*
*Urb. Roosevelt*
*Calle Benigno Reyes 321*
*San Juan, P.R. 00918*
*Tels. (788) 771-7138/(787) 633-7818*

*MAYO 2010*

**Table of Content** **Pages**


| | | |
|---|---|---|
| I. | INTRODUCTION | 1 |
| | A Objective | 4 |
| II. | HYDROLOGIC STUDY | 5 |
| | A Population and Estimated Ground-Water Use | 8 |
| | B Geologic Setting | 11 |
| | C General description of the site | 13 |
| III. | STRATIGRAPHY | 14 |
| IV. | AGE OF STOCKS AND DIKES | 21 |
| V. | DEPOSITIONAL MODEL | 22 |
| VI. | METAMORPHISM | 27 |
| VII. | STRUCTURAL GEOLOGY | 29 |
| VIII. | UNCONSOLIDATED DEPOSIT | 39 |
| | A Streamflow at Río Rosario near Hormigueros exceeds 6 cubic feet per second 90 percent of the time | 45 |
| | B Minimum Flows At Río Rosario At Highway 2 were estimated from downstream records and drainage area adjustments. the–day, 10-year montly minimums range from 1.7 to 3 cubic feet per second | 46 |
| | C Sanitary Quality of Surface Water during base-flow conditions in the Municipal of Hormigueros, Puerto Rico, 1998-99 | 48 |
| IX. | SURFACE WATERS ARE SUITABLE FOR MOST USES | 51 |
| X. | LIMITED SEDIMENT DATA AVAILABLE | 56 |
| XI. | GROUNDWATER AT THE LANDFILL STUDY AREA | 59 |
| XII. | DATA-COLLECTION METHODS | 61 |
| XIII. | SOIL INVESTIGATION PROCEDURES | 61 |
| XIV. | BORINGS AND SAMPLING METHODS | 62 |

**Table of Content (Cont.)** **Pages**


XV. STANDARD LABORATORY TESTS 63

A Visual examination and description 63

B Standard penetration test (SPT) “N” 63

XVI. DYNAMIC SOUNDINGS 63

XVII. WATER TABLE 64

XVIII. CONCLUSION AND RECOMMENDATION 67

XIX. LIST OF REFERENCES 72

# I. INTRODUCTION

The Municipality of Hormigueros with an estimated population of 20,965 in 1998 (U.S. Department of Commerce, 1998a), covers an area of 28.5 square miles ($mi^2$) (fig. 1.). Most of the Municipality north side is characterized by steep topography with approximately 77 percent of the land area having slopes greater than 21 percent (21 feet of vertical displacement per 100 feet in horizontal plane; Larsen and Parks, 1998). Much of the town of Hormigueros is located on the flatter terrace and alluvial plain of the Río Guanajibo, but a substantial part of the urbanized area has spread onto the slopes of the adjacent Río Rosario. Approximately 75 percent of the Municipality population is concentrated within the town limits and the adjacent urban communities. About 35 percent of the population is concentrated within rural communities at Barrios and with the remaining 40 percent about equally distributed within the other Barrios of the Municipality (plate 1).

To meet the increasing need for a safe and adequate supply of water in the Municipality of Hormigueros an integrated surface-water, water-quality, and ground-water assessment of the area was conducted. The major results of this study and other important hydrologic and water-quality features were compiled in this report. Information System, and are presented in figure and map plates to facilitate interpretation and use of the diverse water-resource data.

The integrated hydrogeologic approach used in this study can serve as an important tool for regulatory agencies of Puerto Rico and the Municipality of Hormigueros to evaluate the ground-water resource development potential,

**Figure 1 Hormigueros Municipality with Subdivision ("Barrios")**

examine ground-and surface-water interaction, and determine the effect of land-use practices on ground-water quantity and quality. Stream low-flow statistics document the general hydrology under current land and water uses, special like areas of waste disposal and septic discharges.

Low-flow characteristics may substantially change as a result of streamflow diversions for public supply, increase in ground-water development, waste-water discharges, and flood-control measures; this current analysis provides baseline information to evaluate these impacts and to evaluate the ground-water development potential of each hydrogeologic terranes. Analysis suggests that areas with slopes greater than 15 degrees have relatively low ground-water development potential. Fractures may be important locally in enhancing the water-bearing properties in the hydrogeologic terranes containing volcanaclastic sedimentary ground rocks area, water and spring flow in occurs primarily in alluvial aquifers, which are highly vulnerable to contamination. In these aquifers, the water flows too rapidly and is not in contact with the surrounding material long enough for purification to occur (Tarbuck and Lutgens, 1990). In areas of most vulnerability are the unsewered rural communities, because water moves within fractures or the regolith and along bedding planes where intensive animal husbandry and poultry breeding enterprises are located. Outside of the rural areas, the greatest susceptibility of sanitary wastes contamination is at surface-water supply intakes located along stream courses that do not meet the standards for public water-supply sources, and at wells sited near streams with degraded water quality.

The Hormigueros Municipal Sanitary Landfill (HMSL) is located in the Jagüitas Ward of the Municipality of Hormigueros. It can be accessed through state road PR-338, about 0.5 kilometers to the north of the intersection with PR-345 (Figure 1.). It is bounded to the west and southwest by the state road PR-338 and by unnamed intermittent stream. There are several developed residential structures bordering the landfill. Just to the south, there is a residential neighborhood, a school, a Head Start and Grocery Store. In general, the landfill consists of an earth and waste-filled mound covering the underlying volcaniclastic rocks formation. According to the surface elevation at the landfill varies from about 50 meters to the central and southern limits of the landfill, reaching about 100 meters above mean sea level at the northern limits (164-328 feet).

The facility is presently operating and it has operated for approximately more than 20 years. According to available records the HMSL has been used for disposing non-hazardous solid and domestic waste. It occupies an area of 42.7186 “cuerdas” of land (85,362.7544m$^2$).

## A. Objectives

The primary goal of the investigation was to characterize, to the extent possible, the subsurface geologic and groundwater conditions of the site. A conceptual groundwater flow map generated from the subsurface information gathered will aid in determining a high quality and cost-effective groundwater monitoring system aimed at intercepting migration pathways for contaminants from the landfill drilling and sampling and the strategy location and installation of monitoring wells.

This investigation comprised ground water level measurements, analysis of the soil-rock configuration, and determination of groundwater flow and aquifer properties. The technical information gathered from this investigation and the monitoring work to follow will also help in determining if there will be a need for future corrective action at the site.

## II. HYDROLOGIC STUDY

General description of the site

Guanajibo Region - The Guanajibo Region, located on the west coast of Puerto Rico, covers an area of approximately 146 $mi^2$. The principal population centers in Guanajibo region are San German, Hormigueros, Cabo Rojo and Mayaguez (fig.2.)

The Guanajibo region is characterized by a broad alluvial valley (the Central Guanajibo Valley) covering about 29$mi^2$. This valley is bounded on all sides by

**Figure 2. Río Guanajibo Basin and Study Area**

hills, except to the northwest, where it is $mi^2$ bounded by the Mona Passage. At the coast, the Guanajibo Valley extends northward joining the Río Yaguez Valley. A barrier of low-lying hills almost completely separates the Center Guanajibo Valley from the coast. These hills form a ridge calles The Cordillera Sabana Alta that reaches its greatest elevation in the east. West of these hills, the shore features a fringe of beach and swampy terrain. A large coastal lagoon, Laguna Joyuda, dominates the west-central coast areas.

The Central Guanajibo Valley measures 18 miles in length along its east-west axis, with a width ranging from 6 miles in the east to 12 miles in the west. The Central Guanajibo Valley has an area of about 25 $mi^2$. Elevations within the valley range from mean sea level at the coast tom about 200 feet above mean sea levels. Hills surrounding the valley reach maximum elevations of 1,968 feet above mean sea level in the Cordillera Central.

The major river in the region is the Río Guanajibo, flowing to the west-northwest. It originates along the west side of the Cordillera Central and flows to the sea on the west coast, south of Mayagüez. The principal tributaries to the Río Guanajibo are the Río Rosario, Río, Río Duey, Río Hoconuco, Río Cain, Río Cupeyes, Río Cruces and Río Flores, draining to the west-northwest.

## A. Population and Estimated Ground-Water Use

The total population of the Municipals within the Guanajibo Region in 1980 was about 204,000 (Table 2.3.2.B-1; US Department of Commerce, 1982). Between 1980 and 1990 the population increased by 7% to about 218,000 (US Department of Commerce, 1991). However a large portion of the population in the Municipals of Mayagüez and Maricao is outside the Central Guanajibo Valley.

Ground-water withdrawals in Cabo Rojo, Hormigueros, Mayagüez and San German totaled less than 5.9 Mgal/d in 1982 (Table 2.2.B), Torres-Sierra and Aviles, 1986). According to Torres-Sierra and Aviles (1986), no ground water was withdrawn in the Municipal of Mayagüez from 1980 to 1982. However, Gomez-Gomez and others (1984), reported a withdrawal of 0.45Mgal/d of ground water for 1981 in that Municipal.

During the 1980's, ground water was the only source of water for public supply in Cabo Rojo and Hormigueros. Public-water supply in Mayaguez is from surface-watersources, while in San German both surface and ground water contribute in meeting public water demands.

Public- supply sources provided less than 5.46 Mgad/d for domestic use, while community systems supplied less than 0.43 Mgad/d. Water used for industry, agriculture (livestock), and commerce totaled less than 0.27, 0.25, 0.62 Mgad/d, respectively. Approximate well locations by use are shown in figure 3.

**Figure 3. Water Well Sampling Sites**

**Table 1** Population for the Guanajibo region, Puerto Rico (US Department of Commerce, 1982, table 1; US Department of Commerce, 1991, table 1).

| | 1980 Population | | | 1990 Population |
|---|---|---|---|---|
| MUNICIPAL | TOTAL | URBAN | RURAL | TOTAL |
| | | | | |
| Cabo Rojo | 34,045 | 10,292 | 23,753 | 38,521 |
| Hormigueros | 14,030 | 12,031 | 1,999 | 15,212 |
| Maricao | 6,737 | 1,390 | 5,347 | 6,206 |
| Mayagüez | 96,193 | 82,968 | 13,225 | 100,371 |
| Sabana Grande | 20,207 | 7,435 | 12,772 | 22,843 |
| San Germán | 32,922 | 13,054 | 19,868 | 34,962 |
| Total | 204,134 | 127,170 | 76,964 | 218,115 |

**Table 2** Ground –water withdrawals for public water supply by Municipal for 1980, 1981 and 1982 in the Guanajibo region, Puerto Rico (Torres-Sierra and Aviles, 1986) [Mgad, million gallons per day]

| | Total ground water withdrawals (Mgad/d) | | |
|---|---|---|---|
| MUNICIPAL | 1980 | 1981 | 1982 |
| | | | |
| Cabo Rojo | 3.72 | 3.28 | 2.75 |
| Hormigueros | 0.98 | 1.21 | 1.29 |
| Maricao | 0.01 | 0.00 | 0.00 |
| Mayagüez | 0.00 | 0.45 | 0.00 |
| Sabana Grande | 0.37 | 0.44 | 0.51 |
| San Germán | 1.02 | 1.40 | 1.54 |
| Total | 6.10 | 6.78 | 6.09 |

Value given in Gomez-Gomez and others (1984) for 1981.

## B. Geologic Setting

There are four major lithologically distinct rock groups present in the Guanajibo region (fig. 3.). They are: the Bermeja Complex of Jurassic to early Cretaceous age; a suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Late Cretaceous age; liestone formations of Late Cretaceous age; and alluvial deposits of Quaternary age.

The Bermeja Complex of Jurassic to Early Cretaceous age (Montgomery and others, 1994) consists primarily of serpentines, amphibolites, basalt, and chart. It is highly deformed and metamorphism has destroyed most primary textures, bedding, and litho logical relations. It is most extensively exposed in the southwestern part of the Guanajibo region.

The suite of volcanic, volcaniclastic, plutonic, and sedimentary rocks of Late Cretaceous age predominate in the mountains surrounding the Central Guanajibo Valley (fig. 4.). Subsequent to their formation these rocks were folded and faulted (Colón-Dieppa and Quiñones-Marquez, 1985), and then subjected to extreme weathering and erosion. The Central Guanajibo Valley largely lies within an anticline that has been breached by erosion and is bounded in part by faults (Mattson, 1960, p.321; Colón-Dieppa and Quiñones-Marquez, 1985, p. 10).

The limestone formations of Late Cretaceous age in the Central Guanajibo valley include the Peñones Limestone, Cotui Limestone, Parguera Limestone, and Melones Limestone (Curet, 1986; Volckmann, 1984b and

**Figure 4. Geology of the Central Guanajibo Valley. (Modified from Mattson, 1960)**

1984c). While these various formations vary in coloration, they are generally massive to thick-bedded limestones rich in mollusk fossils. These formations overlie to Bermeja Complex and various of the volcanis, volcaniclastic, plutonic, and sedimentary rocks.

Alluvial deposits of Quaternary age overlie volcanis and volcaniclastic rocks in the southwestern Guanajibo region and the Bermeja Complex in the Central Guanajibo valley (Mattson, 1960; Colón-Dieppa and Quiñones-Marquez, 1985, p. 18). Clay predominates in the surface of the alluvium. These surficial clay deposits in the alluvium are generally underlain by sand lenses and, at greater depths, gravel lenses with the clay-rich alluvium.

## C. General Geology of the Area

The Mayagüez and Rosario quadrangles are underlain by an older complex of amphibolites, serpentinite, and spilitized basalt of pre-Cretaceous to Early Cretaceous age, and by an unconformably superposed younger sequence of volcaniclastic and calcareous rocks known to be of Cretaceous and Tertiary age en the Monte Guilarte quadrangle (Krushensky and Curet, 1984), but known to be of Cretaceous age in this map area. Both sequences are intruded by andesitic and basaltic hypabyssal rocks. Areally, the older complex is restricted a narrow belt outcropping mainly along the central portion of both quadrangles. Volcanic breccias and conglomerates, volcanic sandstone,

siltstone, mudstone, and minor tuffs of the younger sequence are widespread.

Structurally, the area is characterized by brittle failure as opposed to failure through folding. Both sedimentary and intrusive rocks are extensively displaced by north-northwest- and north-northeast- trending faults.

Volcaniclastic rocks have been named following the classification of Fisher (1961). The epiclastic rocks are those in which the major part of the lithic and mineral clasts, especially in the coarser fraction, shows a considerable degree of rounding. The pyroclastic rocks are characterized by clasts in which bounding surfaces, whether curved, concave, or convex, meet at sharp angles or at points, and (or) by clasts in which sharply angular forms or the euhedral shapes of mineral clasts have been preserved. Rocks derived from coeval pyroclastic debris and reworked pyroclastic debris is common throughout the younger sequence. The relative abundance of pyroclastic, reworked pyroclastic, and epiclastic rock fragments varies greatly within on formation and from one location to another.

## III. STRATIGRAPHY

The Yauco Formation as here defined consists predominantly of siltstone and claystone. Rocks included in the formation were originally named the Río Yauco shale (Mitchell, 1922, p. 249) for “strongly bedded shale” exposed along the road

(now Puerto Rico Routes 128 and 372) north of Yauco and along the Río Yauco in the Yauco quadrangle. Hubbard (1923, p. 29) used the term Río Yauco Series to describe "predominantly shale often interbedded with ash and tuff, and with occasional and site flows and intrusive." Mattson (1960, p. 331) redefined the Río Yauco Series as the Yauco Mudstone, a unit composed of "mudstone, minor tuff, and rare conglomerate." The lithic modifier is here dropped and the work formation substituted because the Yauco includes significant quantities of various rock types. In addition the type locality of the Yauco Mudstone (Mattson, 1967, p.29) in the Yauco quadrangle includes volcanic breccias that we would include in another formation.

The Yauco Formation consists predominately of volcaniclastic siltstone and claystone and quantitatively important but lesser amounts of mudstone and sandstone, sparse limestone, and rare conglomerate. Although the claystone appears chiefly epiclastic, the other clastic rocks contain variable amounts of pyroclastic debris. A few are composed almost completely of pyroclasts, but examination in thin section is generally necessary to establish the pyroclastic or epiclastic origin of the rock. The Yauco Formation as exposed in the type area of Mitchell (1922, p. 249) is probably as useful as any other available. It is clear that the conditions noted prevent any one area from adequately representing the Yauco. A number of reference locations are suggested.

Excellent exposures of the Yauco are present in Barrio Jagüitas, Barrio Rosario, and in the part of Barrio Maleza in the Rosario-Mayagüez quadrangle. The claystone invariably lacks the facility characteristic of shale. In an interbedded

claystone-siltstone sequence, the claystone weathers into negative relief and the siltstone into low ledges. The sequence here is about 750 m tick. Higher in the sequence in the same area the siltstone and claystone are interbedded with fine-grained tuffaceous sandstone that contains abundant angular plagioclase clasts. Farther north along the valley of the Río Rosario and apparently higher in the same section, the sequence includes increasing amounts of fine-to coarse-grained volcaniclastic sandstone of epiclastic origin and tuffaceous sandstone; beds are thicker (15 – 20 cm), rarely to 2 m thick, locally graded, and commonly crossbedded. (see Figure 5)

Small-scale tabular and trough-shaped small-ripple bedding (Reineck and Singh, 1973, p. 87) is extremely common in the siltstone and somewhat less so in the sandstone facies of the Yauco Formation.

“Ripple bedding with numerous mud flasers” characteristic of flaser bedding (Reineck and Singh, 1973, p. 98) is common in the Yauco in south-central Puerto Rico; apparently similar structures have been reported (Mattson, 1960, p. 331) as common in the Yauco of southwestern and western Puerto Rico. Graded bedding, although less commonly seen, is widely present in the tuffaceous sandstone facies of the Yauco.

The sequence exposed in roadcuts in the major ridge east of Jaguas consists chiefly of thin- to medium-bedded (1-30 cm) calcareous siltstone, thin- to medium-bedded (1 – 30 cm) calcareous siltstone, thin- to medium-bedded fine-grained sandstone, and thinly laminated (<2 mm) claystone. In the southeast-trending large spur off the main ridge, eight or more soft sediment slump

**Figure 5. Yauco Outcrop Formation at the Hormigueros Landfill**

structures are exposed in a north-west-striking roadcut. The sequence dips to the south-southwest. In the roadcut the slumped rocks are separated from the nonslumped rock by high-angle faults. Apparent dip of the faults in the roadcut is to the southeast, but true dip is to the southwest. Breccia, 15 – 20 cm thick, composed of subangular clasts of siltstone and claystone in a massive mudstone matrix lies along the traces of the fault planes. Traces of the high-angle faults extend for only a few meters in the roadcut before their angle decreases and they become decollement or bedding-plane faults. Typically beds in the heads of the slumps are dragged upward and beds in the nonslumped rock are dragged downward by slump movement.

Subjacent to one slump, where the high-angle fault becomes a decollement, a 4-cm thick bed of mudstone has been “plowed up” by the slumped beds and folded into a recumbent syncline, overturned to the south. Beds within the bases of the slump structures are also folded into hook structures or recumbent anticlines and overturned to the south. Movement indicators that the direction of the paleslope was to the south-southwest.

The sequence exposed in the fault block west of Salto Garzas Central Hydroelectric No. 1 is a monotonous succession of deeply weathered siltstone, claystone, and mudstone that becomes progressively more saprolitized toward the north. Outcrops in the Cordillera Central in the northwest corner of the quadrangle are so deeply saprolitized that fresh exposures are not available. The saprolitized Yauco Formation ranges from a pale-yellow to hematite-red or dark-orange clay.

Study of thin sections indicates that rocks of the Yauco Formation are commonly tuffaceous, but uncommonly tuffs. Only the coarser grained sandstone can be identified consistently and correctly in the field as tuffaceous. The finer grained rocks consist largely of clay-sized particles, variable amounts of angular to subrounded clasts of fresh and weathered plagioclase and lithic materials, but rarely of fresh and angular augite. The claystone contains as much as 15 percent very fine grained fresh and angular plagioclase that is invisible in hand specimen. Claystone commonly has a minor tuffaceous component, but the lack of shard structures in the finer clasts suggests that it is chiefly epiclastic. Pumice has not been identified in the Yauco either in the field or in thin section, and shard structures have not been seen in any thin section of the formation. Thin sections examined also included only rare to sparse microscopic Foraminifera.

Coarser grained rocks of the Yauco may contain conspicuous pyroclastic plagioclase and augite, but they consist predominantly of subrounded to subangular weathered plagioclase and weathered extremely fine crystalline volcanic lithic clasts in variable amounts of clayey matrix. Hand specimens of coarse-grained volcanic sandstone commonly appear to consist of fresh and angular plagioclase set in a dark-colored matrix. Thin sections of the same specimens, however, show, that the matrix consists of well-sorted, dark-colored, and weathered lithic clasts in a similarly colored sparse clay matrix. The siltstone-sandstone beds rarely include rocks composed of 80 to 90 percent fresh angular plagioclase clasts and sparse whole plagioclase crystals in a clayey matrix. These relatively uncommon rocks are tuffs.

Limestone lenses are irregularly interbedded with the sandstone-siltstone facies of the Yauco. Lenses are commonly only a few meters thick and a few tens of meters log. Dark-gray argillaceous limestone crops out in the ridge north of Santo Domingo on the Yauco-Peñuelas quadrangle boundary. The unit has been separated in mapping, but it has not been given a formal member name. It may be conveniently referred to as the limestone of Santo Domingo.

Lack of graded bedding, the generally well-winnowed character of the matrix, the presence of large (to 15 cm long) plates of coralline algae, and the shallow-water fauna suggest that the limestone lenses in this area are not turbidities (Pessagno, 1962, p. 353; Slodowski, 1956, p. 77 – 78), but calcarenites deposited in place in shallow water. Similarly, the lack of graded bedding not related to emplacement of tuffs, the widespread presence of small-ripple bedding in most of the siltstone-sandstone facies, and the presence of features (Mattson, 1960, p. 332; Slodowski, 1958, p.68, 70; Berkey, 1915, p. 21 – 22) now recognized as flaser bedding over wide areas in the claystone-mudstone facies of the Yauco, suggest that within the mapped area the formation is the product of deposition in shallow intertidal areas, probably in restricted basins similar to that west of Punta Ballena on the south coast of Puerto Rico.

The Yauco and Lago Garzas Formations are interbedded over wide areas; the nature of the contacts is discussed after the description of the Lago Garzas Formation.

## IV. AGE OF STOCKS AND DIKES

The age of various stocks and dikes in the map area cannot be determined with precision. All of these intrusive bodies cut rocks of Campanian and Maestrichtian age; therefore, they are Late Cretaceous or Tertiary in age. Clasts in the coarser-grained volcaniclastic deposits are texturally and mineralogically identical with the intrusive stocks, which suggests that the stocks were subvolcanic sources of extrusive rocks making up the Campanian and Maestrichtian volcaniclastic units.

## V. DEPOSITIONAL MODEL

The following model for the sedimentation of thick sections of coarse-grained volcaniclastic material within a shallow-water marine environment is suggested by the geology of the Mayagüez and Rosario areas. Basically, fluvial sediments were supplied to one or more shallow-water basins, and a delta complex was constructed on the periphery of a volcanic island or islands. The volcanic centers were chiefly and probably entirely subaerial, and magma was erupted both as lava flows and pyroclastics. Emplacement of volcaniclastic debris probably included massive debris flows from the subaerial volcanic highlands. Procreation of the delta into progressively deeper marine waters led to increasing instability of the delta front and eventually to slumping of the front, formation of turbidity currents, and downslope slipping of relatively coherent sediment masses. Partial slumping of the delta front could have been triggered by volcano-related earthquakes or by overload produced by a flush of debris-flow materials.

Therefore, debris-flow materials may have been a major sediment source for the construction of deltas along the periphery of the volcanic island complex. The debris flows may also have continued to move downslope and come to rest on the deeper ocean floor. Eruptive activity maintained the steep slopes in the volcanic centers, and heavy rains produced lahars or volcanic debris flows.

Sand and coarse-grained material, products of debris-flow slumps, were carried by turbidity currents and were deposited or redeposited as graded and crossbedded layers. Contacts with underlying beds are sharply defined. Most of the coarse-grained material moved downslope as laminar, subaqueous gravity flow, debris flow, or grain flow. Some of the turbidity flows apparently contained a high particle concentration and, even though most may have moved as laminar flows, some were sufficiently turbulent to have injected material into underlying sediments.

Carbonate banks, including organic reefs and fore-reef and back-reef deposits, bordered the volcanic island complex except in the vicinity of river mouths or downwind from active volcano's, and grew slowly seaward. Parts of the growing bank were broken off and rolled or slid seaward and formed fore-reef talus deposits. Locally, the talus was mixed with volcaniclastic detritus and generated debris-flows, due either to oversteepening of the slope or to earthquakes. Mixed volcaniclastic-reef-generated material was then redeposited in deeper basins.

Depositional mechanisms of the types described are inferred to be active in submarine canyons and submarine fans (Stanley and Unrug, 1972; Walker and Mutti, 1973; Nelson and Nilsen, 1974). These submarine fan deposits commonly

occur or are inferred to have been deposited at bathyal or greater depths. The occurrence of submarine-fan deposits in deep water, however, does not preclude formation of fans in shallow water. A localized sediment source and sharp break in slope might result in the formation of a fan regardless of water depth.

The sedimentary facies in the study area corresponds to inner- and middle-fan deposits described by Walker and Mutti (1973). Specific sedimentary facies recognized in the study area that occur in these depositional environments are, in the terminology of Walker and Mutti (Figure 6.): $A_1$, disorganized conglomerates, $A_2$, graded conglomerates: $B_1$, massive sandstone with dish structures; $B_2$, massive sandstone without dish structures; C, classic turbidite, D, classic turbidite with base cut our; F, beds which have suffered downslope movement after deposition. The widespread occurrence of these facies and their complex interfingering throughout southwestern Puerto Rico (Curet, 1976; Krushensky, 1979, oral commun) suggest that they represent a number of coalescing submarine fans adjacent to a volcanic arc. Thinning towards the west of some of the volcaniclastic units and paleocurrent data strongly indicate a western direction of transport with a source to the east-northeast.

Massive breccias units which occur in many formations throughout southwestern Puerto Rico were chiefly derived from numerous sources. Each of these breccias units probably represents locally derived sediment from either one or several of separate volcanic centers. Explosive eruptions resulted in widespread pyroclastic fallout and intermixing or interbedding of the pyroclastic, volcaniclastic and epiclastic sediments. The variation in composition of the volcaniclastic

**Figure 6. Location of Cross Section and Wells in the Central Guanajibo Valley, Puerto Rico**

sediments suggests that various volcanic sources were providing material to the basin and that the material was being mixed before deposition. When volcanic activity ceased, sedimentation of planktonic foraminifers continued.

Coeval with the volcanic activity was the injection of hypabyssal bodies into the volcanic complex and into the volcanic-sedimentary sequence accumulating in adjacent sedimentary basins. The abundant primary pyroclastic material consists of euhedral crystals, pumice, and glass shards. The composition and texture of some of the volcaniclastic marine sedimentary rocks is identical with the igneous intrusive bodies which cut them.

The Yauco Formation (Maestrichtian and Campanian) – Is a dark-bluish-gray to dark-gray, to dark-greenish-gray, interbedded, calcareous, volcaniclastic sandstone, siltstone, mudstone, claystone, limestone, and subordinate breccias and conglomerate, characteristically thin- to medium-bedded and fine- to medium-grained. Typically, beds range from 5 to 10 cm thick; locally, breccias or conglomerate beds are massive. Stratification is expressed by color banding. Sandstone beds are normally graded. Load clasts and slump folds are common in less competent beds. Folded and otherwise deformed rafts of more competent facies commonly float in less competent calcareous sandstone and mudstone. Scour-and-fill structure and small-scale crossbedding range from rare to common. Flaser bedding is present in claystone and sandstone facies of the formation. Some beds show evidence of extreme bioturbation, and microfossils as well as clast of megafossils are common. The Yauco characteristically weathers to a light-orange-brown saprolite that preserves the texture and

structure of the original rock. Abundant claystone and some siltstone commonly weather into elongate “pencil-like” cylinders which show conchoidal fracture. Volcaniclastic sandstone, which makes up as much as 40 percent of the formation, is composed of angular to subrounded volcanic, lithic, and crystal clasts, glass shards, and pumice in a groundmass of dark-brown clay, chlorite (after glass?), and iron oxides, and locally a sparry cement. Clasts range from relatively fresh easily identified volcaniclastic rocks, to clasts composed of calcite, chlorite, epidote, and quartz. Mineral clasts are chiefly plagioclase, augite, minor hornblende, quartz, and magnetite-limonite. Plagioclase and augite range from fresh to completely altered. Finer grained beds contain greater quantities of microfossils, chiefly foraminifera, and crystal clasts are predominate over lithic clasts. Limestone in the Yauco is chiefly dark gray, thin to medium bedded, and consists of angular to subrounded, poorly sorted macrofossil clasts, come larger foraminifera, and carbonate intraclasts in a micritic matrix. Crystal clasts and fecal pellets locally compose as much as 25 percent of the rock. Very minor breccias and conglomerate consist chiefly of clasts of volcaniclastic rocks that range from 4 -15 cm across and some clasts of limestone, siltstone, mudstone, and chert. The matrix is composed of similar but smaller sand-sized lithic clasts like those noted above, and plagioclase, augite, and hornblende clasts and clay. A minimum thickness of 1,300 m is present in the mapped area.

<u>The Yauco and Lago Garzas formations, interbedded (Maestrichtian and Companian)</u> – Dark purple to grayish-red, massive, polymictic, volcaniclastic breccias, subordinate conglomerates, tuffs, and volcaniclastic sandstone of the

Lago Garzas formation irregularly interbedded with dark-bluish-gray to dark-gray and dark-greenish-gray, calcareous volcaniclastic sandstone, siltstone, mudstone, and claystone of the Yauco Formation.

## VI. METAMORPHISM

Volcaniclastic rocks in the Mayagüez and Rosario quadrangles are locally spotted by zeolites, and the rocks are commonly dull gray where zeolitization is complete. Higher grade prehnite- and epidote-bearing rocks are drab and are more uniformly grayish green in color, these rocks are commonly highly indurated. Typically, the rocks are foliated only near major faults; otherwise original textures of most rocks are well preserved.

Zeolite-facies metamorphism predominates, but higher grade prehnite-pumpellyite, metagraywackers, and greenschist-grade rocks also occur. The classification of low-grade mineral facies and zones used herein is that proposed by Coombs and other (1959) and Brown and Thayer (1963).

The low-grade zeolite facies (heulandites-analcime zone) occurs in rocks of the study area. In addition to the characteristic heulandites-quartz mineral assemblage, associated secondary minerals are montmorillonite, chlorite, calcite, and celadonite. Phenocrysts which occur with this assemblage are commonly unaltered. Most of the secondary minerals probably formed from the alteration of glass. Volcanic glass, probably of andesitic composition, is common to abundant in the volcanic-sedimentary sequence in the study area. It occurs both in the

groundmass of hypabyssal intrusive bodies and as glass shards, pumice, and glassy rock fragments in the volcaniclastic sandstone and breccias.

In the study area, high-grade zeolite facies rocks (laumonite zone) are characterized by the laumontite-quartz assemblage. Associated minerals are albite, clays, chlorite, and calcite. Plagioclase phenocrysts in this facies are commonly extensively altered to albite, minor calcite, and probably some laumontite.

The prehnite-pumpellyite metagraywacke facies is also present in the rocks studied. Pumpellyite is rare, but prehnite and epidote are fairly common. Characteristic mineral assemblages are quartz-prehnite and quartz-prehnite-epidote. Associated minerals are albite, chlorite, calcite, and rare pumpellyite.

The greenschist facies is locally attained near contacts with intrusive bodies. The characteristic mineral assemblage is quartz-albite-epidote-chlorite.

No systematic distribution of the various low- and medium-grade facies was observed in the field. However, Glover (1971) indicated that there is a systematic trend of increasing metamorhphic grade towards the major centers of batholithic intrusion in central Puerto Rico. He also suggested that the stratigraphic distribution of higher-grade facies indicated a major themal event that is possibly Maestrichtian and Paleocene in age. This age coincides with the peak period of batholiths-forming activity.

Jolly (1970) indicated that the rocks, as a result of conditions during burial, have been affected by low-grade metamorhphism to the zeolite prehnite-pumpellyite

facies. He attributed the metamorphism to a short-lived temperature increase resulting from a sudden surge of shallow plutonic activity.

Metamorphic effects observed in the volcanic-sedimentary sequence are probably related directly to the intrusive activity which affected the volcanic pile during Late Cretaceous and early Tertiary times. Contact metamorphic effects adjacent to dikes and stocks are minor. The only effect observed in the field and in thin section is the local silicification of some volcanic-sedimentary units. Serpentinite, near the contact with the two-pyroxene basalt, shows bastite pseudomorphs partially altered to cinopyroxene.

The abundance of hypabyssal igneous rocks in the area may have caused the low-grade metamorphism of the volcanic-sedimentary sequence.

## VII. STRUCTURAL GEOLOGY

The study area is located south of the southern Puerto Rico fault zone (Glover, 1971), which separates the southern and central structural blocks of the island. This fault zone consists mainly of northwest-trending, high-angle faults that are cut locally by north-northeast-trending, high-angle cross faults (Krushensky and Monroe, 1978). This zone has been projected offshore along prominent bathymetric lineaments and along discontinuities on the total magnetic intensity map (Glover, 1971). No major fold structures cross the fault zone, and minor fold axes are commonly subparallel to parallel to the strike of the fault zone (krushensky and Monroe, 1978).

Some of the high-angle faults in southwestern Puerto Rico have been defined as wrench faults with probable left-lateral displacements (Glover, 1871; Glover and Mattson, 1967, 1973; McIntyre, 1975; Krushensky and Monroe, 1978), whereas others are considered normal faults. Evidence of directions and extent of movement is generally lacking (Krushensky and Monroe, 1978). The extensive width of shear zones, overturned folds, and S-shaped, quartz-filled fractures suggest left-lateral wrenching according to Krushensky and Monroe (1975). Glover and Mattson (1967, 1973), and McIntyre (1975) have indicate the presence of left-lateral wrenching in widely separated areas on the southern Puerto Rico fault zone.

The age of wrench faulting is poorly understood. Although Glover (19710 suggested that it began in the Cretaceous, McIntyre (1971, 1975) suggested a post-middle Eocene inception since faulting affected units of that age in the Central la Plata quadrangle. Krushensky and Monroe (1978) indicate that some of the faults in the Peñuelas quadrangle affect the upper part of the Juana Díaz formation of early Oligocene to early Miocene age. Therefore, wrenching in that area is of early Miocene or younger age.

In the northeast part of the Rosario quadrangle, the Cerro Goden fault, a major strand of the southern Puerto Rico fault zone, separates formations of similar age but different character (Yauco and Lago Garzas Formations). No evidence for direction and extent of movement on the Cerro Goden fault was observed in the study area. McIntyre (1975) observed that both movement in subsidiary faults and regional relations indicates left-lateral motion with minor amounts of dip-slip

movement and suggests a post-middle Eocene age movement. Across this fault, a major topographic change is observed. (See Figure 7,8, & 9.)

**Figure 7. Generalized Geologic Map of the Hormigueros Municipal Sanitary**

**Figure 8. Generalized Geologic Sections Hormigueros Municipal Sanitary Landfill**

**Figure 9. Correlation of Map Units**

The southwest, the topography is highly irregular with considerable relief; to the northeast, the topography is subdued and gentle. This suggests that rocks north of the fault have been exposed to weathering in a more stable tectonic environment longer than the rocks south of the fault, and thus that the topography to the south is younger.

South of the Cerro Goden fault, the faults are mainly high angle. Although the actual fault planes are rarely observed, their presence is inferred by such evidence as shear and gouge zones, abrupt juxtaposition of lithologies, and aberrant attitudes. These faults apparently postdate folding and are Maestrichtian or younger in age because they affect Upper Cretaceous rocks. Minor faults and shears are invariably present in the rocks adjacent to intrusive igneous bodies.

The Cordillera fault, named by Slodowski (1956), is apparently one of the youngest faults in the area since it cuts the post-middle Eocene Cerro Goden fault in the adjacent Maricao quadrangle (McIntyre, 1975). McIntyre (1975) suggests 11 km of left-lateral displacement on the basis of displaced folds and plutonic bodies. No evidence for this displacement or magnitude of movement is observed in the study area. The Cordillera fault dies out to the west where it is cut by other cross faults in Barrio Limon.

Few folds occur in the map area. Most of them are present in the Yauco Formation, but they are related to soft-sediment deformation or proximity to an intrusive body. One minor fold is present in the southern part of the Mayagüez quadrangle in Barrio Guanajibo. There, the Yauco and Sabana Grande

Formations are folded into a southeast-plunging syncline. The folding in the study area affected Maestrichtian rocks and, therefore, is Maestrichtian or younger.

Although Mattson (1960) suggested that serpentinites in the mapped area occurred as cores of anticlines, no such anticlines are present. Most of the contacts between the serpentinites and the adjacent volcanic-sedimentary rocks are obscured by the intrusion of two-pyroxene basalt (Río Loco formation of Slodowski (1956) as redefined by Mattson in (1960). In the northern part of the area, attitudes in the volcaniclastic rocks were probably formed by forceful intrusion of these serpentinite bodies rather than by regional structural deformation. The sedimentary sequence does not appear to onlap the serpentinite directly anywhere.

The nature of the contacts of limestone bodies appears allochthonous and most contacts are clearly intrusive. Some limestone lenses mapped by Mattson (1960) as the San Germán formation grade into fine-grained sandstone of the Yauco without interruption. These are not gravity-glide plates; rather, they are simple sedimentary lenses deposited in continuity with surrounding sedimentary alluvial deposit. (See Figure 10)

A single minor shear zone occurs near the contact between igneous rock and the Peñones Limestone in a small roadcut 1 km south of Rosario. The subhorizontal shear zone is characterized by 2-m-thick, red, slickenside-riddled clayey fault gouge, at the base of the limestone. The shear zone occurs exclusively in the underlying porphyrtic pyroxence andesite. The limestone is brecciated near the

contact, and isolated blocks of limestone are present within the shear zone. The northward dip of the shear zone and the presence of contorted masses of pyroxene andesite suggest a recent movement of the limestone block down the present slope.

**Figura 10. Generalized geologic sections in the Central Guanajibo Valley.**

## VIII. UNCONSOLIDATED DEPOSIT

Sedimentary, alluvial & colluvial deposit

Sand and gravel - Deposits of sand and gravel underlie large parts of the Rosario river valley, from Rosario southward to Highway 2. The thickness of these deposits ranges from less than 1 ft along the valley sides to more than 40 ft. in some places nearer the center.

The greatest total thickness of sand and gravel known to have been penetrated is 32 ft in well 39. (Refer to ftg. 5 in pocket.) The sand and gravel occurs in 6 different beds ranging from 2 to 23 ft in thickness. This well in near the deepest part (thalweg) of the valley in that area, and wells drilled closer to the valley walls may be expected to penetrate less sand and gravel. Well 35, which is in the same general area but close to the west side of the valley, reportedly penetrated only about 15 ft of gravel. On other hand, thicker deposits have been encountered near the valley walls a short distance north. Well 28 reportedly penetrated 30 ft. of sand even though it is very close to the west side of the valley. This apparent anomaly illustrates the fact that Río Rosario over a long period has occupied all parts of the valley bottom. Available data are adequate to suggest the approximate location of the thalweg but not to delineate it precisely at all places.

A particle-size analysis of a sample of alluvium from Río Rosario in the middle reach of the valley is shown in figure 11. The graph shows that 32 percent of the sample consisted of gravel which was retained on a sieve having openings of

1.00 mm, and that most of the remaining 68 percent consisted of sand. The log of well 20, which is near the place where the sample was collected, shows 25 ft. of alluvium and gravel that probably is the same material as the river bed.

Sand and gravel is by far the most productive water-bearing material in the valley. The average yield of 49 wells tapping mixed sand and gravel is about 260 gpm (gallons per minute) and individual wells yield up to 1,650 gpm. The average specific capacity of these wells is about 26 gpm per ft. of drawdown, with a range from 4 to 179 gpm per ft.

Sand and gravel may be mixed in the same layer or may occur in separate layers. Where they occur separately, deposits of gravel, with pebbles ranging in particle size from 2 mm in diameter up to large cobbles, yield even larger quantities of water than combined sand and gravel. The average yield of 6 wells tapping gravel only is 330 gpm. Sand consisting of finer particles ranging in size from 0.062 to 2.00 mm, contains smaller pore spaces between its constituent grains and these are less permeable than those in pure gravel. The average yield of 7 wells tapping san only is about 75 gpm, with a range from 12 to 300gpm. The specific capacity of 4 wells tapping gravel averages about 38 gpm

**Figure 11. Cumulative Percent Passed**

per ft. of drawdown in 5 wells reportedly drawing water from sand. The apparent difference in yield and specific capacity between sand and gravel is somewhat uncertain because cuttings collected by drillers are rarely, if ever, measured carefully for particle size.

The yield of wells is related not only to the coarseness of the particles of the alluvium but also to the total thickness of the sand and gravel they penetrate. As shown in figure 6, 22 wells plot in a zone in which the yield increases with increasing thickness of sand and gravel. Wells that also tap the underlying bedrock have been omitted. The two lines on figure 20 have no significance except to call attention to the area in which the data lie. They cannot be used to derive linear relations because other factors, such as well efficiency, have not been taken into account.

Available evidence indicates that sand and gravel are thinner and less permeable toward the north end of the valley, above the narrow neck. The northernmost wells yielding large supplies here indicate that the alluvium, though well sorted, contains a greater percent of fine material than it does farther north. The area just south of the narrow neck of the valley, however, shows possibility of high-yield wells and should be explored further.

Clay and silt – The thickest and most extensive unconsolidated deposits in Tallaboa Valley consist of clay and silt. These fine-grained deposits occur along the entire length of the valley and extend farther north than the sand and gravel. Clay and silt also extend farther uphill on both sides of the valley, although, like sand and gravel, they may be thicker at the center. The average thickness of

clay in 43 wells is about 65 ft., with a range from 2 to about 180 ft. Two wells 50 and 53, penetrated more than 150 ft. of clay, and the greatest thickness reported was 183 ft. in well 33 (if all the "tosca", a driller's term, reported in the driller's log is clay). Only two wells, 34 and 44, were reported to penetrate any silt. The apparent rarity of silt is undoubtedly due to local lack of familiarity with the term.

Clay and silt, consisting predominantly of small particles ranging in size up to 0.005 mm and 0.005 to 0.005 mm, respectively, are very porous but the intergranular openings are extremely small. As a result, the movement of water is slow, and the lowest yield in the valley is obtained from clay. Of two wells reported tapping clay, the yield of well 3 was less than 15 gpm and that of well 33 was less than 5 gpm. Since true clay yields virtually no water, to wells, these figures are high, indicating that silt and sandy clay may have been reported simply as clay, or that the wells may have penetrated more productive units also. The log for well 8, for example, shows that the well obtained all of its water, amounting to only 12 gpm, from 3 ft. of sand overlying 32 ft. of impermeable clay.

As mentioned in the preceding section, clay and silt generally are interbedded with sand and gravel. Where the relatively impermeable clay overlies the more permeable sand and gravel, it serves as a confining layer that retards the movement of water downward into, or upward from, the sand and gravel.

Colluvium – A mixed group of largely calcareous materials mapped in this report as colluviums (see fig. 6), shows all gradations in degree of coherence from loose fragments to recemented material that is dense and compact. Colluvium has been defined (American Geologica Institute, 1957, p. 57) as "…loose and

incoherent deposits, usually at the foot of a slope or cliff and brought their chiefly by gravity Talus and cliff debris are included in such deposits."

Colluvium as used here includes avalanche material, recemented material, and also alluvium in part. Colluvium varies in particle size from extremely fine clay to boulders more than 10 ft. in diameter. The degree of compaction varies from loose powder to completely recemented material known as caliche that is so solid it looks like bedrock.

The alluvial part is thicker at the mouths of small ravines where they join the main valley. The steep slopes on both sides of the main valley facilitate landslides and other gravity movements. In the Río Rosario, colluvium forms a narrow, discontinuous fringe extending along both sides of the valley.

Colluvium is not a source of large amounts of water in Rosario Valley because it is thin (generally less than 40 ft. thick) and is of restricted areal extent. Moreover, it is not very permeable and much of it lies above the water table. The colluviums in figure 6 is show for areas where it is believed to be at least 10 ft. thick and where bedrock outcrops are rare. Evenly where the colluviums is comparatively thick and extends and appreciable distance below the water table, its tightness results in low yield. One well, for example, penetrated 30 ft. of unconsolited material, apparently colluviums. All but the upper 23 ft. was below the water table but the yield before entering bedrock was less than 5 gpm. In general, wells tapping colluviums may be expected to yield only a few hundred to a few thousand gallons per day. Nevertheless, a few shallow dug wells tap it to supply domestic needs.

Comparable yield may be expected wherever the limestone in the valley contains interconnected solution cavities and fractures. Fractures, consisting principally of joints and faults, can transmit moderately large quantities of water if they are open and are extensively developed. I subsequent solution has enlarged and interconnected them, they are even more permeable, and may yield large quantities of water, particularly if the openings are favorably situated with respect to recharge. Openings in the limestone that are in contact with permeable sand and gravel, for example, will yield a much larger quantity of water, other things being equal, than the same openings in the same bedrock overlain by tight clay or other impermeable material. It is obvious; therefore, that the comparatively high yield from the limestone in the valley itself probably was determined in part by the abundance of joints and other fractures here, so that the river eroded the limestone underlying the valley. Stronger rock having fewer joints, faults, and other permeable openings forms the surrounding hills. Yield from bedrock in the valley is not uniformly high. It may be low where openings are poorly developed, are filled with clay, or are unfavorable situated with respect to recharge. The effect of clay layers may be reduced, however, by suitable development of a well.

## A. Streamflow at Río Rosario near Hormigueros exceeds 6 cubic feet per second 90 percent of the time

The streamflow at a given point in a basin is an integration of the effects of climate, topography, and geology. Streamflow provides a distribution of runoff in time and magnitude. This distribution can be expressed by means of a flow duration curve. The duration curve is a cumulative

frequency curve that indicates the percentage of the time that a particular parameter (in this case, streamflow) has been equaled of exceed. The curve shows no chronological order and applies only to the period of record for which the data was collected. Flow duration data can be used for comparing flow characteristics of streams. The slope of the curve is a measure of the variability of flow. A steep slope indicates highly variable flow, where as a flat slope indicates more sustained flow possibly from ground and surface-water storage.

A flow duration curve for a particular station is normally based on mean daily discharges for period of record. This curve, referred to as the "period of record curve", provides no insight into seasonal effects on streamflow nor basin changes such as flow regulation. Partial-record curves can be derived to study regulation effects. In this type of analysis, the periods before and after regulation are studied independently. The seasonal variation of streamflow can be studied from partial monthly curves, in which the data for individual months for all the years of record are analyzed.

***B.*** **Minimum Flows At Río Rosario At Highway 2 were estimated from downstream records and drainage area adjustments. the–day, 10-year montly minimums range from 1.7 to 3 cubic feet per second**

Most of the agricultural land in the Río Rosario is upstream from the Hormigueros gagging station. As streamflow records at the Hormigueros site are representative of the flow leaving the river, estimates of the

amount of water available for irrigation must be adjusted to reflect flows in the central part of the Río Rosario.

Monthly minimum flows at Río Rosario at Highway 2 upstream from Río Rasario (station 1351) were estimated from downstream records and drainage area adjustments as follows:

1. Río Rosario mean-daily flows were estimated at the junction with Río Guanajibo. A drainage area ratio was used.
2. Percentage flow contribution of Río Rosario to Río Guanajibo was determined. A comparison of mean-daily flows at both sites was made during the period of occurrence of the 7-days minimum flow at Río Rosario near Hormigueros station (50138000).
3. Percentage mean-daily flow contribution was determined for Río Rosario upstream from junction. The percentage mean-daily flow contribution of Río Rosario was subtracted from 100.
4. The frequency distribution of the 7-day minimum daily-mean flows for each month at Río Rosario at Highway 2 were determined (fig. 13.). The upper and lower values of each monthly frequency distribution at the gagging station (fig. 12) were adjusted. Reductions for the ratio of flow contribution and drainage area were applied.

The 7-day monthly minimum flows at a 10 percent probability of being less than at Highway 2 range from 1.7 ft. /s in March to 33 ft. /s during October.

During the dry season, surface water supplies are very limited in the Río Rosario.

## C. Sanitary Quality of Surface Water during base-flow conditions in the Municipal of Hormigueros, Puerto Rico, 1998-99

Background

Water-quality standards for surface waters I Puerto Rico have been established by the Puerto Rico Environmental Quality Board (Junta de Calidad Ambiental de Puerto Rico, 1990) on the basis of the designated use (for example, fishing, source of raw water for public supply, and secondary contact recreation, among others). All perennial fresh surface waters in Puerto Rico inland of their estuary segments have been classified as Class SD waters. This classification includes surface water intended for use (or with the potential for use) as a raw source of public water supply, for propagation and preservation of desirable aquatic species, and for primary and secondary contact recreation. The sanitary quality standard for Class SD surface water is based on the fecal coliform or total coliform indicator bacteria (Junta de Calidad Ambiental de Puerto Rico, 1990).

With the exception of surface waters to be used for primary contact recreation, the sanitary quality standard of Class SD-designated use surface waters is based on total coliform and fecal coliform bacteria concentrations as follows: the geometric mean concentration of at least

five samples obtained in sequential order should not exceed 10,000 colonies per 100 milliliters (mL) for total coliform bacteria, or 2,000 colonies per 100 mL for fecal coliform bacteria, and not more than 20 percent of the samples (one in a set of five) can exceed 4,000 colonies per 100 mL of fecal coliform bacteria (Junta de Calidad Ambiental de Puerto Rico, 1990, Article 3, Section 2.4, as amended July 20, 1990). Unlike other regions in the United States, Puerto Rico regulations do not constrain the time period during which the sequential samples must be obtained. In Puerto Rico, however, these standards are applicable only to samples taken when streamflows are greater than the 7-day, 2-year ($7Q_2$) discharge (Junta de Calidad Ambiental de Puerto Rico, 1990). The $7Q_2$ discharge corresponds to the discharge at the 2-year recurrence interval taken from a frequency curve of annual values of the lowest mean discharge for seven consecutive days (the 7-day low flow).

Typical concentrations of the two most common indicator bacteria in contaminated water are given in table 4. Fecal coliform and fecal streptococcus bacteria are not pathogenic, but have been correlated to the presence of several waterborne, infectious disease-causing organisms present in waster from warm-blooded animals, including humans (Myers and Sylvester, 1997). Thus, the concentration of these indicator bacteria is a measure of water safety for consumption or for body contact.

Contamination sources that affect stream sanitary quality during base-flow conditions are distinct for urbanized and rural areas of Hormigueros. In

**Figure 12. Water Flow Frequency Distribution**

urbanized areas, probable major sources of fecal contamination are illegal discharge of sewage to storm-water drains, especially within the older sectors of the town of Hormigueros, overflows from sewer mains into the storm-water drains as a result of malfunctioning of sanitary sewer ejectors or clogged mains, rupture and seepage from sewer mains into the local aquifer. In rural areas , major sources of fecal contamination include gray-water discharges (gray water includes all waste water from household uses except sanitary wastes) from residential and commercial establishments along steam channels, septic tank seepage or overflows, direct contamination by unfenced livestock, runoff from restrained livestock pens near stream courses, and see page from pits containing animal wastes.

## IX. SURFACE WATERS ARE SUITABLE FOR MOST USES

The chemical quality of the surface waters in the Río Rosario makes them suitable for most industrial, domestic, and agricultural uses. Data from streamflow stations and Water well at Río Rosario near Hormigueros, (Figure 13), show that the waters are of the calcium-magnesium bicarbonate types and moderately soft. Dissolved solids are relatively low. Analyses of trace elements previously published (U.S. Geological Survey, 1981) do not indicate any significant concentrations of iron, manganese, or any toxic trace metals.

**Figure 13. Water Quality Sample Río Rosario near Hormigueros**

The sanitary quality of the waters in Río Rosario indicates that sewage is normally discharged into the stream. Concentration of fecal coliform bacteria increases markedly between the San Germán and Hormigueros sites (Figure 14). The presence of feces in the stream should be studied further in conjunction with studies of the bilharzias parasite. In agricultural areas, where workers may be in contact with irrigation waters contaminated with the parasite, special precautions are needed to limit exposure.

**Figure 14. Long- Term Geometric Mean Concentration of Fecal Coliform Bacteria Río Rosario near Highway**

## X. LIMITED SEDIMENT DATA AVAILABLE

The mean annual suspended-sediment discharge at Río Rosario near Hormigueros is about 134, tons per year.

The concentration of suspended sediment affects the suitability of water for domestic, industrial, and agricultural uses. For irrigation, a high suspended-sediment concentration is undesirable, particularly, if the sediment is in the silt-clay particle size-range (less than 0.62 mm).

Sediment data from streams in the Río Rosario are very scarce. Miscellaneous suspended-sediment samples have been collected since 1959 at Río Rosario near Rosario Ward and Río Rosario near Hormigueros. There are no data on the bedload component of sediment or on the size of the suspended particles. The data collected at Río Rosario are sporadic and inadequate for any significant correlations or estimates.

Data from the samples collected at Río Rosario near Hormigueros can be correlated with the instantaneous water discharge. A graphical correlation was developed and used to estimate the mean annual suspended-sediment loads and yields at the site. Techniques described by Miller (1951) were used for the computations. The mean annual suspended-sediment load at the Hormigueros gagging station is about 134,000 tons/year. The suspended-sediment yield at the site is about 1,120 (tons/mi$^2$)/yr.

It is difficult to compare the sediment yield of the Río Rosario basin to other sites in Puerto Rico. The only other site on the Island at which long-term suspended-

sediment records are available is Río Tanamá near Utuado (50028000). Daily samples are collected at the site and an 11-year average of about 48,000 tons/year has been computed. This is equivalent to a yield of about 2,600 (tons.mi$^2$/yr, or nearly three-times higher than Río Rosario. The Río Tanamá basin has steeper slopes, greater and more intense precipitation, and more agricultural development. Increasing agricultural development in the upper Río Rosario basin should result in higher suspended-sediment yields. Additional data, including particle-size information is needed in the future to determine the possible impact of sediment in irrigation water.

As in 1990, however, 1998 use accounted for approximately 62 percent of the public water-supply withdrawals (Wanda Molina, USGS, written commun, 1999). Since the populations of Hormigueros has remained relatively unchanged between 1990 and 1998, the total available public water supply for all uses (domestic, commercial, industrial, and government institutions) may have decreased on a per capita basis from about 90 to 60 gal/d-p. Similarly, the per capita potable water available for household use within the Municipality may have decreased from about 45 gal/d-p in 1990 to 30 gal/d-p in 1998 (60 X 0.62 X 0.80). This reduction in potable water supply would not be equally distributed within the Municipal, but would affect primarily those users farthest from the filtration plants.

As a result of the unreliability of the public water-supply distribution system and the apparent decline in potable water availability, several communities have developed their own water-supply source. In 1998, there were six self-supplied

community water-supply systems in Hormigueros serving approximately 1,000 people (Wanda Molina, USGS, written commun, 1999); the source for five of these system was ground water (well or spring) and one system was supplied by a stream. Moreover, many residents in rural areas have installed rudimentary taps at nearby streams and springs to augment their household supply. These solutions, however, may constitute a health risk, because the possibility of gastrointestinal illness from fecal contamination of local raw water-supply sources could be substantial, given he high population density. In addition, ground-water and spring flow in Hormigueros occurs primarily in bedrock aquifers, which are highly vulnerable to contamination, In these aquifers, the water flows too rapidly and is not in contact with the surrounding material long enough for purification to occur (Tarbuck and Lutgens, 1990). In Hormigueros areas of most vulnerability are the unsewered rural communities, because water moves within fractures or the regolith and along bedding planes; and where intensive animal husbandry and poultry breeding enterprises are located. Outside of the rural areas, the greatest susceptibility of sanitary wastes contamination is at surface-water supply intakes located along stream courses that do not meet the standards for public water-supply sources, and at wells sited near streams with degraded water quality. In the bedrock and shallow alluvial aquifers is the source of water at wells near streams is or in part from streams. This became evident when the reported occur cases of fever with acute gastroenteritis 1977 were related to improper chlorine general bacteriological contamination on water (Hunter and Arbona, 1995).

To ensure an adequate supply of water, the Municipality of Hormigueros request Geological Survey (USGS) to conduct comprehensive surface- and ground-water assessment and water-quality analyses. This information will be an integral part of the territorial development plan being prepared by Hormigueros Municipality, which will take sustainable use of water resources.

To facilitate this effort, thematic developed to delineate the hydrologic a bacteriological (sanitary) conditions, are water-bearing properties of major rock description of the methods and technique conduct the analyses and interpretation given in separate of this report documents the results of the surface-water stream bacteriological conditions, and ground-water chemical conditions.

## XI. GROUND WATER AT THE LANDFILL STUDY AREA

Occurrence and Movement

Ground water occurs below the small River Valley floor of the study area and in some fractured and faulted mudstone and in sand and gravel deposits (fig. 6). Clay also contains water, but because of its fine-grained nature, it is nearly impermeable and does not readily transmit water. Volcanic and other igneous rocks generally are impermeable, but where these rocks are highly faulted or fractured, they may serve as locally important aquifers. Recharge to the aquifer occurs primarily in the upland areas adjacent to the valley where water as overland flow and stream flow comes in contact with permeable material and infiltrates downward into the aquifer. Rainfall may directly recharge the aquifer in areas where permeable materials extend from the water table to the land

surface, but because clay underlie; most of the River Valley floor, most recharge is believed to occur in areas adjacent to the River Valleys . Water in the aquifer move as down gradient from the higher areas into the valley and then approximately follows the land surface gradient to the coast, where the surface and the ground water, discharges to the Guanajibo river and then to the sea.

The predominant rock formation that underlying the entire area of the Hormigueros landfill is the Yauco Mudstone Formation and same layer of fine sandstone. This rock Formation is unimportant as a source of water because of its relatively low permeability. Of three wells drilled in the Landfill at the Yauco Formation, well- was dry; and wells and was reported to yield 5 and 7 gpm, respectively.

Higher yields probably can be obtained in and along valleys cut into this formation and partly filled with permeable and saturated san-and-gravel. Ground water moving through sand-and-gravel recharges the low land aquifer. Wells 74 and 75, draw water from both and overlying sand-and-gravel, and their yield is about 100 and 300 gpm, respectively. Most of the yield in well – 74, and at least part o0f the yield in well-75, comes from sand-and-gravel and fractured rock.

Although extensively weathered this rocks are not an important source of water. They commonly form mountainous terrain where recharge conditions generally are unfavorable because of rapid runoff, even though the rainfall may be greater than in the lowlands. However, small supplies can be obtained locally. Wells 67 and 68, tapping rocks, yielded 5 and about 8 gpm, respectively. The specific capacity of well-65 was 1.1 gpm per ft of drawdown. The rocks are capable of

yielding large amounts near faults, where fracturing has increased their permeability.

## XII. DATA-COLLECTION METHODS

A drilling method was used that allowed the continuous retrieval of lithologic core, as well as the collection of core samples, head measurements, and water-flow estimates, with minimum interruption of the drilling operation.

The exploratory survey and the laboratory tests on samples were made in accordance to standards of the American Society for Testing and Materials (ASTM).

This report is based on test borings drilled and samples tested, and assuming that they represent the strata and some area between boring locations; therefore, the data obtained from the investigation represents subsoil conditions at the precise boring location only.

## XIII. SOIL INVESTIGATION PROCEDURES

Drilling

Test holes HLF-01, HLF-02 & HLF-03 were drilled to depths of 160- 130- 40 ft. respectively. The holes were drilled using a hydraulically driven, reverse-air system. This system uses threaded, seamless, double-walled drill stem and pressurized air to remove cuttings and cores. As drilling progresses, pressurized air is pumped through the annulus of the two walls of the drill stem, forcing

formation water and cores up the center of the drill stem Cores and water are ejected from the discharge pipe into a cyclone container, which dissipates their energy and also serves as a collector. Both test holes were plugged and abandoned after core collection and down-hole data acquisition were completed.

## XIV BORINGS AND SAMPLING METHODS

Split-barrel samples are used to obtain representative soil samples for identification purposes; laboratory testing, and to obtain a measure of the resistance of the soil to penetration of the samples, all in accordance with ASTM Designation D-1586 “Satandard Method for Penetration Test and Split-Barrel Sampling of Soils”.

Water Table – “WT”

The elevation of the water table, measured not less than 24 hours after each boring was drilled, may vary considerably from what was originally encountered. The symbols at the elevation of the water table whenever shown in the boring logs mean:

- Encountered during drilling operations
- Encountered after 24 hours

The elevation of the water table is affected by rainfall; type of soil; location of project; proximity to bodies of water; and season, among other factors. However, the borings do show an approximate location of the water table at the time of the drilling operation.

## XV. STANDARD LABORATORY TESTS

Representative samples obtained from the borings are subjected to routine standard laboratory tests, consisting of visual examination, description and identification.

### A. Visual examination and description

The identification and description of soils for engineering purposes, based on visual examination and simple manual tests, were conducted following the procedures ASTM-D-2488 – "Standard Recommended Practice for Description of Soils".

### B. Standard penetration test (SPT) – "N"

The standard penetration test is the number of blows required to drive a split spoon sampler a distance of twelve (12) inches after an initial penetration of six (6) inches. It is referred as the "n" penetration value pr SPT "n" value. The test is covered under ASTM Standard Method D-1586, to obtain a measure of the resistance of a soil layer to penetration of the sampler. For cohesive soils the consistency is determined and for granular soils, the relative density.

## XVI. DYNAMIC SOUNDINGS

This method consists of driving into the soil layers a 2" O.D. penetration point attached to a standard rod by repeated blows of a 140 pounds hammer falling 30 in. It measures the point and the frictional resistance of the sides of the driving

point. The number of blows required per foot of penetration is the numerical index of penetration resistance. It provides a quick and economical means of roughly determining the in-place condition of subsurface shallow soil layers. Dynamic sounding tests indicate critical zones, which require detailed borings and laboratory testing. This test is used as a partial replacement for conventional borings. To correlate the dynamic sounding results with the subsoil characteristics, a sounding testing shall be conducted near a boring. Unconfined compressive strength of 0.19 tsf. And the more granular was found in a loose state of relative density.

The fourth and last drilled layer consists of a yellowish-brown fine-medium sand with traces of fines. The natural moisture content was of 20.9%. This layer was found in a medium state of relative density.

For additional laboratory tests and detailed descriptions of the soil profile, refer to the boring log included in this soil report.

## XVII. WATER TABLE

During drilling operations, the ground water table was detected at a different depth. In order to measure the variation of the water table, a PVC screen pipe was installed. The ground water level as measured after 24 hours of the drilling operations was detected at fallow.

| Well Number | Topographic Elevation | Depth | Screen Length | Groundwater Level | Potencialmetric Surface |
|---|---|---|---|---|---|
| **HLF-1** | 100 m | 160 | 40 | 140 | NO |
| **HLF-2** | 50m | 130 | 20 | 80 | NO |
| **HLF-3** | 45m | 40 | 10 | 25 | NO |

It should be mentioned that the elevation of the ground water is at a fixed datum line. Its position can vary as a result of amount of precipitation, permeability of the subsoil, topography of the area and the distance from water sources.

Therefore, for more precise ground water levels and monitoring, long term observation wells shall be installed. (See Figure 15.)

**Figure 15. Ground Water Flow Direction at the Hormigueros Landfill Area**

## XVIII. CONCLUSION AND RECOMMENDATION

The predominant rock formation that underlying the entire area of the Hormigueros landfill is the Yauco Mudstone Formation and same layer of fine sandstone. This rock formation is unimportant as a source of water because of its relatively low permeability. Of three wells drilled in the Landfill at the Yauco Formation, well-was dry; and wells and was reported to yield 5 and 7 gpm, respectively.

Higher yields probably can be obtained in and along valleys cut into this formation and partly filled with permeable and saturated sand-and-gravel and fractured rock. Ground water moving through sand-and-gravel recharges the low land aquifer.

Although extensively weathered rocks are not an important source of water. They commonly form mountainous terrain where recharge conditions generally are unfavorable because of rapid runoff, even though the rainfall may be greater than in the lowlands. However, small supplies can be obtained locally. Wells 65 and 66, tapping rocks, yielded 5 and about 8 gpm, respectively. The specific of well-65 was 1.1 gpm per ft of drawdown. The rocks are capable of yielding large amounts near faults, where fracturing has increased their permeability.

The suite of volcanic, volcaniclastic, and sedimentary rocks of Late Cretaceous age predominate in the mountains surrounding the subsequent to their formation these rocks were folded and faulted (Colon-Dieppa and Quinones-Marquez, 1985), and then subjected to extreme weathering and erosion. Valley largely lies

within an anticline that has been breached by erosion and is bounded in part by faults (Mattson, 1960, p. 321; Colon-Dieppa and Quinones-Marquez, 1985, p. 10). The flow pattern indicates that groundwater flows in a general south-southeast direction in general agreement with the gradient and location of the creek to the south of the landfill. The map also indicates that the hydraulic gradient is generally uniform in the area. (See Figure 15)

The estimated groundwater flow velocity estimated for fracture sandstone of the Yauco Formation ranges from 0.02-0.42 ft/day. The data also indicates that the detected groundwater levels are generally consistent with the expected gradient and the elevations at the site.

Well location, design, and construction:

a) Down gradient well locations which result in placement in potential pathways of contaminant migration are acceptable for routine detection sampling programs. The density will vary based on the size of the pathways. When site characterization confirms simple homogenous hydrogeology, without discontinuities or faults in the vicinity of the wells, and when folds and fractures are not expected to channel flows past well designed by qualified geologists, are acceptable for site characterization. Such characterizations are for general delineation of stratigraphy and flow paths and for establishing initial design of well placement, screen length, depth, etc. When unexpected discontinuities of major strata or pathways do not occur.

b) Monitoring well screen lengths should generally not cut across several flow zones but rather furnish depth-discrete measurements. These conditions are acceptable for the purpose of obtaining samples which represent ground water quality at the point of compliance. Conditions: When the strata of concern is □ 10' thick. (See Figure 16)

c) Use of air rotary drilling methods is acceptable for installing monitoring wells. Conditions: Except when drilling through contaminated upper horizons, unless precautions are taken. (See Figure 17)

d) Fluorocarbon resins (PTFE, PFA, FEP, etc.) and stainless steel (304 or 316) are acceptable materials for simple-contact surfaces in new or replacement monitoring Wells where potential sorbing organics are of concern. Conditions: Stainless steel may only be used in non-corrosive conditions. All new or replacement wells to be installed at a given time should be of the same material.

e) Existing wells which do not meet the recommendations in guidance for materials or installation may be proposed for inclusion in the permit. When documented to be free of bias by pairing new PTFE or stainless wells with, for instance, at least ten percent of the old, existing wells.

**Figure 16. Typical Installation of Groundwater Monitoring Wells**

**Figure 17. Monitoring Well Air Rotary Drilling**

## XIX. List of References:


Anders, R.B., 1968, Reconnaissance of the water resources of the Central Guanajibo Valley: U.S. Geological Survey Open-File Report, 15 p.

Bogart, D.B., Arnow, Ted, and Crooks, 1964, Water Resources of Puerto Rico—A progress report: Commonwealth of Puerto Rico Water Resources Bulletin No. 4, 101 p.

Cobb, E.D., 1978, Estimates of 7-day, 10-year minimum flows at Selected streamsites in Puerto Rico: U>S. Geological Survey Open-File Report 78-583, 47 p.

Gelabert, P.A., Alonso, R.M., and Perry, A.O., 1964, Geology of the tunnel and reservoir sites for the Guanajibo River development project: Puerto Rico Department of Public Works Geologic Investigations Bulletin No. 4, 18 p.

Gierbolini, Roberto, 1975, Soil survey of Mayagüez area of western Puerto Rico: Washington, U.S. Department of Agriculture, Soil Conservation Service, 296 p.

Haire, W.J., 1972, Floods in the Río Guanajibo Valley, southwestern Puerto Rico: U.S. Geological Survey Hydrologic Atlas.

Health, R.C., 1980, Basic elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey, Water Resources Investigations Open-File Report 80-44, 86 p.

Johnson, K.G., 1981, Flood of September 16, 1975, in the Guanajibo Valley, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-805.

Mattson, P.H., 1960, Geology of the Mayagüez area, Puerto Rico: Geological Society of America Bulletin, v. 71, p. 319-362.

McGuinness, C.L., 1948, Ground-water resources of Puerto Rico: San Juan, Puerto Rico Aqueduct and Sewer Service, 613 p.

Miller, C.R., 1951, Analysis of flow-duration, sediment rating curve method of computing sediment yield: Denver, U.S. Bureau of Reclamation, 15 p.

National Oceanic and Atmospheric Administration, 1960-1980, Climatological data annual summary, Puerto Rico and Virgin Islands, 1959-1979; National Oceanic and Atmospheric Administration Publication, v. 5 through 25, no. 13.

U.S. Department of Commerce, Bureau of the Census, U.S. Census of Population, Puerto Rico, 1980.

U.S. Geological Survey, 1981, Water resources data for Puerto Rico, Water Year 1978: U.S. Geological Survey Water Data Report PR-78-1, 255 p.

Ward, P.E., and Truxes, L.S., 1964, Water wells in Puerto Rico: Commonwealth of Puerto Rico Water Resources Bulletin no 3, 248 p.

Soiltest, Inc., 1968, Earth resistivity manual: Soiltest Inc., 2205 Lee Street, Evanston, Illinois, 53 p.