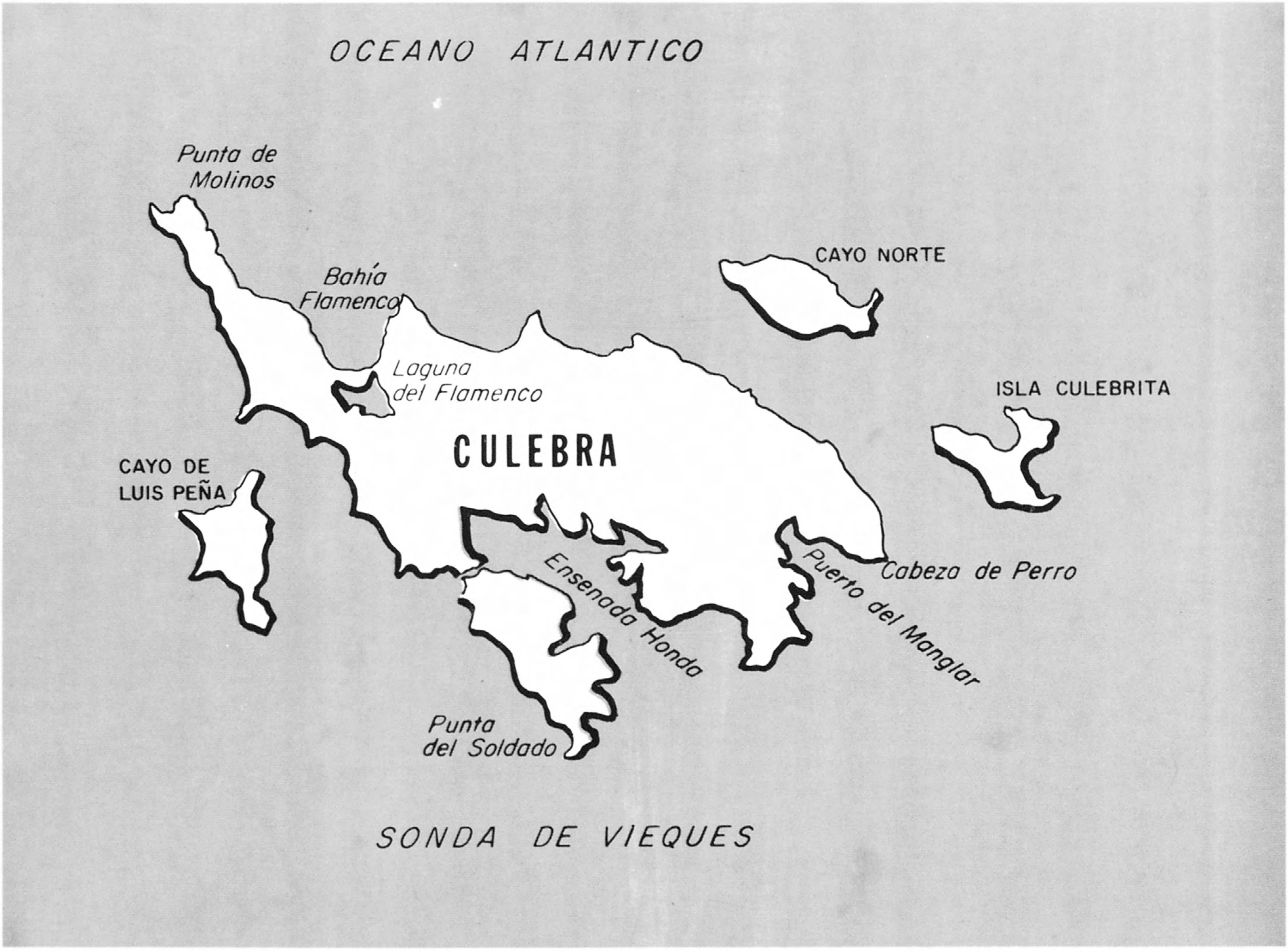
WATER SUPPLY AND WASTE DISPOSAL, CULEBRA, PUERTO RICO

U.S. GEOLOGICAL SURVEY
Water Resources Investigation 3-76



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UNITED STATES DEPARTMENT OF THE INTERIOR

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A dual system of metric (The International System of Units--SI) and English units are used in this report. A table of factors for converting English units to International System (SI) units is given below:

Multiply English units	By	To obtain SI units
	Temperature	
fahrenheit (°F-32)	0.556	centigrade (°C)
	Length	
inches (in)	2.540×10^{-1}	millimetres (mm)
feet (ft)	3.048×10^{-1}	metres (m)
miles (mi)	1.609	kilometres (km)
	Area	
acres	0.4047	hectares (ha)
	4.047×10^{-3}	square kilometres (km^2)
	Volume	
gallons (gal)	3.785	litres
	3.785×10^{-3}	cubic metres (m^3)
million gallons (Mgal)	3.785×10^{3}	cubic metres (m^3)
acre-feet per square mile (acre-ft/mi^2)	4.761×10^{-3}	cubic metres per square kilometre (m^3/km^2)
	Flow	
gallons per minute (gal/min)	6.309×10^{-2}	litres per second (l/s)
gallons per day (gal/d)	3.785	litres per day (l/d)
	3.785×10^{-3}	cubic metres per day (m^3/d)
	Mass	
pounds (lb)	0.4586×10^{-1}	kilograms (kg)
tons (short)	9.072×10^{-1}	tonnes (t)

WATER SUPPLY AND WASTE DISPOSAL, CULEBRA, PUERTO RICO

By D.G. Jordan and B.K. Gilbert

ABSTRACT

Surface- and ground-water resources of Culebra are small because of periodically meager rainfall and a high rate of evapotranspiration (about 95 percent of rainfall). The annual average surface-water and ground-water yields are about 6 and 20 million gallons per square mile (8,800 and 29,200 cubic metres per square kilometre), respectively.

The principal aquifers are fractured volcanic rocks with a probable storage capacity of less than 1 percent by volume. Thus ground-water yield is closely related to the availability of recharge from rainfall. Ground-water quality, however, is poor, generally exceeding 1,000 milligrams per litre dissolved solids. This is caused by the relatively high concentration of dissolved solids in rainfall, and their further concentration in ground water by evapotranspiration.

Owing to the thin soil cover over much of the island, prospective areas for solid-waste disposal are limited to a few areas of relatively thick alluvium. With proper treatment, liquid effluent from sewage treatment plants probably could be used for irrigation of pastureland or, with more extensive treatment, for recharge to the aquifer supplying the municipal well field.

INTRODUCTION

The island of Culebra lies approximately 17 mi (27 km) east of Puerto Rico, 12 mi (19 km) west of St. Thomas, Virgin Islands, and 9 mi (14 km) north of the island of Vieques. The total area of the island is slightly more than 7,000 acres (28 km^2).

The island may be on the verge of an important social and economic transition. Until recently, activities on the island were limited due to use of part of the island by the United States Navy. Navy installations have been deactivated but the cultural impact on the island has been considerable.

The purpose of this report is to evaluate the potential of the island's water resources so that adequate plans can be made to ensure its future water supply. The subject of solid waste and sewage disposal is also discussed, not in terms of an ultimate solution to the problem, but in terms of possible alternatives for disposal of liquid effluents and solid wastes. The water resources of Culebra have not been investigated in detail as long-term data are not available. It has been necessary, therefore, to extrapolate information obtained from water-resources investigations of similar hydrogeologic areas in the Virgin Islands and Puerto Rico, and transfer this knowledge to Culebra.

CLIMATE

Rainfall data have been collected on Culebra since 1938. Annual rainfall has decreased rather consistently in the past 30 years. From 1941-50 the average annual rainfall was 42.88 in (1,089 mm); from 1951-60, 35.40 in (899 mm); and from 1961-70, 31.82 in (808 mm). During 1938-71 the maximum annual rainfall was 59 in (1,500 mm) in 1942 and the minimum was 16 in (410 mm) in the drought of 1967.

Rainfall is seasonal--nearly half falls from August through November. Figure 1 shows the average monthly rainfall for 1961-70. The average monthly rainfall shown is less than the long-term average but more closely represents recent conditions.

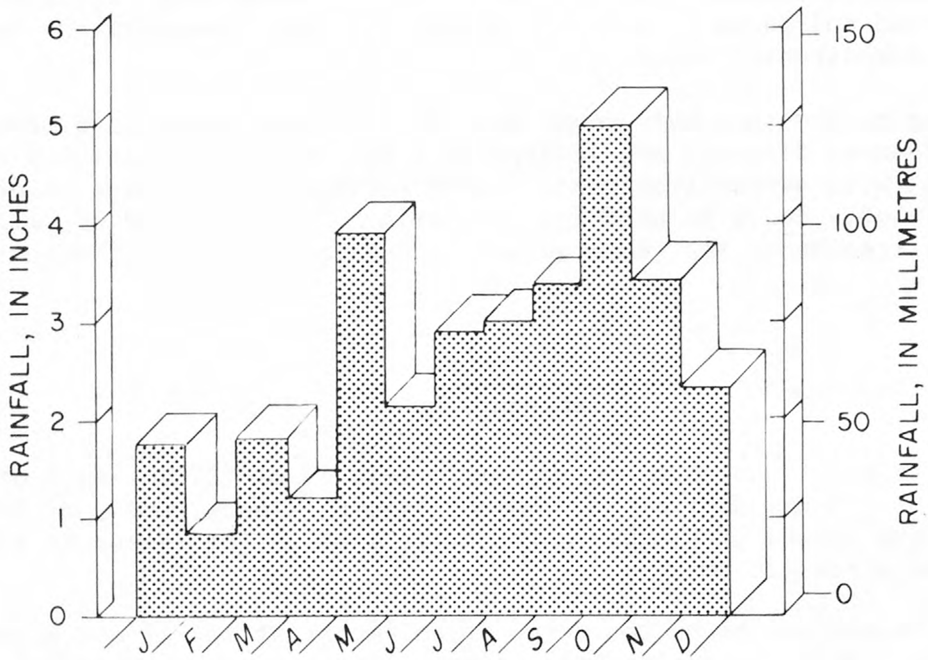

Figure 1.--Average monthly rainfall, 1961-70 (based on records of the National Oceanic and Atmospheric Administration).

During 1957-71 the mean number of days per year when 0.1 in (3 mm) or more of rain fell is 57. Only 18 days per year had half an in (13 mm) or more. Larger storms (fig. 2) are even more rare; rains that exceed 2 in (50 mm) in 24 hours occur about twice a year, and rains that exceed 2 in (50 mm) in 48 hours occur about three times a year. The importance of the major rains to the water resources of the area is discussed later in this report.

Data on air temperature are not available for the island, but temperatures probably are similar to those on the east coast of Puerto Rico. There, air temperatures range from a mean annual minimum of 74.4°F (23.6°C) to a mean annual maximum of 85.7°F (29.8°C).

Prevailing winds generally blow from the north-northeast in winter and from the east in summer. Wind speeds are probably greatest in mid-summer, similar to those of eastern Puerto Rico. Average wind speed is estimated to be about 10 mi (16 km) per hour.

Most of the water in the soil zone returns to the atmosphere by evaporation or transpiration by plants (evapotranspiration). In the Virgin Islands evapotranspiration continues throughout the year, and 90 to 95 percent of the rainfall is returned to the atmosphere (Jordan and Cosner, 1973, p. 8). Similar evapotranspiration rates are believed to occur in Culebra.

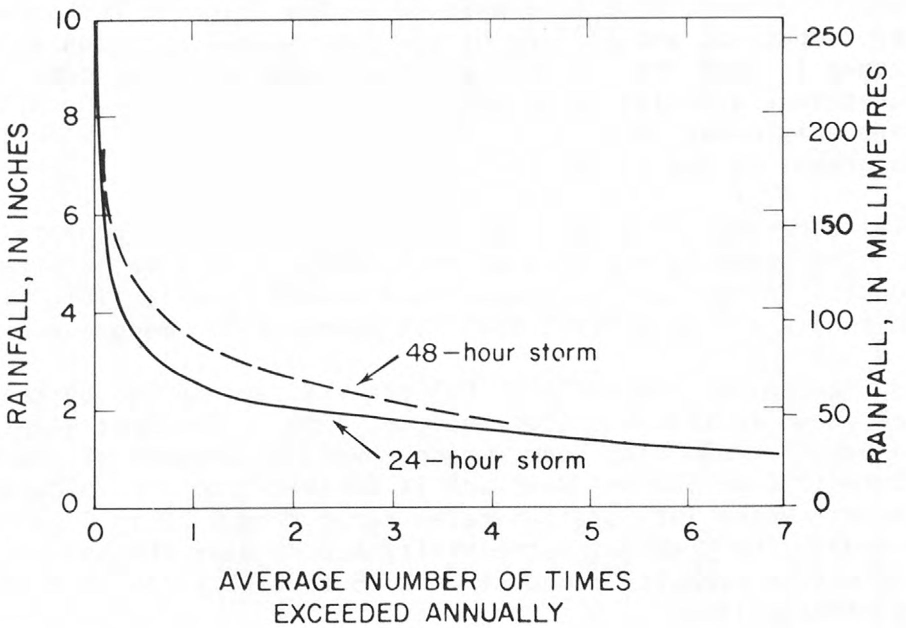

Figure 2.--Average rainfall intensity from major 24- and 48-hour storms, 1957-71.

The tendency of the soil to granulate is conducive to evaporation. This occurs as water is evaporated from an upper layer of a saturated tight soil, exposing a deeper layer to the circulation of air, and allowing further rapid evaporation of soil moisture.

Transpiration is an important process by which water is removed from the soil zone and also from the upper part of the aquifer, if the water table is near land surface. Grasses and other shallow-rooted plants transpire water from only the upper few feet of the soil zone, but many varieties of deep-rooted trees transpire water from depths of 20 ft (6 m) or more.

GEOLOGY AND SOILS

The geology of the island was studied by T. W. Donnelly in 1959 (p. 164-171). The geologic map, figure 3, is predominately his work but contains minor modifications resulting from a brief investigation by members of the Culebra Study Group (Puerto Rico Environmental Quality Board, 1971).

Culebra and adjacent islands are underlain by volcanic and intrusive rocks, probably of Late Cretaceous age--andesite lava and tuff are clearly dominant. The tuff and lava in north central Culebra have been intruded by diorite and on the adjacent island of Luis Peña by diorite porphyry.

Porosity that might once have existed in the volcanic rocks has been destroyed by compaction and filling of the pore spaces with quartz and calcite. Permeable zones in both the volcanic and the intrusive rocks consist solely of open fractures that diminish in number and size with depth. Open fractures in the rocks probably occur in a mantle about 300 ft (90 m) thick following the general topography of the island.

Alluvial deposits are predominantly silt and clay but contain some sand and gravel. The deposits are located principally in the major stream valleys near the coast. In the coastal areas the alluvial deposits interfinger with coral beach sand and organic silt and clay deposited in mangrove areas.

Over 90 percent of the soils of Culebra are represented by the four named series shown in figure 4 (Boccheclamp, 1969). The most widespread soil is the Descalabrado Clay Loam, which covers 52 percent of the island; it is 10 to 20 in (250 to 500 mm) deep and is derived from the volcanic and intrusive rock. Water infiltration rates range from 0.20 to 2.00 in (5 to 50 mm) per hour. The greatest permeability occurs near the bedrock surface. The water retention capacity ranges from 0.15 to 0.20 in/in (3.8 to 5.0 m/m) (Rivera and others, 1970).

Soils in the Volcanic Rock Series are found on about 30 percent of the island, but the soils are thin and lie in pockets between rocky outcrops that make up 50 to 70 percent of the land surface. Infiltration rates and water-retention capacity are similar to those of the Descalabrado Clay Loam.

The third major soil series is the Amelia Gravelly Clay Loam, which covers about 9 percent of the land surface. This soil is found principally in

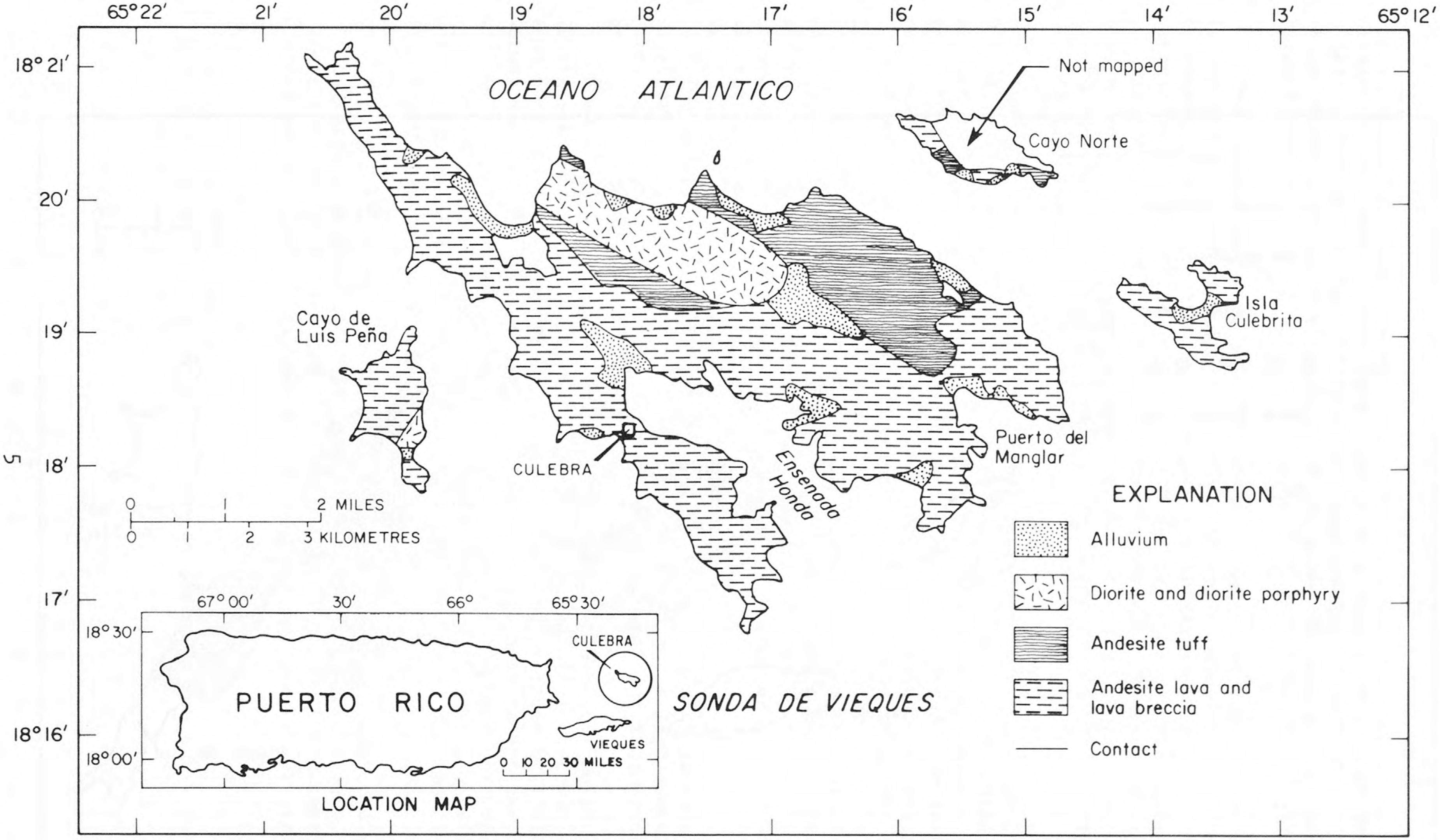

Figure 3.--Generalized geology of Culebra and outlying islands (after T.W. Donnelly, 1959, and modified by P.R. Environmental Quality Board, 1971).

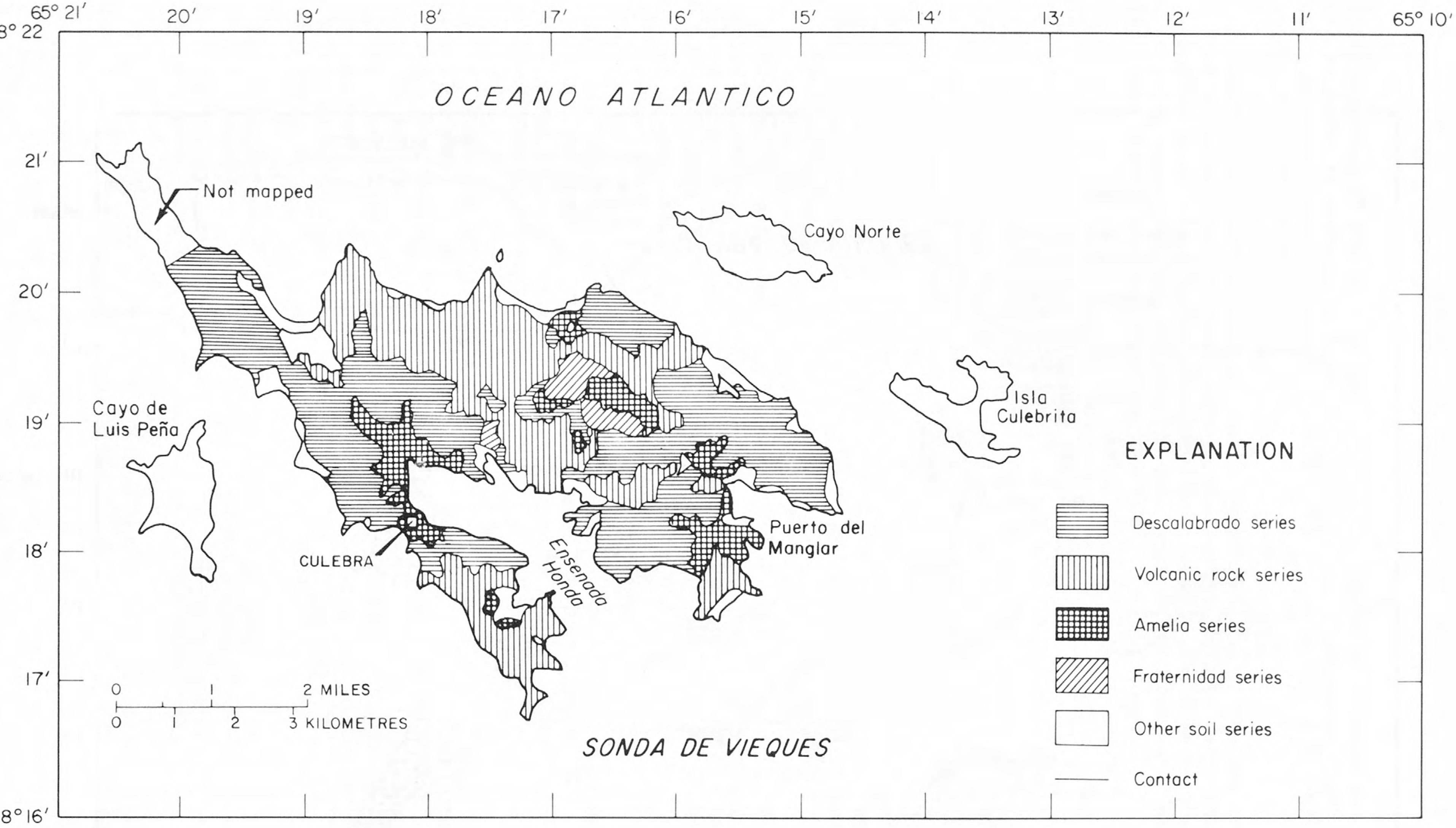

Figure 4.--Major soil series of Culebra. Soils of outlying islands not shown.

stream valleys and alluvial fans, and is more than 5 ft (1.5 m) thick in places. This series has infiltration rates ranging from 0.20 to 2.00 in (5 to 50 mm) per hour but, because of its gravelly composition, has a water-retention capacity of 0.10 to 0.15 in/in (2.5 to 3.8 mm/mm) of soil.

The Fraternidad Clay constitutes only about 2 percent of the soils of the island and is found principally in the high valley about 2 to 3 mi (3 to 5 km) northeast of the community of Culebra. The infiltration rate of the soil ranges from 0.06 to 0.20 in (1.5 to 5.0 mm) per hour and the water-retention capacity is 0.15 to 0.20 in/in (3.8 to 5.0 mm/mm). The soil has a very high shrink-swell potential and becomes granular when dry. Under field conditions it can have a very high infiltration rate for short periods of time because of its granular composition when dry.

The soil zone over much of Culebra is seldom more than 1 or 2 ft (0.3 or 0.6 m) thick. It has, however, the ability to accept large volumes of water--as much as 2 in (50 mm) per hour. When dry, the soil is coarsely granular, owing to clumping of clay and silt particles. As a result the soil has a high permeability until saturated; but once saturated, it becomes less permeable, retains water in the pore spaces between particles, and rejects any excess.

Observation of similar soils in St. Thomas, Virgin Islands, indicates that the soil zone, when dry, will usually accept about 2 in (50mm) of rain before some water is rejected or moves to the underlying bedrock. Fully saturated, the soil will retain as much as 2 in of water per ft (50 mm/30 cm) of depth.

The capacity of the soil to absorb and retain large volumes of water, together with the infrequency of major rainstorms and a high evapotranspiration rate, reduce considerably both ground-water recharge and storm runoff.

Bowden (1968), computed potential evaporation and soil moisture deficiency at six stations in St. Croix, Virgin Islands. Potential evaporation ranged from 58 to 69 in (1,470 to 1,750 mm) per year and averaged 62 in (1,570 mm). Actual evaporation (derived from potential evapotranspiration and changes in soil moisture) ranged from 41 to 46 in (1,040 to 1,170 mm) per year and averaged 43 in (1,090 mm). Bowden's data show a soil-moisture deficiency for 9 to 11 months of the year at the six stations--surplus soil moisture occurred only from September to November.

Figure 5 shows the monthly soil-moisture deficiency computed by Bowden for the area of Frederiksted in western St. Croix, Virgin Islands. It is very likely that soil-moisture deficiency is slightly greater in Culebra because average annual rainfall is several inches less than that in St. Croix.

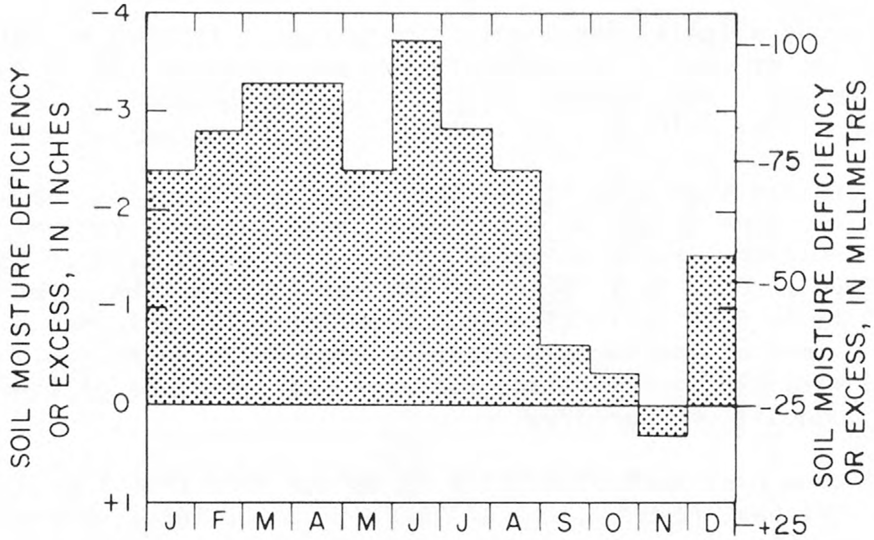

Figure 5.--Estimated monthly soil-moisture deficiency or excess (from data for Frederiksted, St. Croix, Virgin Islands by Bowden, 1968).

WATER SOURCES, FACILITIES, AND DEMANDS

In 1970, the average daily demand on the public water supply of Culebra was 29,000 gal (110 m^3)--a consumption of about 36 gal/d (140 l/d) per capita. This demand does not include the water supplied from individual household cisterns, which probably is 30 to 40 gal/d (110 to 150 l/d) per household. Homes in rural areas not served by the public water system rely almost entirely on rainfall catchments for water supply.

The Naval detachment formerly stationed on the island obtained water from roof catchments supplemented by water barged from Puerto Rico.

Since September 1971, the principal source of public water supply for Culebra has been two vapor compressor desalinization plants, each with a 15,000 gal/d (57 m^3/d) capacity. These plants barely supply the average daily water demand of 29,000 gal/d (110 m^3/d). Supplemental supply when the plants are down for maintenance, or when demand exceeds plant capacity, is obtained from the municipal well field drilled in the high plain about 2 mi (3 km) northeast of the community of Culebra.

The municipal well field consists of five wells (fig. 6), 55 to 70 ft (17 to 21 m) deep, constructed in 1963 and 1964. The wells yield about 20 gal/m (1.3 l/s) each, but the water is relatively high (see table 3) in mineral concentration and is not particularly palatable for drinking and

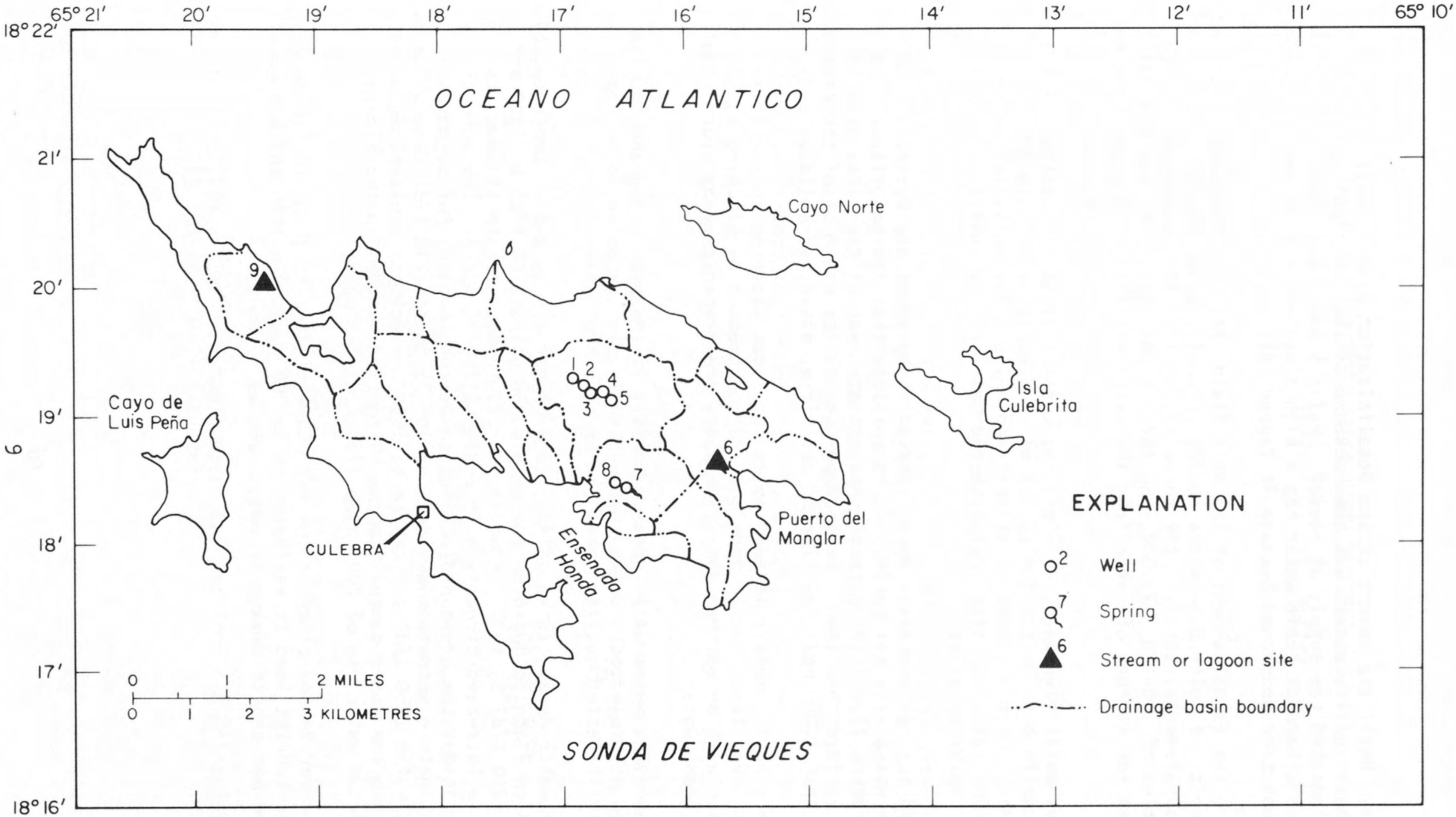

Figure 6.--Location of selected wells, spring, stream, and lagoon sites, and major drainage basins. (See table 3 for those sites where samples were collected for chemical analysis.)

cooking uses. Until the advent of the desalinization plants, well 2, which yields the best quality water, was the backbone of the municipal supply. Well 3 supplemented the supply as needed. Wells 4 and 5 were used only on an emergency basis because their water has a high dissolved-solids concentration, and well 1 has been abandoned because it tapped salty water.

Prior to the establishment of the well field, rainfall catchments located in the community of Culebra were the source of public water supply. They now serve as a supplemental supply. The three cisterns of the catchments, which have capacities of 110-000, 129,000, and 162,000 gal (416, 488, and 613 m^3) are also used for storage of water from the desalinization plants and from the well field.

Numerous wells have been dug along the coastal areas of Culebra. These wells are usually 8 to 15 ft (2.4 to 4.6 m) in diameter and 10 to 20 ft (3 to 6 m) deep, with concrete or stone-lined walls. The wells tap water in silty alluvium, talus deposits, or weathered bedrock. Ordinarily the wells are used for watering stock.

Thirteen springs and seeps were observed in November and December 1970. Because this was a very wet period, it is possible that the majority of the springs and seeps flow intermittently and are dry much of the time. Few of the springs yielded more than a few gallons per minute and most of the water had greater than 1,000 mg/l (milligrams per litre) dissolved solids.

There are approximately 18 farm ponds for stock watering on the island. They usually cover less than an acre and are constructed by blocking a drainage basin with an earthen dam. The ponds are replenished by storm runoff and contain fresh water.

The demand for water will increase rapidly if the population and tourism industry grow as projected. Demand per capita is also expected to increase significantly if better quality water can be made available.

Present water demand is 45 gal/d (170 l/d) per capita and is projected by the Puerto Rico Planning Board to increase to 50 gal/d (190 l/d) by 1980 and to 55 gal/d (210 l/d) by 1990. However, in St. Thomas, Virgin Islands, the per capita use increased directly with availability of water. The authors therefore, consider the above projections to be too low and, for purposes of planning, estimate a permanent-resident use of 75 gal/d (280 l/d) per capita by 1980 and 100 gal/d (380 l/d) per capita by 1990. Also, the projections do not seem to include the water demand imposed by tourism; hotels in the Virgin Islands report a water use of 200 gal/d (760 l/d) per guest.

Future water demand based on the various estimates is shown in figure 7. The overnight tourist load is estimated to be 200 guests in 1980 and 500 guests in 1990 The per capita demand is summarized as follows:

Demand per capita--(gallons per day)		
Year	*PRPB	Authors
1972	45	45
1980	50	75
1990	55	100

*Puerto Rico Planning Board

WATER RESOURCES

The water resources of Culebra have not been investigated intensively because it has generally been accepted that the island is so poor in natural water supply that the effort was not warranted. The following discussion is based on a reconnaissance made by the U.S. Geological Survey (H.R. Anderson, written commun., 1971) and the extrapolation of the information on the water resources of the nearby Virgin Islands and the La Parguera area of southwest Puerto Rico, where similar hydrogeologic conditions prevail.

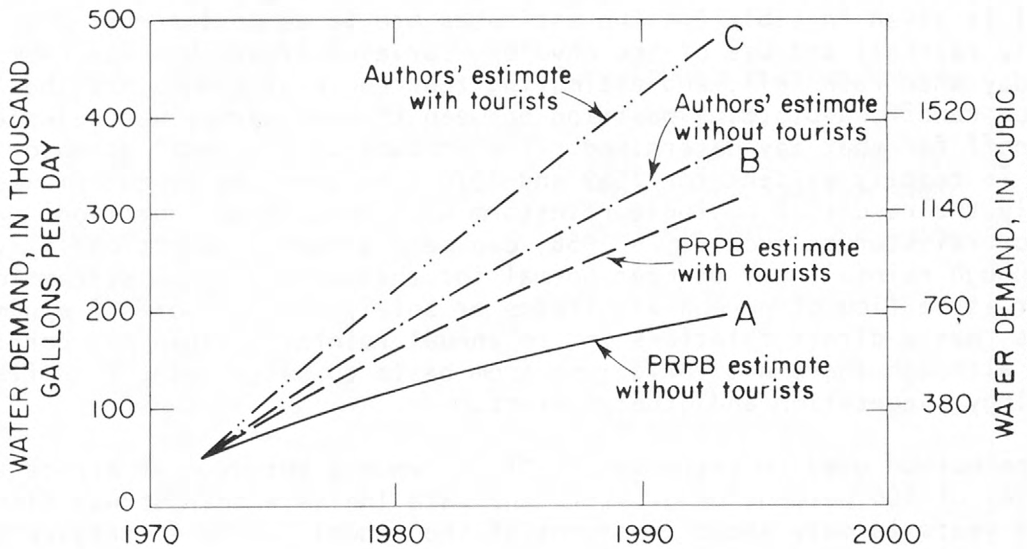

Figure 7.--Estimated water demand (based on data from P.R. Planning Board and St. Thomas, Virgin Islands).

Surface Water

Streams in Culebra are predominantly ephemeral, flowing only in direct response to rainfall. Flow, when it does occur, results from high-intensity rainstorms and is usually flashy. Streams of some of the larger basins draining to the south coast in years of above average rainfall may have intermittent reaches where there is flow during the wet season. H. R. Anderson (written commun., 1971) reported several intermittent reaches of streams on the south coast in November 1970, when rainfall was well above average.

Culebra's average streamflow (almost all storm runoff) is estimated to be less than 2 percent of the average annual rainfall. In extremely wet years streamflow (storm runoff and flow in intermittent streams) may approach 25 percent of the annual rainfall. Runoff from individual storms may amount to 20 percent of the rainfall but generally is less than 5 percent.

Figure 8, based on the rainfall-runoff relationship of Turpentine Run, St. Thomas, Virgin Islands, gives an indication of the runoff that can be expected from rain that falls in periods of as much as 48 hours. The limits of the envelope curve are related to antecedent runoff conditions. The curve to the left shows the relationship when there has been runoff in the previous 5 days; the curve to the right shows the relationship when there has been no runoff for the previous 30 days. The curves show that a 2-in (50-mm) rain would produce about eight times more runoff when antecedent conditions have been wet than when they have been dry.

An estimate of the annual storm runoff per square mile on Culebra for 1961-71 is given in table 1. The estimates are based on inspection of records of daily rainfall and use of the envelope curve of figure 8. For example, for a day when rain fell, and estimating the length of time since the last previous runoff; a plotting position between the two curves was selected, and the runoff for that day determined. The production of runoff by major rainstorms is readily evident for 1969 and 1970. In both years, runoff was almost entirely the result of a single rainstorm of several days' duration. A lack of major rainstorms, such as in 1966, can mean a marked reduction in runoff, even though rainfall may be near normal for the year. Annual streamflow, whether it be flow of perennial streams or solely storm runoff of ephemeral streams, has a direct relationship to annual rainfall within any particular basin, although there are variations from basin to basin owing to differences in geology, vegetation and other factors.

The method used to estimate runoff is tenuous but even if errors are on the order of 100 percent or greater, the data indicate that stream discharge in most years is only about 2 percent of the annual rainfall. Figure 9 is a plot of the estimated storm runoff against rainfall (from table 1) for a presumed typical stream basin of Culebra. The graph provides some basis by which to estimate annual runoff if rainfall is known.

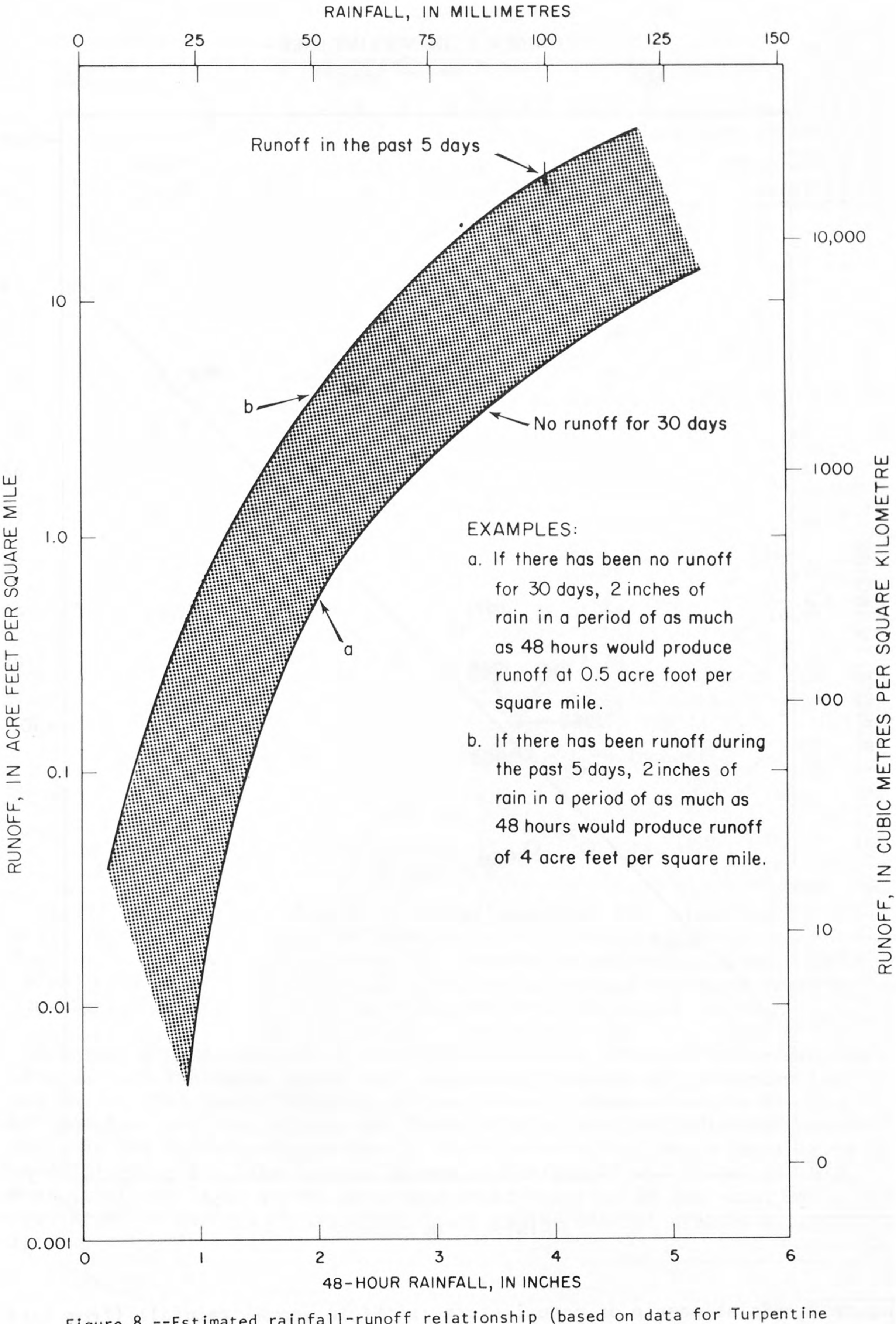

Figure 8.--Estimated rainfall-runoff relationship (based on data for Turpentine Run, Virgin Islands).

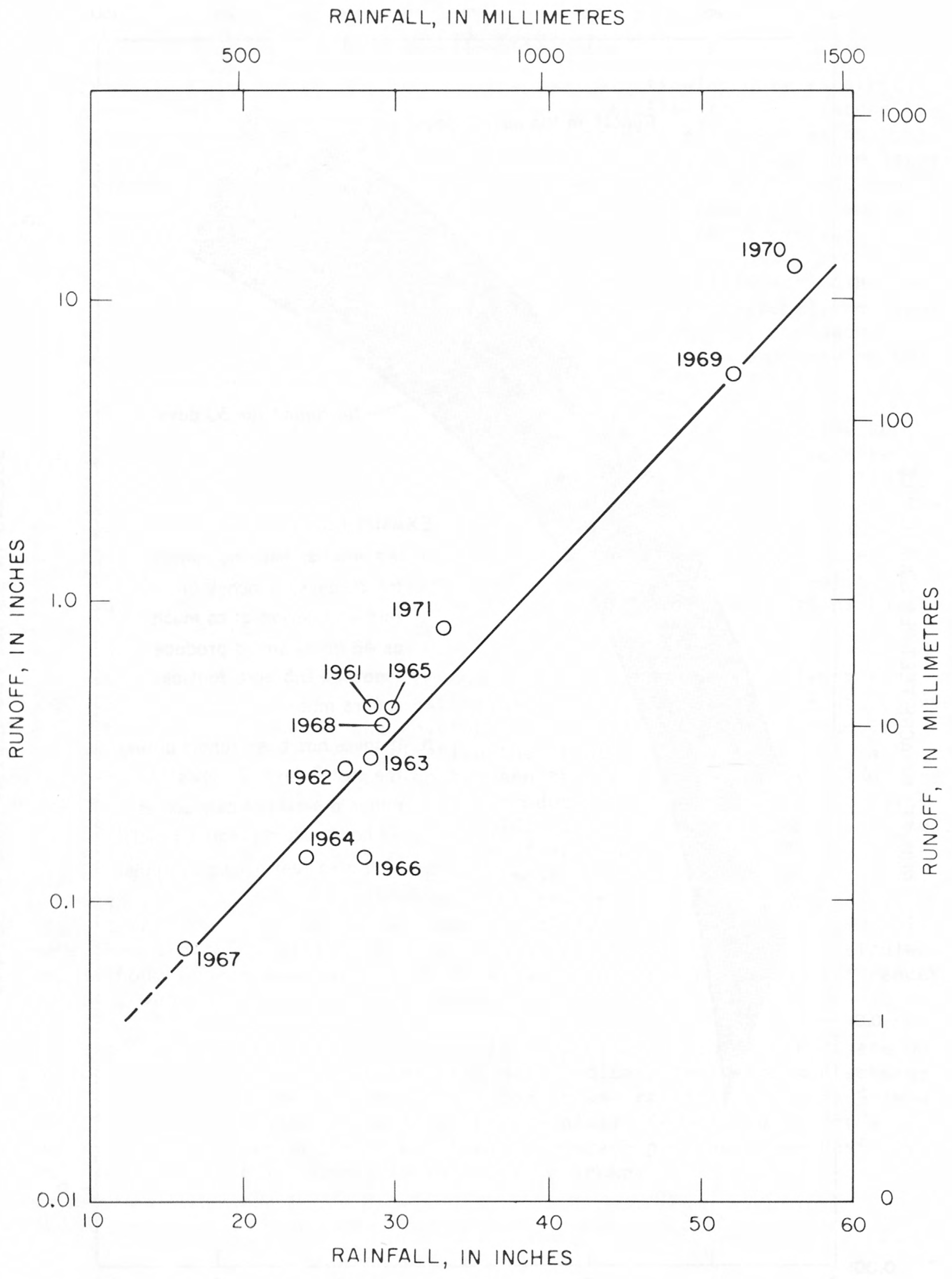

Figure 9.--Relationship of annual storm runoff to annual rainfall (from table 1).

Table 1.--Estimated annual storm runoff per square mile.

Year	Rainfall (inches)	RUNOFF Acre-feet per square mile	Inches	Percentage of rainfall
1961	28.00	25	0.47	1.7
1962	26.73	15	.28	1.0
1963	28.20	16	.30	1.1
1964	24.12	7.3	.14	.6
1965	29.66	24	.45	1.5
1966	27.93	7.3	.14	.5
1967	16.23	3.6	.07	.4
1968	29.06	20	.38	1.3
1969	52.08	300	5.62	10.8
1970	56.24	680	12.75	22.7
1971	33.12	43	.81	2.4

(Average annual rainfall, 1961-71, 31.94 inches)

Ground Water

Ground water is available in nearly all parts of the island but, in general, yields of wells are sufficient only for individual domestic supplies or for livestock. Most of the water is slightly to moderately mineralized. One area where water quality and yields to wells warrant the development of public supply has already been tapped by the municipality of Culebra.

Although ground water is found in the rocks and alluvium throughout the island, each of the major topographic basins of figure 6 is, in effect, an individual aquifer, with little or no ground-water movement between basins. Ground water, therefore, is derived almost solely from the infiltration of rainfall on the surface of the basin. Within the basin, ground water moves seaward following the same general course as surface flow. It is unlikely, however, that any large volume of ground water reaches the sea--most of it is removed from the surface of the water table in the coastal area by evapotranspiration.

Water recharging the bedrock aquifer fills the interconnected fractures. The specific yield is the ratio of (1) the volume of water that saturated rock will yield by gravity drainage to (2) the rock's own volume. The specific yield of the bedrock aquifer tapped by the municipal well field was estimated by two methods: by comparing decreases in water level with records of pumpage, and by comparing estimates of recharge with increases in water level. Specific yields of 0.009 and 0.008, respectively, were obtained by the two methods. The specific yield of about 1 percent agrees with estimates for similar bedrock aquifers in the Virgin Islands.

Significant recharge to the bedrock aquifer occurs on an average of about three times a year--usually during the fall rainy season--although a year or more can elapse without recharge. Recharge is invariably the result of a high-volume rainstorm of 1- to 4-days' duration. Fluctuations of the water level in response to rainfall and pumping are shown in the hydrograph (fig. 10) of well 2 in the Culebra municipal well field. Because the water levels shown are of the pumping level in a production well, recharge from all but the largest storms is masked.

The hydrograph of well 2 shows that following a major rain, such as in October 1970, ground-water levels continue to rise for 3 to 4 months. This is not an unusual condition in the volcanic-rock aquifers of the nearby islands, where a thick soil zone or fine-grained alluvium overlies the bedrock. The high water capacity (about 2 in/ft or 170 mm/m of depth) enables the soil to act as a storage reservoir that slowly releases water to the underlying bedrock. Even though the soils over most of Culebra are thin, the Amelia Series of soils which underlies the area of well 2 is thick.

An example of recharge to an aquifer in response to individual rainstorms is shown in figure 11, based on data collected at La Parguera, Puerto Rico. Infiltration rates of the soils and underlying rocks are similar to Culebra's. As specific yield of the aquifer at La Parguera is about 5 percent in contrast to about 1 percent in Culebra, the scale showing change in water level has been modified to reflect conditions on Culebra by multiplying the water-level change by 5. The data show that there is but slight chance of recharge from rainstorms of less than 2 in (50 mm) because of soil moisture deficiency.

It can be estimated from figure 11 that recharge from a storm of 2- to 4-days' duration is about one percent of the rainfall. It has been shown previously that runoff from a major storm is usually less than 5 percent of the rainfall. Therefore, about 95 percent of the rainfall is retained in the soil zone from which it is returned to the atmosphere by evaporation and transpiration.

Estimated annual recharge to the rock aquifer in the Culebra municipal well field, 1967-71, is given in table 2. This period includes the driest year and the second wettest year of record. Rain from all storms and showers is included in the annual total, whether recharge was produced or not. Estimated annual recharge ranges from 0 to 6.8 percent of annual rainfall.

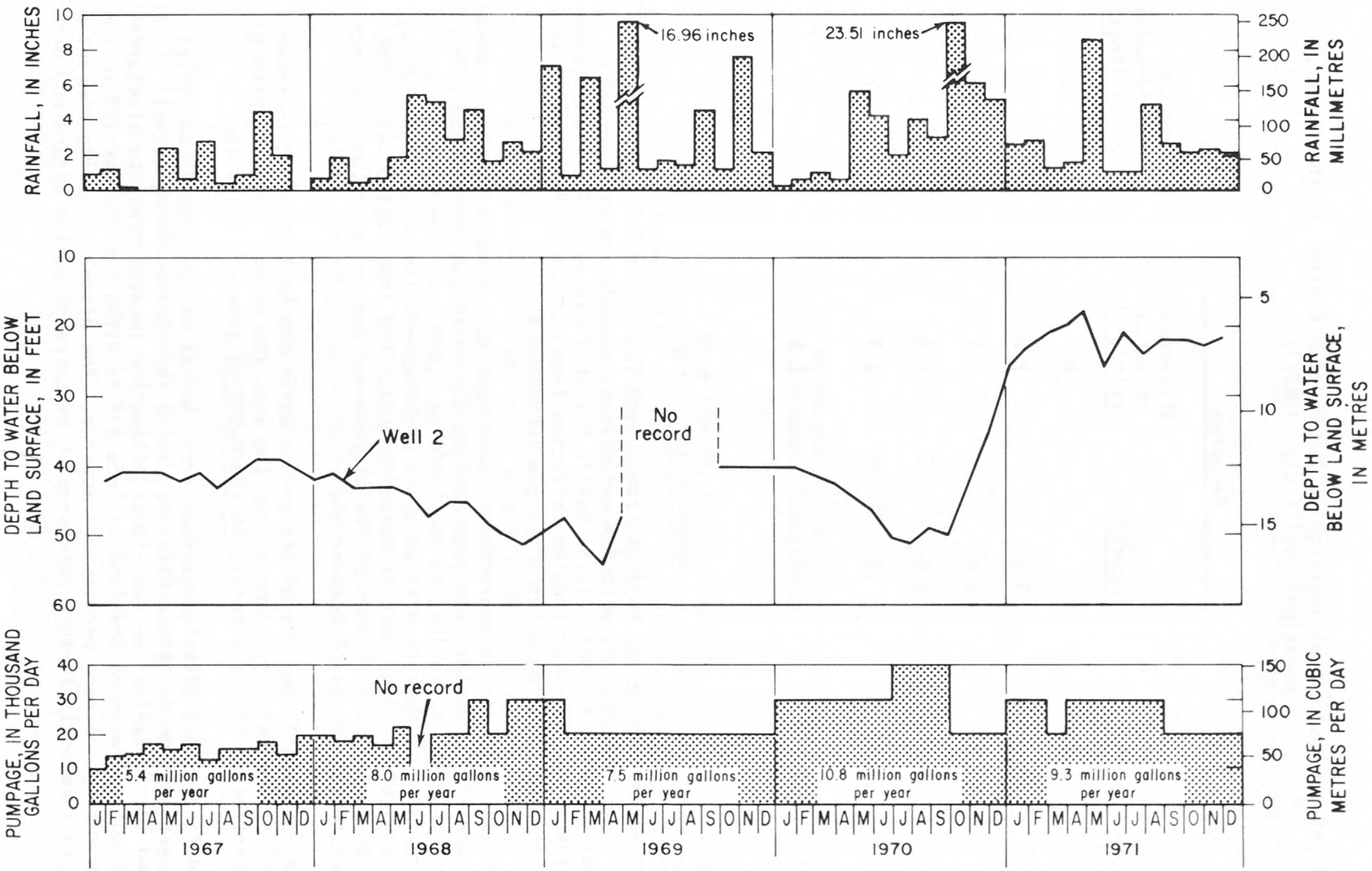

Figure 10.--Monthly rainfall at Punta Pedilla; pumping water level, well 2; and average daily pumpage by months, Culebra municipal well field.

Table 2.--Estimated annual recharge to the bedrock aquifer in the Culebra municipal well field, 1967-71

Year	Rainfall (inches)	Recharge (inches)	Recharge (Percentage of annual rainfall)	Increase in ground-water level (feet)
1967	16.23	0	0	0
1968	29.06	0.8	2.8	8
1969	52.08	2.9	5.6	29
1970	56.24	3.8	6.8	38
1971	33.12	.7	2.1	7
AVERAGE:	37.35	1.6	3.5	

Water Quality

The water from wells, springs, ponds, and lagoons in Culebra is high in mineral concentration and, with few exceptions, exceeds the recommended standards for drinking water (U.S. Public Health Service, 1962). Results of chemical analyses of water samples collected from various sources are given in table 3 and the sampling sites are shown in figure 6.

Specific conductance measurements were made at several sites in November and December 1970. Water from some shallow dug wells and springs had a low specific conductance, indicating about 500 to 1,000 mg/l dissolved solids; but water from the deeper, drilled wells and the majority of springs and dug wells, had 1,000 mg/l or more dissolved solids. The lower dissolved-solids content of the water from some of the springs and dug wells probably reflects recharge from the rains of October 1970.

The undesirable quality of the ground water can be attributed to several factors: salt-water encroachment from the sea, the general lack of recharge, and concentration of the minerals in the water by evapotranspiration.

One factor that affects water quality, but is seldom considered, is air-borne minerals from the atmosphere that reach the land surface, either dissolved in rainfall or as dust (bulk fallout). In arid areas particularly, bulk fallout collects on the land surface and is dissolved and carried to the aquifers during the rare periods of recharge. The dissolved solids concentration of this water is further increased by evapotranspiration before and after

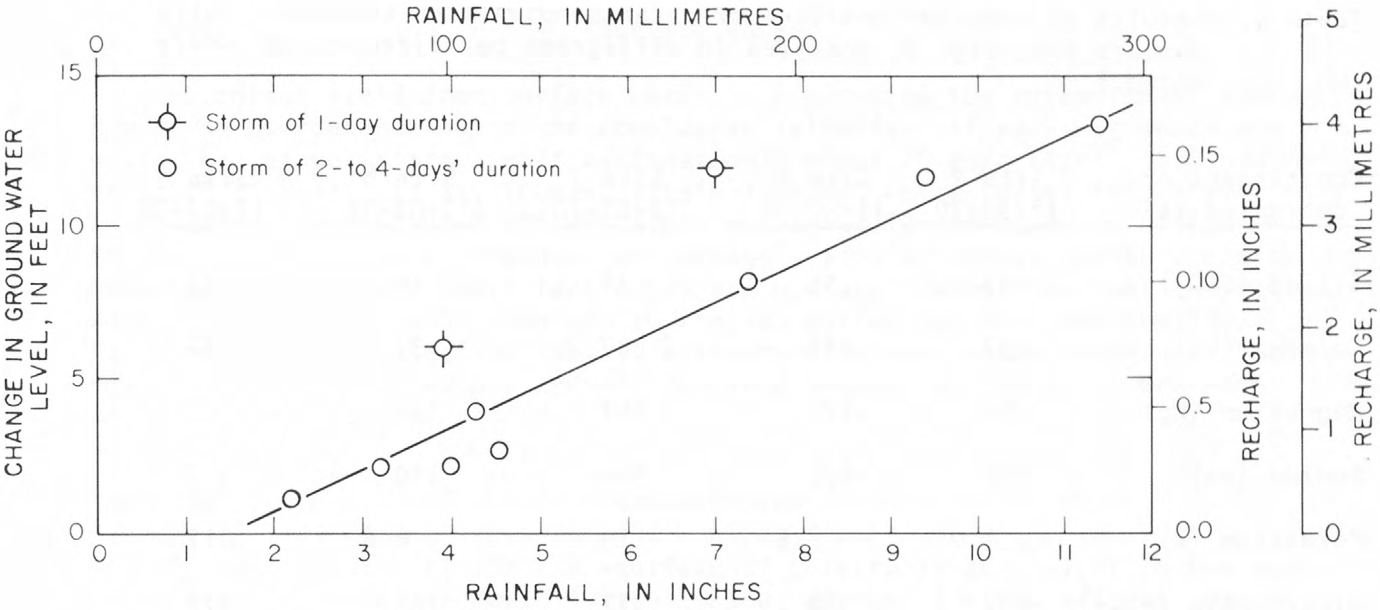

Figure 11.--Estimated recharge to bedrock aquifer by individual rainstorms (based on data for La Parguera, Puerto Rico).

reaching the water table. As a result, recharge enters the aquifer with a relatively high initial concentration of dissolved solids and is further concentrated in the aquifer. Utilizing data obtained in the Virgin Islands, it is estimated that the bulk fallout on Culebra is concentrated about 30-fold, producing an initial chloride concentration of about 200 mg/l in the water that reaches the aquifer.

The dissolved solids concentration of the ground water tapped by the municpal well field is apparently due solely to bulk fallout and further concentration by evapotranspiration as the well bottoms are above sea level and are not subject to salt-water encroachment from the sea.

Bulk fallout also contributes to the mineralization of surface water because some of the bulk fallout is dissolved and carried by storm runoff. Where the surface water is trapped by farm ponds or lagoons, the dissolved solids concentration of the water is further concentrated by evapotranspiration.

Potential Yield

The potential yield of the natural water supplies of Culebra is small, and is limited by the periodically low rainfall, a high evapotranspiration rate, small aquifer storage, and the small size of the island.

Table 3.--Results of chemical analyses of water samples from Culebra. (Site numbers from fig. 6; analyses in milligrams per litre except where noted.)

Constituent or characteristic	Site 2 11-30-70	Site 6 11-30-70	Site 7 12-02-70	Site 8 12-02-70	Site 9 12-02-70
Silica (SiO_2)	43	35	38	14	18
Calcium (Ca)	97	234	207	27	74
Magnesium (Mg)	54	127	167	24	52
Sodium (Na)	351	670	996	130	357
Potassium (K)	1.0	8.6	19	6.6	17
Bicarbonate (HCO_3)	532	388	332	164	272
Carbonate (CO_3)	0	75	24	0	0
Sulfate (SO_4)	113	260	172	27	27
Chloride (Cl)	450	1340	2000	218	660
Fluoride (F)	.5	.6	.2	.2	.2
Nitrate (NO_3)	13	6.0	.8	.9	1.3
Phosphate (PO_4)	.10	.00	.00	1.3	.69
Dissolved solids, calculated	1380	2950	3790	530	1340
Hardness as $CaCO_3$, calcium, magnesium	464	1110	1200	166	399
Hardness as $CaCO_3$, noncarbonate	28	663	891	32	176
Specific conductance (micromhos at 25°C)	2370	5090	6710	964	2470
pH	7.1	9.1	8.6	8.2	7.5
Temperature °C	28	26	26	25	26
Source	Culebra well	Stream fed by flowing well	Spring	Dug well	Swamp in target area

Surface Water

Potential yield from surface water is limited to the retention of storm runoff--a source that cannot be considered reliable. If very wet years are neglected, annual storm runoff averages only about 20 acre-ft/mi^2 (6.5 Mgal/m^2 or 9,500 m^3/km^2). In St. Thomas, Virgin Islands, water losses from a seemingly well-sealed pond averaged 105 in (2,670 mm) annually--about 60 in (1,520 mm) to evaporation and the remainder to leakage. Similar losses probably can be expected on Culebra. Small farm ponds are useful, however, in that they store water that normally would run off to the sea during storms; they provide water for stock; and leakage from them is a source of ground-water recharge. Large reservoirs for water supply are not feasible because of the small drainage basins and the lack of runoff.

Ground Water

The potential yield of the aquifers of Culebra is equivalent to the estimated average annual recharge (.6 in)--about 20 Mgal (76,000 m^3) per year per per mi^2 or 55,000 (gal/d)/mi^2 {(80 m^3/d)km^2} of aquifer.

Although the quality is poor, the ground water does have potential as a source of supply because of the advances being made in demineralization of water. Wells in the major valleys on the north side of Ensenada Honda (fig. 6) would have a combined yield of about 40 Mgal (150,000 m^3) per year. Demineralization would yield 26 to 30 Mgal (98,000 to 114,000 m^3) per year--almost three times the present water demand.

Other Water Sources

Ground water and surface water are not the only potential sources of supply for Culebra. Other possibilities include seawater desalinization, a pipeline from Puerto Rico, and rainfall catchments.

Seawater desalinization is already used for water supply in Culebra. Its biggest advantage is an unlimited source of raw water. Its biggest disadvantage is cost that can be as great as $10 per 1,000 gal (4 m^3) and rarely less than $5, particularly for small plants with less than 100,000 gal/d (380 m^3/d) capacity (R. Bakish, Fairleigh Dickinson University, oral commun. 1972). In addition, competent operators are scarce, and in most plants maintenance is required constantly.

An underwater pipeline from Puerto Rico to Culebra is currently (1975) under study by the Commonwealth of Puerto Rico. Although the initial expense would be great, the advantages may well outweigh the cost. The pipeline could provide a water supply capable of meeting future demands and would eliminate the necessity for complex water-production and treatment equipment.

Rainfall catchments have long been used for water supply in many Caribbean islands and have been proven to be excellent sources of water when demand is small. Catchments are seldom feasible for large or even moderate water demands because of space requirements, the large water-storage facilities needed, and construction costs.

Studies in St. Thomas, Virgin Islands, (for example, Cosner, 1972) have shown that large hillside catchments have a recovery efficiency of about 70 percent of annual rainfall. However, it is feasible to store only about 90 percent of the recovered rainfall--to store all the rainfall would more than triple the cistern requirements.

In Culebra a catchment capable of yielding 30,000 gal/d (110 m^3/d) would require an area of about 17 acres (6.9 ha) and a cistern storage of 4.4 Mgal (16,700 m^3). In a drought year such as 1967, the catchment would yield about 15,000 gal/d (57 m^3/d). This shows one of the greatest disadvantages of obtaining water supply from rainfall catchments--the necessity of relying on day-to-day rainfall.

In view of the high evapotranspiration rates, further investigation of the usefulness of properly-engineered covered reservoirs or holding basins for runoff might be warranted.

WASTE DISPOSAL

At present, waste-disposal methods in Culebra are not up to date. Disposal of solid wastes has been principally accomplished by burning in an open dump, although efforts are now being made to develop a sanitary landfill. Sewage wastes are still the concern of the individual householder, who copes with the situation either with a septic tank or a privy, or by dumping raw sewage in the nearby sea.

Solid-Waste Disposal

The standard method for constructing a sanitary landfill is to excavate a trench, which is then gradually filled with solid waste that is compacted daily and covered with a layer of soil. Where subsurface drainage might be a problem, the wastes are compacted on the land surface and covered with soil, thus constructing a hill. Either method, however, requires soil, preferably clayey, that will compact well and create the best possible impermeable seal over, under, and around the waste.

One major problem with sanitary landfills has resulted from the leaching of waste materials by the percolation of rainwater. The composition of the leachate depends on the composition of the waste, which usually contains large quantities of metals.

Some requisites for a successful sanitary landfill operation are: proper drainage so that leachates will not contaminate a usable aquifer or other water body; sufficient thickness of soil or unconsolidated material in which to dig a trench; and a sufficient source of suitable cover material, whether the landfill is to be in a trench or placed on the land surface. In Culebra the fractured bedrock surface should be sealed so as not to expose it to the waste material.

Nearly 90 percent of Culebra could be eliminated as candidate area for landfill sites because of the thin or nonexistent soil cover. Areas best meeting the basic requirements would be the valleys containing soils of the Amelia or Fraternidad Series, as shown in figure 4. The Amelia soils are predominantly a gravelly clay and the Fraternidad soils are a fine-textured clay; both series are well drained and thick.

The most extensive area of these two soil series is the high interior valley where the Culebra municipal well field is located. The danger of pollution to the well field would, of course, eliminate the valley as a landfill site.

Two small valleys (fig. 4) containing Amelia soils drain to Puerto del Manglar on the east end of the island. There are probably no extensive, thick deposits of these soils except in the center of the valleys near the sea. The valleys drain to a bioluminescent bay fringed by mangrove swamps, and the bay has large areas of excellent bone-fishing grounds. Leachates from a sanitary landfill might be detrimental to these rare and valuable natural resources.

The valley at the head of Ensenada Honda (fig. 4) seems to offer the greatest potential for a sanitary landfill. There is sufficient thickness of unconsolidated material for trenching and backfill far enough inland to reduce to a minimum the possibility of leachates reaching Ensenada Honda. The bedrock aquifer contains brackish water; therefore, unless an all-out effort is made to develop brackish ground water for desalinization, the possible contamination of this aquifer would not be a deciding factor for construction of a landfill.

Sewage Disposal

The urban areas of Culebra will eventually be served by a municipal sewage system. An extensive discussion of sewage treatment is beyond the scope of this report; it is believed more appropriate to briefly discuss methods of disposal of solid wastes and liquid effluents resulting from the treatment of sewage.

Treatment Methods

Most raw sewage on Culebra will probably continue to be from domestic sources; it is unlikely that large quantities of industrial wastewater will be produced. The average composition of domestic wastewater in the United States is given in table 4. The composition of wastewater in Culebra may differ somewhat from that of the table, depending on the source of water supply. Use of desalinized water would greatly reduce the mineral concentration of the wastewater from that shown, whereas use of local ground water would increase the mineral concentration.

The quantity of wastewater produced in Culebra will probably keep pace with water use because consumptive use would be minimal. On this assumption the estimated maximum wastewater output would be 400,000 gal/d (1,500 m^3/d) by 1990.

Table 4.--Average composition of domestic wastewater in the United States [a/]

State of solids	Solids: Mineral	Solids: Organic	Solids: Total	5-day, 20°C BOD	COD
(1)	(2)	(3)	(4)	(5)	(6)
Suspended	65	170	235	110	108
Settleable	40	100	140	50	42
Nonsettleable	25	70	95	60	66
Dissolved	210	210	420	30	42
Total	275	380	655	140	150

a/ Values are in milligrams per litre (Source: Fair, Geyer, and Okum, 1971, p. 309.)

A schematic diagram of wastewater treatment processes is shown in figure 12.

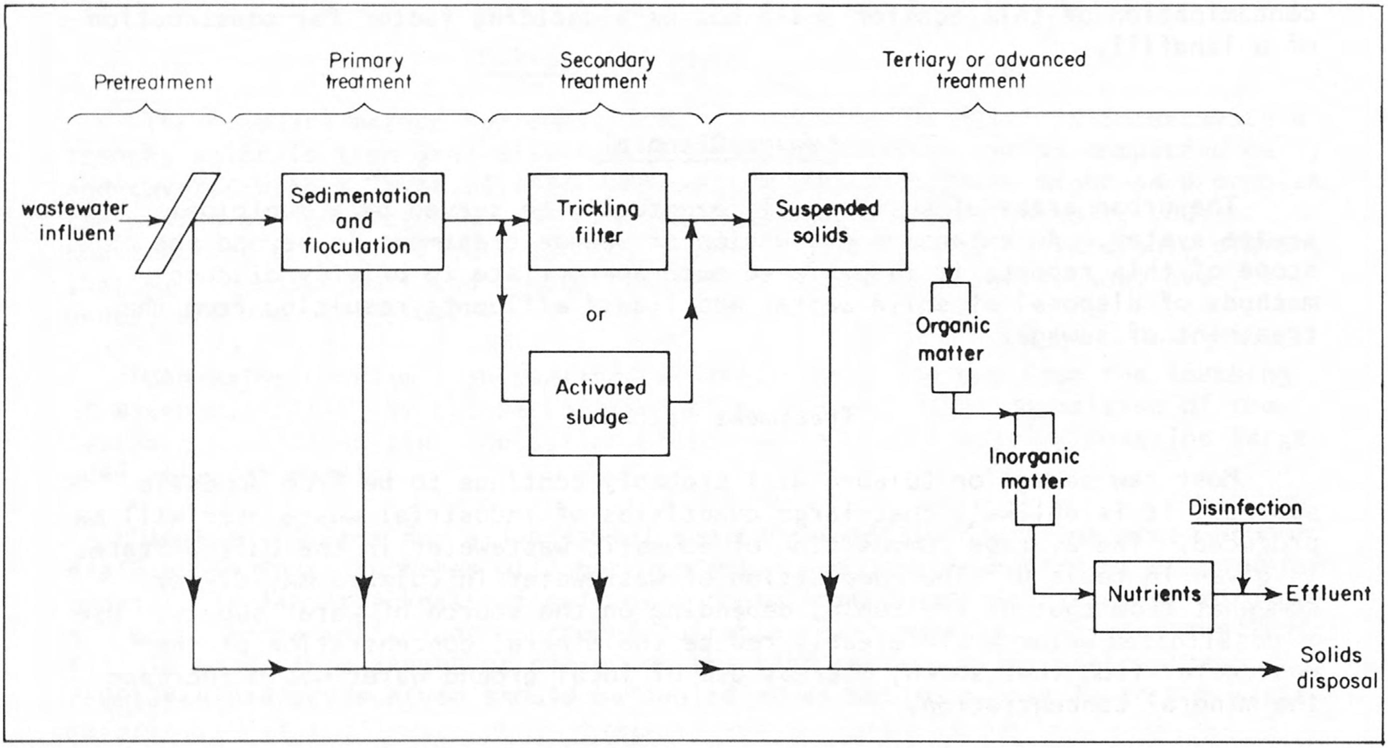

Figure 12.--Wastewater treatment process (idealized).

Pretreatment devices are bar screens, barminutors, and grit chambers; these are essential to remove debris and trash that might damage or plug pumps, or interfere with in-plant flow of wastewater.

Primary treatment is performed in sedimentation tanks, designed to provide sufficient detention time so that heavy solids can settle to the bottom, while grease or other light materials can float to the surface where they can be skimmed off. Primary treatment would remove the greater part of the settleable solids but would have no effect on the nonsettleable and dissolved solids, bacterial content, or BOD (biochemical oxygen demand) and COD (chemical oxygen demand).

Secondary treatment provides an environment where wastewater is exposed to living organisms (bacteria) that consume the dissolved and nonsettleable organic material remaining in wastewater after primary treatment. Conventional treatments are aerobic bacteriological processes, which consist of trickling filters or activated-sludge units. The activated-sludge process produces water of better quality than trickling filters. Secondary treatment removes 80 to 90 percent of the suspended solids and BOD, 70 to 80 percent of COD, and nearly 100 percent of the coliform bacteria, but little of the nitrogen and phosphorus compounds in the dissolved soils.

Tertiary treatment is a process that removes additional contaminants from wastewater, such as suspended solids, organic and inorganic matter, and nutrients (nitrogen and phosphorus compounds). Tertiary treatment can produce water that is nearly free of all mineral and organic material. Usually, the reduction of nutrients is the principal objective of tertiary treatment.

Disposal of Treated Wastewater

The degree of refinement in wastewater treatment depends on the intended use of the water, or the desired impact of the effluent on the receiving environment.

Non-use of treated wastewater.--The effluent from sewage treatment is usually discharged to a nearby stream, lake, or sea, where the impact on the environment is determined by the diluting capabilities and the chemistry of the receiving water.

For Culebra, the sea seems to be the most appropriate discharge zone for wastewater. But the coral reefs surrounding the island extend more than a mile offshore except in a small area along the west coast near the municipality of Culebra. Even there the reef is nearly half a mile wide. Outside the reefs the water is shallow--less than 100 ft (30 m) deep for several miles in all directions.

Ensenada Honda is very shallow and seems to have poor water circulation and, therefore, probably could not be considered for an outfall site.

In order to avoid damage to the shallow-water environment, wastewater outfalls would have to extend beyond the reefs. Because of the shallow water and numerous islands near Culebra, the pattern of sea currents cannot be predicted reliably, and so it is difficult to predict the extent and position of the dispersion zone of an outfall. This might not prove to be too significant a problem becuase of the relatively small volume of wastewater to be discharged--about 400,000 gal/d (1,500 m^3/d) by 1990.

Use of treated wastewater for ground-water recharge.--In recent years considerable attention has been given to the use of wastewater for recharging aquifers. Recharge may be accomplished in numerous ways--by pits, ditches, water-spreading, percolation beds, recharge basins, or injection wells--depending on the physical and chemical characteristics of the recharge area, the objective of the recharge activity, and the quality of the wastewater. The objective of a recharge program is an important consideration. For example, if recharge is to provide a freshwater barrier against seawater encroachment, the recharge water could probably contain considerable quantities of nitrogen and phosphorus compounds without objection. If the objective is to recharge an aquifer to supply drinking water, then large quantities of nitrogen and phosphorus compounds would be objectionable. In addition, if minerals in the recharge water precipitate or form new compounds in the presence of the host water, clogging of the recharge facility or the aquifer may result.

The advisability of using tertiary treated sewage plant effluent as ground-water recharge for drinking water supply needs careful advance consideration. After further study, if a decision were made to use treated effluent in this manner, the implementation of the plan should as a minimum, be preceded by a pilot investigation and should be accompanied by careful laboratory control and adequate health safeguards. It would be important that such an operation be under the control of adequately trained personnel and endorsed by responsible authorities.

Some of the factors affecting a wastewater-recharge program in Culebra are as follows:

1. Topography - Topography would probably determine the selection of the method of recharge. The generally steep slopes of the island would be suited to the development of contoured terraces for water spreading. Other methods might be used but probably less effectively.

2. Geology - The thicker soil zones would be preferable as they would offer additional bacteriological removal by filtration that would not be available in the thin soils and the underlying bedrock. The fractured bedrock aquifer generally will transmit and store water but only in small quantities; this has been proven by field experience.

3. Infiltration capacity - The Amelia Series of soils is the only one on the island that is thick, has a good infiltration capacity, and is of sufficient areal extent for recharge.

4. Storage capacity - Storage capacity of the bedrock aquifer is only about 1 percent by volume. One in (25 mm) of recharge would occupy nearly 10 ft (3 m) of vertical storage in the aquifer per unit area.

5. Available water - Water for recharge would have to be delivered to the selected area by pipeline, or a treatment plant would have to be constructed in the recharge area.

6. Water quality - Some type of tertiary treatment would be required to remove those excessive nitrogen, phosphorus, and other compounds that could be detrimental to health. Continuous recycling of recharge water would cause a gradual increase in dissolved solids concentration. Representative samples of the proposed recharge water would have to be carefully analyzed for compatability with the host water in the aquifer so as to determine the effects of mixing the two on equipment and the aquifer.

7. Social acceptance - A public information and education program should be instituted early in the planning process to disseminate factual information on all aspects of the wastewater-recharge proposal.

It might be assumed that the future water supply of Culebra will rely primarily on a pipeline from Puerto Rico or desalinization of seawater. Each source would supply good quality water of low dissolved solids concentration. Treated wastewater from these sources would contain only about one-fifth the concentration of the existing municipal ground-water supply.

Recharge of treated wastewater to the aquifer tapped by the municipal well field would have advantages and disadvantages:

1. Part of the well field area is underlain by Amelia Series soils that have favorable characteristics for recharge.

2. The aquifer can serve as a large storage reservoir; this would be of great importance in case of interruption of water supply from the primary sources. About 30 Mgal (114,000 m^3) of useable water could be stored in the aquifer--more than 2 months' supply at the maximum demand estimated for 1990.

3. Continuous recharge could rapidly fill the aquifer because of its small storage capacity. If the water were not removed by pumping, lower areas of the valley might become waterlogged. More likely, perennial streamflow would develop to discharge the excess water.

4. The quality of the water in the aquifer at first could be improved by dilution and replacement by recharge water. However, continuous recycling could cause the dissolved solids concentration to increase and eventually could affect the potability of the water. This trend could be reversed by periodically dewatering the aquifer and wasting the highly mineralized water to the sea or using it for irrigation. The aquifer could then be refilled with effluent water derived from the primary sources.

Use of treated wastewater for irrigation.--Wastewater from sewage treatment has long been used for irrigation, particularly for forage and crops that are not eaten raw. Nitrogen and phosphorus compounds and other chemicals essential for plant growth are normally found in domestic wastewater; thus, use of wastewater for irrigation could reduce the need for chemical fertilizers. Industrial effluents that sometimes contain undesirable mineral constituents are not expected to become a problem in Culebra.

Wastewater will be of greater salinity than the primary water because of the addition of dissolved minerals from sewage, and care would be necessary to prevent a salt buildup in the irrigated soils. Adequate drainage and application of sufficient water to flush excess salt would help to protect the soil. Approximately 65 percent of the soils of the island are suitable for irrigation; the others are rocky soils or beach deposits.

The use of sewage effluent for irrigation can present problems, particularly if the effluent has received primary treatment only. Pathogenic bacteria, viruses, protozoa (cysts) and worm eggs can survive primary treatment and even moderate chlorination. The contamination problem is greatly reduced when effluent has received secondary treatment and post-chlorination.

Pasture for beef cattle is expected to continue to be the major land use in Culebra. In 1971, 3,058 cuerdas (1 cuerda is approximately 1 acre, or 0.4 ha) were in pasture--54 percent was improved and the rest was natural pasture. Good pasture on Culebra is usually available only about 3 months of the year--during the fall rainy season, when soil-moisture deficiency is least.

The grass yield and the grazing capacity of the pastureland could be improved considerably by irrigation. Whereas ground-water and surface-water supplies are not available in sufficient quantities to be of great benefit for irrigation, wastewater is an ever-increasing source.

Soil-moisture deficiency (fig. 5) is estimated to average 3 in (76 mm) per month in the dry season and slightly less than 1 in (25 mm) per month in the wet season. Irrigation with wastewater would have to be about 3 in (76 mm) per acre per month 8 months of the year, and about 1 in (25 mm) per month the remaining 4 months to assure some flushing of the soil to prevent a buildup of salts. An estimate of the acreage that could be irrigated is shown in figure 13 using the minimum and maximum projected water use. Other schemes could be used if it were desirable to irrigate more land. It might be possible to grow a good crop of grass with an application of 1 in (25 mm) of water per month and then during the rainy season apply an excess of water to flush accumulated salts from the soil.

Disposal of Sludge

In addition to the effluent, the final products of wastewater treatment are slurries or sludges, which are not in a finished state. They are watery, bulky, and require treatment to ensure hygienic safety and to eliminate odors. The composition of sludge depends partly on the extent and method of wastewater treatment, particularly in terms of the amount of organic material removed by the process. Commonly, sludge contains water, organic and inorganic settleable solids, chemicals added during treatment, and biomasses generated by living organisms during treatment.

It is estimated that 120 pounds (54 kg) of solid wastes per day would be generated by secondary wastewater treatment for 1,000 persons in Culebra. Annual waste production would amount to about 22 tons (20 t) at present (1975) but could increase to about 70 tons (63.5 t) by 1990.

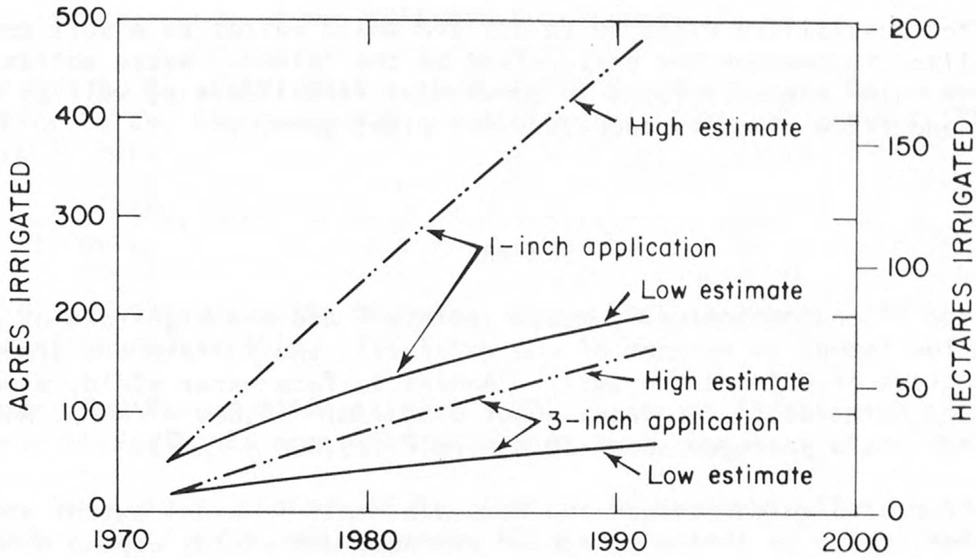

Figure 13.--Estimated acreage of pasture that could be irrigated monthly by wastewater effluent.

Satisfactory disposal of sludge can be extremely costly. Disposal can be accomplished by incineration, dumping at sea, using the material as a fertilizer base, burial in sanitary landfill, or as an agricultural soil conditioner.

Incineration is a continuous process and probably would not be feasible because of the small quantity of wastes.

Dumping at sea is a possibility but the small quantity would likely require stockpiling of wastes until a sufficient amount accumulated to justify barging to deep water. However, with regard to this waste-disposal option, recent water-pollution-control legislation prohibits the disposal of sewage sludge in U.S. navigable waters except in accordance with a permit issued by the Environmental Protection Agency. The issuance of a permit is based on the meeting of certain criteria to define the acceptability of such sewage sludge for waste disposal. The Marine Protection, Research, and Sanctuaries Act of 1972 also prohibits disposal of sewage sludge to ocean waters except by permit from EPA. The Environmental Protection Agency may designate recommended sites or times for such disposal practices.

Probably there would not be sufficient solid wastes for profitable processing as a fertilizer base. Solid wastes could be disposed of by utilizing a sanitary landfill as discussed previously. The wastes probably would have to be disinfected by chlorination or some other process to destroy bacteria, viruses, and worm eggs.

Another possibility might be to use the solid wastes as a soil conditioner and fertilizer to improve the pastureland on the island. Waste solids usually contain the major elements found in commercial fertilizers as well as many of the minor and trace elements necessary for plant growth.

SUMMARY

Because of the periodically meager rainfall and the high rate of evapotranspiration (about 95 percent of the rainfall), the surface and ground-water resources of Culebra are small. Annual surface-water yield, almost solely from storm runoff, averages about 6 $Mgal/mi^2$ (8,800 m^3/km^2). Annual ground-water yield averages about 20 $Mgal/mi^2$ (29,000 m^3/km^2).

The fractured volcanic-rock aquifers are small in areal extent and contain little water; there is little carryover storage, and yields depend on recharge from rainfall. The aquifers yield water of poor quality that usually does not meet drinking-water standards established by the U.S. Public Health Service (1962). The most likely area for ground-water development has already been tapped by the Culebra municipal well field. The wells yield about 30,000 gal/d (114 m^3/d) of highly mineralized water but the field is now used only intermittently for standby or emergency purposes.

In order to meet the increased water demands of the future, Culebra will probably have to rely on other sources--either water transported from the main island of Puerto Rico or seawater desalinization. Desalinization plants now in operation supply most of the current demand.

Culebra is also faced with the problem of garbage disposal and sewage treatment. Prospective areas for sanitary landfill are few because of the thin soil cover over much of the island. The only area that seems suitable for a sanitary landfill is the alluvial valley at the head of Ensenada Honda.

Liquid effluent and solid wastes from sewage treatment plants could be disposed of at sea. In view of the lack of water on the island, liquid effluents that are properly treated could be used for irrigation of pastureland or, with more extensive treatment, for ground-water recharge to the aquifer supplying the municipal well field. Solid wastes from sewage treatment plants could be disposed of by sanitary landfill or as a soil conditioner for pasturelands.

SELECTED REFERENCES

Boccheclamp, R. A., 1969, Soil survey of the Humacao area: San Juan, Soil Survey Party, San Juan, P.R., Soil Conserv. Service, U.S. Dept. Agr., unpubl. map.

Bowden, M.J., 1968, Water balance of a dry island: Geog. Publ. at Dartmouth, no. 6, 89 p.

Cosner, O.J., 1972, Water in St. John, U.S. Virgin Islands: U.S. Geol. Survey open-file rept., 46 p.

Development and Resource Corporation, 1971, Wastewater reclamation reconnaissance study, Ponce area: consultants' rept., San Juan, P.R., 83 p.

Donnelly, T.W., 1959, Geology of St. Thomas and St. John, Virgin Islands: unpubl. thesis, Princeton Univ., 178 p.

Fair, G.M., Geyer, J.C., and Okum, D.A., 1971, Elements of water supplies and waste-water disposal: John Wiley & Sons, Inc., New York, N.Y., 752 p.

Jordan, D.G., and Cosner, O.J., 1973, A survey of the water resources of St. Thomas, Virgin Islands: U.S. Geol. Survey open-file rept., 55 p.

Kugelman, I.J., 1972, Status of advanced waste treatment: U.S. Environmental Protection Agency, 79 p.

National Oceanic and Atmospheric Administration, 1938-71, Monthly summaries of rainfall: U.S. Dept. Commerce.

Puerto Rico Environmental Quality Board, 1971, An island in transition, Culebra, 1970: San Juan, P.R., 106 p.

Rivera, L.H., and others, 1970, Soil survey of the Virgin Islands of the United States: U.S. Dept. Agr., Soil Conservation Service, 78 p.

U.S. Public Health Service, 1962, Public Health Service drinking water standards: San Juan, P.R., 61 p.