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Geological Survey

WATER IN ST. JOHN, U.S. VIRGIN ISLANDS

by
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with a chapter on
Alternatives of Water Supply

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ABSTRACT

Water for domestic and municipal supply on St. John, in the past, has been obtained from rain catchments, dug wells, and barge shipments from St. Thomas and Puerto Rico. As a result of this study, small ground-water supplies have been developed for the Virgin Islands National Park.

Ground water occurs in significant but limited quantities in the fractured volcanic rock throughout most of the Island. Yield of wells in this aquifer ranges from less than 100 to about 2,000 gpd (gallons per day). The average long-term yield of the three drilled wells in use by the National Park Service in 1967 was about 1,000 gpd. Yield of 1,000 to 5,000 gpd may be expected in the Coral Bay and the Reef Bay areas.

Estimated total recharge of the fractured volcanic rock on St. John, based on a recharge of 1 to 3 inches per year, is 1,000,000 to 3,000,000 gpd. Perhaps as much as a quarter to a third of this water could be developed practically, depending on the rainfall in a given year. The chemical quality of the ground water in the fractured-rock aquifer in areas uncontaminated by sea water ranges from 600 to 2,000 mg/l (milligrams per liter) or more dissolved solids. Water from formations in the higher altitudes is of better quality than that in the lower formations.

Small quantities of ground water are available from beach sand, alluvium, and fractured rock near the sea. However, these sources tend to be brackish and are subject to salt-water encroachment.

There are no perennial streams on St. John. There are a few spring-fed pools in stream channels, however, that are sustained except in severe drought. Storm runoff is estimated to average 1 inch over the island annually, and evaporation from open water surfaces is about 70 inches per year. Ponds can be developed, but because of the high evaporation they may be unreliable during droughts.

Rain water collected in cisterns from roofs and catchments yield about 50 gpd per 1,000 square feet of catch area during an average year of rainfall. This is the main method of water supply for domestic use on the Island; it will probably be continued even if a public distribution system is made available, because of the limited quantity of other natural water.

PREFACE

Water has always been in short supply on St. John, U.S. Virgin Islands. After the collapse of agriculture in the 1700's and early 1800's there was a long period of doldrums, during which water supply became a matter of meeting current, low-level needs. In addition, the means of obtaining water had come to be based on expediency. Increasing population and the advent of tourism brought about the realization that water supply required serious and immediate attention.

Officials of the National Park Service and of the Government of the Virgin Islands, therefore, requested the Water Resources Division of the U.S. Geological Survey to evaluate the extent of the natural water resources of St. John and the alternatives of source and means of water supply. The project started in 1963, and, for the purposes of this report, ended in 1968. The work included test drilling, and monitoring rainfall, ground-water levels, streamflow, springflow, and the chemical quality of water.

Similar studies were conducted simultaneously on St. Thomas and St. Croix. The climate, geology, and hydrology of St. Thomas and St. John are highly similar, and in many cases the findings on one are applicable to the other. Therefore, references to data obtained in St. Thomas are found throughout this report.

The data compiled during this study are available for inspection at the U.S. Geological Survey office in San Juan, Puerto Rico.

The author acknowledges contributions by principals and personnel of the Virgin Islands National Park and of the Department of Public Works, Government of the Virgin Islands. Well drillers Robert Clark, operating under his own name, and Kenneth Bryan, of Boyle Brothers Drilling Company, drilled test wells under difficult conditions. Other people and other agencies provided information and various kinds of assistance.

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Table 1.--Monthly and annual average rainfall, U.S. Virgin Islands [Data from National Weather Service]

Month	Rainfall, inches
January	2.71
February	1.78
March	1.47
April	2.45
May	4.54
June	3.30
July	3.73
August	4.49
September	6.18
October	5.56
November	4.84
December	3.33
Annual	44.38

The direct rays of the sun are hot, but the air temperature is moderate because of the persistent trade wind. The prevailing direction of the wind is east-northeast, but east and southeast winds are common; west winds are rare. Relative humidity averages about 75 percent, and the mean annual temperature is about 27° C. From 1921 to 1967, the highest and lowest recorded temperatures at Cruz Bay, St. John, were 35 and 15°C, respectively. (See fig. 2, in pocket, for site locations.) The hot sun and steady wind produce a high rate of evaporation.

Tropical storms move through the area and occasionally deluge the islands with heavy rain. However, the incidence of direct hits by such storms in recent years is low. The last extensive damage by a hurricane was in 1928.

Land Cover

Most of the island interior and slopes are covered by second growth-tropical hardwoods. But some areas have been cleared for pasture, and some pastures since 1960 have reverted to dense brush cover. Several species of cactus and other plants typical of desert vegetation intermingle with this cover and are especially numerous in dry places, such as East End and Lind Point. Many lagoonal areas are rimmed by mangrove. The beaches are generally bordered by sea grapes, which give way to coconut palms a short distance inland. Figure 3 shows some of the contrasting types of vegetation on the island.

Historical Sketch

The Virgin Islands were discovered by Columbus in 1493 on his second voyage to the New World. At that time, the islands were inhabited by Carib Indians, who had driven out the more peaceful Arawaks. Although the islands were under British, French, and Spanish rule at various times, the Danes and Dutch were the main colonizers. The first permanent settlement on St. John was made by Dutch settlers after the Danish Governor of St. Thomas, with a few soldiers, planters, and slaves, occupied the island in 1717. The island was divided into estates and the settlers prospered.

The main crops were sugarcane and cotton, and the land was cultivated and terraced to the mountain tops. Roads were built and large estate houses with many outbuildings were constructed. Annaberg (fig. 4) was typical of these estates. Its water supply came from dug wells, roof catchments, and a small reservoir on the gut (stream) below Ajax Peak.

The island had a thriving economy during the first third of the 18th century, when as many as 5,000 slaves were engaged in farming and milling. A drought in 1733 destroyed most of the food supply and triggered a slave revolt against the Danes, and plantation agriculture never regained its earlier glory. St. John remained an agricultural island, but with the abolition of slavery and the advent of new sources of sugar and cotton its economy grew weaker. Most of the estates were abandoned in the 19th century, and the island supported a small population of less than 1,000 thereafter.

The United States purchased the islands from Denmark in 1917. The economy of St. John was at a low ebb then, and it remained so until after World War II. In December 1956, the Virgin Islands National Park was established. It has helped to develop tourism, which now is the main industry of the island.

History of Water Supply

Little is known of how the Indians living on

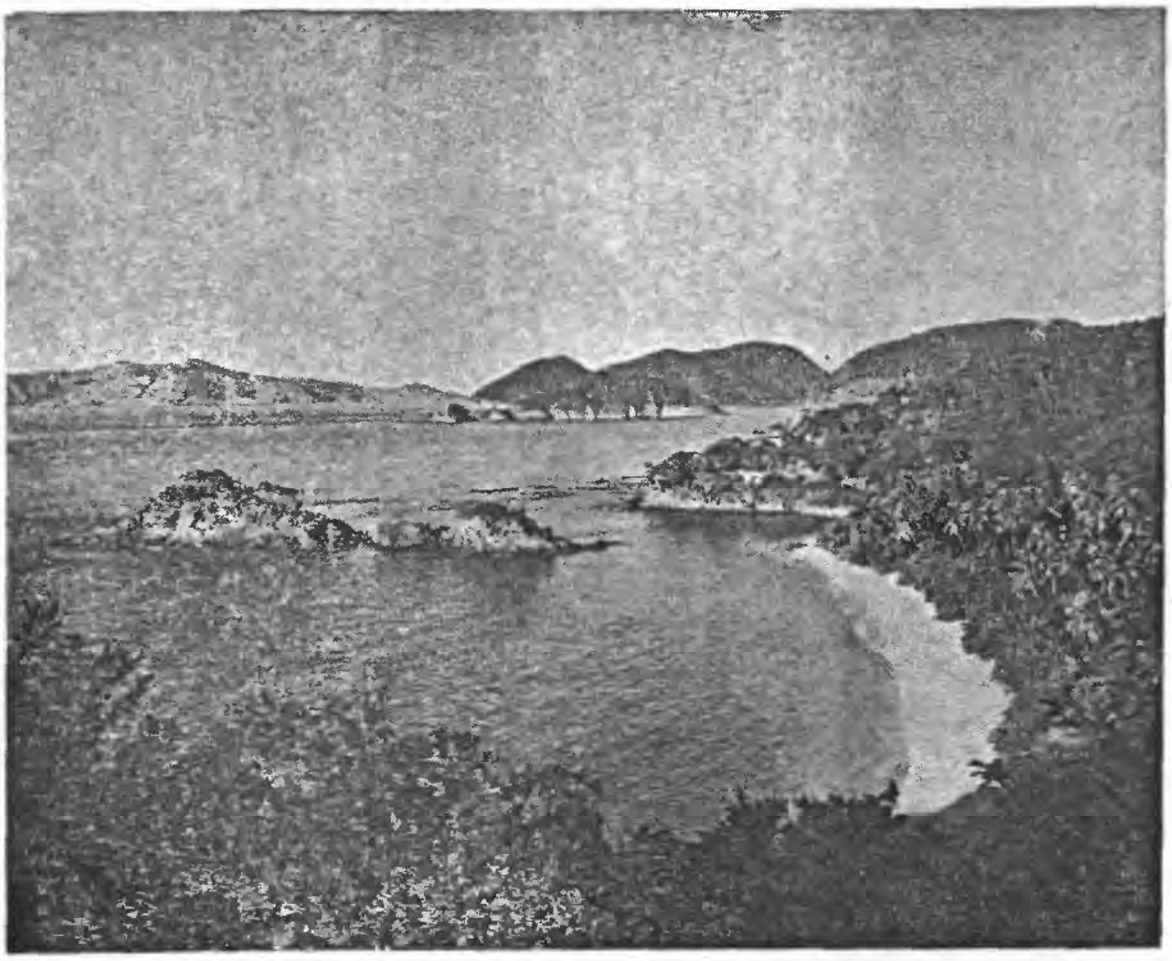


Figure 3.--Land cover on St. John. Above: Trunk Bay, second growth tropical hardwoods on the higher slopes; sea grapes and coconut palms in beach area. Below: Lind Point above Cruz Bay; dry south-facing slope with desert-type vegetation. St. Thomas is in the background. Photographs by National Park Service.

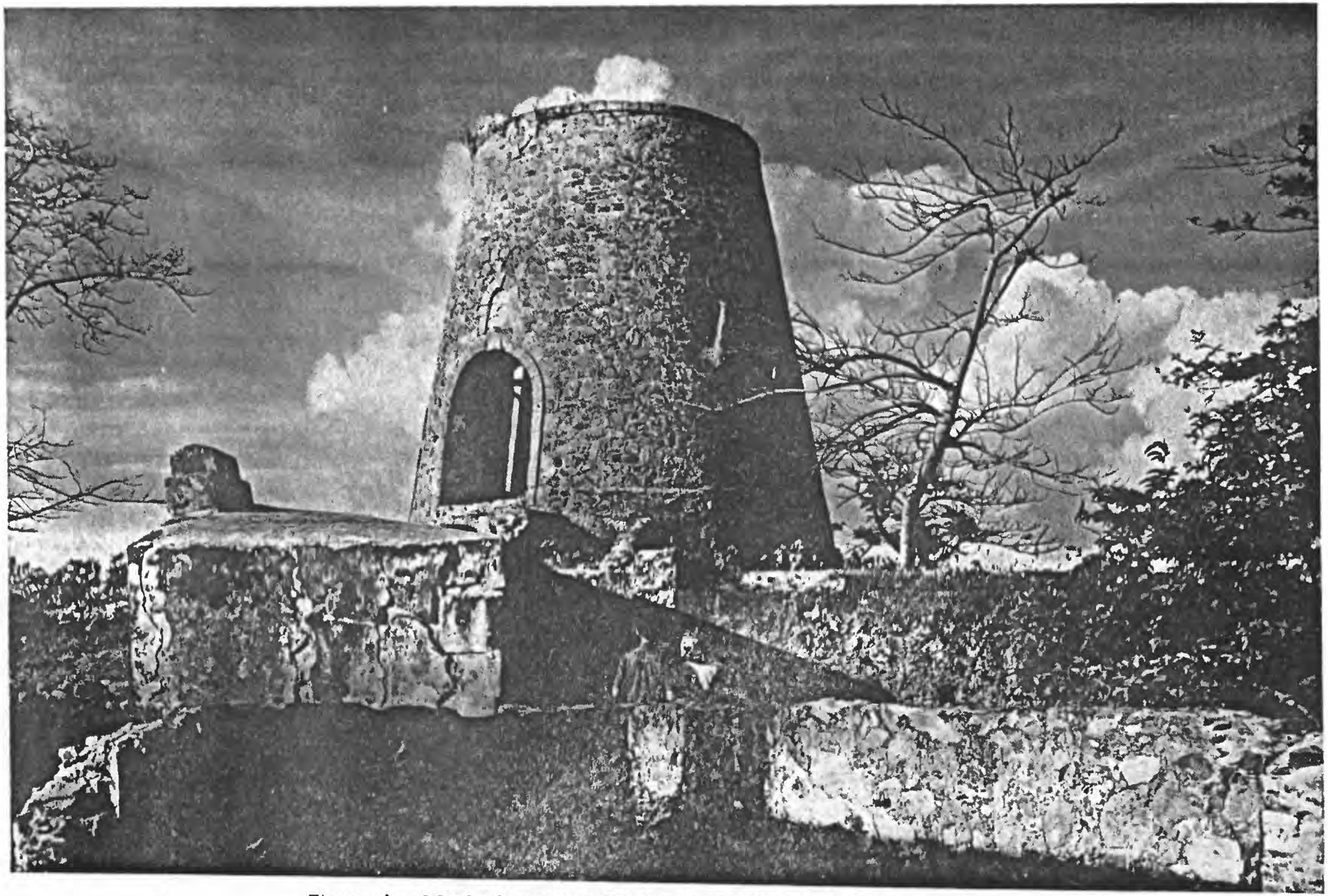


Figure 4.--Windmill tower and bake oven at Estate Annaberg sugar-mill ruin. Photograph by National Park Service.

St. John managed their water supplies. However, potsherds found near the spring at Cinnamon Bay and the petroglyphs at the spring near Reef Bay (fig. 5) show that water supply was an important factor in locating their camps. It is doubted that St. John ever supported a large Indian population because of limited natural water supplies. With the coming of the Danes, settlers of each new estate dug wells and built cisterns supplied by roof catchments. In some places they dammed stream channels and developed springs. However, springs never became substantial sources of water. Many wells were in beach areas and yielded brackish water. That such water was used attests to the fact that adequate water supply was a problem even in those early days.

The Virgin Islands law requires that residences have gutters to collect rainfall and that each dwelling have a cistern. Generally a roof catchment with a proper-size cistern is suitable for careful domestic use. During dry spells, householders must ration their meager water supply.

A small paved catchment and cistern serve the community of Cruz Bay through a few public hydrants. During droughts, water is barged from Puerto Rico to supplement this supply. A few of the old Danish wells are used occasionally for stock water and construction, but most have been abandoned.

Caneel Bay Plantation, a resort with rooms for 180 guests, has a paved catchment with large cisterns, roof catchments, and a 30,000 gpd (gallons per day) sea-water distillation plant (plant operation was discontinued about 1967). Water is barged from Puerto Rico during droughts and periods of high demand.

ENVIRONMENT OF ST. JOHN

Topography and Drainage

St. John is composed of a main eastward trending ridge with steep slopes to the north descending to the sea. In contrast, the south side of the ridge has several prominent spur ridges extending southward from it. Bordeaux Mountain, altitude 1,277 feet, is the highest point on the island and forms one of the spur ridges. Camelberg Peak, altitude 1,193 feet, also forms a spur ridge. The highest point on the main ridge is Mamey Peak, altitude 1,147 feet. East End, a long, irregular peninsula, extends southeastward about 3 miles from the main ridge. Mary Point, 578 feet high, is another prominent ridge connected to the north side of the island by a low isthmus.

The largest drainage basins on St. John are those of Reef Bay Gut and Fish Bay Gut, both of which contain 1.77 sq mi (square miles). Other basins are Coral Bay Gut, 1.69 sq mi, and Guinea Gut, 0.72 sq mi.

The seas separating Puerto Rico and the Virgin Islands (except St. Croix) are shallow. The general topography of the sea floor surrounding the islands is shown in figure 6. The sea floor slopes gently to a depth of 200 to 300 feet close (only a few hundred feet) to the 100-fathom line. Here the sea floor steepens greatly and descends to great depths. This feature is locally known as the drop-off. The 100-fathom line on figure 6 approximates the limits of a larger land mass, of which Puerto Rico and the Virgin Islands are the highest points. The sea floor between the islands and the drop-off probably represents a surface that was developed at the time when sea level was about 200 feet lower than at present. This surface and other erosional surfaces at 280 and 900 feet above the present sea level show that the islands have not been stable in Holocene time.

Villages and Park Installations

St. John has two villages, Cruz Bay on the west end and Coral Bay near the east end (fig. 7), connected by a scenic hard-surface road. Cruz Bay, the larger village, is served by scheduled flying boats and ferries from St. Thomas. Several privately operated tourist facilities are located on the island.

The major beaches in the National Park are

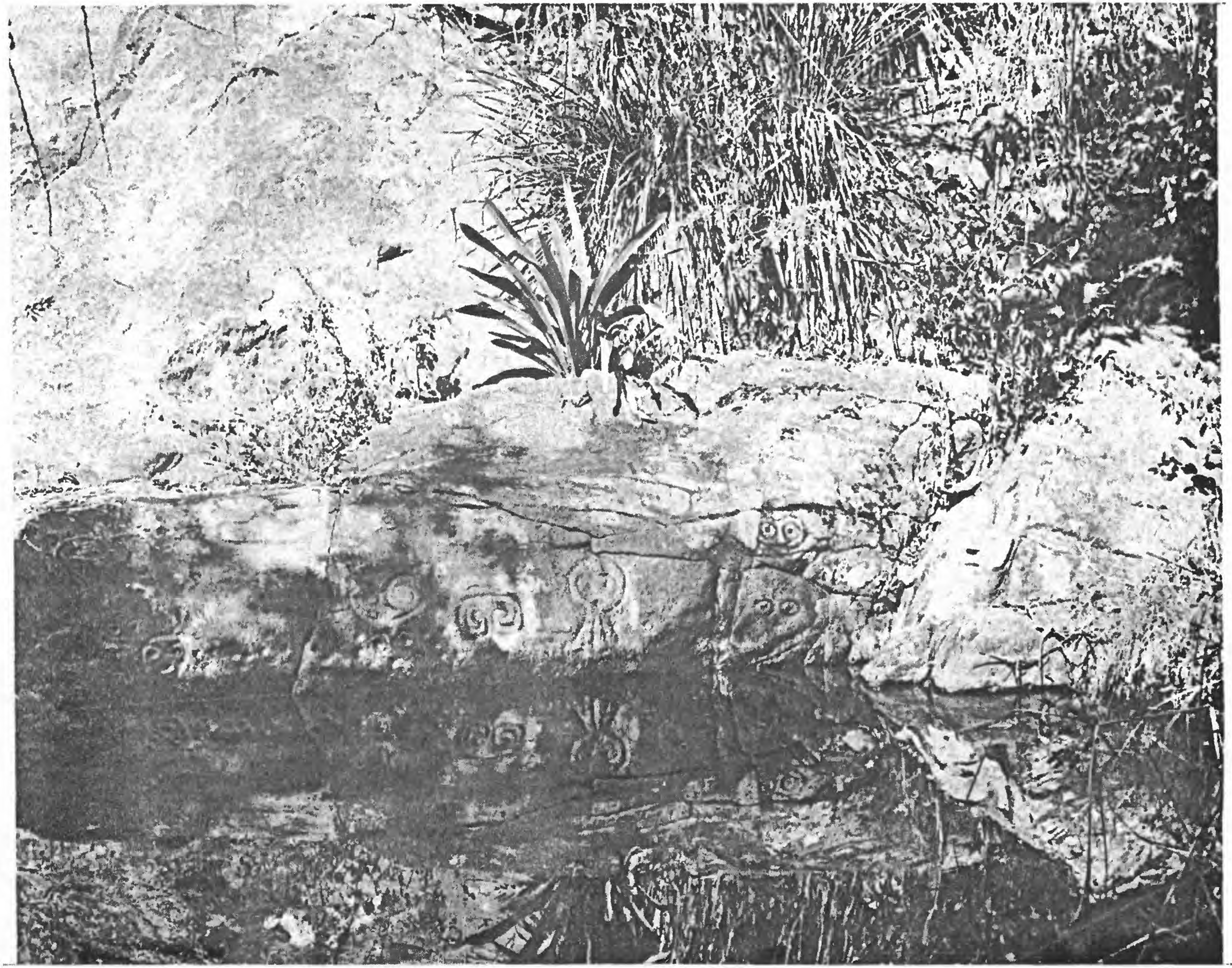


Figure 5.--Petroglyphs in rock face at spring-fed pool in gut above Reef Bay. Photograph by National Park Service.

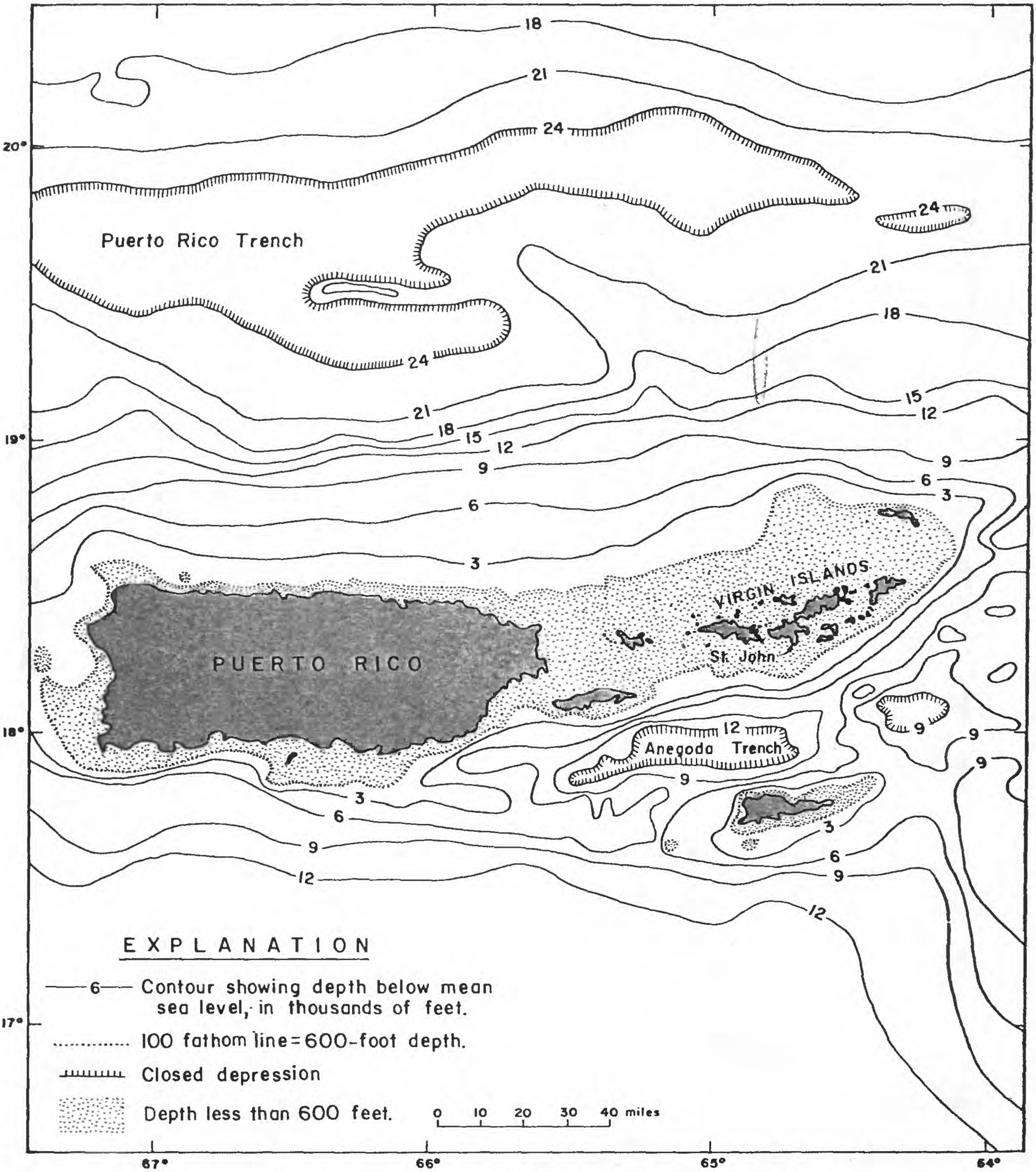
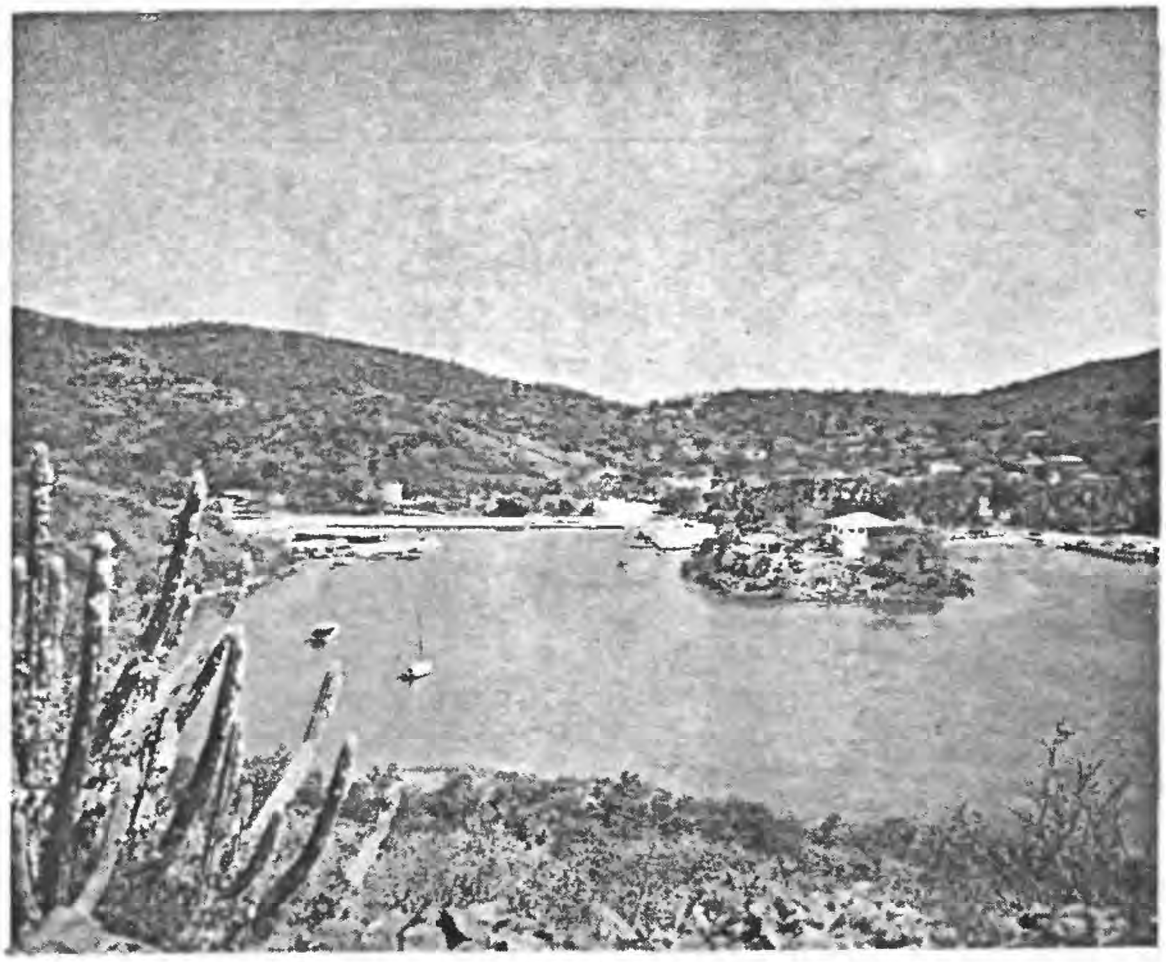


Figure 6.--Bathymetric chart of the Puerto Rico-Virgin Islands area (after Hess, 1966).



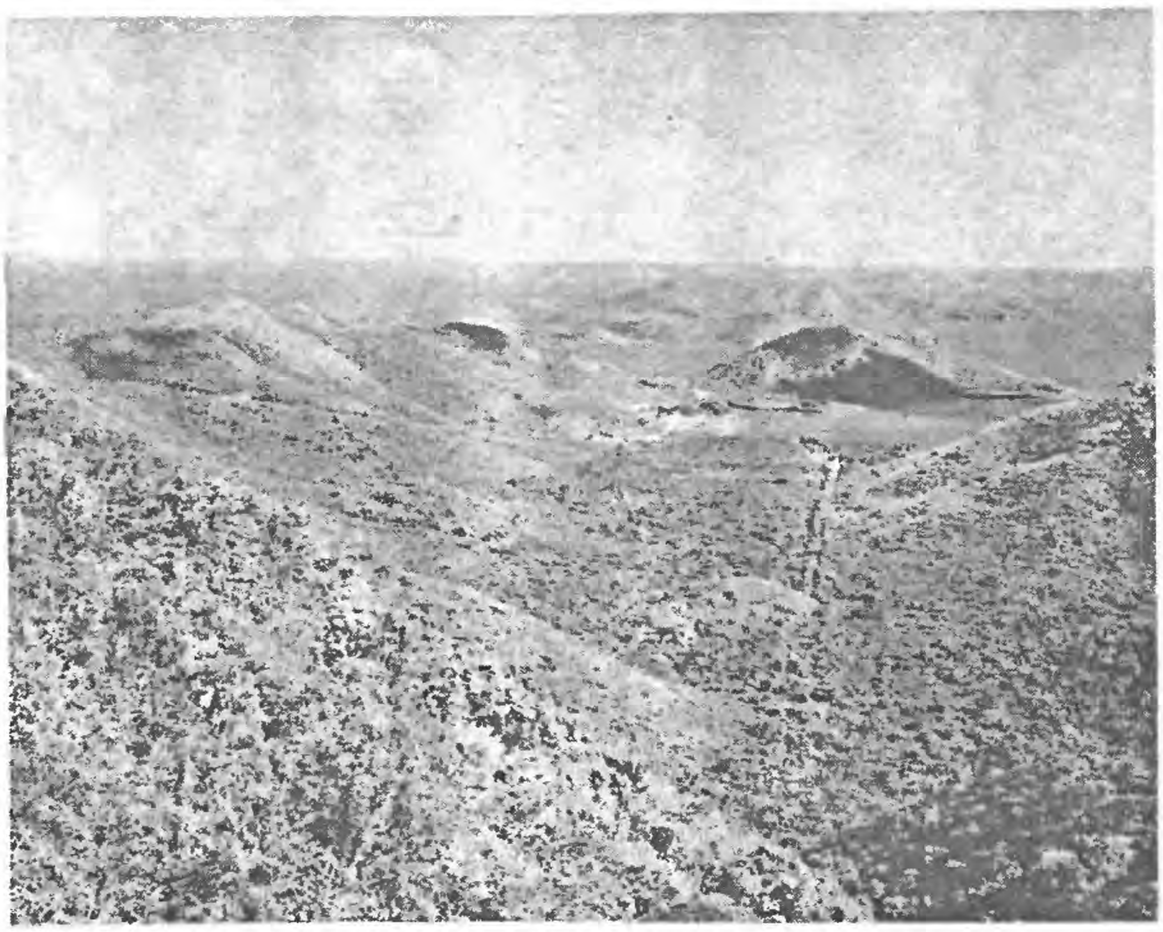


Figure 7.--St. John villages. Above: Cruz Bay; National Park Service visitor's center and marina left of center; Government administration building and post office right of center; public beach and dock far right. Below: Coral Bay from Center Line Road: East End in middle background. The small islands in the far background are part of the British Virgin Islands. Photographs by National Park Service.

along the north shore of the island and are served by a paved road from Cruz Bay. Hawksnest Beach has swimming and picnic facilities. Trunk Bay Beach, considered to be one of the world's most beautiful beaches, has a snack bar and facilities for swimming and picnics. It is also the site of an underwater nature trail, one of the outstanding attractions of the Park. Cinnamon Bay Beach has 43 sites for camping and 16 guest cottages (in 1967). Table 2 gives pertinent information about these and other places in the Park.

How the Islands Were Formed

St. John is composed of layered volcanic rocks, which dip steeply to the north, forming a monocline. Figure 8 illustrates the present geologic setting.

The oldest rocks, the Water Island Formation of Donnelly (1960), crop out along the south slopes of the island. Of uncertain geologic age, but probably Early Cretaceous, they seem to be

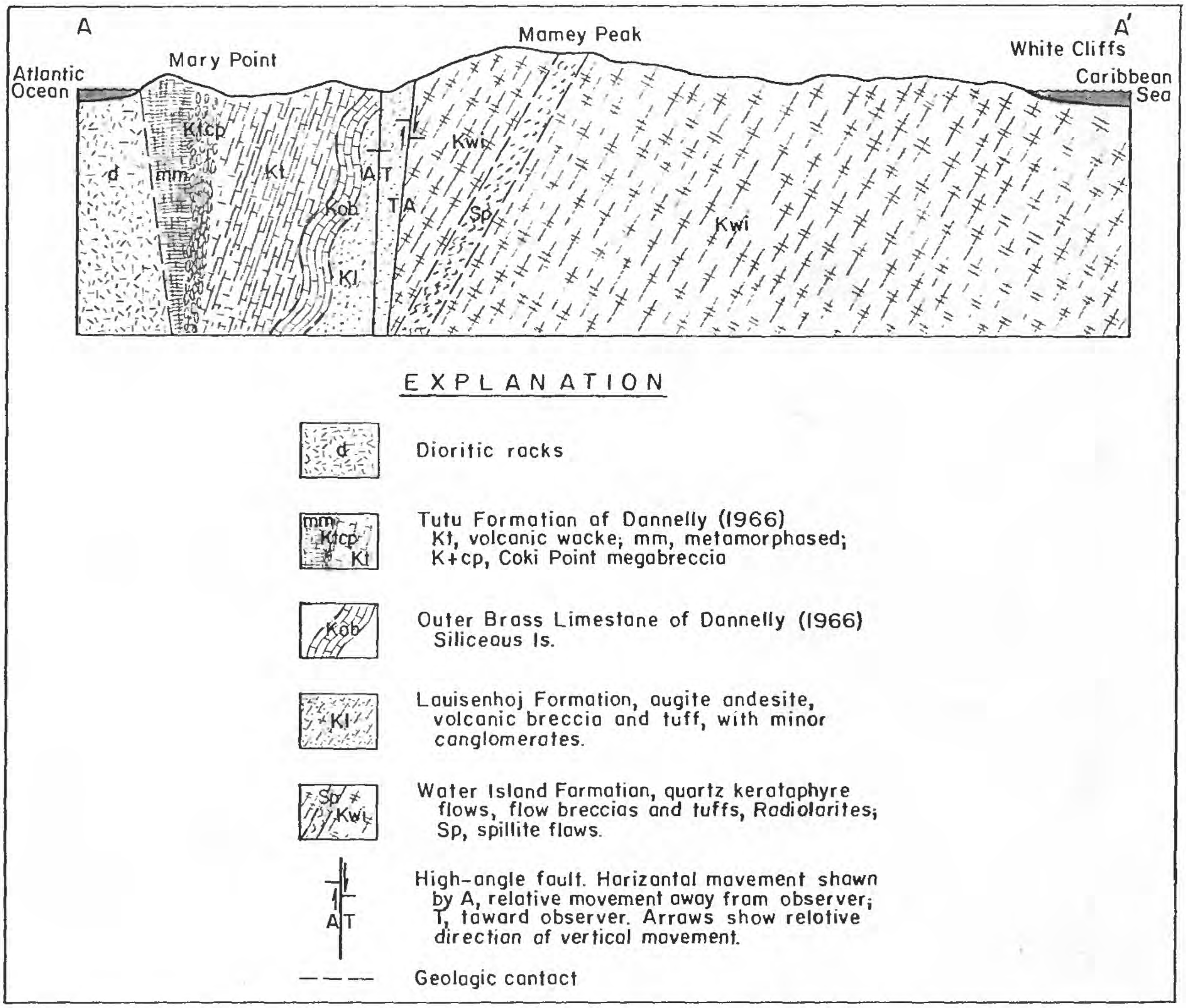


Figure 8.--Geologic cross section of St. John. See figure 2 for location (after Donnelly, 1966).

Table 2.--Points of interest in the Virgin Islands National Park, St. John

Park installations & points of interest	Location	Main access	Facilities & attractions	Water supply
Cruz Bay visitors' center	Cruz Bay	1) Paved road. 2) Boat from St. Thomas.	Visitors' center, comfort station, marina and National Park office.	Cistern supplied by roof catchment.
Hawksnest Beach	North shore	1) Paved road. 2) Boat.	Covered picnic tables, comfort station, swimming.	Cistern supplied by roof catchment.
Trunk Bay Beach	North shore	1) Paved road. 2) Boat.	Snack bar, covered picnic tables, comfort stations with showers, underwater nature trail, swimming.	Wells NPS-5 & NPS-14 supply cistern for snack bar and showers. NPS-16 (dug well) used for flushing.
Cinnamon Bay Beach	North shore	1) Paved road. 2) Boat.	Campsites, guest cottages, commissary, comfort stations, beach showers, swimming.	Wells NPS-9 & NPS-6 supply cistern for campsites, comfort station, commissary, and beach showers. Cottages have roof catchments with individual cisterns.
Francis Bay Beach	North shore	1) Boat. 2) Foot trail from paved road.	Picnic table and comfort station, swimming.	None.
Annaberg	North shore	1) Paved road & jeep trail.	Danish sugar-mill ruin. Picnic table & comfort station.	None.
Lameshur Bay	South shore	1) Paved road & jeep trail. 2) Foot trail from Reef Bay. 3) Boat.	Ranger station, picnic table & comfort station, research station.	Roof catchment & cistern for ranger station. No public supply.
Reef Bay	South shore	1) Paved road & foot trail. 2) Foot trail from Lameshur Bay. 3) Boat.	Danish sugar-mill ruin. Reef Bay spring and petroglyphs.	None.

the initial phase of island building. They were deposited on the sea floor and consist of subaqueous lava flows with associated beds of volcanic debris.

After a period of emergence, erosion, and tilting, another sequence of volcanic rocks, called the Louisenhoj Formation of Donnelly (1960), was deposited during Late Cretaceous time. Unlike the submarine deposits of the Water Island Formation, the Louisenhoj rocks were deposited on the flanks of a volcano and in the shallow surrounding sea. The size of some of the volcanic ejecta indicates a nearby volcanic vent, probably located in Pillsbury Sound between St. Thomas and St. John. Erosion leveled the volcano, forming a smooth plain, and submergence of the land mass followed. On this plain, additional deposits were formed in a shallow sea. They are the Outer Brass and the Tutu Formations of Donnelly (1960), which crop out on St. John, and several younger rock formations, which crop out in the British Virgin Islands to the north.

The rocks were deposited during a 50 million-year period that ended about 70 million years ago. After their deposition, folding and faulting tilted the rocks to their present attitude, and they were intruded by magmas, as indicated by numerous dikes and plutons. The Puerto Rico Trench to the north and the Anegada Trough to the south (fig. 6) were probably formed during these periods of crustal movement.

How Water Comes and Goes on St. John

The movement of water on the earth is identified by the term "hydrologic cycle." Water follows a repetitive pattern that has three storage areas; the sea, the land, and the atmosphere. The sun supplies the energy for the cycle. Water moves from sea and land by evaporation and transpiration to the atmosphere and is returned by precipitation. Water also moves by gravity from the land to the sea. These processes and the storage characteristics of the land determine how much water is available for use by man. Figure 9 shows the cycle as it applies to St. John.

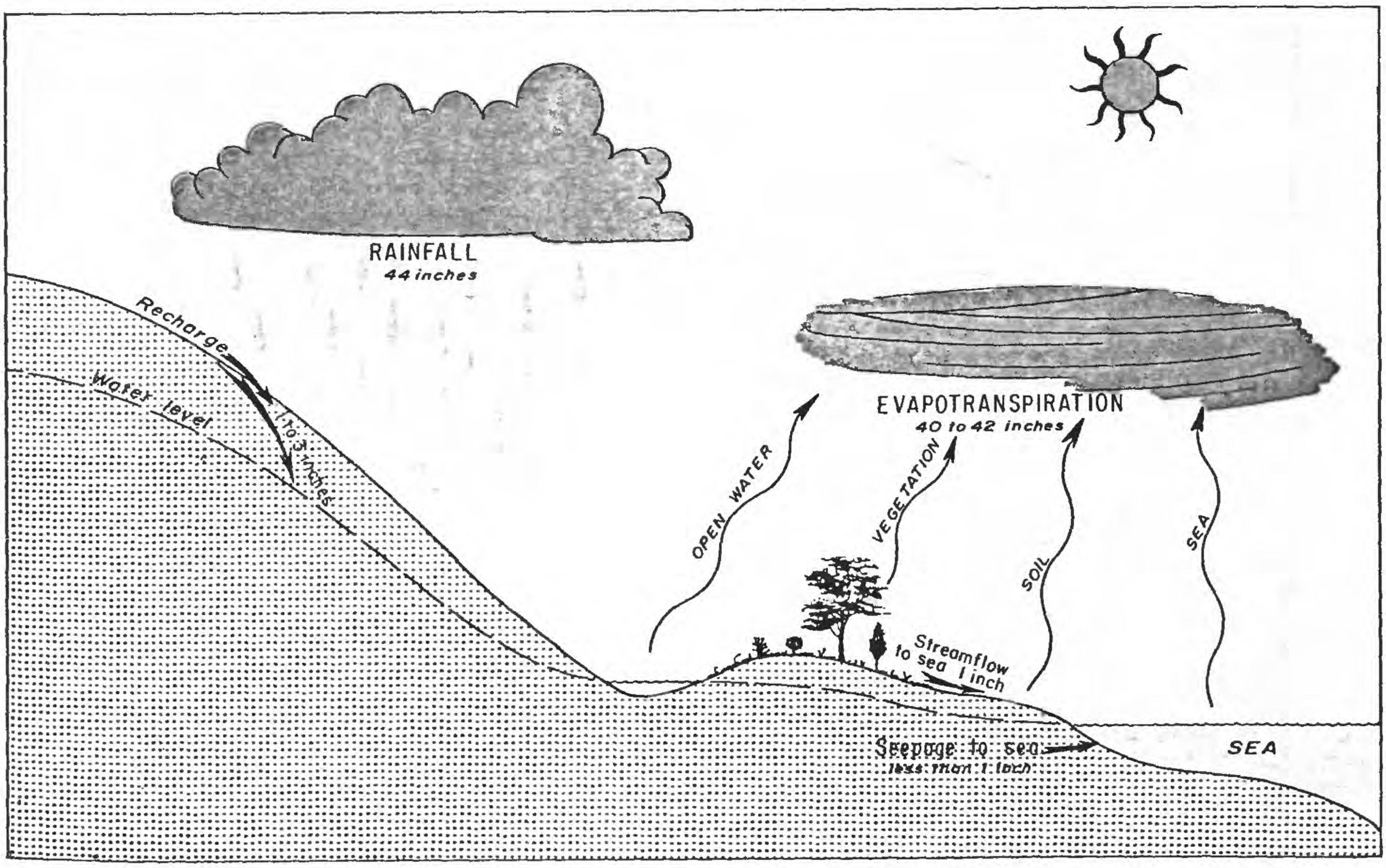


Figure 9.--The hydrologic cycle as it applies to St. John.

Rainfall

Rainfall, the source of all natural fresh water on St. John, averages about 44 inches annually over the island. Much of the rain comes in short showers of only a few hundredths to a few tenths of an inch. Based on National Weather Service records at Cruz Bay, rains of 1 to 2 inches can be expected about 6 times per year; rains of 2 to 3 inches about 3 times in 2 years; and rains of more than 3 inches about once a year. Heavier rains occur less frequently and generally accompany tropical storms.

Soil Moisture

The soil absorbs and temporarily holds most of the rain that falls on St. John. The capacity of the soil to absorb and hold water affects the natural water supply because the soil must be wet before water can move through it to the streams and to the water table. Soil-moisture conditions on the island vary in space and time, so that different amounts of rain are required to wet the soils in different areas. Data from St. Thomas and St. John, however, indicate that the soil can hold at least 2 inches of rain.

Evapotranspiration

Evapotranspiration is active in all seasons of the year on St. John, and accounts for 90 to 95 percent of the rainfall. Probably the greatest part is transpired by the vegetation. It is estimated that one medium-sized tree can take up to 100 gallons of water per day through its roots, if the water is available. The tree then releases most of this water to the atmosphere.

Streamflow

About 2 to 4 inches of the annual rainfall is all that is left for fresh-water supply in the ground and streams. Of this amount, probably less than 1 inch enters the sea as streamflow. The exception to this is surface runoff from severe storms. During such storms, or during a sequence of lesser storms spaced a few days apart, surface runoff may range from 20 to 75 percent of the rainfall. Further information on streamflow is given in the section of this report on surface water.

Ground Water

About 1 to 3 inches of water annually enters the soil and stream-channel deposits. It percolates downward through loose material and into small openings in the rock. The water continues to move downward until it reaches the water table, the surface of which is a subdued replica of the land surface. From there the water moves downgradient toward the sea.

In the hills of St. John, the water table may be as much as 100 feet below the land surface, but generally it is less than 50 feet. At the shoreline the water table is close to land surface, only a little above sea level. Some of the ground water enters the sea, but much of it is used by the vegetation in the valleys and along the shore, where the water table is shallow. Aside from rainfall, ground water constitutes the major fresh and brackish-water source on St. John.

Minerals in Water

All natural waters have some dissolved mineral matter. Water vapor condenses in the atmosphere around dust and minute crystals of various chemicals to develop raindrops. During periods of windy weather, salt from the sea is blown into the atmosphere. Salt particles can be observed by shining a light in the air on a breezy night. The particles reflect the light and appear as a fine "snow." As the rain passes through the atmosphere it absorbs some of the salt; the rain thus contains some mineral matter, as indicated in table 3.

The "washing effect" of rainfall on the air mass has been observed recently in Puerto Rico. Concentration of sea salt in rain diminishes in a downwind direction along the island. This effect likely occurs in St. John also, but not so markedly because St. John is small.

Airborne salt also accumulates on the land surface and on vegetation, and is washed off by rain. Most of the rain that enters the soil is evaporated, and the dissolved salt is concentrated in the soil. During storms, some of the salt is redissolved by rain; part may enter the ground-water reservoir, and part may return to the sea in streams.

Table 3.--Concentration of common chemical constituents in the natural waters of St. John and St. Thomas

Source	Date of collection	Milligrams per liter															Specific conductance micromhos (25°C)	pH	Temperature °C
															Hardness as $CaCO_3$				
		Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids		Calcium, magnesium	Non-carbonate			
Rainfall, St. Thomas	Dec. 1965	--	--	0.34	0.27	3.49	0.14	1	0.96	6.2	--	0.01	--		--	--	27	5.4	--
Guinea Gut at Bethany Church, St. John (base flow)	Jan. 19, 1966	30	0.00	74	77	287		636	66	376	0.5	5.0	1,240		501	0	2,160	8.0	--
Turpentine Run at Mariendal, St. Thomas (storm runoff)	Dec. 10, 1965	18	.04	18	25	50		172	26	59	.3	5.2	319		148	7	530	7.1	--
Well NPS-9 Fractured volcanic-rock aquifer, St. John	July 21, 1966	38	.00	82	50	260		562	38	335	.4	1.1	1,100		410	0	1,900	7.7	--

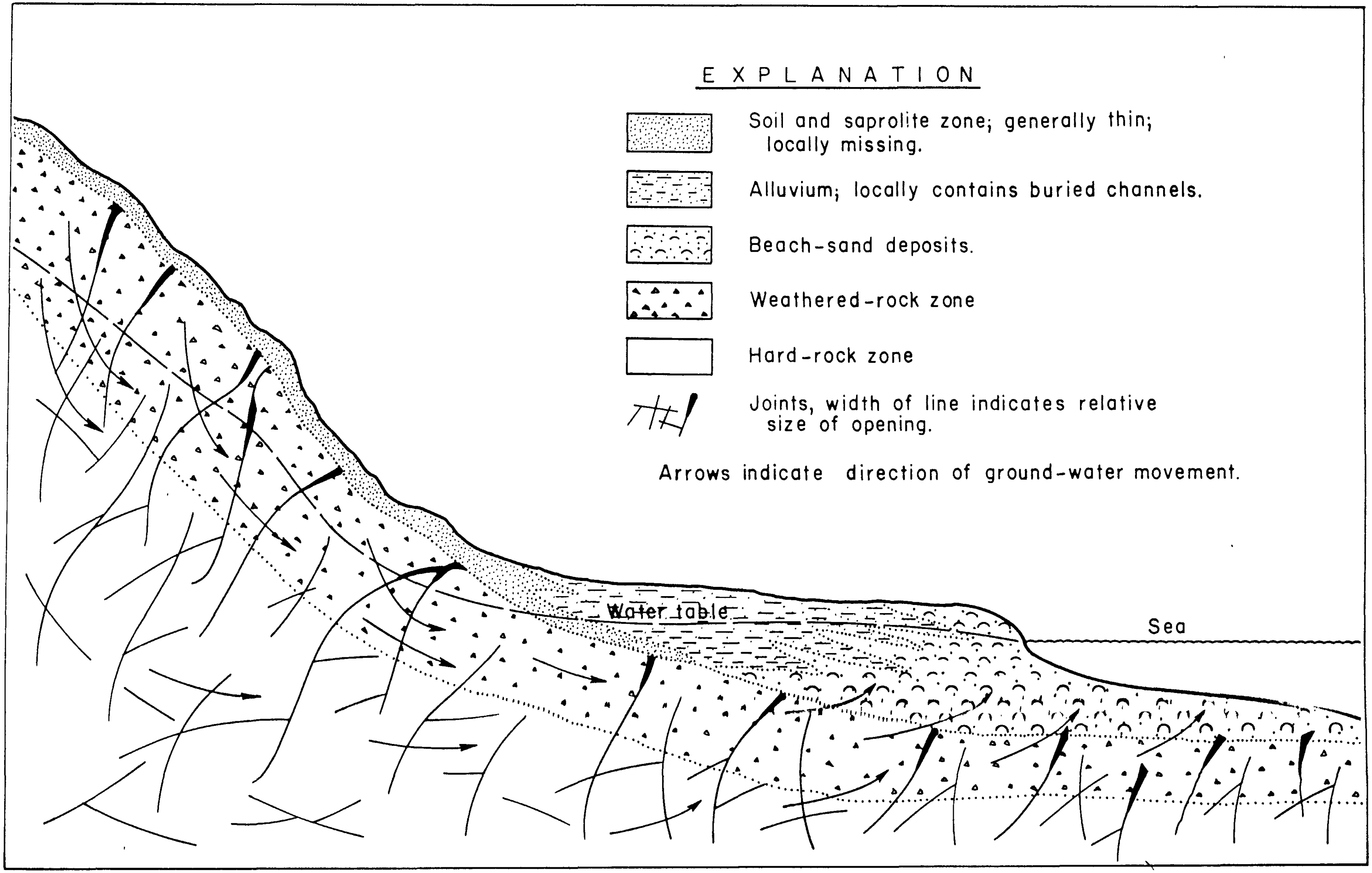


Figure 10.--Geohydrologic rock units and movement of ground water in St. John.

As water moves through zones between the soil and the water table and through the rocks below the water table, it dissolves minerals from the soil and the rocks. Table 3 shows the concentration of common chemical constituents in the natural waters of St. John and St. Thomas. More detailed discussion of the chemical quality of water on St. John is in the section on water sources.

WATER SOURCES

Water in Fractured Volcanic Rock

The most important source of ground water on St. John is the fractured volcanic rock. It is composed of lava flows, water-laid tuffs and breccias, flow breccias, and one interbedded limestone.

The angular volcanic rubble that became the tuff and breccia originally had much pore space, which has been almost totally destroyed. The pore space now in these rocks consists mainly of openings along joints and of openings developed by weathering and solutioning around mineral grains and along joints.

Three geohydrologic zones are recognizable in most fractured-rock aquifers: a zone of soil and saprolite (highly weathered rock); a zone of weathered but still recognizable rock; and a zone of hard, unweathered rock. Figure 10 shows in cross section the volcanic-rock aquifer and its relation to the major hydrologic units on St. John.

The soil zone is the first unit to receive rain water. If the zone is thick and permeable, it will assist recharge to the ground-water reservoir. If it is of low permeability and has little storage capacity, water will run off and enter stream channels. The soil on the slopes of the mountains of St. John generally is thin but highly permeable; in the valleys it is thicker and less permeable.

The saprolite zone is generally absent and, at best, poorly developed on St. John. In most places the soil zone directly overlies the weathered-rock zone.

The weathered-rock zone ranges in thickness from a few feet to 50 feet, as determined from drilling samples. One sample indicated weathering along joints has occurred at a depth of 180 feet. Weathering is important because subsequent solutioning of weathering products tends to open the joints and allows water to pass along them more easily.

The unweathered, or hard-rock, zone contains water along joints, which are more numerous and more open near the surface than they are at depth.

All the major drainage basins of St. John have formed along fault zones and the minor valleys along lesser faults and joint zones. In general, fault zones act as conduits for ground water to move from the head of a valley to its mouth. The rock along a fault may be so pulverized and altered that it is nearly impermeable; but some distance back from the fault, the rock generally is fractured, thus facilitating the movement of water.

Recharge to Ground-Water Reservoirs

Recharge to ground-water reservoirs moves through the soil into the fractured rock and downward to the water table. During heavy rainfall, the soil may not be able to absorb all the water, so some water enters stream channels and soaks into the gravel of the streambed. When rain is sufficient to cause streams to flow, large quantities of water move through the soil and the streambed. Recharge through stream channels probably is more frequent, but the total recharge through the soil probably is greater. This is because the bulk of the recharge to ground-water reservoirs happens after heavy rains that saturate the soil.

Antecedent soil-moisture conditions play a dominant role in recharge. If the soil is dry prior to a rainstorm, recharge may be small even if streams flow, because the water is trapped by the soil and channel deposits and then is transpired by vegetation. The rainfall-runoff ratio for both St. John and St. Thomas indicates that dry soil can receive and hold several inches of rainfall in a period of a few hours.

Changes in ground-water level--that is, changes in the altitude of the water table--indicate that water has either entered or has been removed from storage. By plotting periodic measurements of the water level, the effect of rains, droughts, and pumping can be visualized. Thus the hydrograph of well USGS-16 may be compared with a graph of rainfall near Bethany Church for the same period, as shown in figure 11. During the period of record only negligible amounts of water were pumped from the aquifer, so that the declines in water level were due to natural discharge by vegetation and by flow out of the area. Rises in the water level indicate recharge from rainfall. Levels in well USGS-16 were affected by pumping, however, after March 1, 1967.

During the period of record shown in figure 10, the Virgin Islands experienced a severe drought. Ground-water levels in May 1965 probably were the lowest in recent years. The heavy rain of late May 1965 reversed the downward trend, but the small rise shows that most of the rainfall replenished soil moisture. Lesser rains in the last three months of 1965 had a much greater effect because soil-moisture content was greater at that time.

Movement of Ground Water

Ground water moves downgradient in the same manner as surface water, but at a much slower rate. The velocity generally is from a few inches to a few feet per day. Water in the volcanic rocks must flow in an irregular path following the joints and openings. Traveling downslope, it thus traverses a much greater distance than the direct point-to-point distance.

The irregularity of the path has the effect of decreasing the slope of the water table. The water table beneath steep slopes probably has a stair-stepped configuration, being steeper in areas of few joints and less steep where joints are numerous. Water-level data are lacking to document this situation. Tests of wells penetrating highly permeable zones, however, give results that indicate the movement of large quantities of water, if the apparent point-to-point gradient is used.

In areas where ground water meets rocks of low permeability, it may be forced to emerge at the land surface in springs and seeps. These generally are found along a stream channel, such as Guinea Gut near Bethany Church, Fish Bay Gut, and at the petroglyphs on the west fork of Reef Bay Gut. In some places the water does not reach the surface, but rises in the soil, where it supplies the roots of vegetation. The trees and shrubs remain green during dry spells, while the surrounding vegetation wilts.

Ground water that does not return to the atmosphere by evapotranspiration continues downgradient along fractures in the rock until it reaches alluvium or beach sand near the seashore. Where these deposits are absent, ground water may discharge directly from the fractured rock to the sea.

Wells in the Fractured Volcanic Rock

Two types of wells, dug and drilled, have been constructed in the fractured-rock aquifer. Wells dug by hand generally are 5 to 10 feet in diameter and extend from 2 to 5 feet below the water table. The only wells on St. John before this investigation were dug wells.

A dug well functions much as a storage reservoir. When water is removed, the level of water in the well drops slightly below that of the water table. Ground water then gradually seeps into the well, raising the water level to a position of equilibrium with the water table. Dug wells usually have low sustained yield, but a large quantity of water can sometimes be taken from a well in a short time, if the water level is allowed to recover between withdrawals. Dug wells generally are located where the water table is less than 20 feet below land surface. However, one well on Carolina Estate at Coral Bay was 29 feet deep in 1963 and may have been deeper originally.

Most drilled wells in St. John are 6 to 10

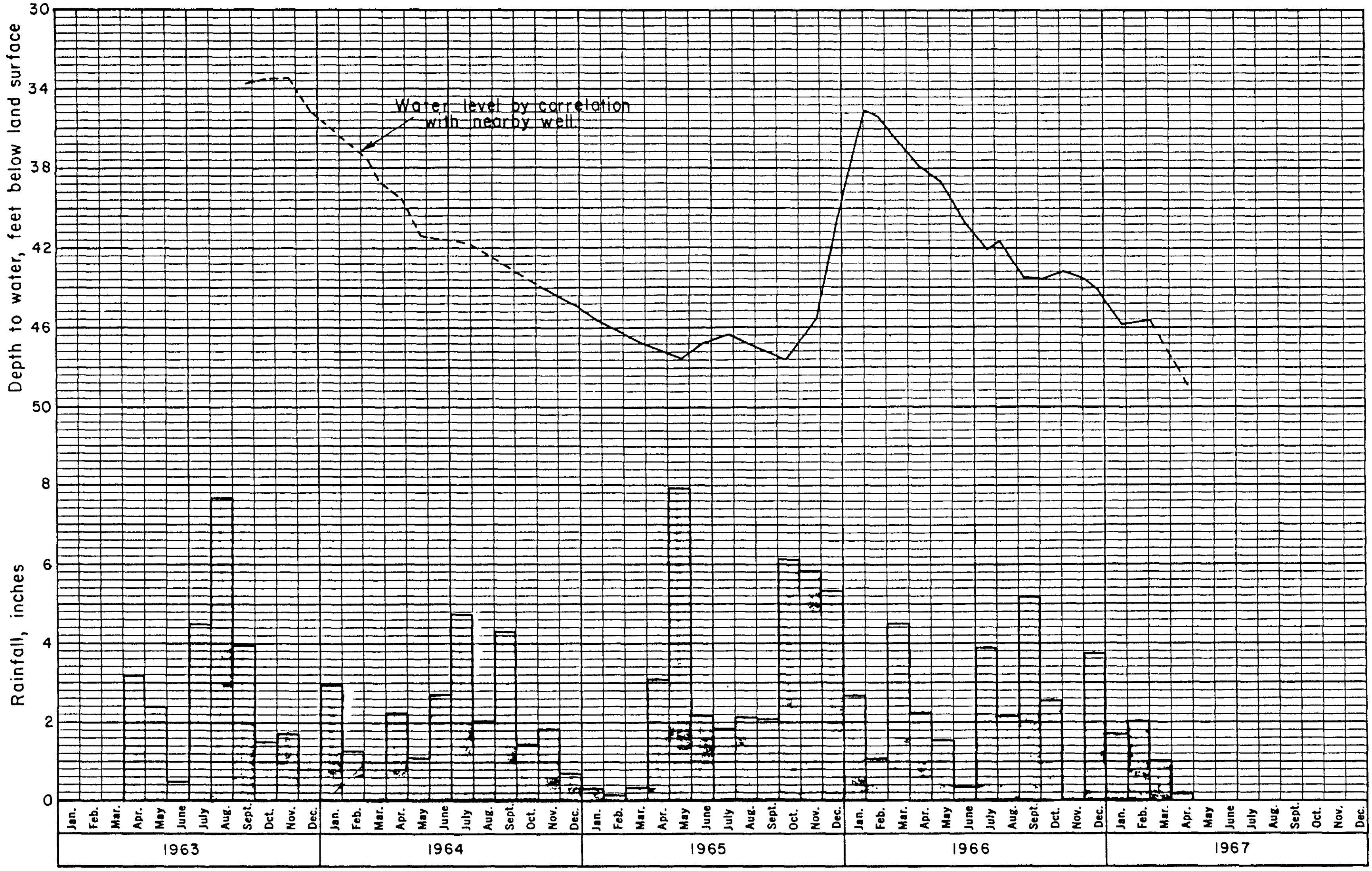


Figure 11.--Hydrograph of well USGS-16 and rainfall at Bethany Church,
St. John. Aquifer is fractured volcanic rock.

inches in diameter, cased with steel pipe to hard rock, and open-hole in the rock below the casing. Water enters a drilled well through joints in the rock and slots in the casing. The well functions when the water level in the well is drawn down below the level of the water in the rock. The difference in head then forces the water through the joints into the well. For this reason wells drilled in fractured rock extend to a considerable depth below the water table to intersect the deeper joints, so that a significant head change can be induced. Joints near the water table generally supply small quantities of water because only a small head differential can be induced by lowering the level in the well. Such a well likely will be a low producer and will function like a dug well, with the hole below the joints providing storage.

Test Drilling

Fourteen vertical test wells and two horizontal test wells have been drilled in the fractured volcanic rock of St. John, up to 1967. In addition, 23 vertical test wells have been drilled in fractured volcanic rock on St. Thomas. Of the total of 37 wells, 4 were dry and 5 had a short-term yield of 1 gpm (gallons per minute) or less. The remaining 28 wells yielded from 2 to 150 gpm in tests lasting from 6 to 72 hours, which points out the high variability of the aquifers.

Vertical test holes have been drilled to depths as great as 220 feet in the fractured volcanic rock of St. John and to 300 feet in St. Thomas. This drilling indicates that ground water generally is found in the first 100 feet below the water table. Zones producing water at depths of more than 100 feet are not as numerous as those at shallower depths. Figure 12 summarizes the data obtained from the test-drilling program. In almost every well, ground water enters through single joints or through joint zones only 1 or 2 feet in thickness. In some wells the position of the lesser-producing zones was not identified during drilling, but their existence was indicated by increased yield after drilling was completed.

Details of test wells and selected other wells in fractured volcanic rock, alluvium, and beach sand are given in table 12 in the Appendix. Although several wells were tested by pumping, the complexity and variability of the fractured rock make the transfer value of the data extremely dubious. The chief usefulness of the tests was in estimating suitable pumping rates for long-term yields. It was found in every case that the wells had sustained yields less than that indicated by the pumping tests.

Two horizontal test wells were drilled in the National Park in 1966: NPS-13 at Hawksnest Bay, and NPS-14a at Trunk Bay, as shown in figure 2. They were drilled by the rotary diamond core method to lengths of 562 feet in NPS-13 and of 803 feet in NPS-14a. The holes were inclined 4° below the horizontal to facilitate circulation of drilling mud.

It was hoped that the horizontal wells would intersect water-bearing fractures that had sufficient head to cause water to flow from the wells. NPS-13 did not produce any water, even though several open fractures were drilled through. They were either non-water-bearing or the head was insufficient to cause water to flow.

The first water-bearing zone in NPS-14a was at 249 feet, and it flowed about 0.2 gpm. Later the well had to be cased, shutting off the water from the surface to 249 feet. The well produced 1,300 gallons per day (nearly 1 gpm) when first placed in production; but the rate dropped to 600 gpd after 4 months of continuous flow. The water from NPS-14a was used to recharge NPS-5 in 1967.

The horizontal drilling was not as successful as expected, and it appears that vertical wells are more practical from an economic standpoint. Eight to ten vertical test wells could have been drilled for the cost of the two horizontal test holes.

Long-Term Yield of Wells

Production data is the most reliable indicator of long-term yield of a well. This involves metering water and collecting water-level measurements over a period of months or years. This has been done on three wells in St. John. Short-term pumping test data, long-term production figures, and estimated long-term yield of these wells are given in table 4.

Records of use have been kept of 3 wells on St. Thomas in the fractured volcanic rock during 1965-67. One well yielded an average of about

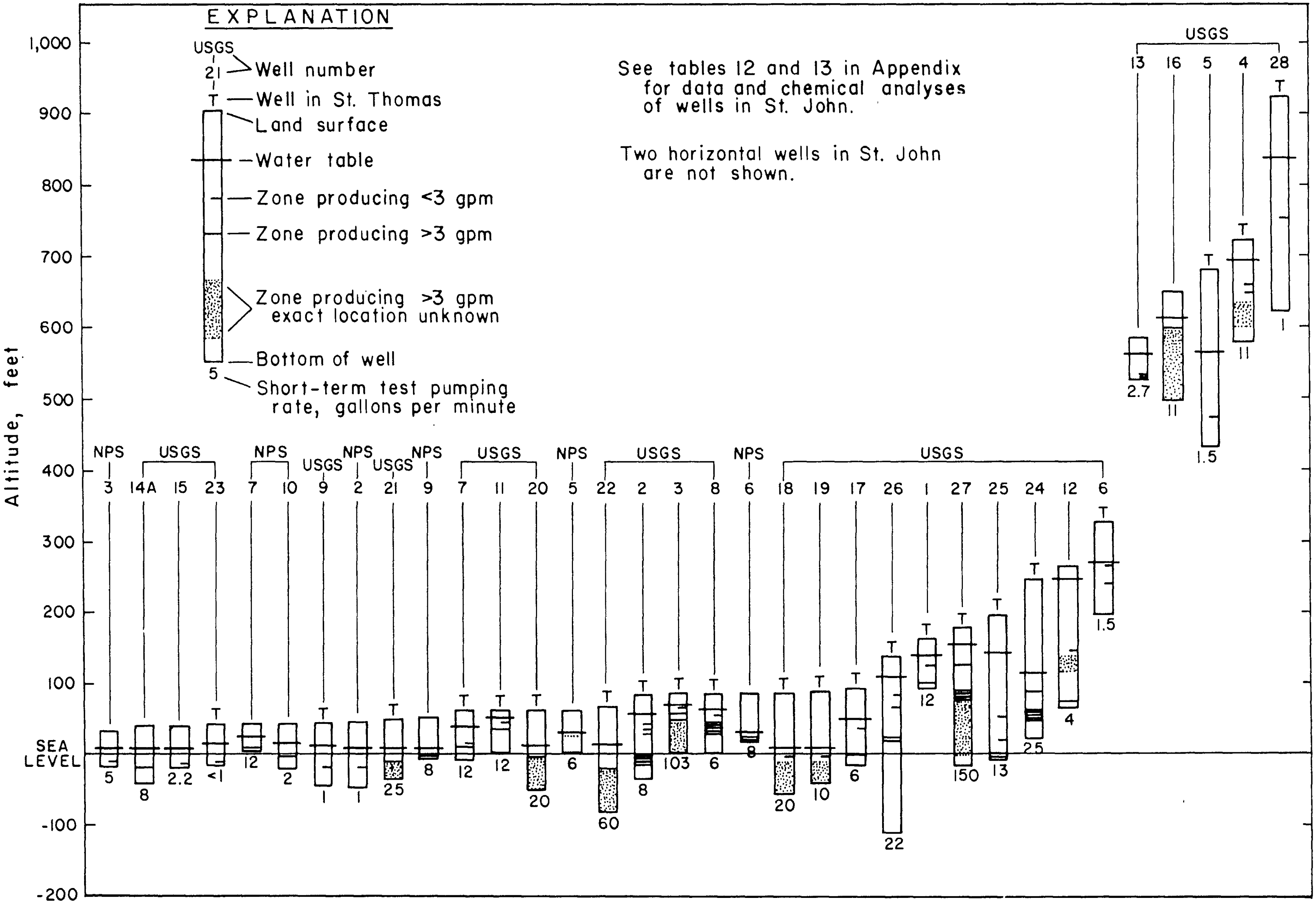


Figure 12.--Producing zones, water-table altitude, and test-pumping rate of test wells in fractured volcanic rock, St. Thomas and St. John.

Table 4.--Test data, water use, and estimated yield for three wells in St. John

Well number & location (fig. 2)	Pumping test rate & duration	Period of pumping	Peak use		Avg. use		Estimated long-term yield, gpd
			gpd	days	gpd	days	
NPS-3 Cruz Bay	5 gpm 10 hr 15 min	5-7-65 to 7-27-67	1,500	9	392	811	400
NPS-5 Trunk Bay	6 gpm 17 hr 9 min	6-30-65 to 7-27-67	4,540	14	1,055	758	1,000
NPS-9 Cinnamon Bay	8 gpm 6 hr	11-6-64 to 7-27-67	4,970	10	1,529	993	1,500

10,000 gpd and during this period. The other 2 wells had estimated long-term yields of 5,000 and 2,000 gpd. These yields point up the possibility of finding higher yield wells on St. John, because the two islands have similar hydrologic characteristics.

Springs

There are several springs and spring-fed pools on St. John. They are of low yield and become intermittent during drought. The spring-fed pool on Guinea Gut, discussed under "Streams", probably has the highest yield on the island. It also is less affected by drought than other springs. In the case of Guinea Gut, much of the base flow is from the spring-fed pool. The base flow of Guinea Gut and the discharge of the spring at Cinnamon Bay were measured regularly during this study. Cinnamon Bay spring discharge is given in the table below:

Date	Flow, gal/hr	Date	Flow, gal/hr
Sept. 15, 1962	78	Jan. 23, 1964	1.3
Oct. 25	75	Mar. 2, 1964 to Aug. 25, 1965	Dry
Nov. 23	75		
Sept. 20, 1963	40	Nov. 12, 1965	2
Oct. 25	150		
		Jan. 4, 1966	2
Nov. 22	130	Jan. 18, 1966 to Dec. 28, 1967	Dry
Dec. 23	62		

Note that the spring was dry during extended periods in 1964 through 1967 and, therefore, is not a reliable water supply.

Quality of Ground Water

The minerals in solution in the ground water come from two main sources, the sea and the land. The sea is the major source of the following: sodium (Na), potassium (K), magnesium (Mg), sulfate (SO_4), and chloride (Cl). Salt reaches the fresh ground water in the interior of St. John indirectly by the accumulation of air-borne sea salt on land surface and plant surfaces. The salt is dissolved by rainwater and carried into the soil. In most cases, the moisture returns to the atmosphere by evapotranspiration, and the salt is concentrated in the soil. However, during and after heavy rain, much of the salt is redissolved and is carried to stream channels and to the ground-water reservoir.

In low-lying areas sea water can mix with the fresh ground water by diffusion, or it can be induced by overpumping.

The salt from the land comes from the chemical breakdown of the rock minerals and from the decay of vegetation. The rocks of St. John, mainly andesitic and basaltic rocks, contain minerals that are rich in calcium (Ca) and silica (Si); and, when weathered, they are the main source of these elements in the water. The respiration and decay of vegetation furnishes bicarbonate (HCO_3) indirectly by producing carbon dioxide (CO_2), which then is dissolved by rain

Table 5.--Concentration, source, and effect of chemical constituents of water in the fractured volcanic rock

Constituent	Concentration, mg/l	Probable source	Characteristic effect on water use
Silica (SiO_2)	Lowest 23, highest 47; usually about 35.	From the chemical decay of rock minerals in the soil and weathered-rock zone. (Not present in sea water.)	May cause scale in pipes, is not an offensive chemical for normal water use. It is in the water as a colloid and not in solution.
Iron (Fe)	Generally absent, 0.02 to 0.05 in wells NPS-5 and NPS-14.	Iron-bearing rock minerals and iron pipes. Usual source is iron pipes.	Stains clothing when laundered; stains fixtures reddish brown.
Calcium (Ca)	Lowest 38, highest 106; usually between 50 & 70.	Mostly from chemical decay of rock minerals in the soil and weathered-rock zone. A small amount from sea salts.	Forms scale in cooking utensils and pipes, and together with Mg causes most of the hardness (see hardness below).
Magnesium (Mg)	Lowest 46, highest 168; usually between 50 & 80.	Same as for calcium.	Same as for calcium.
Sodium (Na) and potassium (K)	Lowest 53, highest 802; usually about 200 to 300.	Mostly from airborne sea salts and sea-water intrusion. A small amount from the chemical decay of rock minerals.	Highly corrosive to metals such as iron when combined with chloride. Is a chemical constituent of common salt (NaCl).
Bicarbonate (HCO_3)	Lowest 272, highest 738; usually 400 to 650.	Dissolved carbon dioxide (CO_2) from the soil zone. The CO_2 comes from plant respiration and decay.	Since CO_2 is a gas in solution, at a high level of concentration it is easily lost by heating or agitation which starts precipitation of $CaCO_3$. This forms scale in pipes and water containers.
Sulfate (SO_4)	Lowest 11, highest 316; generally 40 to 70.	Mostly from airborne sea salts. Higher concentrations from sea-water intrusion. A small amount from the chemical decay of minerals.	May cause laxative effect if water contains high Na and/or Mg concentration. Causes objectionable taste in water at high concentrations.
Chloride (Cl)	Lowest 85, highest 1,250; generally 300 to 600.	Mostly from airborne sea salts. Highest concentrations from sea-water intrusion.	Highly corrosive to metals such as iron. A chemical constituent of common salt. Causes water to taste salty at higher concentrations. Taste threshold varies with individuals and concentration of other salts.
Fluoride (F)	Lowest 0.1, highest 0.6; usually 0.3 to 0.6.	From the chemical decay of rock minerals.	Concentration between 0.6 and 0.8 mg/l in water retards decay of teeth, but in excess of 0.8 may cause mottled enamel in children's teeth.
Nitrate (NO_3)	Lowest 0.0, highest 12; usually 0.0 to 2.	Roots of nitrogen-fixing plants.	Presence may indicate pollution by human or animal wastes. Concentration in excess of 45 mg/l is potentially dangerous for infant feeding.
Dissolved solids	Lowest 612, highest 3,040; usually 750 to 1,400.	All dissolved mineral-matter sources as indicated above.	Used as an indication of water quality. Water containing more than 1,000 mg/l generally has an objectionable taste.
Hardness as equivalent $CaCO_3$	Lowest 317, highest 956; generally between 350 and 650.	Mostly due to Ca and Mg in conjunction with HCO_3.	Increases consumption of soap before lather forms. Hard water forms scale in boilers, hot water heaters, and cooking utensils. Water with less than 60 mg/l is considered soft; 61 to 120 mg/l moderately hard; more than 180 mg/l very hard.

water in the soil. Plants that fix nitrogen in their roots, such as the false tamarind, probably are the main source of nitrate (NO_3) in the water. Since nitrate also is a product of animal and human waste, untested-well water used for drinking could be dangerous.

Table 5 gives the salient features of the common chemical constituents in the water in the fractured volcanic rock. Based on Public Health Service drinking-water standards (1962), the water in the aquifer is of inferior quality, as far as taste and use for cooking are concerned. The mineral concentration in some of the water is high enough to cause laxative effects in sensitive, infrequent users. However, the effect is transitory because people become used to the water in a short time. The water does not contain a toxic quantity of any of the common minerals. Wells may be polluted by septic tanks, pit privies, or by farm animals.

The quality of the ground water in the fractured-rock aquifer is variable, depending on several factors. For instance, water at the higher altitudes generally has less dissolved solids and chloride than water at the lower altitudes. Exposure, topography, and distance from the sea are other factors that probably affect quality. Pertinent data for selected wells on St. John are shown in table 6. Note that the first three wells in table 6 are above 200 feet altitude and are the farthest from the sea (fig. 2). The water from them has less dissolved solids and chloride content than that from any other well on St. John.

The data are insufficient to evaluate each factor mentioned completely, but the following inferences are indicated:

1. Areas that have the least recharge have the poorest quality ground water. Terrain with south and east exposure has less rainfall and less recharge than other exposures and, therefore, tends to have poorer quality ground water.

2. In low-lying areas and areas near the sea, ground water often is of poor quality because of the accumulation of windblown sea salt and, in some places, because of mixing of ground water and sea water aided by tidal fluctuations and by seasonal fluctuation of the water table.

Water from well NPS-9 (table 7) can be considered as typical ground water on St. John, having 964 mg/l (milligrams per liter) dissolved solids. About half of this mineral matter is dissolved sea salt, and half is from the soil and rocks of the island. In contrast, water from USGS-15 has a dissolved-solids content of 3,040 mg/l.

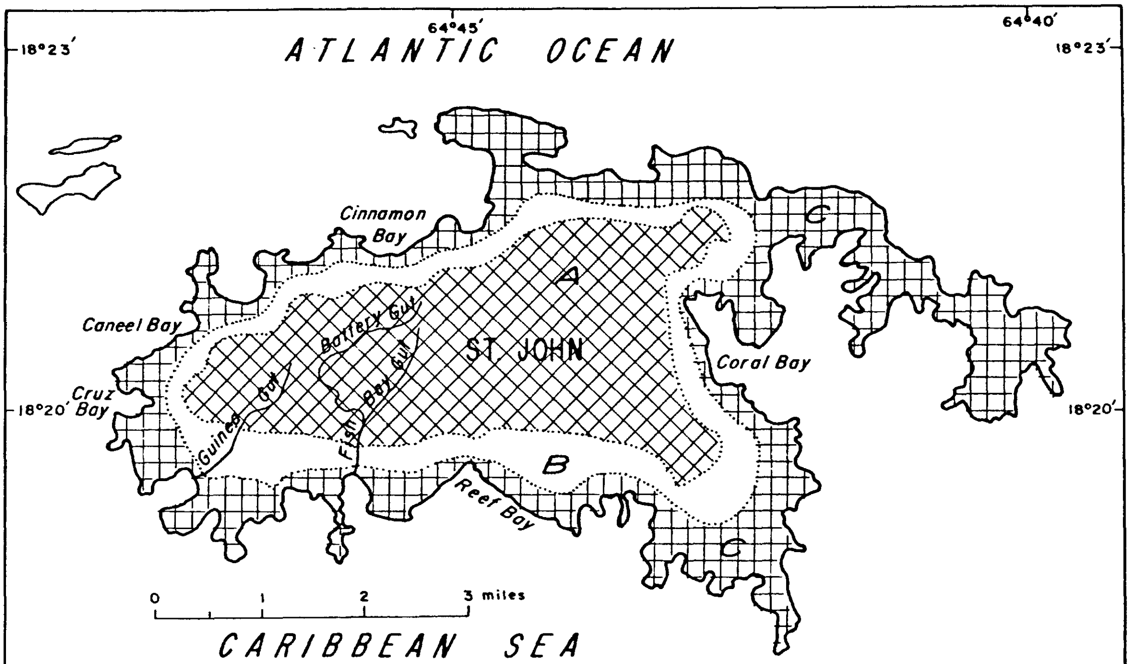
Judging from the high chloride concentration, sea water probably had dispersed into the ground water in the area of well USGS-15, for there was no pumping in the area to cause sea-water intrusion. However, in the areas of wells NPS-9, USGS-13, and USGS-16, the chloride concentration is much lower, indicating no direct intrusion by sea water.

Table 6.--Some factors affecting quality of water in selected wells

Well (see fig. 2)	Topography of location	Exposure of drainage area	Altitude above msl, ft	Distance from sea, ft	Chloride content, mg/l	Dissolved solids, mg/l
USGS-16	Interior valley	Protected	650	3,600	90	817
USGS-13	Hillside	South	580	4,000	222	750
USGS-12	Narrow interior valley	Northwest	220	2,800	85	612
NPS-5	Narrow valley	North	60	800	300	988
NPS-6	Bottom of hill	North	60	1,000	400	1,900
NPS-9	Bottom of hill	North	50	1,100	275	964
NPS-10	Valley	South	40	1,000	1,000	2,380
USGS-15	Bottom of hill	East	40	600	1,250	3,040

Table 7.--Selected chemical analyses of water from the fractured volcanic rock and analysis of sea water

Well	Aquifer	Date of collection	Milligrams per liter														Specific conductance, micromhos at 25°C	pH	Temperature °C
			Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Non-carbonate			
NPS-9	Volcanic rock	10-6-64	36	0.0	58	71	183		504	30	275	0.5	0.0	964	436	23	1,610	8.1	27
NPS-10	Do.	10-30-64	23	.04	70	111	--		544	--	1,008	.3	.9	2,380	631	185	4,090	7.8	29
USGS-13	Do.	8-25-64	23	.0	42	67	180		530	22	222	.3	.0	751	380	0	1,490	8.0	28
USGS-15	Do.	9-22-64	30	.0	106	168	802		738	316	1,250	.6	.0	3,040	956	351	5,080	7.8	29
USGS-16	Do.	10-23-64	36	.0	52	51	161		646	22	90	.6	11	817	339	0	1,310	8.2	26
Source																			
Cinnamon Bay Spring		2-22-63	33	.0	82	48	299		658	25	345	.5	.0	1,160	402	0	2,020	8.1	23
1 percent solution of sea water			--	--	4	14	112		1.5	28	194	.01	--	352	68	67	--	--	--
Sea water (Atlantic Ocean, north coast of Puerto Rico)		1-30-69	.5	--	450	1,380	10,800	399	150	2,750	19,400	1.2	--	35,200	6,800	6,680	48,700	8.1	24



Area A.--Island interior, generally above 200 ft altitude. Drilled wells 100 to 300 ft in depth, bottomed not less than 50 ft below the water table and above sea level, will produce from 500 to 5,000 gpd of water having up to 1,000 mg/l dissolved solids. In the most favorable valleys, such as at Reef Bay and Coral Bay, a few wells may produce up to 10,000 gpd. Locally, where the water table is less than 20 ft below land surface, dug wells will produce up to 500 gpd. (A few drilled wells will be dry or will produce poor-quality water.)

18°15′ 18°15′

Area B.--Island perimeter, generally at least 50 ft above sea level and up to 200 ft above sea level. Drilled wells 50 to 200 ft in depth, bottomed not less than 20 ft below the water table and generally above sea level but in some cases can be as much as 50 ft below sea level, will produce 500 to 2,500 gpd of water having 1,000 to 2,000 mg/l dissolved solids. Locally, where the water table is shallow, dug wells will produce up to 500 gpd. Pumpage must be controlled to avoid sea-water encroachment.

Area C.--Island perimeter, generally less than 50 ft above sea level, but includes high ground on peninsula. Drilled wells generally will be subject to sea-water encroachment, and water contains more than 2,000 mg/l dissolved solids. Water generally suitable for sanitary purposes only. Locally, dug wells will produce small quantities of better quality water.

64°45′ 64°40′

Figure 13.--Ground water in fractured volcanic rock, St. John.

Table 8.--Estimated yield and chemical quality of water from the fractured volcanic-rock aquifer

Area (fig. 13)	Yield, gpd		Chemical quality, mg/l	
	Maximum	Minimum	Chloride	Dissolved solids
A. Island interior generally above 200 feet altitude.	400,000	200,000	80 to 250	600 to 1,000
B. Island perimeter between 50 and 200 feet altitude.	200,000	100,000	200 to 800	1,000 to 2,000
C. Island perimeter below 50 feet altitude.	100,000	25,000	400 to 18,000	Generally more than 2,000

In table 7, the analysis of a 1 percent solution of sea water shows what quantity of the various ions would be added by mixing a small amount of sea water with ground water. The sea-water sample, taken from the ocean at Puerto Rico, should have nearly the same composition as sea water around the Virgin Islands.

Chemical analyses of water from wells in the fractured volcanic rock, alluvium, and beach sand can be found in table 13 in the Appendix.

Ground-Water Areas in Fractured Volcanic Rock

Three ground-water areas in the fractured volcanic rock are shown in figure 13, based on the chemical quality and availability of the ground water. It is emphasized that the areas are generalized and that the location of their boundaries is arbitrary. Note that in area A wells are not subject to sea-water encroachment; therefore, they may have higher long-term yield than wells in area B. The average permeability of rock penetrated below the water surface probably will be higher in area B, but sea-water encroachment is possible under uncontrolled pumping. The ground water in area C generally is susceptible to sea-water encroachment, so that most water will be suitable for sanitary purposes only.

Estimates of yield and quality.--The amount of water that can be obtained from the fractured-rock aquifer of St. John in a truly practical sense is unknown. But technically it might be possible to pump out one-quarter to one-third of the annual recharge. This would be 300,000 to 700,000 gpd, based on the recharge presented in the section "Recharge to Ground-Water Reservoirs" in this chapter.

Estimates of yield and quality have been made for the three ground-water areas, as given in table 8. These estimates are crude and tentative but could be re-evaluated when more experience with wells on St. John is obtained.

More than the physics of ground-water movement and the mechanics of wells, however, is involved in tapping the fractured rock. Factors, such as the cost of a farflung system of wells and pipelines and the esthetics of powerlines and pipelines, also may be important considerations.

Water in Alluvial Deposits

The alluvial deposits on St. John are small, generally at the valley mouths. The alluvial materials in the larger valleys have been reworked and sorted to some extent, thus developing channels of sand and gravel, which later were buried. These channels serve as conduits for ground water. Deposition in the larger valleys has been more or less continuous since the end of Pleistocene time (about 25,000 years ago), with large amounts of sediment being contributed during storms. The amount and duration of runoff during and after storms has been sufficient to clean the fine material from the channel deposits, making them more permeable.

In the smaller valleys, such as those behind the beaches on the north shore, the alluvial deposits are poorly sorted and contain much clay and silt. Deposition in the smaller valleys has been more sporadic. The largest storms lay down a sheet of poorly sorted alluvial material over the whole valley bottom behind the beach. Only slight reworking of this material has occurred because such storms are infrequent and the runoff is of short duration. Figure 14 shows the relation of the alluvium to the bedrock, the beach sand, and the sea.

The upper reaches of the stream channels on St. John have steep gradients. The valleys are narrow, and they are cut into bedrock. Locally, they contain 1 to 3 feet of gravel and boulders. In the lower reaches of the valleys, at altitudes of 60 to 160 feet, the channels have a break in slope, with a noticeable lessening of gradient. At this point a flood plain takes shape. It consists of alluvium that widens and thickens in the downstream direction. The alluvium fills channels that were cut in the bedrock when the sea stood lower in relation to the island than it does now.

The water-bearing alluvium generally is below 100 feet altitude on St. John. The lower valleys of the major drainage basins contain water-bearing alluvium that may be a significant source of ground water. These valleys are outlined in figure 15.

Data are lacking to define the water table in each of the alluvial aquifers. However, water-level measurements in some indicate that the water table at the mouth of the valleys is at or near sea level. The water table extends upstream and has a shallower gradient than the land surface. Thus, the depth to water increases upstream. The stream channels usually are dry, and the water table is from a few feet to a few tens of feet below the channel. The upstream limit of the alluvial aquifer is where the altitude of the bottom of the buried bedrock channel is equal to the altitude of the water table. Upstream from this point the alluvium is above the water table and is dry most of the time.

Ground water enters the valleys by recharge through the stream-channel deposits and by

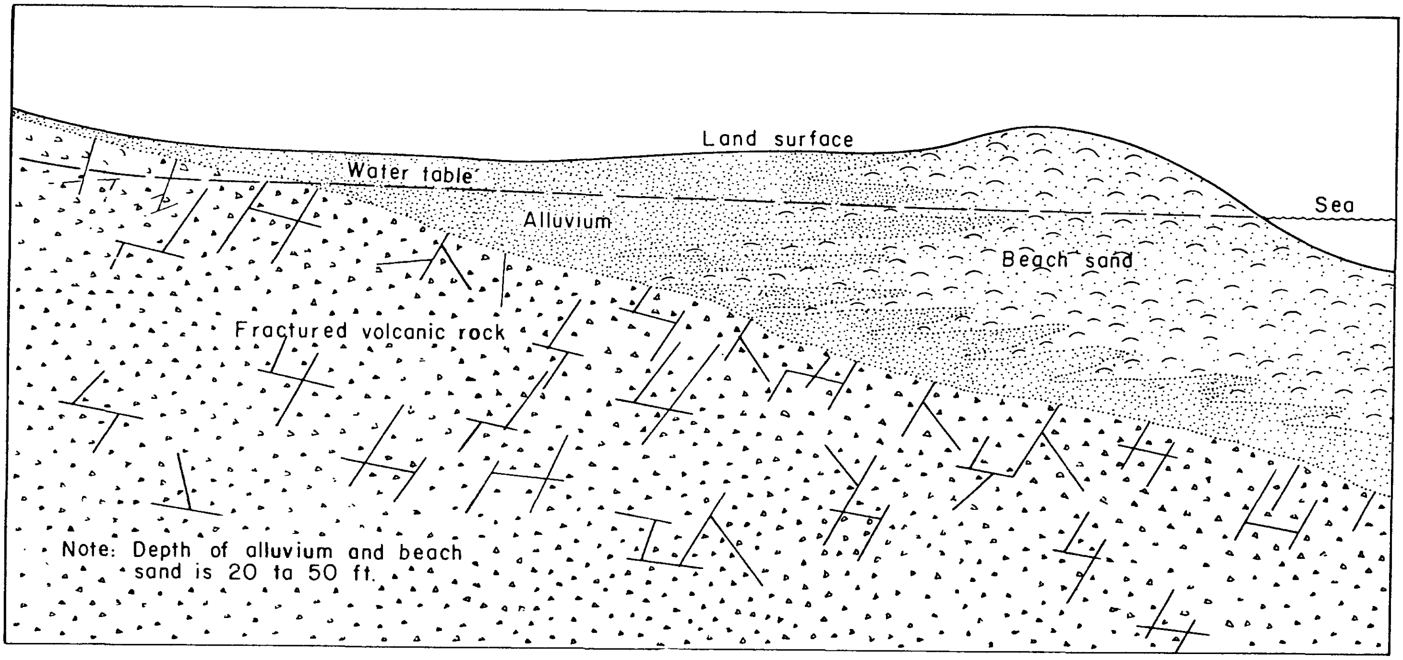
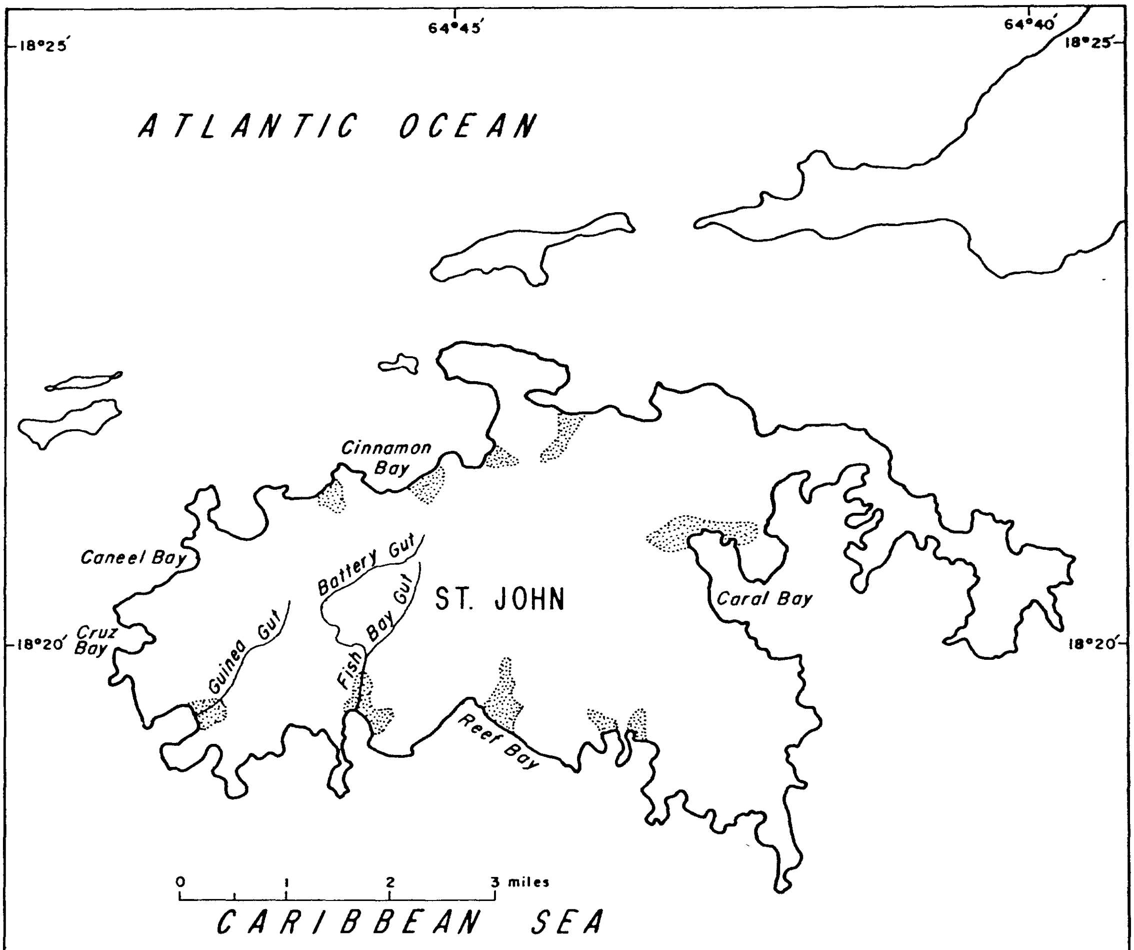


Figure 14.--Diagrammatic section of typical valley and beach area. The geometry of the alluvium and beach sand varies with the evolution and size of the valley above the beach.



Dug wells will yield 500 to 2,000 gpd of good-quality water away from the sea. Drilled wells that penetrate alluvium or beach sands to depths greater than 5 to 10 ft below water table will yield up to 2,000 gpd. Quality will be variable in the beach sands and adjacent alluvium. Wells that bottom at or below sea level are subject to seawater mixing and, if overpumped, to seawater encroachment.

Figure 15.--Alluvial and beach-sand areas that contain ground water.

recharge from floodflows, which occasionally cover the flood plain. Lesser amounts of recharge come from rain falling directly on the flood plain and from underflow in the hard-rock aquifer.

The water in the alluvium moves downgradient toward the sea but only a part of it reaches the sea. This is because the flood plain usually is covered with trees and brush that send roots down to the capillary zone just above the water table. This phenomenon was observed in digging well NPS-11 at Cinnamon Bay. A few roots were found from the surface to 25 feet depth. Between 25 and 26 feet a mat of roots was found. The water table was 26.2 feet below the surface. It is probable that a similar mat of roots is present just above the water table in the other flood-plain deposits of St. John.

Test Wells

Two wells were dug at Cinnamon Bay during the study. One, NPS-11, is 5 feet in diameter and 27 feet deep. It produced 1 gpm of fair-quality water for 2 hours. At a depth of 27 feet, which was less than a foot below the water table, the well was subject to going dry with a slight decline in the water table. It was not practicable to dig the well to a greater depth. Wells dug 5 to 10 feet below the water table probably would produce significant quantities of water.

The other dug well, NPS-12, was a borrow pit dug by bulldozer to a depth of 14 feet. It was converted to a gallery and was filled with cobbles and boulders to the level of the water table. The gallery is capped with a concrete slab, and it has a concrete standpipe. The well has been pumped only for testing, so no long-term data are available. However, the pumping tests indicate it will produce 500 to 3,000 gpd, depending on antecedent recharge conditions. The chemical quality of the water from the well will vary from fair to brackish, depending on surf and antecedent recharge conditions.

McGuinness (1946) made a reconnaissance of St. Thomas and St. John in search of a public water supply for St. Thomas when there was need for 200,000 gpd. He had two test wells dug in alluvium on St. John (the wells no longer exist). The first was at Coral Bay, 1,100 feet inland from the sea. It was 30 feet deep, with saturated alluvium below 27.7 feet; it was pumped dry after 44 minutes at rates from 10 to 84 gpm. The second test well was dug to a depth of 29.5 feet in alluvium, 2,000 feet inland from the sea in the valley of Reef Bay Gut. Water-bearing alluvium was present in the bottom 1.3 feet. The well was pumped dry after 15 minutes at about 34 gpm.

The test pumping of these wells was insufficient to shed much light on long-term yield, and further tests of similar wells at lower rates may be warranted. From these test wells and estimates of natural recharge, however, McGuinness concluded that there was insufficient water in St. John to supply both St. Thomas and St. John. Because of the transmission cost involved, the wells were not considered for use even for the Cruz Bay community, and the rainfall catchment now in use was installed.

Types of Wells

Because of the thinness of the saturated part of the alluvial deposits, and because of their proximity to the sea, large-diameter shallow wells are best suited to develop these deposits. Large-diameter dug wells will produce more water of better quality than drilled wells because it is not necessary for dug wells to penetrate the zone of diffused sea water; and their large storage capacity will function as a cistern.

Drilled wells penetrating a thin section of saturated alluvium will produce only small quantities of water.

Quality of Water in Alluvial Deposits

The chemical quality of the water in the alluvium that is unaffected by sea-water mixing or encroachment is somewhat variable, mainly because of antecedent recharge conditions. The water in the alluvium is a mixture of water recharged directly through stream channels and through the flood-plain deposits, and of water entering the alluvium below the land surface from the fractured-rock aquifer. During droughts, the main source of the water in the alluvium is the fractured-rock aquifer; whereas during wet periods most of the water comes from recharge directly into the alluvium. In general, dissolved solids in alluvial ground water are less than in fractured-rock water; but during droughts the quality of the alluvial water may approach that of the water in the fractured-rock aquifer.

The chemical quality of alluvial ground water near the sea also is affected by intrusion of sea water, which makes the quality of this water extremely variable. For example, the water in well NPS-12 in July 1963 had only 350 mg/l (milligrams per liter) chloride; but water from the same well had 5,350 mg/l chloride in October 1964. A period of high surf preceded the October 1964 sample, causing sea water to move inland. The well is about 300 feet inland from the beach and penetrates only alluvium, but beach sand lies immediately below the bottom of the well.

Water in Beach Sand

The configuration of the beach sands in relation to the alluvial deposits, the bedrock, and the sea is shown in figure 14. The position of the beach sands will vary from beach to beach, depending on the erosional and depositional history of each valley. However, the situation should be much the same for all beach areas of St. John, because sea level has been rising during the recent geologic past. This imposes a limitation on location of beach sand: namely, that it is found not more than about 5 feet above the present sea level. It is thickest in the larger valleys and thinnest in the smaller valleys; the average thickness is estimated to be 20 to 30 feet. The sand is made up almost entirely of shell and coral fragments, and it ranges in size from very fine sand to coarse sand.

The beach deposits in general are loose and uncemented, but locally they may be cemented with calcium carbonate and may contain varying amounts of gravel, cobbles, and boulders derived from the bedrock. The cemented deposits that form at or near sea level along the beach are called beach rock. The beach rock is relatively impermeable, but it contains thin loose sandy layers that are permeable. There is evidence indicating that beach rock forms where fresh ground water discharges to the sea. It is present on several beaches on St. John, one of the best exposures being at Hawksnest Beach, on the north shore of the island.

Recharge to Beach Sand

Beach sand is recharged directly from rainfall and from accumulation of surface runoff behind the beach berm. The sand is permeable and is able to receive large quantities of rainwater, but limited area of exposure restricts the total quantity of that kind of recharge. Locally, ground water discharged from the bedrock and alluvial deposits behind the beach also passes through the beach sand.

Ground-Water Levels

The water table in the beach sand is subject to rapid change in elevation--see the hydrograph of well NPS-15 in figure 16. The water table responds to the tides, high surf, and rainfall. Rainfall causes the greatest change, but the effect is dissipated rapidly, as can be seen by comparing rainfall with the change in water table. The water table usually is a little above sea level, generally less than 1 foot; but after heavy rains the level may be 3 or 4 feet above sea level.

Types of Wells

Two types of wells, driven well points and gallery wells, both shallow, are suitable for development of the fresh and brackish water in the beach sand. Although they may produce 3 to 50 gpm, pumping at lower rates to prevent sea-water encroachment may be necessary. One pumping regimen for wells in the beach sand is pumping for 30 minutes to 1 hour at a low rate, followed by several hours rest. Another regimen would be to pump continuously at a lower rate. This would reduce the chance of salt-water encroachment and would probably produce a greater amount of acceptable water, up to the maximum possible. In effect, the top layer of ground water would be skimmed off.

Quality of Water in Beach Sand

The quality of water in the beach sand is variable, and it deteriorates with depth. Usually there is a thin layer of fresh water from a few inches to a few feet thick resting on top of brackish water, below which is sea water. These water zones are subject to variation in space and time; thus the fresh-water layer may thicken or become thinner, depending on antecedent recharge conditions. Sea water may be introduced to the fresh-water zone during periods of high surf or by overpumping. The fresh-water zone may contain as little as 300 mg/l or less of chloride and as little as 1,000 mg/l or less of dissolved solids

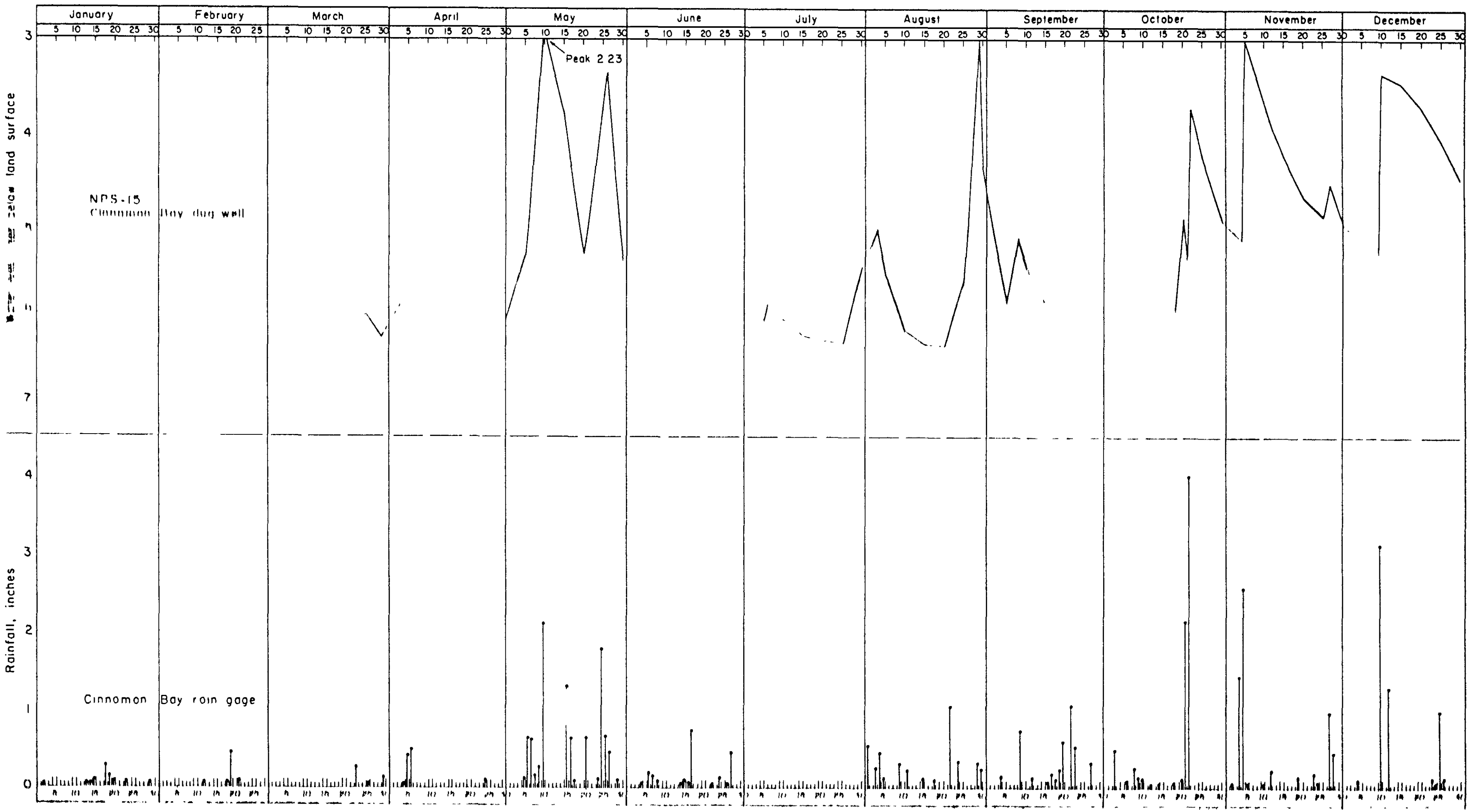


Figure 16.--Water levels and rainfall in beach area at Cinnamon Bay, 1965.

near its surface; but the quality deteriorates with depth to the brackish zone, which starts where the chloride concentration reaches about 1,000 mg/l.

None of the wells in beach sands in the National Park have been used long enough to obtain data on long-term yield and on the effect of controlled pumping on quality. However, short-term data are available for well NPS-12 and for well points at Trunk Bay and Cinnamon Bay.

The water in well NPS-12 contained 350 mg/l chloride in July 1963. The well was not pumped again until October 1964, when it was test pumped on four consecutive days. Rainfall was deficient after October 1963, and several periods of high surf occurred between October 1963 and October 1964. At the beginning of pumping in October 1964, the chloride concentration was 5,350 mg/l, indicating that the quality of the water had deteriorated owing to the drought and to the high surf during the period of nonuse. However, as the pumping continued, the water quality improved, and at the end of the test the water contained 2,830 mg/l chloride.

During one 12-hour period, the well produced 2,500 gallons of water, and the water level declined 1.17 feet. The well was then allowed to recover for 10.5 hours, but the water level rose only 0.24 feet. This small recovery indicates that the well will produce only 500 to 1,000 gpd during droughts. Under more favorable conditions of rainfall, the well may produce 3,000 gpd of water containing less than 1,000 mg/l chloride.

Data from the well-point tests at Trunk Bay and Cinnamon Bay indicate that one well point may produce 500 gpd or more. However, this water would be subject to quality changes similar to those described above for well NPS-12.

Water from Rain Catchment

Rainfall can be collected from any impervious surface such as roads, roofs, airport runways, or catchments constructed for the special purpose of collecting rainfall (fig. 17). All these surfaces have been used for collecting potable water in the Virgin Islands. It is only necessary to provide collection apparatus, such as gutters and piping, and adequate storage facilities, such as reservoirs and cisterns. In fact, the catchment method of water supply is used on St. John today and presently is the major source of potable water. Whether more catchments will be constructed is a management decision based on evaluation of alternatives. (See the last chapter.)

Few catchment systems are leakproof. In addition, some rain is evaporated from the catch surface. Chinn (1965) recorded 93-percent recovery of rainfall from an experimental asphalt-paved catchment in Hawaii the first year of operation. However, after two additional years of operation, the catchment surface had deteriorated, and recovery dropped to 78 percent because of leakage through the surface. The author made a study of the West Indian Company catchment in St. Thomas in which the average recovery was 65 percent of the rainfall, considerably lower than the figure reported for the Hawaii catchment.

The above discussion points out the variability of catchment efficiency. The 65-percent recovery from the West Indian catchment possibly indicates leakage. Since there are no data available in the Virgin Islands on the recovery from a tight catchment, it is necessary to make estimates. The figure of 70-percent recovery is used by some local builders and engineers. It is conservative for a watertight system in the opinion of the author, and it was used in the computations that follow, for the want of a more accurate figure.

The size of the cistern (storage tank) in relation to the size of the catch area is an important factor in utilizing the yield of a rain catchment. During wet periods, a too-small cistern would overflow, and water from the catch surface would be wasted, whereas a larger cistern would be able to store most or all of the water. The practical size for a cistern for any period can be determined from a mass curve of rainfall. However, the indicated size will vary, according to rainfall distribution in time and whether the rain in the period used to develop the mass curve was above average, below average, or average. In computing the size of a cistern, the assumption is made that use of water from the cistern will be at a constant rate. Of course this is not always the case, so the size of a cistern may be determined by the regimen of use, as well as by the amount and frequency of rainfall.

In Chinn's study, the average runoff from the experimental catchment was 118 gpd per 1,000 square feet of catchment. From a mass curve of rainfall, he determined that a cistern equal in volume to one-third the annual catch would suppl[y] this amount.

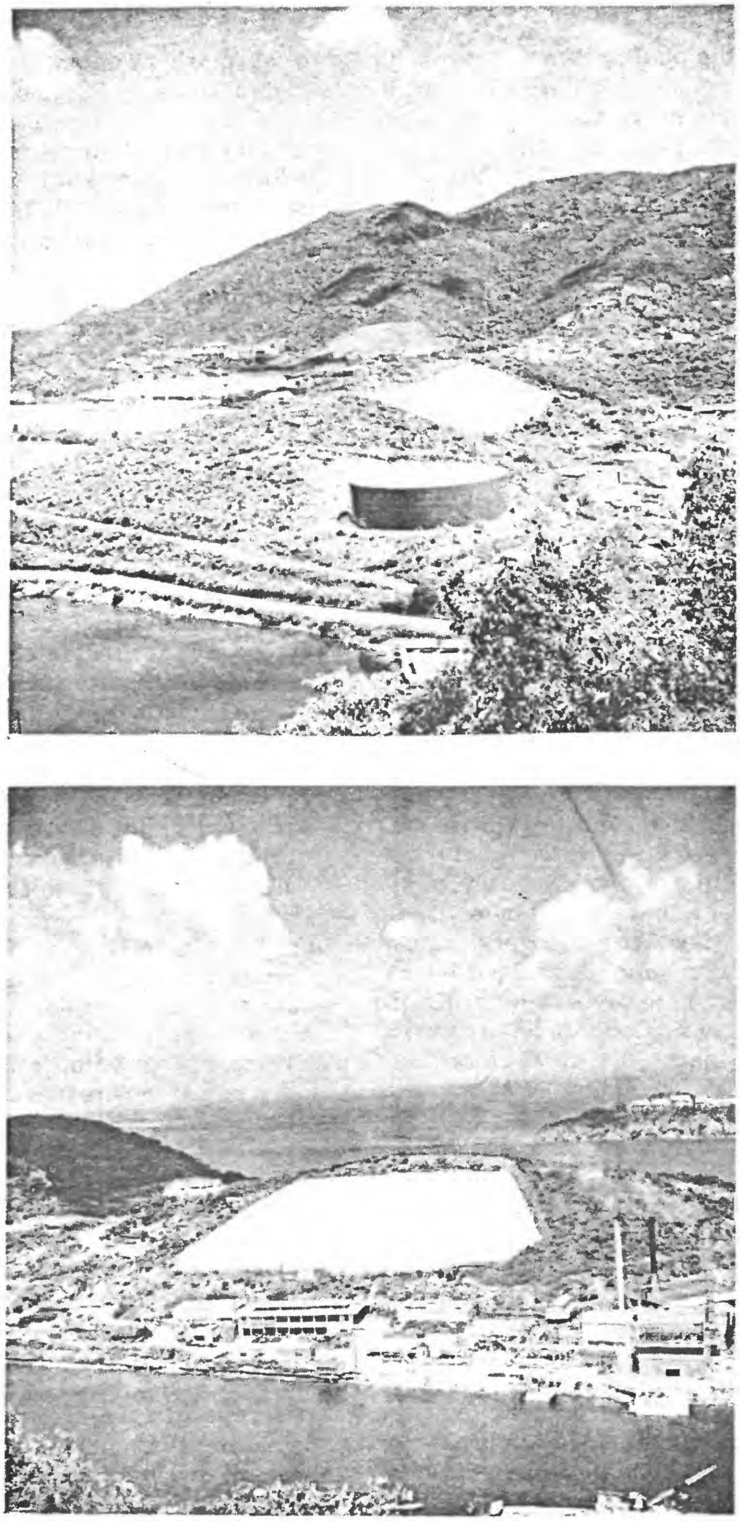


Figure 17.--Rainfall catchments in St. Thomas, Virgin Islands. Above: one of Sara Hill near Krum Bay, in middleground; one on lower slopes of Crown Mountain, in background. Below: catchment near desalting and power plants, Krum Bay.

The author made a mass curve of rainfall at Charlotte Amalie, St. Thomas, for the 10-year period 1955-64. Assuming 70-percent efficiency, computations based on the mass curve indicate that the average runoff would have been 48 gpd per 1,000 square feet of catchment and that a cistern equal in volume to the annual catch would be required to supply this amount. For comparison, the table below shows the yield of various-sized cisterns during this same period.

Size of cistern, percent of volume of annual catch	Yield in gpd from 1,000 square feet of catchment
20	41
33	46.4
50	47.5
67	48
100	48.5

These figures indicate that little is to be gained by constructing a cistern larger than one-third the annual catch, if water is to be used at a constant rate.

The Virgin Islands code requires that a cistern with a volume of 10 gallons per sq ft (square foot) of roof area be constructed with each new dwelling. Assuming a catch efficiency of 70 percent, about 50 gpd (18,500 gal per yr) of water per 1,000 sq ft of catch area, can be obtained during an average year of rainfall at Cruz Bay, St. John. The cistern volume required by the code is about 54 percent of the average annual catch.

Chinn (1965) developed a nomograph that has been modified slightly to fit the range in values expected in the Virgin Islands (fig. 18). The average catch from various-size catchment areas can be determined from figure 18 if the average annual rainfall and the efficiency of the catch system is known; or catch efficiency can be determined if the average use rate, area of catch, and average rainfall are known. Cistern size for 1/5, 1/3, 1/2, 2/3, and all of average annual catch also is given. Its use is shown by the following samples.

Example A.

Given: Rainfall = 50 inches per year
Efficiency of catch system = 80 percent
Roof area = 3,000 sq ft

To find: Yield
Storage volume for 1/3 annual yield

Solution:

1. Draw a line from 50 inches on R scale (fig. 18) through 80 percent on the E scale and project line to locate a point on pivot line.

2. Draw a line from pivot point through 3 (for 3,000 sq ft) on the A scale and extend it to intersect the Q scale.

3. Read the average yield 200 gpd on the Discharge scale.

4. Draw a horizontal line from this point to the 1/3 year storage scale and read necessary storage 24,000 gal.

Example B.

Given: Rainfall = 45 inches
Efficiency of catch system = 80 percent
Desired yield = 100 gpd

To find: Area of roof catchment
Storage for 2/3 annual catch

Solution:

1. Draw a line from 45 inches on the R scale (fig. 18) through 80 percent on the E scale and project the line to locate a point on pivot line.

2. Connect the pivot point with 100 gpd on the Discharge scale.

3. Read the required area 1,700 sq ft where the line crosses the Area scale.

4. Extend a horizontal line from 100 on the Discharge scale to the 2/3 year storage scale and read necessary storage 24,000 gal.

Water in Streams

Storm runoff rushing down a narrow gut after a heavy rain on St. John is impressive, and the question often is asked why this water is not stored in reservoirs and used for public supply. It is evident from casual observation that some water could be obtained in this manner, but the hydrologic studies conducted on St. John and the other Virgin Islands show that casual observation can be misleading.

Streamflow in Guinea Gut below Bethany

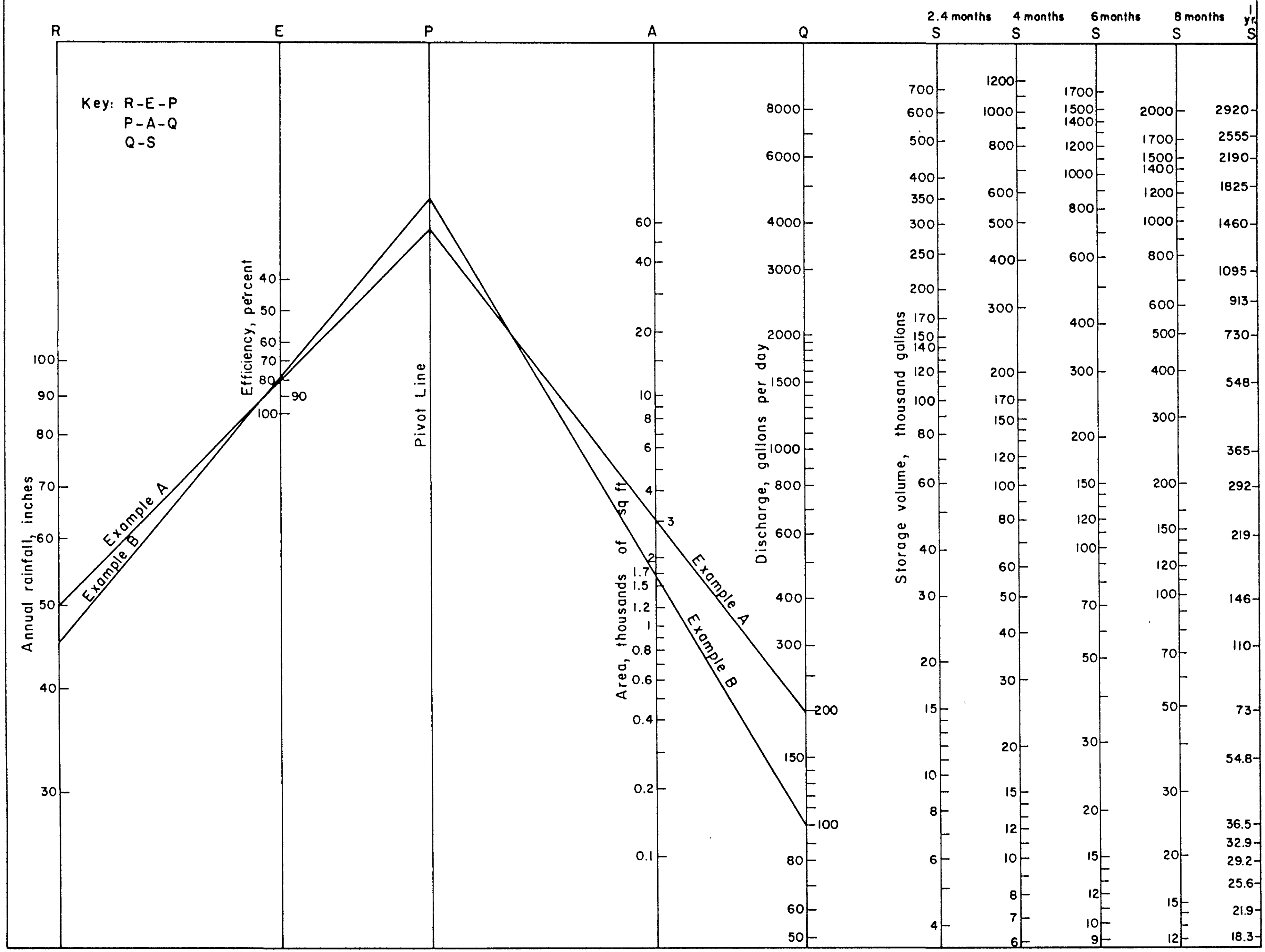


Figure 18.--Nomograph of rainfall and runoff from catchments, U.S. Virgin Islands (modified from Chinn, 1965).

Table 9.--Storm rainfall and runoff at gages on Guinea Gut at Bethany Church. Drainage area 0.37 square mile

Storm		Direct runoff		
Date	Rainfall, inches	Gallons	Inches over basin	Runoff/Rainfall, percent
Apr. 5-9, 1963	2.6	290,000	0.045	1.7
July 6-7	2.0	4,300	.00067	.03
Aug. 27-29	4.4	2,200,000	.335	7.7
Sept. 6	1.4	3,700	.00058	.04
Sept. 26-27	1.6	3,500	.00054	.03
July 1, 1964	1.7	5,900	.00092	.06
Apr. 5-6, 1965	2.2	15,000	.0023	.1
May 8-9	3.2	1,800,000	.28	8.7
May 24-25	1.9	1,900,000	.30	15.9
Oct. 20-21	4.0	340,000	.053	1.3
Nov. 3-4	2.9	2,800,000	.44	15.1
Nov. 25	1.5	93,000	.014	1.0
Dec. 9-12	3.7	1,400,000	.22	6.1
Jan. 12-13, 1966	1.7	84,000	.013	.8
Mar. 19	3.1	79,000	.012	.4
Mar. 22	.5	24,000	.0038	.7
Sept. 8-9	1.8	4,600	.00072	.04
Sept. 27-28	2.5	3,900	.00061	.02

Church (fig. 2) was gaged from 1963-67. The stream at this point has a drainage area of 0.37 square mile.

Streamflow commonly is divided into base runoff (discharge from ground water) and direct runoff (storm runoff). Base runoff of Guinea Gut ranged from 0 (dry) to 4.8 gpm during the period of record at the gage. Periods of no flow occurred from December 1964 to May 1965 and from March 1967 to August 1967. These data show that the stream at this point does not produce a continuous supply of water without storage facilities.

Periods of storm runoff are given in table 9.

Note that the runoff-rainfall ratio given in the last column is extremely variable, because runoff is influenced by antecedent conditions. For example, the storm of April 5-6, 1965 was preceded by several months of dry weather. Only 0.1 percent of the 2.17 inches of rainfall appeared as storm runoff; whereas during and after a similar storm November 3-4, 1965, havi 2.93 inches of rainfall, 15.1 percent in storm runoff passed the gage. This storm was precede by a heavy rain just 2 weeks earlier.

Total flow past the gage and runoff-rainfall ratios are given in table 10. In 1965, the year of record having the most flow, 92 percent of th

Table 10.--Annual rainfall and runoff at gages on Guinea Gut at Bethany Church

Year	Streamflow				Rainfall, inches	Runoff/Rainfall, percent
	Gallons	Inches over basin	Avg. daily flow			
			gpm	gallons		
1963	3,800,000	0.58	7.2	10,000	35.5	1.7
1964	550,000	.09	1.0	1,500	26.8	.3
1965	9,200,000	1.4	18.0	25,000	37.9	3.8
1966	1,100,000	.17	2.1	3,000	30.4	.6

flow came from seven storms; whereas during 1964 only about 1 percent of the flow came from storm runoff.

The average annual discharge during the period 1963-66 at the gage on Guinea Gut was 3,700,000 gallons, or about 10,000 gpd (gallons per day). In order to put this water to use it would be necessary to provide storage. The desirable size of the reservoir would depend on the rate the water is used and on the amount of discharge during the periods of storm runoff.

The amount of evaporation from free water surfaces on St. John is unknown, and there are few reliable data from the other Virgin Islands. Average annual evaporation of 72 inches is reported for an evaporation pan operated in the 1930's at Annas Hope in St. Croix. This figure seems low in view of the average of 82 inches reported by National Weather Service for three stations in Puerto Rico (Bogart, 1964). The loss by evaporation is a major consideration and must be accounted for before the yield from an open reservoir can be determined.

The yield of a reservoir with free water surface will be less than the flow into it. For instance, with 70 inches per year of evaporation, slightly more than 10,000 gpd would be lost from a 2-acre surface. On the other hand, rainfall on a 2-acre free-water surface would have added slightly less than 5,000 gpd during the period 1963-66 at Bethany Church. Because the average inflow would have been about 10,000 gpd, a 2-acre reservoir on Guinea Gut near the site of the gage would have yielded a net of about 5,000 gpd.

The foregoing, of course, is only an approximation, but it gives an idea of magnitude. There are points on streams--notably Fish Bay Gut and Reef Bay Gut--where the drainage area and presumably the runoff are several times greater than those at the gaged point on Guinea Gut. Although the flow would be intermittent, it possibly could be utilized.

Reservoirs, such as the one mentioned, could serve as retention storage from which the water would be withdrawn rapidly for artificial recharge to the ground-water aquifer or directly for use. Underground storage would not be subject to the high rate of evaporation of a surface reservoir. The yield from a system would depend on factors, such as method of artificial recharge, well location, pumpage, and size and configuration of the aquifer; but, if all these factors are considered and the system is properly managed, the yield might be greater than the yield from a surface reservoir. However, it is doubful that the yield would justify the cost of an extensive installation on Guinea Gut.

A few farm ponds have been built on St. John, but most are unsuccessful, probably because of leakage through the alluvial bottoms. Two farm ponds on St. Thomas that supply water for livestock, however, held water during the period 1963-67. On the north slopes of St. Thomas are several ponds having surface areas of a few hundred square feet that serve to collect and store water for irrigation. Actual yield is not known for any of the ponds.

SUMMARY AND CONCLUSIONS

Water always has been in short supply in the Virgin Islands. During 18th and 19th centuries, when the Islands were under Danish rule, St. John was almost entirely under cultivation for sugarcane. The colonists developed limited water supplies from many large-diameter dug wells, a few natural springs, small surface reservoirs along streams, and rainfall catchment. A few of the original Danish wells and the springs were continued in use in modern times for sanitary purposes and for stock watering; however, these small supplies were unreliable because of periodic droughts and shallow depth of wells.

As the use of springs and wells decreased, more and more dependence was placed on roof and hillside rainfall catchment and on importation of water. These methods of water supply are costly, and the need for development of natural supplies was apparent to the National Park Service and to the Virgin Islands Government. The resulting studies of the Geological Survey on

St. John have lead to the development of small but significant ground-water supplies.

Ground water is found in three types of aquifers on St. John. They are alluvial-filled valleys, beach sand, and fractured volcanic rock. Water in alluvial-filled valleys occurs in only a few locations on St. John and is of minor importance. Water in the beach sands is more abundant, but the chemical quality ranges from poor to brackish and is variable. Dissolved solids range from 1,000 mg/l (milligrams per liter) to more than 10,000 mg/l. Water in the fractured-rock aquifer is the most abundant of the three types, and the chemical quality of this water ranges from fair to brackish. Dissolved solids have been found to range from 612 mg/l to more than 3,000 mg/l. Streamflow and springflow yield small quantities of water, which, in some cases, are sufficient for domestic and stock-water supplies. However, they are not reliable enough for development as public supplies.

Through the test-drilling program, water supplies were developed for the Cinnamon Bay Campground, a concession and beach installation at Trunk Bay, a watering point at Cruz Bay, and a watering point on Center Line Road near Herman Farm.

All sources of fresh water are limited on St. John. Water from roof catchment is sufficient for most households except in time of drought. There is wide opportunity to develop ground water from the fractured volcanic-rock aquifer to supplement roof and hillside catchment. Extensive use of ground water might eliminate or greatly reduce the need for importing water.

The use of brackish water and sea water for sanitary systems would relieve part of the demand for fresh water, but disposal of the waste water would contaminate fresh-water supplies on the edge of the sea.

Sound water management and development would be necessary in developing the water in the fractured volcanic-rock aquifer to prevent overpumping and salt-water encroachment. An adjunct to sound management would be a program of monitoring ground-water levels and chemical quality.

ALTERNATIVES OF WATER SUPPLY

by Dean B. Bogart

The shift from the old agricultural economy to the present tourist-oriented economy on St. John provides an opportunity for considerable freedom of action in selecting alternative water supplies.

There is no sizable source of natural fresh water at any one place anywhere in St. John. But there are many small sources that aggregate a sizable supply, at least at current demand levels. This implies to the author that an open mind can be maintained about both the source and the quantity of water available. It seems that obtaining and moving enough water from where it is to where it is wanted would entail consideration of a system that uses several sources.

Such a system could be realistic. It would be fitted to the seasonal availability of natural supplies and to the seasonal demand. It also would provide flexibility in the event of breakdown in one of the components of the system, thus avoiding the vulnerability of the "all the eggs in one basket" approach. A useful adjunct to this report could be an analysis of the best combination of sources and means in terms of reliability of supply and least cost.

To make the point on alternatives of water supply--and, hopefully, to excite imagination--possible sources and means of water supply for St. John are outlined in table 11. It _is_ exciting to realize that there are at least seven sources of water and ten means of obtaining it. There are more, although some of them are on the extreme side--like "milking" trees or crushing plants and fruits.

The ensuing discussion is in tabular format to

Table 11.--Sources of water in St. John and means of obtaining it

Means \ Source	Rainfall	Streamflow	Ground water	Sewage	Sea	Atmosphere	Importation
Catchment	X						
Run of river		X-----	→				
Pond		X-----	→				
Well			X				
Gallery			X				
Treatment		X-----	→ ←	---X			
Desalting			X		X		
Solar distillation			X	X	X		
Extraction						X	
Tanker or barge							X

reduce wordiness and it is not intended to be an exhaustive treatment of the subject. Cost is referred to only in vague relative terms because cost of the various means of obtaining water is in a constant state of flux. And, as are the other relative terms--quantity of water, space required, storage required, esthetics--cost is in context of the Virgin Islands. What an adequate supply would cost in the Virgin Islands would be outrageous for the same quantity, say, in North Carolina. The land required for an installation might be large in Virgin Islands terms but negligible in North Carolina.

No recommendation of one source-and-means over another is given, for the discussion is meant to be provocative of flexible planning. Each should be considered for its present and future utility to the community, and it is suggested that cost and space requirements should not be applied too arbitrarily in evaluating them. As an example, importing water by tanker or by towed container may be one of the more expensive methods; but it also may be one of the easiest to effect, and capital outlay could be small.

A detailed discussion of power to obtain and move water, and of the size of water storage capacity needed by the community, is not included either. Power and storage are intimately related to continuity of water supply in the face of ordinary breakdown, of natural disaster, and of National emergency.

The community must have reserve capacity in both equipment and storage to meet breakdowns that are bound to occur. But a natural disaster such as a major hurricane or a major earthquake likely would destroy power lines and piers, putting water-supply facilities out of commission for a longer period than for a breakdown. The Virgin Islands also is peculiarly vulnerable to cutoff of fuel-oil supplies, which almost inevitably would occur in the event of a National emergency. These extreme conditions could be considered in planning storage, but, in the end, reliance might have to be placed on the most simple methods of obtaining water: dug wells (pumped by wind power?) and rainfall catchment.

Two other aspects of water supply in St. John might be termed negative water supply. The first is the persuasion of people to use less water, either by education or by restriction. This may be difficult to get across to visitors and new residents, most of whom come from the United States, where water, compared with St. John, is used extravagantly. But it may be realistic in the sense that capital investment would be less for the same per capita use; or conversely, more people could be served by the same quantity of water.

The second aspect is to reduce the use of water by vegetation, thereby making more water available for other use. This will not be a popular idea, for it means cutting down trees. The size of the stream channels in St. John and waterworn rocks at some places show that streamflow (and thereby ground water) once was more plentiful. There is reason to believe that the native vegetation was replaced by deeprooted trees (phreatophytes) that literally suck out much of the water and transpire it to the atmosphere.

Replacing trees in an orderly program might be worth considering.

Catchment of rainfall

Quantity: can be any amount; is intermittent.
Quality: good.
Complexity: one of the simple methods.
Capital cost: high if constructed for purpose; low if area used for other purposes (roofs, shopping centers, parking lots).
Op. & maint. cost: low.
Space required: large, directly proportional to quantity.
Storage required: large, to bridge dry periods.
Esthetics: poor (large structure).
Other: can be built at almost any place.

Streamflow, run of river

Quantity: small to moderate; is intermittent.
Quality: good, but variable.
Complexity: most simple (intake in pool).
Capital cost: negligible.
Op. & maint. cost: negligible.
Space required: negligible.
Storage required: large, to bridge dry periods.
Esthetics: negligible problem.
Other: necessary to remove sediment; best use is to recharge aquifers.

Streamflow, ponds

Quantity: small to moderate; may be intermittent.
Quality: good, but variable.
Complexity: simple.
Capital cost: moderate to high, depending upon possible size of dam or dike.
Op. & maint. cost: low.
Space required: moderate.
Storage required: not applicable.
Esthetics: attractive when full; might be unsightly when empty.
Other: would act as sediment trap if large enough; best use may be to detain flood flow to recharge aquifers by seepage through the bottom of ponds and by controlled release to stream channels which also would act as distributors; evaporation is in range of 7 to 8 feet annually.

Wells (in terms of many wells)

Quantity: small near coast; moderate in upland.
Quality: poor near coast; fair in upland.
Complexity: simple as a unit; many wells would require network of pipelines and powerlines.
Capital cost: moderate.
Op. & maint. cost: low.
Space required: small.
Storage required: community safety standard.
Esthetics: small problem as a unit; may be problem for network.
Other: network provides protection against breakdown; cost of pipelines may be offset by cost of distributing pipelines (a factor common to all systems).

Collection galleries

Quantity: small; may be intermittent.
Quality: poor.
Complexity: simple.
Capital cost: moderate.
Op. & maint. cost: moderate.
Space required: moderate.
Storage required: large, to bridge dry periods.
Esthetics: negligible problem, can be landscaped.
Other: application limited to coastal valleys.

Desalting

Quantity: small, if coastal ground water; unlimited, if seawater.
Quality: chemically excellent, but may need mixing with other water to be more palatable.
Complexity: very high.
Capital cost: high.
Op. & maint. cost: high.
Space required: moderate, near coast.
Storage required: community safety standard, on the high side to bridge breakdowns.
Esthetics: poor per se; possibly could be disguised.
Other: if coastal ground water is used, loss as waste water would be excessive; if seawater is used, discharge of hot concentrate is a problem. If only one unit provided, alternative system is needed in case of breakdown.

Importation

Quantity: can be any amount within reason.
Quality: same as source.
Complexity: simple.
Capital cost: low.
Op. & maint. cost: low (maintenance of unloading station).
Space required: small.
Storage required: size of vessel and community safety standard.
Esthetics: negligible problem.
Other: can be contracted; cost probably high; source can be other Virgin Islands or Puerto Rico.

Extraction from atmosphere

Quantity: probably large.
Quality: good.
Complexity: high.
Capital cost: high.
Op. & maint. cost: high.
Space required: large.
Storage required: community safety standard.
Esthetics: poor (large structure).
Other: untested, still in experimental stage.

Solar distillation

Quantity: large.
Quality: probably good.
Complexity: moderate.
Capital cost: high.
Op. & maint. cost: moderate.
Space required: large.
Storage required: community safety standard.
Esthetics: poor (large structure).
Other: largely untested on sizable scale; probably near sea, necessary to dispose of concentrate.

Treatment of sewage

Quantity: community output.
Quality: depends upon degree of treatment.
Complexity: high.
Capital cost: high, but will be required of community anyway.
Op. & maint. cost: high.
Space required: moderate.
Storage required: none, unless not recycled immediately in water supply.
Esthetics: poor, if recycled; acceptable if used indirectly. (See below.)
Other: best use for public acceptance is to recharge aquifer.

All of these methods require competent technical direction. Although methods involving artificial recharge and desalting require a highly specialized work force, some of the more simple methods require no work force or only a small one. Thus, at times, the availability of trained personnel may be more important than cost.

SELECTED BIBLIOGRAPHY

Bogart, D. B., Arnow, Ted, and Crooks, J.W., 1964, Water resources of Puerto Rico: Commonwealth of Puerto Rico Water Resources Bull. 4, 120 p., 58 fig., 15 tables.

Chinn, S.W., 1965, Water-supply potential from an asphalt-lined catchment near Holualoa Kona, Hawaii: U.S. Geol. Survey Water-Supply Paper 1809-P, 25 p.

Donnelly, T.W., 1960a, Geology of St. Thomas and St. John, Virgin Islands: Dissert. Abs. v. 20, no. 7, p. 2756.

______ 1960b, The geology of St. Thomas and St. John, Virgin Islands: 2d Caribbean Geol. Conf., p. 153-155.

______ 1964, Evolution of eastern Greater Antillean island arc: AAPG, v. 4, no. 5, p. 680-696.

______ 1966, Geology of St. Thomas and St. John, U.S. Virgin Islands in Hess, H.H., ed., Caribbean Geol. Inv. GSA Memo. 98, p. 85-176.

Grossman, I.G., 1959, Ground water from St. Thomas, Virgin Islands: U.S. Geol. Survey open-file report, 35 p.

Hendrickson, G.E., 1963, Ground water for public supply in St. Croix, Virgin Islands: U.S. Geol. Survey Water-Supply Paper 1663-D, 27 p.

Hess, H.H., 1960, Caribbean research project: GSA Bull. v. 71, p. 235-240.

______ 1966, Caribbean research project, 1965, and bathymetric chart: Geol. Soc. America Memo. 98.

Ingerson, Earl, and Pearson, F.J., Jr., 1964, Estimation of age and rate of motion of ground water by the C-14 method, in Recent researches in the field of atmosphere, hydrosphere, and nuclear geochemistry: Sugawara Festival Vol., Maruzen Co., Tokyo, p. 263-283.

Johnson, A.F., 1936, Water supply for St. Thomas, Virgin Islands: U.S. Bur. Reclamation, mimeo. rept., 26 p.

McGuinness, C.L., 1946, Ground-water reconnaissance of St. John, Virgin Islands: U.S. Geol. Survey open-file rept., 23 p.

______ 1953, Summary of the water resources of the Virgin Islands: U.S. Geol. Survey open-file rept., 8 p.

Pearson, F. J., Jr., and White, D. E., 1967, Carbon 14 ages and flow rates of water in Carrizo Sand, Atascosa County, Texas: Water Resources Research, v. 3, no. 1, p. 251-261.

Tippetts-Abbett-McCarthy-Stratton, 1958, Potable water supply for St. Thomas, Virgin Islands: Consultants rept., 55 p.

U.S. Public Health Service, 1962, Public Health Service drinking water standards: 61 p.

U.S. Weather Bureau, 1961, Generalized estimates of probable maximum precipitation and rainfall-frequency data for Puerto Rico and Virgin Islands: Hydrol. Services Div., Coop. Studies Sec., U.S. Weather Bur., Tech. Paper 42, 94 p.

Vaughan, T. W., and Kidwell, C. H., 1920, The ground water resources of the West Indian Islands, St. John, St. Thomas, Culebra, Vieques, and the eastern end of Puerto Rico: U.S. Geol. Survey open-file rept., 53 p.

Ward, P. E., and Jordan, D. G., 1963, Water resources of the Virgin Islands, a preliminary appraisal, 1963: U.S. Geol. Survey open-file rept., 44 p., 7 figs., 4 tables.

Whetten, J. T., 1966, Geology of St. Croix, U.S. Virgin Islands: in Hess, H. H., ed., Caribbean Geol. Inv., GSA Memo. 98, p. 177-239.

APPENDIX

Tables 12 and 13

Table 12.--Record of wells in St. John

Designation		Construction Data										Hydrologic Data					Supplementary Data		
					Casing record			Finish					Water level						
Well number on map (fig. 2)	Location	Type	Year completed	Depth, feet	Diameter, inches	Depth, feet From	Depth, feet To	Type	Depth, feet From	Depth, feet To	Type of lift	Surface altitude, feet	Depth below land surface, feet	Date measured, month & yr	Water-bearing material	Yield, gpm	Use	Temperature °C	Remarks
NPS-2	Cruz Bay	Drilled	1964	99	4	0	20	0	20	99	None	60	40.0	6-64	Vt	<1	T,O	28	
NPS-3	Cruz Bay	do.	1964	54	6	0	25	0	25	54	None	40	26.5	6-64	Vt	5	T,O	28	
NPS-4	Lind Point	do.	1964	200	6	--	--	0	0	200	None	176	Dry	6-64	--	--	--	--	Casing pulled, hole destroyed.
NPS-5	Trunk Bay	do.	1964	60	6	0	12	0	12	60	None	60	32.1	7-64	Vb	6	T,O	27	
NPS-6	Cinnamon Bay	do.	1964	70	6	0	50.7	0	50.7	70	None	60	56.9	11-64	Vt	8	T,O	27	
NPS-7	Hawksnest Bay	do.	1964	36	6	0	27	0	27	36	None	40	17.1	8-64	Vb	12	T,O	27	
NPS-8	Cinnamon Bay	do.	1964	50	6	--	--	0	0	50	None	20	Dry	9-64	--	--	T	--	Casing pulled, hole destroyed.
NPS-9	Cinnamon Bay	do.	1964	60	6 4	0 0	39 60	S	50	60	Sub-mersible	50	42.9	10-64	Vt,Vb	8	P	27	
NPS-10	Lameshur	do.	1964	66	6 4	0 0	52 67	S	47	67	None	40	28.5	10-64	V	2	O	29	
NPS-11	Cinnamon Bay	Dug	1963	27	60 1-1/4	-- 0	-- 27	P	0	27	None	30	26.2	7-63	Qal	1	T,O		Well filled; 1-1/4 in. well point installed.
NPS-12	Cinnamon Bay	do.	1963	14	--	--	--	--	--	--	None	12	10.2	6-66	Qal		T,O		14 x 20 feet trench well.
NPS-13	Hawksnest Bay	Drilled	1966	568	3	--	--	--	--	--	--	22	--	--	--	--	T	--	Horizontal well, dry.
NPS-14	Trunk Bay	do.	1966	803	3	0	420	0	420	803	None	50	(a)	7-66	Vb,Vt	.5	P		Horizontal well.
NPS-15	Cinnamon Bay	Dug	--	9	80	0	9	--	--	--	None	7	5.0	10-62	Qal/Qb	--	O	--	
NPS-16	Trunk Bay	do.	--	9	80	0	9	--	--	--	Suction	7	4.9	1-63	Qb	--	O,P	--	
USGS-12	Herman Farm	Drilled	1964	192	6	0	151	P 0	111 151	151 192	None	260	21.0	2-64	Vb	4	O		In fault zone.

Table 12.--Record of wells in St. John--Continued

Designation		Construction Data										Hydrologic Data					Supplementary Data		
					Casing record			Finish					Water level						
						Depth, feet			Depth, feet										
Well number on map (fig. 2)	Location	Type	Year completed	Depth, feet	Diameter, inches	From	To	Type	From	To	Type of lift	Surface altitude, feet	Depth below land surface, feet	Date measured, month & yr	Water-bearing material	Yield, gpm	Use	Temperature °C	Remarks
USGS-13	Estate Adrian	Drilled	1964	60	6	0	54	0	54	60	None	580	27.3	8-64	Vb	3	O		
USGS-14a	Coral Bay	do.	1964	84	6	0	40	0	40	84	None	40	36.5	9-64	Vb	8	O		
USGS-15	Calabash Boom	do.	1964	62	6	0	60.5	0	60.5	62	None	50	44.4	9-64	Vb	2	O		
USGS-16	Lameshur Bay	do.	1964	158	6 4	0 0	22 158	-- S	-- 50	-- 158	Sub-mersible	650	44.1	10-64	Vb, Vt	11	P		
4	Coral Bay	Dug	1946	30	130	--	--	--	--	--	None	30	27.7	1-46	Qal	10	T	--	Destroyed.
5	Reed Bay	do.	1946	29.5	130	--	--	--	--	--	None	35	28.3	1-46	Qal	10	T	--	Destroyed.
13	Estate Adrian	do.	--	22	120	0	22		--	--	Cen-trif-ugal	620	13.3	4-63	Qal,Vb	--	C	24	

Finish: 0 - open hole. S - slotted. P - well point.

Water level, depth: (a) - head, 24.5 pounds per square inch.

Water-bearing material: Vb - volcanic breccia. Vt - volcanic tuff. V - volcanic undifferentiated.
Qal - alluvium. Qb - beach sand.

Use: T - test. O - observation. P - public supply. C - construction.