Relation of Bulk Precipitation and Evapotranspiration to Water Quality and Water Resources, St. Thomas, Virgin Islands

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1663-I

Prepared in cooperation with the Government of the Virgin Islands of the United States

Relation of Bulk Precipitation and Evapotranspiration to Water Quality and Water Resources, St. Thomas, Virgin Islands

By DONALD G. JORDAN *and* DONALD W. FISHER

CONTRIBUTIONS TO HYDROLOGY OF LATIN AMERICA AND THE ANTILLES

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data

Jordan, Donald George, 1926–
Relation of bulk precipitation and evapotranspiration to water quality and water resources, St. Thomas, Virgin Islands.

(Geological Survey water-supply paper ; 1663–I)

Bibliography: p.

Supt. of Docs. no: I 19.13:1663-I

1. Water quality—Virgin Islands—St. Thomas. 2. Precipitation (Meteorology)—Virgin Islands—St Thomas. 3. Evapotranspiration—Virgin Islands—St. Thomas. I. Fisher, Donald W., joint author. II. Virgin Islands of the United States. III. Title: Relation of bulk precipitation and evapotranspiration to water quality . . . IV. Series:
United States, Geological Survey, Water-supply paper ; 1663–I.

TC801.U2 no. 1663–I [TD233.V5] 553'.7'0973s
[553'.7'09729722] 77–608024

For sale by the Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202

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SYMBOLS

Cl*bf*	Chloride concentration of base flow in milligrams per liter.
Cl*bp*	Average chloride concentration in bulk precipitation in milligrams per liter.
Cl*gw*	Initial chloride concentration in ground water in milligram per liter.
$Clgw_2$	Final chloride concentration in ground water in milligrams per liter.
ET	Evapotranspiration in inches.
fc	Concentration factor.
Rr	Residual recharge in inches.
Rt	Initial recharge in inches.
Ps	Storm runoff in inches.
Pt	Total precipitation in inches.

CONVERSION FACTORS

This report is written using English units. For those who are more familiar with or have a need to use SI units (International System) this table is included and parallel parenthetic units are included in the text. The table contains a conversion factor with which to multiply the English unit to yield the SI unit. Conversion factors are shown to four significant figures but units in the text are rounded to be consistent with the accuracy of the English unit.

English	*Multiplication factor*	*SI*
inches (in)	25.40	millimeters (mm)
feet (ft)	30.48	centimeters (cm)
	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
acres	0.4047	hectares (ha)
gallons (gal)	0.003785	cubic meters (m^3)
gallons per minute (gal/min)	0.06309	liters per second (L/s)
gallons per day (gal/d)	0.003785	cubic meters per day (m^3/d)
gallons per acre (gal/acre)	0.009352	cubic meters per hectare (m^3/ha)
tons per square mile (T/mi^2)	0.3502	tonnes per square kilometer (t/km^2)

CONTRIBUTIONS TO HYDROLOGY OF LATIN AMERICA AND THE ANTILLES

RELATION OE BULK PRECIPITATION AND EVAPOTRANSPIRATION TO WATER QUALITY AND WATER RESOURCES, ST. THOMAS, VIRGIN ISLANDS

By DONALD G. JORDAN and DONALD W. FISHER

ABSTRACT

St. Thomas, Virgin Islands, lies in what can be considered a true maritime regime, being 600 miles (1000 kilometers) from the nearest continental landmass.

The island is composed almost entirely of volcanic rocks mantled by a thin soil seldom more than 2 feet (60 centimeters) thick. Rainfall, averaging about 40 inches (1020 millimeters) annually, has an orographic distribution related to the central ridge of the island, altitude 600 to 1500 feet (180 to 405 meters), and the easterly to northeasterly trade winds.

The mineral content of bulk precipitation falling on the island is derived principally from the sea although soil dust contributes much of the calcium, sodium, and bicarbonate. Two-thirds of the sulfate in the precipitation is provided by sea salts; the remainder is derived from other sources. The concentration of the constituents of bulk precipitation fluctuates widely month to month, but the load of the constituents shows little monthly variation.

Bulk precipitation is concentrated on the land surface and in the soil zone. From there it is carried into the ground water during recharge or is removed by storm-water runoff. It is the principal source of minerals in the waters of the island.

Soil-moisture demand and evaporation limits recharge to 1 to 2 inches (25 to 50 millimeters) annually for the greater part of the island. Evapotranspiration also occurs directly from the aquifer. The salts left further increase the mineralization of the ground water. Water loss from the aquifer by evapotranspiration ranges from 40 to 80 percent of the recharge.

Recharge to the aquifers and evapotranspiration of ground water determined by ratios of chloride concentrations in bulk precipitation, surface water, and subsurface water agree favorably with recharge and ground-water loss computed by other means.

INTRODUCTION

Numerous chemical studies of rainfall in continental areas have demonstrated the presence of substantial amounts of mineral salts in precipitation. A few of these studies include estimates of total annual mineral loads or average concentrations from which approximations may be made of the contribution of atmospheric precipitation to the chemical quality of natural waters. Knowledge of the composition of atmospheric precipitation from purely maritime regions and its contribution of mineral salts to the natural water, however, is very scanty.

Precipitation on St. Thomas averages more than 40 in (1020 mm) per year. Although rainfall is abundant by continental standards, the island's ground- and surface-year resources are meager and poor in quality. This report presents information on the chemical composition of bulk precipitation, its contribution to the natural water quality, and the effect of evapotranspiration on the water resources and water quality of St. Thomas.

ACKNOWLEDGMENTS

The authors are indebted to Arlo Gambell, formerly of the U.S. Geological Survey, for designing and installing the precipitation sampling network and to Oliver J. Cosner and L. Grady Moore of the U.S. Geological Survey for maintenance of the stations and collection of samples. They also wish to thank Mr. Robert Calvesbert, formerly National Weather Service Climatologist for Puerto Rico and Virgin Islands, for preparation of the isohyetal map of St. Thomas.

LOCATION AND SETTING

The Virgin Islands form part of the Antilles Island Arc. They are located about 1100 mi (1800 km) southeast of Miami, Fla.; 600 mi (1000 km) northeast of the north coast of South America; and 1300 mi (2100 km) east of the nearest point in Central America. The islands, therefore, can be considered relatively free of the influences of continental landmasses.

St. Thomas lies about 50 mi (80 km) east of Puerto Rico and is the second largest of the more than 50 islands and cays composing the Virgin Islands of the United States (fig. 1). The island is approximately 14 mi (22 km) long, 2 to 3 mi (3 to 5 km) wide, and has an area of 32 mi^2 (83 km^2).

A central ridge 600 to 1500 ft (180 to 406 m) in altitude runs the length of the island (fig. 2). Slopes commonly exceed 35° and are dissected by numerous dry stream courses. The general ap-

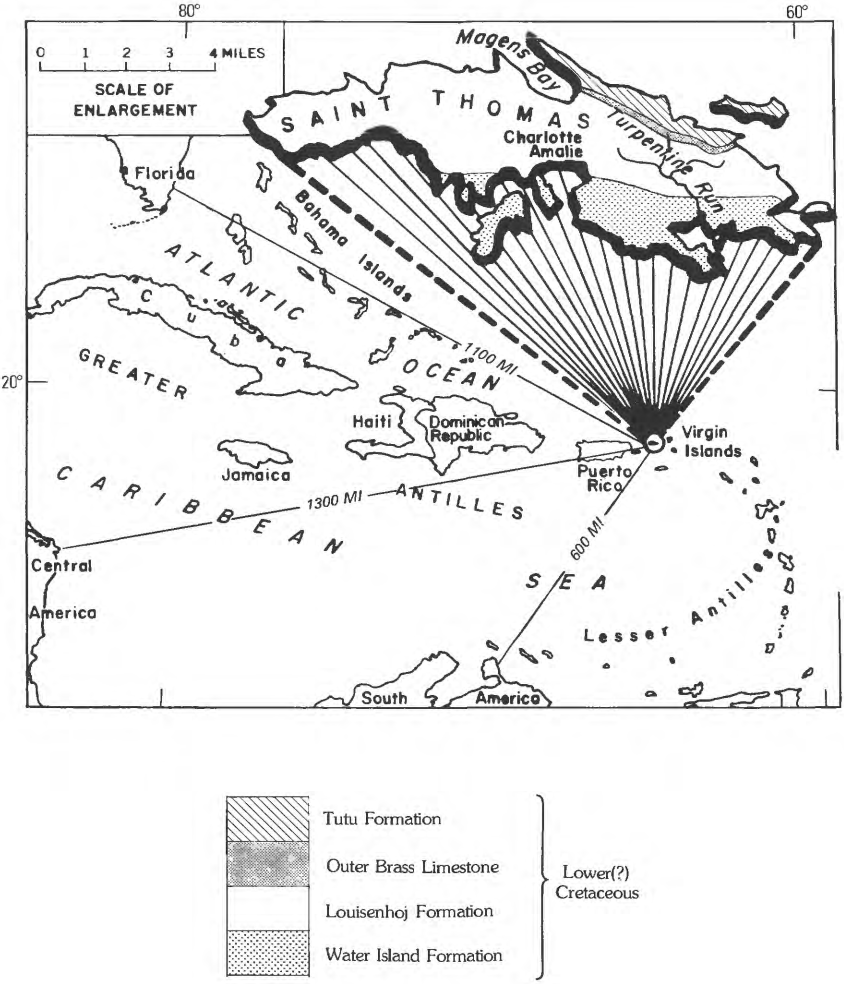


FIGURE 1.—Location and general geology (Geology after Donnelly, 1966).

pearance is a panorama of steep interstream spurs and rounded peaks. Flat land is confined to the Charlotte Amalie area and to alluvial fans at the mouths of a few valleys. The only variation from these typical surface features is found in the upper valley of Turpentine Run in eastern St. Thomas. The valley has relatively gentle topography consisting of rolling hills in a basin surrounded by steep slopes and sharp ridges.

At one time almost all the land including the steep slopes was under cultivation, either as pasture or for growing sugarcane

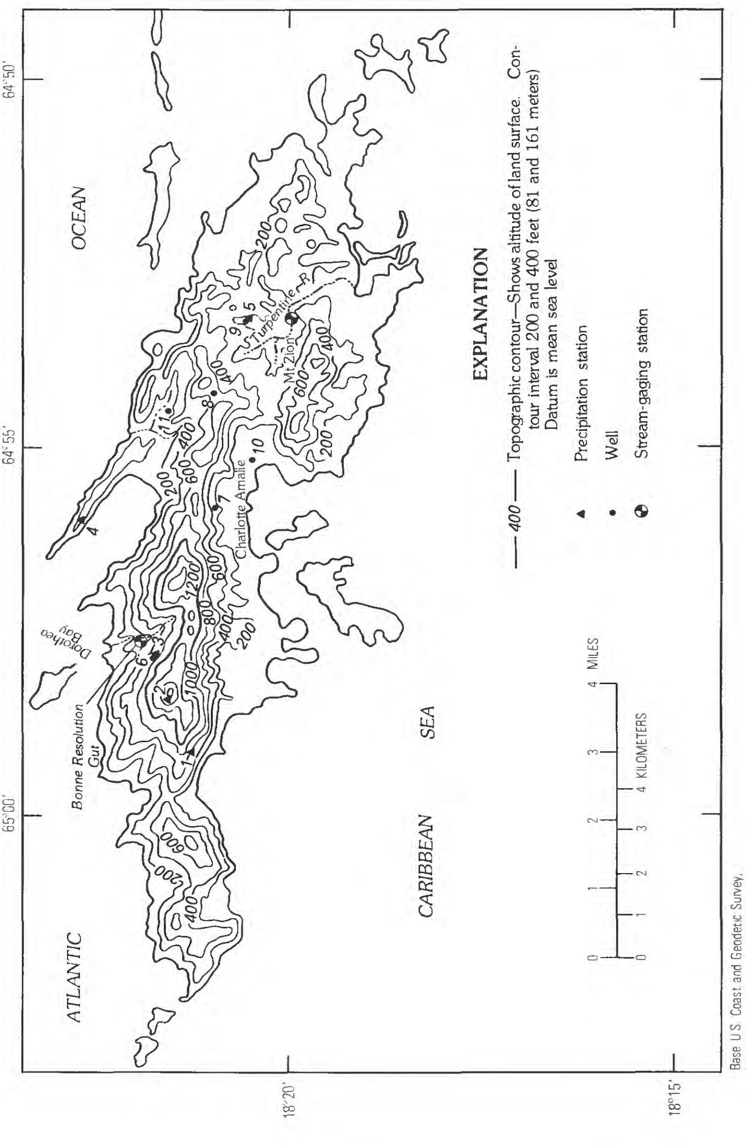


FIGURE 2.—General topography and location of precipitation stations, wells, and stream-gaging stations.

and cotton. As of 1966 a few square miles in the eastern part were still used for pasture and about 10 acres (4 ha) were used for truck farming in the north central part of the island. Much of the remainder of the island was in brush and secondary forest.

RAINFALL

Rainfall is seasonal, with a rainy season from August through November and a secondary rainy period in May. Rainfall generally occurs as brief intense showers of a few tenths of an inch. Major rainstorms, those exceeding 1 in (25 mm) in 24 hours, occur but six or seven times a year. The monthly rainfall during the study and the long-term normal monthly rainfall at Charlotte Amalie are shown in figure 3.

Average areal distribution of rainfall, shown in figure 4, is controlled by topography and the prevailing easterly to northeasterly winds.

GEOLOGY

The rocks of St. Thomas are predominantly volcanics of Cretaceous age. Lava flows and flow breccias (spilites and keratophyres) of the Water Island Formation, and breccias, tuffs, and flows (augite andesites) of the overlying Louisenhoj Formation are the principal rocks. Along the north coast the Outer Brass

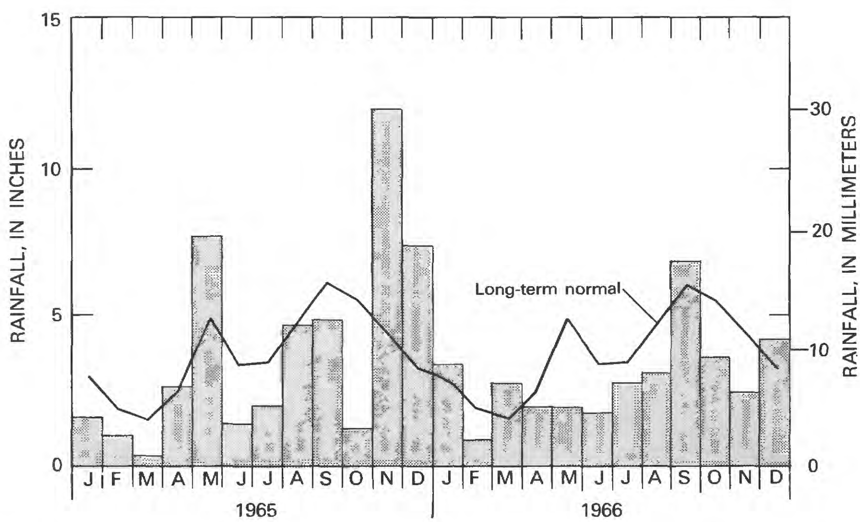


FIGURE 3.—Monthly rainfall 1965–66 and long-term normal rainfall at Charlotte Amalie. (Data from National Weather Service records.)

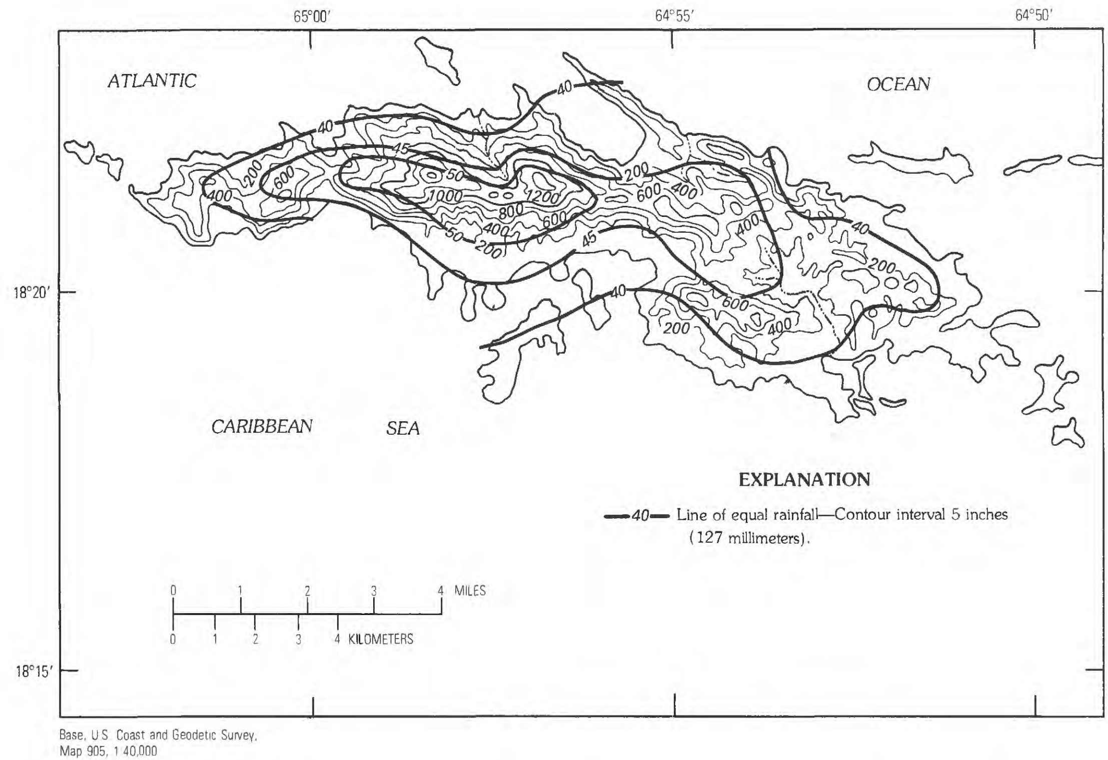


FIGURE 4.—Average annual distribution of rainfall 1931–60. (Analysis by National Weather Service climatologist for Puerto Rico and Virgin Islands.)

Limestone, a graphitic, tuffaceous, siliceous limestone overlies the Louisenhoj Formation. It, in turn, is overlain by the Tutu Formation, which is composed almost entirely of rubble derived from the Louisenhoj Formation.

Alluvial deposits of Pleistocene and Holocene age are thin and are confined to the stream courses of the major valleys. The deposits are composed of pebbly-to-bouldery silt and clay and contain lenses of sand and gravel. In the embayments, alluvial deposits interfinger with beach sand.

A generalized geologic map adapted from Donnelly (1966) is shown in figure 1. Geologic names are those used by Donnelly (1960) and have not been adopted by the U.S. Geological Survey.

Chemically the rocks of the Water Island Formation are high in sodium and low in potassium. Calcium-magnesium carbonate is negligible in the keratophyres though normal or even high in the spilites, whereas, silica (as quartz) is common in the keratophyres and negligible in the spilites. The Louisenhoj and Tutu Formations are high in sodium, calcium, and magnesium and have little or no potassium.

SOIL MOISTURE AND EVAPOTRANSPIRATION

The soil zone of St. Thomas is seldom more than 2 ft (0.6 m) thick, and when dry is coarsely granular, owing to clumping of clay and silt particles. Prolonged saturation is necessary before the granules break down. As a result, the soil has a moderate permeability until well saturated, but once saturated it becomes poorly permeable and retains water in the pore space between the particles, rejecting any excess.

Rivera and others (1970) reported an infiltration rate of 0.2 to 2.0 in (5 to 50 mm) per hour for the major soils of St. Thomas. Observations during rainstorms indicate that the typical soil zone will absorb about 2 in (50 mm) of water before some water is rejected to overland flow or moves through the soil zone to recharge the underlying bedrock. Fully saturated, the soil will retain about 3 in (75 mm) of water per foot (0.3 m) of depth (Rivera and others, 1970).

On St. Thomas evapotranspiration is nearly constant throughout the year and amounts to 95 percent or more of the rainfall. Most of the water trapped in the soil zone returns to the atmosphere by this process. As water is evaporated from the surface of the saturated, tight soil, the soil again becomes granular and exposes the soil at depth to the circulation of air. Consequently, further rapid evaporation of soil moisture results.

Bowden (1968) computed potential evapotranspiration and soil moisture deficiency at six stations in St. Croix, Virgin Islands, utilizing all available historical rainfall, temperature, and pan-evaporation data. Potential evapotranspiration ranged from 58 to 69 in (1470 to 1750 mm) per year and averaged 62 in (1570 mm). Actual evapotranspiration (derived from potential evapotranspiration and changes in soil moisture) ranged from 41 to 46 in (1040 to 1170 mm) per year and averaged 43 in (1090 mm). Bowden's data show a soil moisture deficiency ranging from 9 to 11 months of the year at the six stations—surplus soil moisture occurred only from September to November.

Evapotranspiration is also a major means by which water is removed from the upper part of the aquifer if the water table is near land surface. Grasses and shallow-rooted plants can transpire water only from the upper few feet of the soil zone, but many trees and much of the brush of the island are deep-rooted and can transpire water from depths of more than 20 ft (6 m).

The effects of evapotranspiration can be seen in the channel of Bonne Resolution Gut (fig. 2) in north-central St. Thomas (Jordan and Cosner, 1973). The stream flows in a channel a few feet wide underlain predominantly by bedrock for about 1500 ft (460 m) before reaching the alluviated embayment at Dorothea Bay. Base flow of the stream, when less than 10,000 gal/d (37.8 m^3/d), disappears in this reach. The loss is attributed partly to evaporation from the water surface but principally to transpiration by the dense growth of brush and trees bordering the stream. From the appearance of the vegetation in a dry period, a strip about 100 ft (30 m) wide with a total area of about 3 acres (1.2 ha) benefits from the stream. A minimum water loss of 10,000 gal/d (37.8 m^3/d) or 3.6×10^6 gal (13,000 m^3) annually, would indicate an approximate evapotranspiration rate of 1.2×10^6 gal/acre (11,200 m^3/ha) or 44 in (1120 mm) per year.

STREAMFLOW

Most of the stream channels on St. Thomas are dry and carry only infrequent storm runoff. There are but two streams on the island having perennial reaches—Bonne Resolution Gut and Turpentine Run.

Annual runoff of the perennial streams ranges from about 2 to 8 percent of the rainfall on their basins, of which 50 to 75 percent is storm runoff. The variation of runoff from the basins is dependent upon topography, soil moisture, exposure, and vegetation. Base flow (ground-water outflow) seldom reaches the sea—

the flow usually infiltrates into alluvial deposits in the lower reaches of the streams or is lost to evapotranspiration.

GROUND WATER

The principal ground-water supplies are contained in a surficial mantle of fractured and weathered rock about 300 ft (90 m) thick. Beneath this mantle, fractures containing water are few and small. The effective storage capacity of the rocks varies with the number and size of interconnected fractures and is estimated to be about 1 percent or less for most of the island.

Ground water moves toward the valleys and thence to the sea. Each valley, therefore, is an individual ground-water basin separated from adjacent basins by a ground-water divide, which more or less follows the topographic divide.

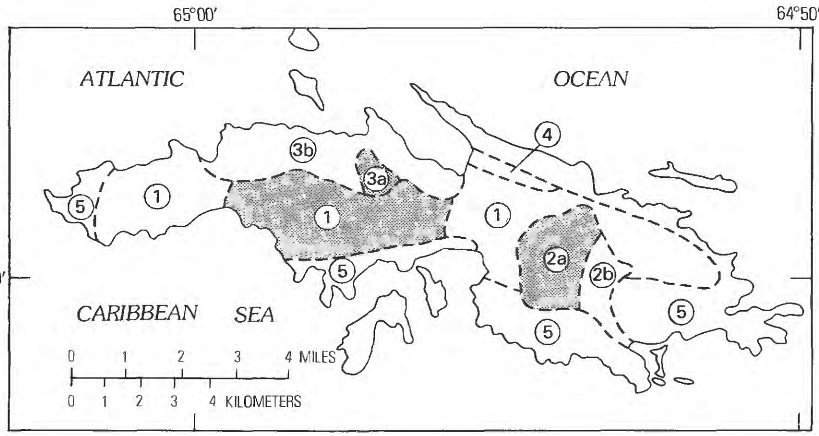
The bedrock aquifer usually receives recharge about three times a year. The amount of recharge depends on antecedent rainfall and the degree to which soil moisture has been depleted by evapotranspiration since the last rain. After a rainless period, a major rainstorm or the equivalent in frequent showers may initiate recharge to the bedrock aquifer. However, with the same antecedent conditions the amount of rainfall necessary for recharge varies from one part of the island to another. On the north slope, for example, 1 in (25 mm) of rain may cause recharge, whereas on the south slope 3 in (75 mm) or more may be required.

Less frequent recharge on the south slope is attributed to the greater solar radiation received, which results in increased evapotranspiration and a greater soil-moisture deficiency. Consequently, a greater volume of water is necessary to overcome the soil-moisture deficiency before recharge can take place.

Average annual recharge to the bedrock aquifer is estimated to range from 0.2 in (5 mm) on the east and west ends of the island to more than 5 in (125 mm) to the Outer Brass Limestone in the Lovenlund Valley in the north (Jordan and Cosner, 1973). Estimates of recharge to ground-water areas of St. Thomas, selected on the basis of geology, soil, topography, rainfall, and exposure, are shown in figure 5.

PRECIPITATION SAMPLING

Five precipitation sampling stations were established as shown in figure 2. Station 2 was close to the peak of Crown Mountain, the highest on the island, altitude 1556 ft (475 m). Stations 1 and 3 were about halfway up the lee and windward slopes, respectively. Station 4 was close to the ocean on the windward side,



AREA		RECHARGE	
Map No.	Square miles	10^6 gallons per year	Inches per year
1	13.6	164	0.7
2a	2.3	130	3.3
2b	1.1	18	1.0
3a	.5	20	2.3
3b	4.1	81	1.1
4	.4	36	5.3
5	10.0	36	.2

FIGURE 5.—Estimated average annual recharge to ground-water areas. Shaded areas referred to in text.

but high enough so that the mineral contribution from direct sea spray would be slight. Station 5 was located on the roof of a residence in a low-lying interior area surrounded by higher land.

The rain collector used at each of the sampling sites consists of a 5-in (127-mm) inside-diameter plastic cylinder over a polyethylene funnel with a Pyrex wool filter in the neck. Rain filters through the glass wool, then runs through a small plastic drain tube and a hollow polyethylene stopper into a graduated polyethylene canister. The canister is closed during the collection period except for the drain tube and a capillary air vent. A white enameled aluminum ice chest fastened to vertical steel posts houses the reservoir canister and provides a mounting base for the funnel. A ring of aluminum spikes surrounding the funnel serves as an effective bird deterrent (Egnér and others, 1949).

In addition, an automatic collector designed to open only during periods of precipitation was installed alongside the continuously open collector at station 2. It was hoped that concurrent data on composition of samples from this pair of collectors would provide information on the compositional differences between rain and dry fallout.

Total precipitation volumes were noted on the last day of each month during the sampling period. Samples for chemical analysis were drawn from the graduated reservoirs, which were then emptied, cleaned, and returned to the insulated chests. Fresh glass wool filters were inserted in the necks of the funnels at this time.

The precipitation compositions reported herein are representative of the mixture of airborne material that settled in the collector funnels during dry periods as well as the salts brought down by rain. Analysis of this mixture, termed bulk precipitation by Whitehead and Feth (1964), provides a measure of the total soluble mineral matter deposited on the land surface during the sampling period.

GROUND-WATER AND SURFACE-WATER SAMPLING

Samples of ground water obtained from privately owned wells and test wells drilled by the Geological Survey were taken only after the wells were pumped or bailed a sufficient time to insure a representative sample could be obtained. Spot samples were taken at different depths in the aquifers during drilling of wells, and composite samples were taken of the total water-bearing zone tapped by a well.

Samples of water from the streams were taken monthly at the gaging stations at the time discharge measurements were made.

ANALYTICAL METHODS

Laboratory determinations ordinarily included measurements of pH and concentrations of chloride, calcium, magnesium, sodium, potassium, sulfate, nitrate, ammonium, and bicarbonate in each of the samples. Surface- and ground-water samples were analyzed by methods described in Rainwater and Thatcher (1960). Chemical analyses of the precipitation samples were accomplished by the same procedure except for calcium, magnesium, and chloride. Calcium concentrations in samples of 1965 were determined by a glyoxal bis-(2-hydroxyanil) colorimetric method reported by Kerr (1960). Magnesium concentrations in these samples were estimated by a spectrophotometric Eriochrome Back T method. A detailed description of this procedure is reported in Gambell and Fisher (1966). Atomic absorption spectrophotometry was used to determine calcium and magnesium in the precipitation waters of 1966. Chloride concentrations were determined spectrophotometrically by an indirect method devised by Iwasaki and others (1952).

TREATMENT OF THE DATA

Rainfall on St. Thomas is highly variable from place to place on the island (fig. 4). For this reason, precipitation-weighted concentrations of the ionic constituents for each station were averaged in order to estimate composition of monthly precipitation over the entire area. Average annual concentrations were also calculated for each station in order to permit an assessment of the variations due to geographical and meteorological locations. Seasonal and annual loads were also determined for the entire island.

Precipitation depths were calculated from reported sample volumes. A collection efficiency of 100 percent was assumed for the samplers. Comparison of the calculated rainfall at station 3 (Dorothea, fig. 2) with U.S. National Weather Service data for Dorothea over the same period indicates that the assumption is justified, and that the computed loads and average concentrations are reasonable approximations.

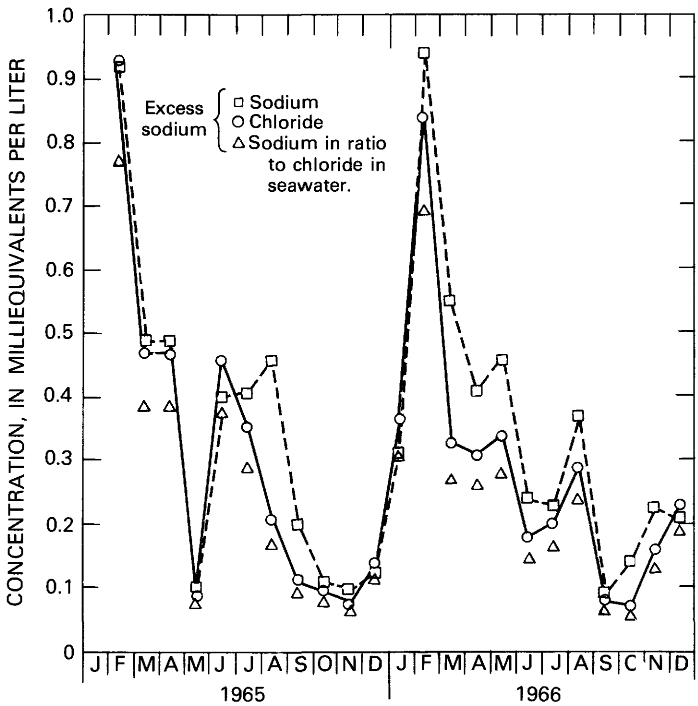


FIGURE 6.—Seasonal pattern of sodium and chloride concentration in bulk precipitation.

The samples of March 1965 were too small to permit chemical analyses. For this reason, the precipitation was allowed to accumulate through April. The concentrations and loads determined for the combined samples were arbitrarily assumed to be equal for the 2 months.

WATER QUALITY

PRECIPITATION COMPOSITION

Oceanic salts would be expected to contribute significantly to the mineral composition of precipitation on St. Thomas. Graphs of average monthly concentrations of chloride and of sodium in milliequivalents per liter, the principal ions in seawater, are shown in figure 6. Chloride concentrations in precipitation reach values greater than 30 mg/L (milligrams per liter) during the drier months.

Whereas the concentration of chloride and other constituents fluctuated widely from month to month, the monthly loads of the other constituents in bulk precipitation showed little variation. Monthly deposition of chloride, for example (fig. 7), usually amounted to 1 or 2 T/mi^2 (0.35 to 0.70 t/km^2), although higher values were observed during the winter of 1965–66.

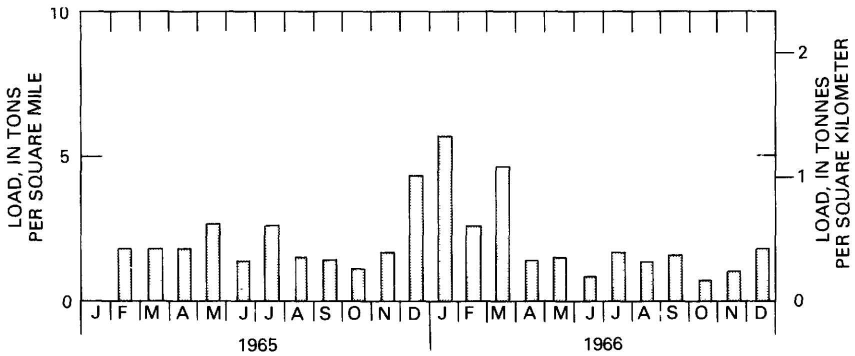


FIGURE 7.—Monthly average chloride loads in bulk precipitation.

The seasonal pattern of sodium concentration (fig. 6) is generally similar to that for chloride. However, ratios of sodium to chloride in precipitation usually exceed the near-constant seawater value ratio of 0.82 (in milliequivalents per liter). If chloride, as a conservative ion,[1] is an accurate indicator of sea-

[1] An ion that does not change in concentration under usual conditions.

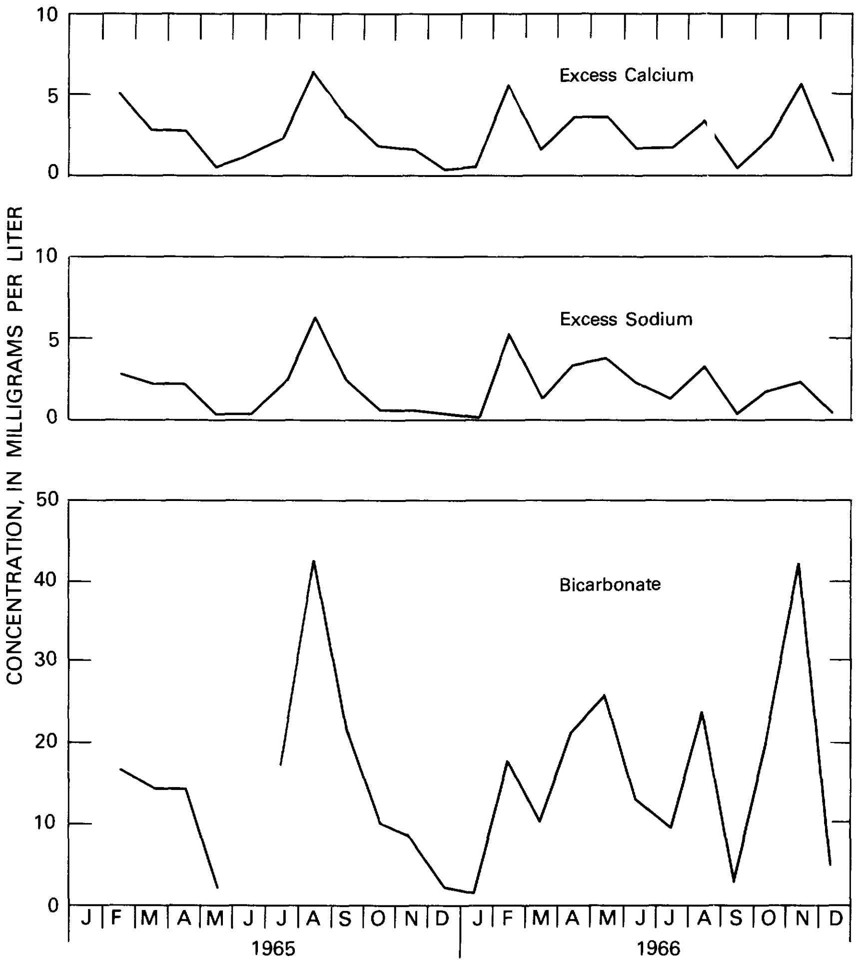


FIGURE 8.—Seasonal pattern of bicarbonate and excess sodium and calcium concentration in bulk precipitation.

salt aerosols, then an additional source must supply the excess of sodium.

Concentrations of excess sodium and calcium were computed from the corresponding total concentrations less the expected sea-salt contribution as estimated from the chloride values. Average results for the five sampling stations, together with monthly bicarbonate concentration data, are plotted in figure 8. A close similarity in the concentration patterns is evident from the figure, suggesting a common source for the bicarbonate and excess cations. Individual station data (table 1), however, indicate marked differences in the relative amounts of excess cations and alkalinity at various points on the island. Thus, localized sources, probably soil dust, account for the bicarbonate and the excess of sodium and calcium in precipitation over the amounts contributed from sea-salt aerosols.

Calcium and bicarbonate concentration is much less, and chloride concentration except for station 4 is somewhat greater from the open collector at station 2, altitude 1520 (463 m) than for other stations on the island. Apparently airborne mineral constituents derived from the soil and rock of the island are in greater concentration at lower altitudes and in locations sheltered from the prevailing winds (stations 1 and 5) and in lesser concentration at higher altitudes and windward locations (stations 2 and 3). Sea-derived mineral constituents appear to prevail on windward slopes and particularly at high altitudes, as seems logical because sea-derived minerals have the entire sweep of the ocean to be carried to the higher altitudes.

TABLE 1.—*Average concentrations of principal mineral constituents in bulk preciptation, February 1965 through December 1966*

[See fig. 2 for station location. Constitutents given in milligrams per liter]

	Station					Station mean
	1	2	3	4	5	
Total:						
Calcium	2.78	1.11	1.99	1.88	2.56	2.06
Magnesium	.57	.53	.62	.92	.63	.65
Sodium	4.73	5.00	4.63	7.27	4.79	5.28
Potassium	.32	.29	.26	.42	.30	.32
Chloride	5.82	7.97	5.74	10.2	5.82	7.11
Bicarbonate	14.4	4.8	12.2	10.6	13.7	11.1
Sulfate	1.46	1.89	1.48	2.22	1.36	1.68
Nitrate	.07	.06	.04	.10	.09	.07
Excess:						
Calcium	2.65	0.94	1.87	1.66	2.43	---
Magnesium	.18	0	.24	.24	.24	---
Sodium	1.52	.60	1.46	1.64	1.58	---
Potassium	.20	.13	.15	.22	.18	---
Sulfate	.65	.78	.68	.80	.55	---
Average annual precipitation, in inches 1965–66	48.1	62.1	53.3	33.0	41.5	---
Altitude, in feet	600	1520	700	250	200	---

The magnitude of the local alkaline component of bulk precipitation is apparent from the data of table 1. Monthly deposition of bicarbonate exceeded concurrent chloride deposition except during the winter of 1965–66.

Sulfate is an important component of precipitation throughout North America and Europe. On St. Thomas, considerable amounts of sulfate are supplied to rainfall by sea-salt aerosols, in which the sulfate to chloride ratio in milligrams per liter should be 0.14. However, computation of the ratio of sulfate to chloride in precipitation collected over the 23-month sampling period shows that sulfate ordinarily exceeds that available from sea salt. A graph of average monthly excess sulfate concentrations is shown in figure 9. No annually recurring feature is noticeable. The peak value in February 1966 coincides with an excess cation concentra-

FIGURE 9.—Seasonal pattern of excess sulfate concentration in bulk precipitation.

tion peak; in other respects the seasonal pattern is not very similar to the excess cation distribution. Different origins for the sulfate and bicarbonate may be inferred from the dissimilarities in the distributions. Volcanic, industrial, and biological emissions of sulfur dioxide and hydrogen sulfide into the global atmosphere undoubtedly provide much of the excess sulfur in precipitation on St. Thomas; however, the reactive mechanisms that lead to the observed sulfate concentrations are unknown.

Continental rainfall often contains appreciable amounts of nitrate and of ammonium (Junge, 1958). These ions were regularly determined in the St. Thomas network samples; however, concentrations of both species were very low. Range of nitrate concentrations over the 23-month study period was from 0.01 to 0.33 mg/L, with a median value of 0.05 mg/L. Median ammonium concentration was less than 0.1 mg/L, although three samples contained ammonium in excess of 0.5 mg/L. Very probably these high values indicate organic contamination of the sample.

Values of pH were determined routinely in the St. Thomas precipitation samples. Median pH for 105 samples was 6.7; the range was from 4.8 to 8.1.

CONTRIBUTION OF DRY FALLOUT TO OVERALL PRECIPITATION COMPOSITION

Analyses of concurrent samples from the automatic collector and the adjacent continuously open sampler on Crown Mountain (station 2) were expected to provide data from which accurate estimates could be made of the nature and relative amounts of minerals deposited in dry fallout. Whitehead and Feth (1964) have shown that dry fallout can be the most important means of depositing minerals from the atmosphere in some locations. Unfortunately, the lid-operating mechanism and the rain-sensing unit of the automatic collector on St. Thomas broke down frequently during the sampling period, so that assessments of the dry fallout contribution noted below are rough approximations only.

Comparative data were obtained from six pairs of samples collected during months when the automatic collector was judged to be operating satisfactorily. Estimates of dry fallout loads (amount in open collector minus that in automatic collector) indicate that dry deposition accounts for 17 percent of the bicarbonate, about one-third of the common cations and sulfate, and almost one-half of the total chloride load. If the dry-fallout chloride is associated with other chemical constituents in proportion to the amounts found in seawater, then all the magnesium and most of the sodium, potassium, and sulfate in dry fallout at station 2 can be ascribed to sea salts. Most of the calcium, on the other hand, seems to be associated with bicarbonate and to be land derived.

SURFACE- AND GROUND-WATER COMPOSITION

Throughout the island airborne salts are deposited on the land surface as dry fallout or washed from the atmosphere by precipitation. The essentially constant load of salts reaching the land surface (as indicated by the monthly chloride load in fig. 7) by minor rains is believed to be conducive to the concentration of salts in the soil zone. There they remain until they are dissolved by rain from the occasional major storm and are carried to the ground-water reservoir, or are leached from the soil and incorporated in storm-water runoff.

SURFACE WATER

Large quantities of soluble minerals are leached by storm runoff from the soil of St. Thomas. This effect is illustrated in the analysis of a surface-water sample (analysis 12, table 2) taken when streamflow was nearly all storm runoff following a 5-in (127 mm) rain over the watershed. Chloride, calcium, and sulfate concentrations in the runoff are 10-fold greater than corresponding average values in precipitation, while relative increases of magnesium, sodium, and bicarbonate are even greater. The high concentrations in surface water indicate a ready availability of soluble minerals near the surface. The minerals may

TABLE 2.—*Analysis of water of St. Thomas*

[Constituents given in milligrams per liter except as indicated]

Location	6	7	8	9	10	11	12	13	[1] 14
Date	9–29	11–19	10–14	1–2	12–22	5–11	8–29	5–2	----
Year	1964	1963	1963	1964	1964	1965	1963	1966	----
Silica (SiO_2)	33	23	28	36	32	33	20	29	----
Iron (Fe)	0	0	.04	0	0	.09	.13	.02	----
Calcium (Ca)	14	48	59	48	38	94	20	56	2.06
Magnesium (Mg)	15	45	57	46	34	68	11	49	.65
Sodium-potassium	245	464	372	293	295	359	81	432	5.28
(Na and K).									.32
Bicarbonate (HSO_3)	524	726	730	758	668	772	188	886	11.1
Sulfate (SO_4)	37	90	131	32	35	142	17	56	1.68
Chloride (Cl)	112	432	305	200	200	362	70	350	7.11
Fluoride (F)	.4	1.2	.9	1.0	.8	1.0	.3	.6	----
Nitrate (NO_3)	3	17	28	9.4	10	.3	.6	1.3	.07
Dissolved solids	727	1440	1300	963	994	1470	[2]313	1430	[2]23
Specific conductance (micromhos at 25°).	1210	2490	2200	1670	1680	2400	541	2350	----
pH	8.1	8.0	7.9	7.9	7.7	7.7	7.4	8.3	----

[1] Average bulk precipitation February 1965 through December 1966.
[2] Calculated.

EXPLANATION

Location and sources of water analyzed. Location in figure 2.

Wells:

6–10. In volcanic rock of Louisenhoj Formation.

11. In Outer Brass Limestone.

12. Turpentine Run near Mt. Zion storm runoff; discharge 1700 gal/min (107 L/s).

13. Turpentine Run near Mt. Zion base flow; discharge 10 gal/min (0.63 L/s).

well provide the localized alkaline aerosol component of precipitation on the island.

GROUND WATER

Comparisons of the bulk precipitation, surface-water, and ground-water data of table 3 indicate that the overall chemical character of the ground and surface water is established rapidly for the major ions. Ratios of sodium, magnesium, and bicarbonate with respect to chloride are uniformly higher in ground water than they are in the incident precipitation. Much or all of the increase apparently occurs as rainfall percolates through the soil zone during times of recharge, as indicated by the corresponding ratios for the storm-runoff water. Calcium chloride ratios, however, are low in the ground water as compared with these ratios in rainfall and storm runoff, suggesting precipitation or exchange of calcium in the aquifers or in the weathered rock zone.

TABLE 3.—*Ratios of equivalent concentrations relative to chloride*

[See fig. 2 for locations. See table 2 for analyses]

Location	Ratios, millequivalents per liter constituent to milliequivalents per liter chloride						
	Ca/Cl	Mg/Cl	(Na+K)/Cl Na/Cl	(Na+K)/Cl K/Cl	HCO_3/Cl	SO_4/Cl	NO_3/Cl
GROUND WATER							
6	0.22	0.39	3.4		2.7	0.24	0.02
7	.20	.30	1.6		.98	.15	.02
8	.34	.54	1.9		1.4	.32	.05
9	.42	.67	2.3		2.2	.12	.03
10	.34	.50	2.3		1.9	.13	.03
11	.46	.55	1.5		1.2	.29	.00
SURFACE WATER							
12	0.51	0.46	1.8		1.6	0.18	0.00
13	.28	.41	1.9		1.4	.12	.00
PRECIPITATION							
14	0.51	0.27	1.1	0.04	0.91	0.17	0.01

Nitrate concentrations in water from the Louisenhoj Formation are relatively high. Ground-water ratios of nitrate/chloride are all higher than the corresponding value for precipitation (table 3), and indicate additions of nitrate to the aquifers by sources other than the local precipitation. Presumably the nitrate in this aquifer is derived from the leaching by recharge water of products of organic decay from the soil. (False tamarind, a legume, is a principal component of the brush cover of the island.) Nitrate is low in water from the Outer Brass Limestone, whose outcrop area is covered predominantly by grass pasture.

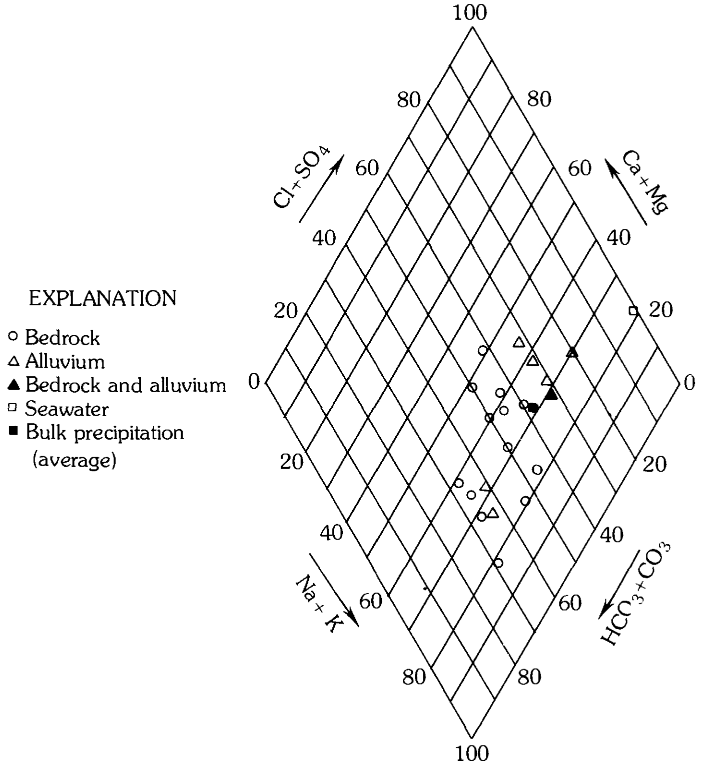


FIGURE 10.—Chemical classification diagram of ground water.

Ground waters are similar in chemical type throughout the island (fig. 10) except in areas affected by saltwater encroachment. Drilled wells bottomed above sea level or slightly below sea level and inland yield water with a chloride content ranging between 100 and 500 mg/L. Analyses of water collected during drilling often showed an increase in chloride concentration with depth from the surface of the water table even in places above sea level.

Variations in mineralization of ground water in upland and inland areas are not associated with seawater intrusion. In general, as shown in figure 11, chloride concentration, which is proportional to total dissolved solids concentration, decreases with increasing altitude. A higher chloride concentration at lower altitude might be attributed to exposure or sea spray as is indicated by the high sodium and chloride concentration in the composition of bulk precipitation at station 4 (table 1 and fig. 2) at an altitude of 250 ft (75 m). Sea spray has occasionally been observed at

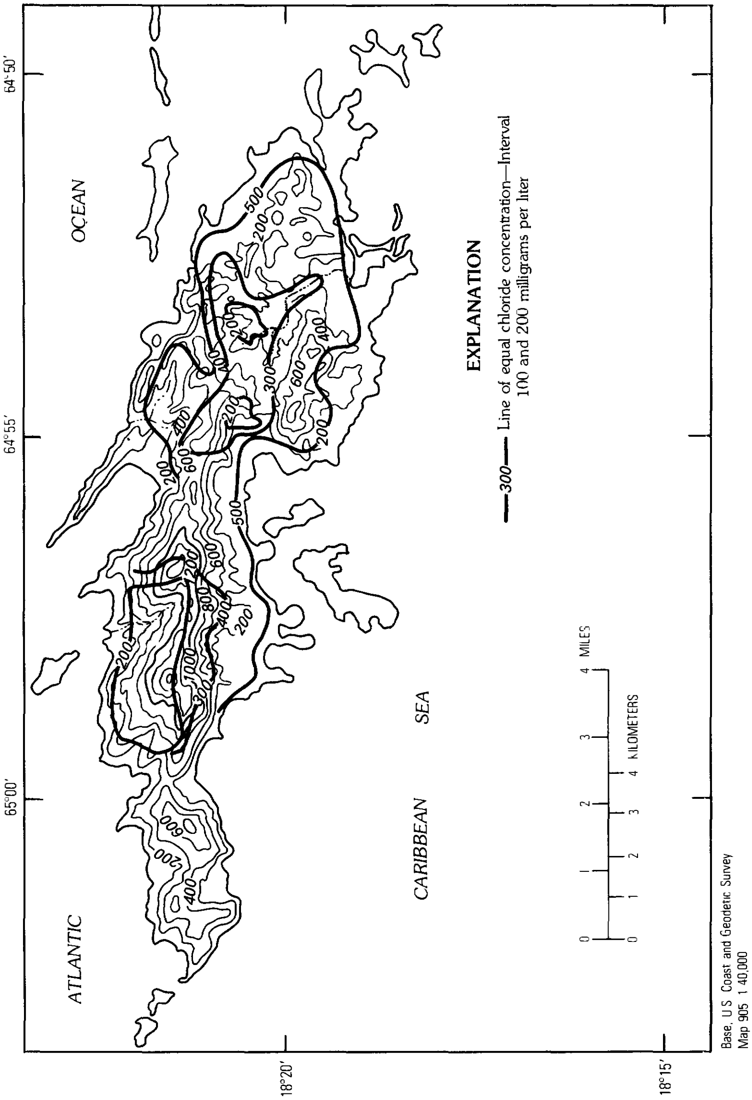


FIGURE 11.—Distribution of chloride concentration in ground water.

an altitude of more than 300 ft (90 m) on the north coast; however, it is doubtful that sea spray has any appreciable effect on ground-water quality above an altitude of 300 ft (90 m).

In the authors' opinion the mineral content of the inland ground water is derived from the concentration of bulk-precipitation minerals carried to the ground water in recharge and the concentration of minerals in the ground water by evapotranspiration as the water moves through the aquifer toward the sea. Ground water at higher altitudes should, according to this hypothesis, be lower in mineral content than water farther downslope.

RELATIONSHIP BETWEEN CHLORIDE CONCENTRATION, RECHARGE, AND GROUND-WATER LOSS

A relationship between changes in chloride concentrations, recharge, and ground-water losses with respect to evapotranspiration is discussed below for three different areas of St. Thomas (fig. 6). The computations involving chloride concentrations are

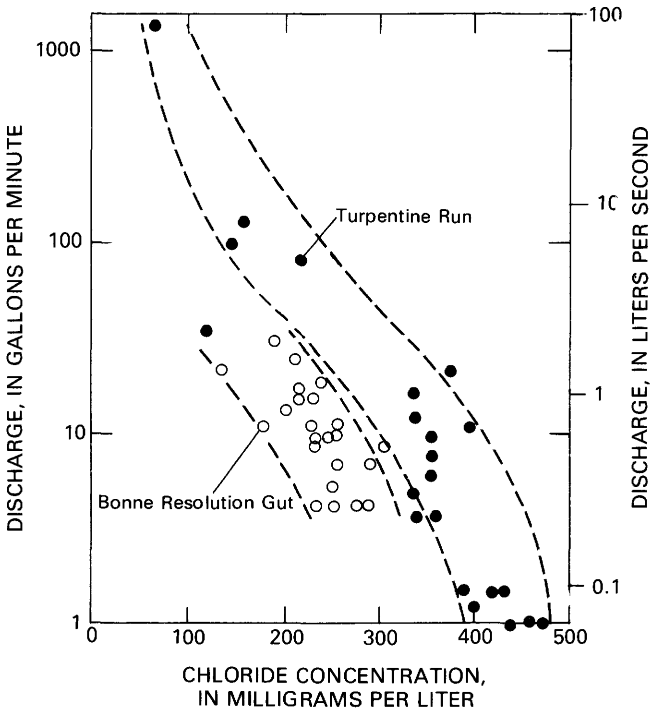


FIGURE 12.—Variation of chloride concentration of water with discharge of Turpentine Run near Mt. Zion and Bonne Resolution Gut at Bonne Resolution.

based on the assumption that the chloride is derived wholly from bulk precipitation and is retained in solution in the aquifers.

BONNE RESOLUTION GUT BASIN

Bonne Resolution Gut drains a small basin on the north slope of central St. Thomas. The stream was gaged in a perennial reach about halfway down the slope. The reach has a drainage area of 0.5 mi^2 or 1.3 km^2 (area 3a, fig. 5). Average annual base flow (ground-water outflow) is about 10×10^6 gal (37,850 m^3), which is one-fourth of the total flow and about 2.5 percent of the rainfall. The chloride concentration of the stream ranges between 200 and 300 mg/L as shown in figure 12.

Average recharge for area 3a is 2.3 in (58 mm) per year based upon the estimated annual recharge for area 3b (1.1 in or 28 mm) with the addition of the base flow of Bonne Resolution of 1.2 in (30 mm) per year. The base flow of the stream is considered to represent the additional recharge reaching the aquifer in this basin which is principally grass covered as compared with area 3b which is brush covered.

Ground water in the upper part of the basin has a chloride concentration, which is based on analysis of water from a single well on the west edge of the basin, of about 110 mg/L. The average chloride concentration of precipitation was 5.7 mg/L at precipitation station 3, also on the west edge of the basin. Precipitation in the area is about 45 in (1140 mm) per year, of which 3.4 in (90 mm), 7.5 percent, is discharged as storm runoff; the remainder, 41.6 in (1050 mm), is available for evapotranspiration or recharge.

If it is assumed that evapotranspiration from the soil zone consumes available water until the chloride level is increased from its initial value of 5.7 mg/L in precipitation to a level of 110 mg/L as recharge, then the recharge can be estimated from the relative chloride concentrations and the precipitation as follows:

$$fc = \frac{\mathrm{Cl}gw}{\mathrm{Cl}bp}$$

$$= \frac{110}{5.7} = 19.3.$$

Where *fc* is the concentration factor Cl*gw*, is the initial chloride concentration in the ground water in milligrams per liter, and Cl*bp* is the average chloride concentration in bulk precipitation in milligrams per liter.

Recharge will be

$$Rt=\frac{Pt-Ps}{fc}$$

$$=\frac{45-3.4}{19.3}=2.16 \text{ in or } 55 \text{ mm.}$$

Where Rt is recharge to the aquifer in inches, Pt is total precipitation in inches, and Ps is storm runoff in inches.

Recharge by the conservative ion method is slightly less than that estimated.

If evapotranspiration continues to concentrate the ground water so that the chloride concentration in the aquifer increases from 110 to 250 mg/L (the average chloride concentration of base flow in the gut), then the residual of the recharge and evapotranspiration losses can be calculated. Thus,

$$Rr=\frac{Rt}{\mathrm{Cl}bf/\mathrm{Cl}gw}$$

$$=\frac{2.16}{250/110}=0.95 \text{ in or } 24 \text{ mm or}$$

$$Rr=\frac{Pt-Ps}{\mathrm{Cl}bf/\mathrm{Cl}bp}$$

$$=\frac{45-3.4}{250/5.7}=0.95 \text{ in or } 24 \text{ mm.}$$

Where Rr is residual recharge in inches, and $\mathrm{Cl}bf$ is the chloride concentration of base flow in milligrams per liter. Theoretically the residual recharge should equal or be slightly greater than the base flow of the stream. In this instance, however, the residual recharge of 0.95 in (24 mm) is about 20 percent less than the base flow of 1.15 in (29 mm).

Water moved from the aquifer by evapotranspiration (ET) would be

$$ET=Rt-Rr$$

$$=2.16-0.95=1.21 \text{ in or } 31 \text{ mm.}$$

Recharge to the aquifer based on the increase in chloride concentration was about 6 percent less than that calculated by hydrologic means. Ground water loss to evapotranspiration based on the increase in chloride concentration in the aquifer was 56 percent, whereas the loss based on the differences between calculated recharge (2.3 in or 58 mm) and base flow (1.15 in or 29 mm) was 50 percent.

TURPENTINE RUN BASIN

The upper reaches of Turpentine Run drain an interior basin (area 2a, fig. 5) of 2.3 mi^2 (6 km^2) in east-central St. Thomas. Average annual rainfall is about 42 in (1070 mm), nearly all of which (38 in or 970 mm) goes to replenish soil moisture. Storm runoff is about 0.4 in (10 mm) or 15×10^6 gal (56,800 m^3) annually—less than 1 percent of the rainfall. Annual recharge to the basin aquifer is about 3.3 in (84 mm) or 130×10^6 gal (492,000 m^3), as computed by changes in ground-water levels in relation to rainfall (Jordan and Cosner, 1973). Ground water discharges as base flow of Turpentine Run only when ground-water levels are high in the basin. The greater part of the ground-water discharge is subsurface to the lower Turpentine Run basin through a bedrock divide at Mt. Zion (fig. 2). Annual ground-water discharge from the basin averages about 10×10^6 gal (37,850 m^3) as base flow and about 25×10^6 gal (94,600 m^3) as subsurface flow. The difference of 95×10^6 gal (360,000 m^3) between recharge and ground-water discharge is attributed to evapotranspiration loss from the aquifer.

Precipitation station 5, located in the basin, had an average chloride concentration of 5.8 mg/L. The chloride concentration of the ground water in the basin ranges from about 110 mg/L near the surface of the water table to about 400 mg/L at depths of 150 to 200 ft (46 to 61 m) below the surface of the water table. The chloride concentration of water in the stream ranges from less than 100 to 500 mg/L; average base flow concentration is about 350 mg/L (fig. 12).

Calculations similar to those used for the Bonne Resolution Gut basin yield a chloride concentration factor for this area of

$$fc = \frac{Clgw}{Clbp}$$

$$= \frac{110}{5.8} = 19.$$

Recharge (assuming storm runoff negligible) then would be

$$Rt = \frac{Pt}{fc}$$

$$= \frac{42}{19} = 2.2 \text{ in or } 56 \text{ mm}.$$

This amount is equivalent to an annual recharge of 88×10^6 gal (333,000 m^3) or about two-thirds the recharge calculated previously by hydrologic means.

Recharge to the aquifer can also be estimated by comparing the concentration of storm runoff with that of bulk precipitation. The storm runoff water sample from Turpentine Run (analysis 12, table 2) was taken a day after cessation of the rain. By this time the diluting effect of the precipitation was assumed negligible, and runoff composition was assumed to be very similar to that of water recharging the aquifer.

Computation of recharge using these values gives

$$fc = \frac{Clgw}{Clbp}$$

$$= \frac{70}{5.8} = 12.1$$

$$Rt = \frac{Pt}{fc}$$

$$= \frac{42}{12.1} = 3.5 \text{ in or } 89 \text{ mm.}$$

The annual recharge of 3.5 in is equivalent to 138×10^6 gal (522,000 m^3), which is quite close to that obtained by hydrologic means.

Annual water loss from the aquifer by evapotranspiration derived by hydrologic means was 95×10^6 gal (360,000 m^3)—73 percent of the recharge to the aquifer. Water loss from the aquifer can also be estimated from differences in chloride concentration of water from shallow (110 mg/L) and water from deep (400 mg/L) zones in the aquifer.

$$ET = Rt - Rr$$

$$= Rt - \frac{Rt}{Clgw_2/Clgw},$$

where $Clgw_2$ is final chloride concentration in ground water in milligrams per liter. If

$$Rt = 3.3 \text{ in or } 84 \text{ mm.}$$

then

$$ET = 3.3 - \frac{3.3}{400/110} = 2.4 \text{ in or } 61 \text{ mm.}$$

The water loss from the aquifer due to evapotranspiration is about 73 percent of the recharge—the same as that calculated by hydrologic means. The volume of water loss from the aquifer, however, depends upon the amount of recharge as the percentage of loss will remain constant as long as there is no change in the ratio of chloride concentration.

Water loss from the aquifer by evapotranspiration also may be calculated from storm runoff and base-flow chloride concentration of Turpentine Run. If these values (70 mg/L and 350 mg/L) are considered equal to initial and average concentrations, respectively, of the ground water, then a five-fold concentration has occurred in the aquifer, and the water loss from the aquifer is then 80 percent of the initial recharge.

A number of combinations of recharge to and evapotranspiration loss from the aquifer of the upper Turpentine Run basin can be obtained from the foregoing computations. A summary of those discussed is given in table 4.

Computations of recharge to the aquifer by comparison of chloride concentrations ranged from 2.2 to 3.5 in (56 to 89 mm)

TABLE 4.—*Annual water budget of Turpentine Run as computed by different means*

Method	1		2		3		4		5	
	inches	10^6 gallons	inches	10^6 gallons	inches	10^6 gallons	inches	10^6 gallons	inches	10^6 gallons
Rainfall	42	1677	42	1677	42	1677	42	1677	42	1677
Storm runoff.	.4	15	.4	15	.4	15	.4	15	.4	15
Ground-water recharge.	3.3	130	2.2	88	3.5	138	3.3	130	3.5	138
Initial ET loss.	38.3	1532	39.4	1574	38.1	1524	38.3	1532	38 1	1524
Base flow	.3	10	.3	10	.3	10	.3	10	.2	10
Ground-water discharge.	.6	25	.3	14	.7	27	.6	25	.5	18
ET loss from aquifer.	2.4	95	1.6	64	2.5	101	2.4	95	2.8	110

NOTES.—
1. Hydrologic means; ET from aquifer 73 percent.
2. Chloride concentration shallow-ground water to bulk precipitation; ET from aquifer 73 percent.
3. Chloride concentration storm runoff to bulk precipitation; ET from aquifer 71 percent.
4. Chloride concentration shallow ground water to chloride concentration deep ground water; ET from aquifer 73 percent.
5. Chloride concentration storm runoff to chloride concentration base flow; ET from aquifer 80 percent.

as compared with recharge of 3.3 in (83 mm) obtained by hydrologic means. Similarly, computations of evapotranspiration from the aquifer by comparison of chloride concentrations ranged from 1.6 to 2.8 in (41 to 71 mm) as compared to an evapotranspiration of 2.4 in (61 mm) by hydrologic means. Water loss from the aquifer, however, ranged from 71 to 80 percent of the recharge as computed by the different methods.

Obviously the choice of the proper chloride values is critically important to the estimation of aquifer recharge as aquifer loss based on chloride concentration in ground water, or in base flow, or storm runoff. Nevertheless, there is general agreement between results obtained by hydrologic measurements and those arrived at by assuming conservation of the chloride anion.

SOUTH SLOPE, CENTRAL ST. THOMAS

There are no intermittent or perennial streams on the south slope (part of area 1, fig. 5) of central St. Thomas—only a few intermittent springs. The minimum chloride concentration of the ground water is about 300 mg/L at higher altitudes (fig. 11). Estimated recharge to the area is about 0.7 in (18 mm) per year based on response of ground-water levels to rainfall and estimated storage capacity of the aquifer. Storm runoff occurs only about every 2 years. The average chloride concentration of bulk precipitation at station 1 on the south slope was 5.8 mg/L.

If the minimum chloride content of the ground water is 300 mg/L, then the concentration factor is

$$fc=\frac{\mathrm{Cl}gw}{\mathrm{Cl}bp}$$

$$=\frac{300}{5.8}=52$$

Recharge then would be

$$Rt=\frac{Pt}{fc}$$

$$=\frac{45}{52}=0.87 \text{ in or } 22 \text{ mm.}$$

Again, agreement between the different methods is quite good.

As shown in figure 11, the chloride concentration of the ground water increases to about 500 mg/L downslope. The increase would require a water loss through evapotranspiration of about 40 percent—somewhat less than that computed for other areas. As the water-table surface generally is 50 ft (15 m) or more below land surface except in the major valleys, the greater depth to ground water over much of this area could account for the smaller water loss.

SUMMARY

Oceanic salts would be expected to contribute significantly to the mineral composition of precipitation on St. Thomas. The ratios of common mineral constituents to chloride, however, exceed those found in seawater, thus indicating land-derived minerals as well. The excess cations and anions in bulk precipitation are also those in abundance in the rocks of the island; thus a ready source is available, with the exception of sulfate for which no origin could be determined. The sea-derived mineral constituents are greatest to the windward and at higher elevations, whereas the land-derived minerals comprise a greater percent of the bulk precipitation at lower elevations and to the leeward.

Throughout the island airborne salts are deposited on the land and concentrated in the soil zone by minor rains. The salts remain there until they are carried to the ground-water reservoir or leached from the soil zone and are incorporated in storm-water runoff during the rare major rainstorms. Comparison of the mineral content of bulk precipitation and ground water, and surface water shows that the overall chemical character of the ground and surface water is established rapidly and is in essence a concentration of the bulk precipitation.

The chloride concentration of the ground water compared with that of bulk precipitation shows a nearly 20-fold concentration occurs initially in the soil zone due to evapotranspiration. Additional evapotranspiration from the aquifers, ranging from 40 to 80 percent of recharge, further increases the mineral content of the ground water.

By assuming a conservation of dissolved chloride in the ground water, estimates of recharge to and evapotranspiration losses from the aquifers can be obtained that compare favorably with similar estimates made by hydrologic means.

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