GROUNDWATER GEOCHEMISTRY OF THE ST. CROIX CARBONATE AQUIFER SYSTEM

Ivan P. Gill
Dennis K. Hubbard

August, 1986

Project No. 02

Agreement No. 14-08-0001-G1050

Technical Report No. 27
Caribbean Research Institute
College of the Virgin Islands
St. Thomas, U.S.V.I. 00802

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West Indies Laboratory
Teague Bay, St. Croix
U.S. Virgin Islands 00820

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Contents of this publication do not necessarily reflect the views and policies of the U. S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the the United States Government.

ABSTRACT

Samples from public and private wells representing a variety of locations across the carbonate plain on St. Croix were collected and analyzed according to U. S. Geological Survey specifications. Almost all samples analyzed exceeded US EPA recommended limits for chloride and dissolved solids content. Several of the samples exceeded EPA limits for sulfate. However, limits for these constituents are based on esthetic and taste considerations rather than considerations of health. Mean levels of sodium in the groundwater, however, ranged from 99 to 937 ppm and are a potential health risk to those on sodium restricted diets.

Chemical modeling calculations show that the groundwater is generally saturated with respect to quartz, and in several cases with kaolinite and gibbsite. Coastal wells, but not inland wells, were calculated to be saturated with respect to calcite, probably as a result of seawater influence. One well sample was calculated to be simultaneously undersaturated with respect to calcite and supersaturated with respect to dolomite.

The major sources of groundwater mineralization on St. Croix are seawater mixing and diagenetic interactions. Concentration of rainwater through evapo-transpiration, though widely cited, is at best of minor importance. Diagenetic interactions were of greatest importance to groundwater mineralization in the inland portions of the aquifer. Toward the coasts, seawater mixing tended to overprint any diagenetic effects in the groundwater. All major elements tested except for potassium and magnesium plotted above the mixing curve for rainwater and seawater. In general, silicate phases play an unexpectedly large role in the chemistry of this dominantly carbonate aquifer. In addition to the dissolution of carbonate minerals, cation exchange and silicate mineral transformations probably contribute to the chemical make-up of the groundwater.

ACKNOWLEDGEMENTS

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INTRODUCTION

St. Croix draws a significant and increasing fraction of its water from the limestone aquifers of the central plains region. Despite this, there is a major lack of information regarding the geology of the aquifer system, and more to the point of this report, a major lack of information on the quality and chemistry of the groundwater itself. Past information on St. Croix groundwater is adequate for general description of groundwater trends, but was collected more than a decade ago (Cederstrom, 1950; Robison, 1972; and Jordan, 1975; among others). Little information is available on the techniques used in the collection and analysis of the samples, and few published sources include sufficient parameters to allow modeling of the various water and mineral reactions in the aquifer.

These last two points are important in determining the sources of mineralization of the groundwater, and in understanding the possible chemical reactions occurring in the aquifer system. Geochemical information may be used as an independent check on hydrologic models of the aquifer and will aid in understanding the diagenetic reactions within the carbonate section.

The objectives of this report are to:

1) provide reliable, self-consistent data on St. Croix groundwater adequate for geochemical modeling and proposed hydrologic analysis;

2) produce information on both private and public wells throughout the limestone aquifer system;

3) briefly tie-in the chemistry of the groundwater to the on-going research on the subsurface geology of the Kingshill Limestone.

Water samples were taken from wells in a variety of locations in the St. Croix limestone region and analyzed at Louisiana State University and the West Indies Laboratory. This report deals with the initial results of the groundwater analyses. This project is part of an on-going doctoral research effort and refinements and additional results will no doubt be made in the near future.

STUDY AREA

St. Croix lies at the northwestern edge of the Lesser Antilles arc, approximately 176km (95mi) southeast of Puerto Rico (Fig. 1). At its widest points, the island is 39 km (21 mi) long, 9 km (6 mi) wide and covers a total of 207 sq. km (84 square miles). St. Croix is tectonically and geologically distinct from the rest of the primarily igneous islands of the Lesser Antilles.

The mountainous eastern and western ends of the island are formed by well-lithified siliciclastic rocks of Cretaceous age (Fig. 2). These rocks are sedimentary, and are composed of tuffaceous and volcanoclastic material deposited in deep water (Whetten, 1966). Diorite and gabbro intrusives cut this sedimentary material at several points on the island.

The central plain of the island is formed by deposits of alluvium and exposures of the underlying carbonate (limestone) rocks (Fig. 2). The carbonate units supply the majority of groundwater, range from 0 to 500 feet thick, and are underlain by dark, low-permeability Jealousy Formation clays that exceed 1400 feet in thickness (Cederstrom, 1950).

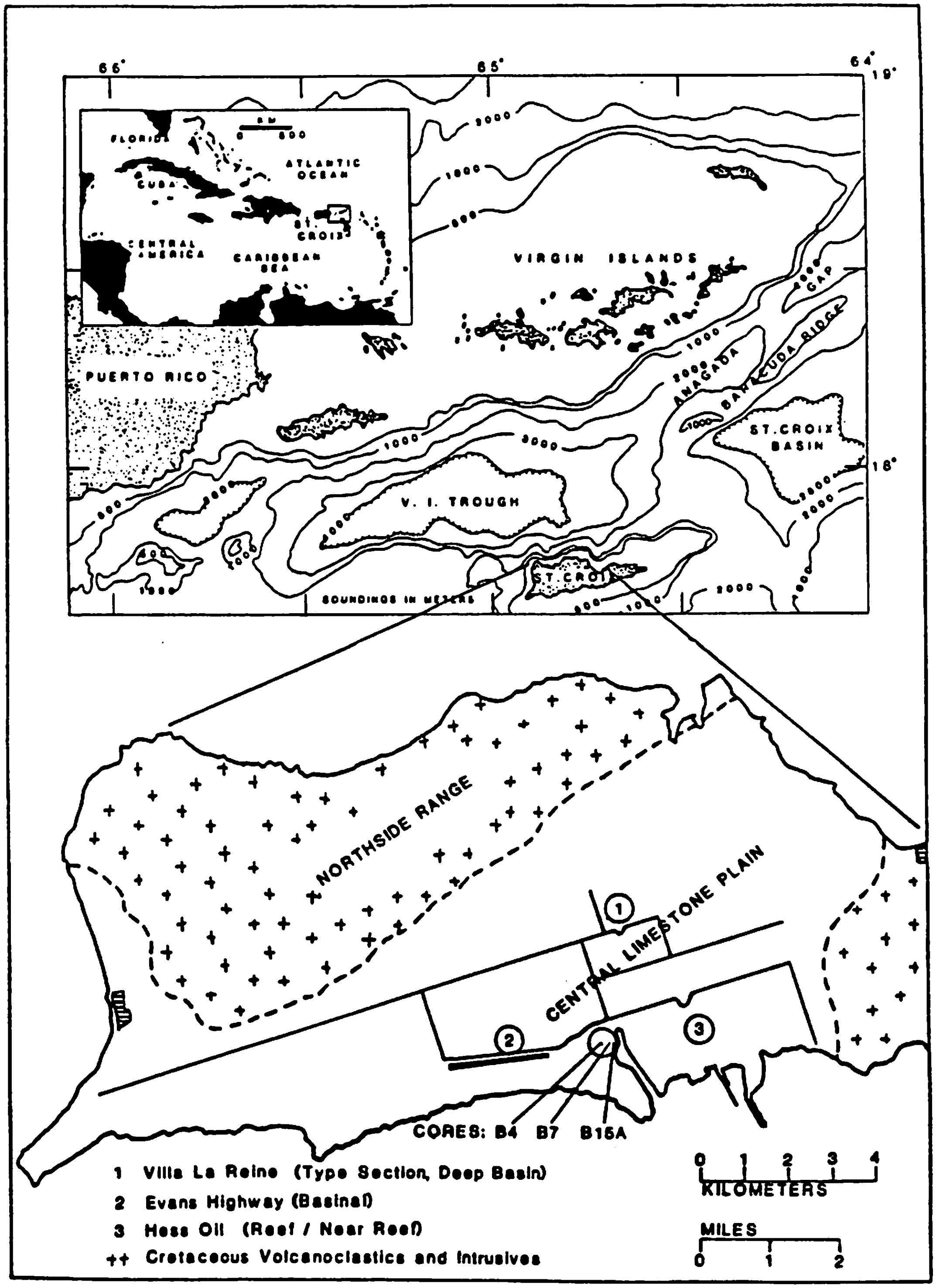

Figure 1. St. Croix location map and study area.

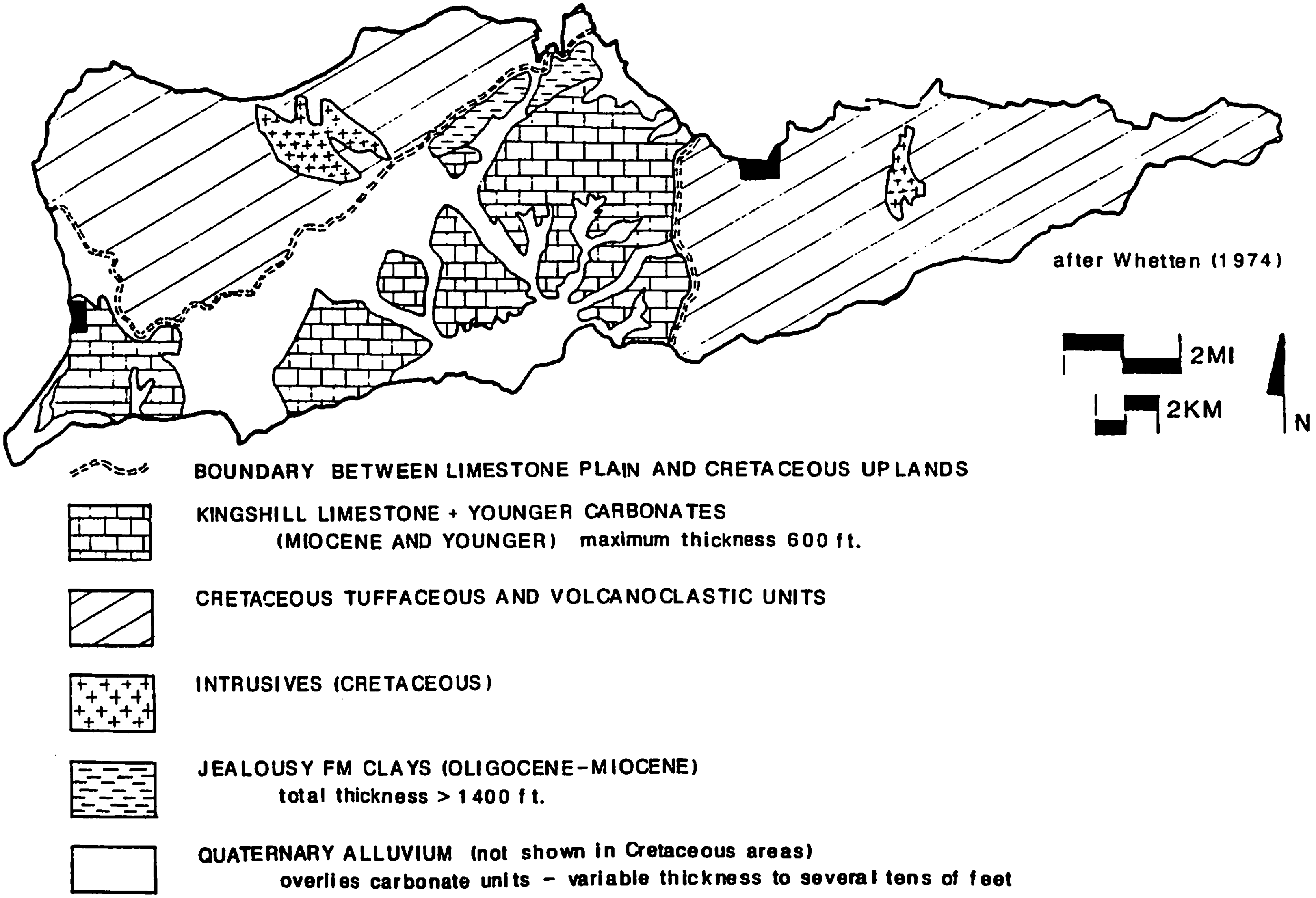

Figure 2. Generalized geologic map of St. Croix.

The impermeable nature of the Jealousy Formation allows it to function as an aquitard, and it is probably safe to assume that it limits the incursion of salt water from below (Jordan, 1975). Because of the underlying clays of the Jealousy Formation and the layered nature of the Kingshill Limestone the Ghyben-Herzberg model of island hydrololgy does not apply to St. Croix.

The lithology and depositional characteristics of the carbonate units are variable. It should be noted that most of the limestone contains significant quantities of lithic material and clay minerals. Gerhard et al. (1978) found acetic acid insoluble residue ranges from 0 to almost 99 percent in beds of the Kingshill Limestone. Percentages of illite, kaolinite and montmorillonite also vary throughout the section. Lithology and depositional characteristics of the limestone units are described in more detail in Multer et al. (1977); Gerhard et al. (1978); Gill and Hubbard (1985); and Gill and Hubbard (1986).

Wells sampled in this report are scattered throughout the central plain region (Fig. 3), and draw their water primarily from the Kingshill Limestone and younger carbonate units. Some, such as the public well field at Fairplain and the private wells in the Glynn and Concordia estates receive groundwater from overlying alluvium as well. Two wells were sampled in Estate Solitude, on the eastern end of the island to contrast water from a siliciclastic aquifer with water from the carbonate-dominated central plain.

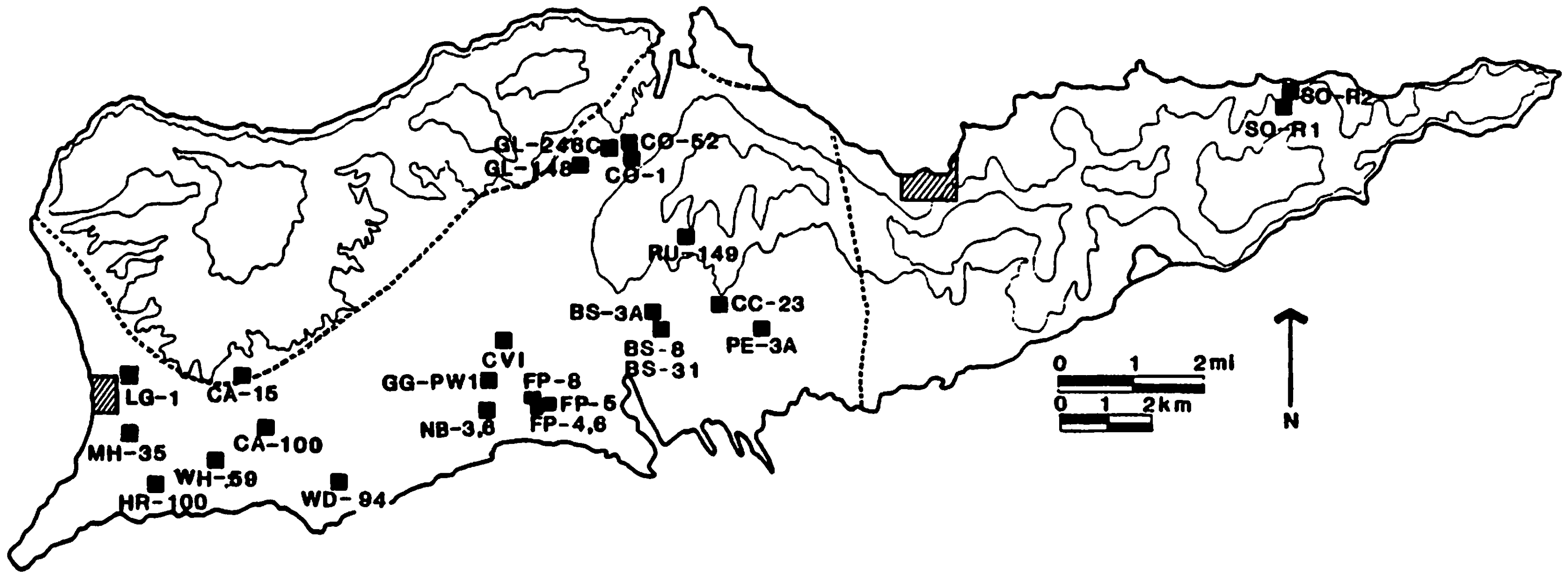

Figure 3. Well sample locations.

PREVIOUS WORK

Data on chemical groundwater quality are found in Cederstrom (1950), with analyses dating back to 1919. Detailed analyses are contained within several tables divided by aquifer type; other tables contain chloride content data along with brief lithologic logs of the wells in question. Information on pH, temperature, and method of analysis is not available. Cederstrom (1950) found that the chemistry of the groundwaters showed far higher degrees of mineralization than did surface waters. He attributed this to several processes: leaching of salts from the Kingshill Limestone, organic contamination, precipitation and re-solution of soil-borne alkali salts, and cation exchange. It should be noted that cation exchange should not result in a change in solution mineral content.

Hendrickson (1963) contains a history of development of the public well fields, including hydrologic and construction details of many of the public supply wells installed before 1963. Many of these wells are still in use. Water-quality information is limited to chloride content of the well water.

Robison (1972) presents a general overview of hydrologic conditions in the central plains region, including recommendations on secondary treatment of groundwater, water supply and water quality. Regarding water quality, the chemistry of individual well analyses is not shown. Instead, groundwater analyses are grouped into "normal" and "high-saline" waters, and averages for the groups are tabulated. Parameters include: Ca, Mg, Na, HCO_3 + CO_3, SO_4, Cl, F, TDS, and hardness.

Robison (1972) shows that in his "normal" water grouping, chloride content increases sharply with depth, the inflection point on the curve corresponding to mean sea level (Fig. 4). Robison (1972) explains the high degree of mineralization in the water by: hypersaline "connate" water from dissolution of evaporites, dewatering of Jealousy Formation clays or fault-restricted groundwater circulation. Robison (1972) suggests that ionic diffusion and mixing with seawater may also be responsible for many of the groundwater characteristics. He estimates that shallow groundwater has been concentrated at least 30 times by evapo-transpiration, accounting for the increase in chloride content from that of Virgin Island rainwater.

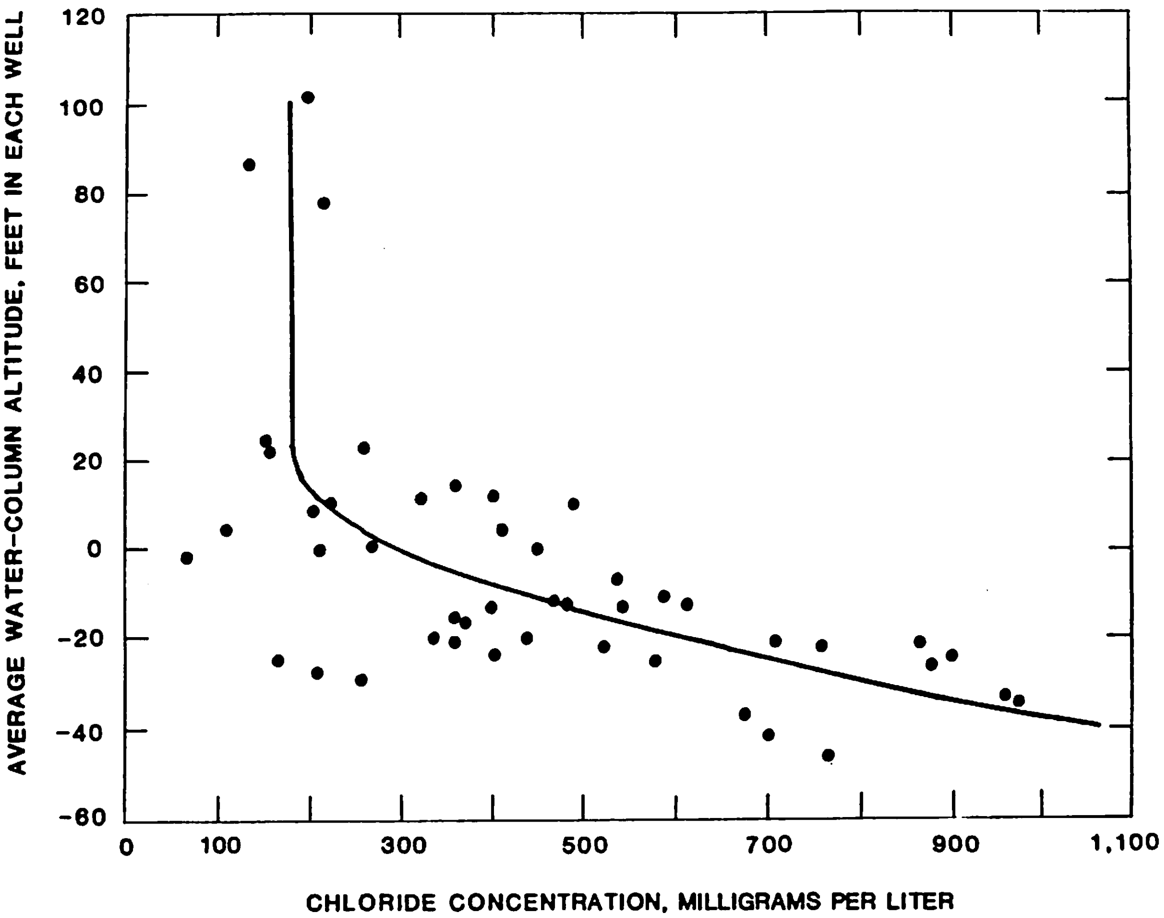

Figure 4. Water column altitude vs. chloride content (after Robison, 1972).

Jordan (1975) produced a comprehensive report dealing with many aspects of supply, treatment, development and quality of St. Croix groundwater. His discussion is not limited to the central plains region, and summarizes many of the previous reports on St. Croix groundwater. Groundwater and surface water chemical data are tabulated, including: SiO_2, Fe, Mn, Ca, Mg, Na, K, HCO_3, SO_4, Cl, F, NO_3, Total Dissolved Solids (TDS), hardness, specific conductivity, pH, and temperature.

No information on collection or analytical techniques is supplied, and the pH values given are anomalously high, in some cases approaching or exceeding seawater values even on samples of low ionic strength. These high values may be a result of sample degassing before pH measurement. Jordan (1975) explains the mineralization of the groundwater as a combination of processes starting with the evaporative concentration of rainwater as suggested by Robison (1972). After concentration, groundwaters are modified by mineral dissolution, ion exchange and mixing with "connate" water.

Black, Crow and Eidsness (1976), a hydrologic consulting company, produced a groundwater management plan that includes specific recommendations for St. Croix. Some chemical groundwater data are included, but the parameters listed are averages of public well fields only, and include Cl, conductivity, hardness, Ca, Mg, CO_3 and HCO_3. No values for pH, temperature or Na are included. Black, Crow and Eidsness (1976) state that the factors that most strongly affect groundwater quality are solution, concentration and evapo-transpiration. No information on collection or analytical techniques is supplied.

Buros (1976), then affiliated with Black, Crow and Eidsness, produced a study of the hydrology of the Golden Grove area during an artificial groundwater recharge project. This report contains detailed information on the geologic setting of the Golden Grove/River Gut area and contains extensive data listings of the groundwater and surface water quality in this particular area. Parameters listed include Cl, specific conductivity, hardness, Ca, Mg, CO_3, HCO_3, NO_3, NH_3, P, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Organic Carbon (TOC) and coliforms.

The most recent general work on groundwater in the Virgin Islands was produced by Geraughty and Miller Inc. (1983 a and b). The report on groundwater conditions (Geraughty and Miller, 1983a) contains information on several of the public well fields on St. Croix; the appendix contains detailed analytical data on samples from both public and private wells on St. Croix. Temperature and pH data are not included on these tables; however, tests on trace heavy metals and organic pollutants were run on several public well field waters, and the results are listed in the report.

The groundwater management plan (Geraughty and Miller, 1983b) summarizes the findings of the first report and presents suggestions to the Virgin Islands Government on water management.

The most recent and comprehensive chemical data are those from Garcia and Canoy (1984). Published by the U. S. Geological Survey, the report contains complete information on major and minor elements and on organic pollutants. Collection methods used for the groundwaters are cited, and follow established U. S. Geological Survey guidelines. Nineteen wells were sampled in the U. S. Virgin Islands, eight of them on St. Croix.

Summary

Most of the existing information on St. Croix groundwater is usable for general purposes such as regional trends and health regulations. However, due to lack of information on several important geochemical parameters, many of the reports do not contain sufficient information for geochemical modeling. In addition, many of the data are from reports more than a decade old, and the collection and analytical procedures used are not cited.

METHODS

The methods of collection and preservation of samples can critically affect the usefulness and reliability of the analytical data. This report follows U. S. Geological Survey guidelines, for the most part those of Wood (1976) and Claasen (1982).

Sample Collection

Samples were collected from wells only after the water chemistry had stabilized according to repetitve tests for temperature, pH and specific conductivity. Buffers for the pH determination were kept at ambient groundwater temperature through the use of a water flow bath. All samples were taken as close as practicable to the well head, and were collected through inert plastic tubing and fittings. All samples were filtered through 0.45 micron filters and preserved in accordance with the type of subsequent analysis.

Aliquots for major and trace elements were acidified and stored in sealed, tightly capped polyethylene bottles. Aliquots for sulfate and nitrate analysis were preserved with mercuric chloride in polyethylene bottles. Aliquots for alkalinity and stable isotope analysis were stored in sealed glass jars. All storage and delivery vessels were chemically cleaned and dried in the laboratory, and repeatedly precontaminated with the sampled water before final collection.

Alkalinity was either analyzed immediately in the field, or within 24 hours at the West Indies Laboratory. Duplicate to quadruplicate runs were made on each sample following a Gran-type titrimetric procedure (Gieskies and Rogers, 1973) and the end-point calculated from a linear regression curve.

Temperature to the nearest 0.1 degree C, pH to the nearest 0.01 unit and specific conductivity to the nearest 10 micromhos/cm were determined in the field. Specific conductivity was measured at ambient water temperature in micromhos/cm^2, and was not temperature compensated. Field-determined salinity was read from a temperature-compensating specific conductance/salinity meter. Specific conductivity corrected to 25 degrees C and the sum of dissolved constituents were calculated later and are listed in the appendix. For this report, we consider the terms 'salinity' and 'dissolved solids' synonymous, and are referring to the conductivity-determined salinity.

Well Selection

Both public and private wells were sampled for this project. In general, public well fields utilize steel-cased wells and are equipped with oil-lubricated pumps. Private wells were almost invariably equipped with submersible pumps and PVC casing. Private wells were selected on the basis of geographic distribution and accessability.

Analysis

Major and minor elements were analyzed at Louisiana State University on an ICP spectrophotometer. Chlorides were determined titrimetrically by the Mohr procedure, or on a laboratory chloridometer. Sulfate was measured turbidimetrically or by ion chromatography. Alkalinity was analyzed in the field or within 24 hours of collection after storage in tightly sealed glass bottles. Wet chemical techniques generally followed Skougstad et al. (1979) or American Public Health Association (1971).

Alkalinity titrations followed the Gran method as given in Gieskes and Rogers (1973). End points for this titration were determined by a linear regression of the Gran plot. Data points in the linear regression were selected objectively by a simple numerical technique developed for this project. This numerical technique determines the first-derivative slope of the Gran function and eliminates those points that occur prior to where the function becomes linear.

Quality control procedures for analytical data followed guidelines set forth in Skougstad et al. (1979) and Friedman and Erdmann (1982).

Modeling

Data sets selected on the basis of electrical neutrality were numerically modeled for thermodynamic speciation by the PHREEQE computer model (Parkhurst et al. 1980). Assumptions used in the model were:

1) The presence of a solid phase was assumed in the saturation calculations.

2) A pe of 12 was used in all calculations. This value assumes mildly oxidizing and near-neutral pH conditions in the groundwater.

RESULTS

Concentration Levels

A total of 34 samples were taken from 27 wells, rainwater and seawater. The well locations represent a cross-section of public and private wells on the island, and are distributed across the central plain (Fig. 3). Well locations were chosen on the basis of geographic distribution and accessibility. Water samples were analysed for Ca, Mg, K, Fe, Mn, Total alkalinity, Cl, V, Ba, Sr, Si, SO_4, Al, Cr, Cd, Cu, Zn, Co, and Ni. Temperature, pH, specific conductance and salinity (by conductance) were measured in the field. In general, the values obtained for this report correspond well to those of earlier publications.

Although the correspondence between measured dissolved solids and salinity measured by conductance is not exact, it is precise enough for the purposes of this report. In this report we will use the terms dissolved solids and salinity interchangeably, and the terms will refer to the conductively determined salinity listed in the Appendix.

Of the wells sampled, only five met federal standards for chloride content, and only one met federal standards for dissolved solids (Appendix).

Federal drinking water standards are listed in the Appendix along with the analytical results. Organic compounds were not analyzed for this report. Of the 23 samples analyzed for sulfate, four exceeded the recommended maximum limit of 250 mg/L. These wells were from the Fairplain and Barren Spot well fields. Sodium was present in quantities from less than 99 mg/L to 937 mg/L, or a range of almost an order of magnitude. Although no federal standards exist for sodium, these levels are quite high and create a potential risk for those on sodium-restricted diets.

Geographic Trends

The geographic distribution of chloride in the groundwater closely matches that of Geraughty and Miller (1983). Chloride values increase markedly near the coast-lines and decrease inland (Fig. 5). No zones of anomalously high chloride or dissolved solids values were found, although such zones were discussed in Robison (1972) and Jordan (1975). As mentioned in Geraughty and Miller (1983a), this type of diagram should be interpreted with caution. Well data displayed in this manner do not take into account depth, lithology or information on pumping and usage.

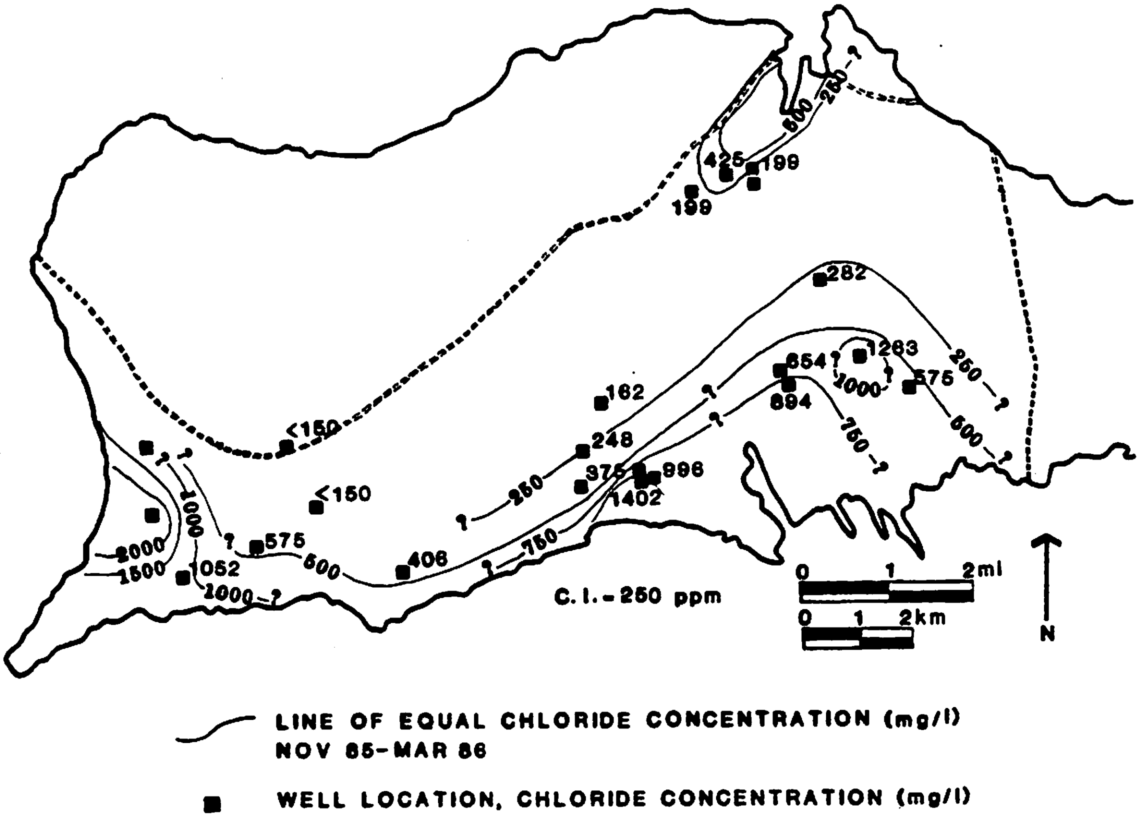

Figure 5. Chloride concentration isopleth map.

However, such diagrams can be useful for broad geographic trends.

The geographic distribution of sodium closely follows that of chloride, increasing rapidly toward the coast (Fig. 6). However, the ratio of sodium to chloride (Na/Cl) in groundwater shows the reverse geographic trend (Fig. 7), increasing rapidly away from the coast. This implies that the proportion of sodium *relative* to chloride increases inland.

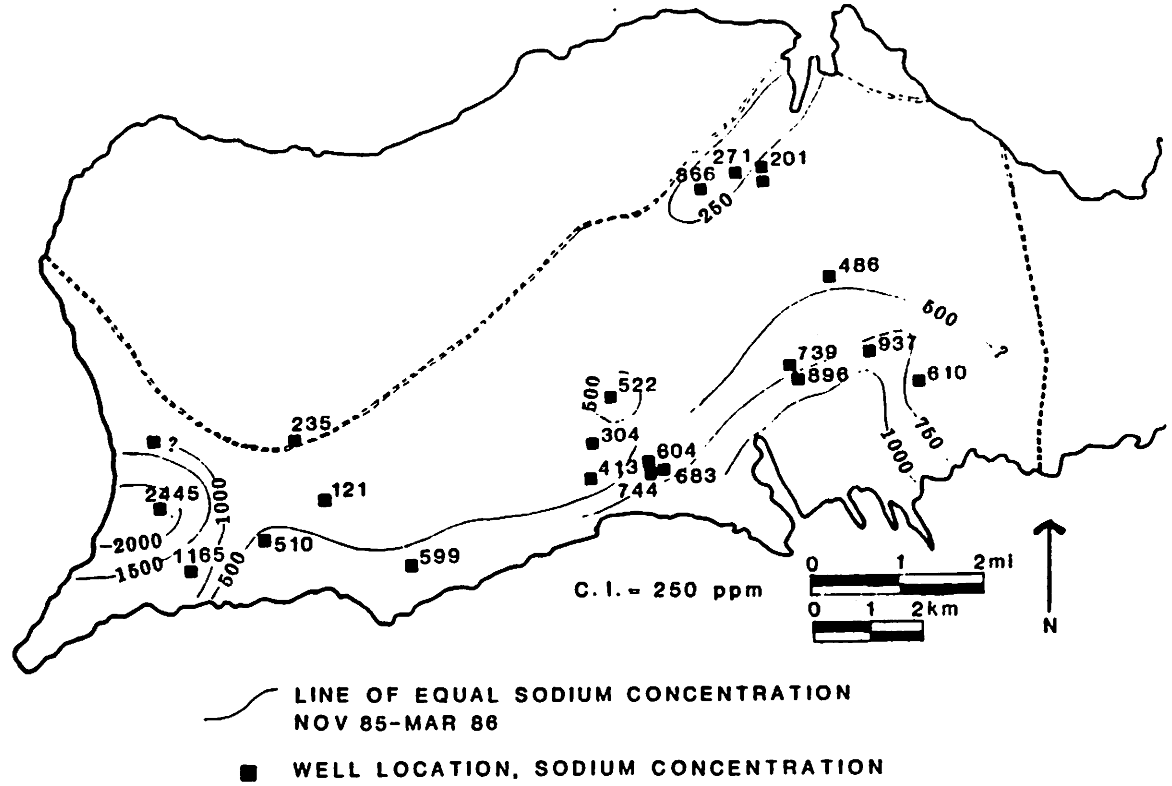

Figure 6. Sodium concentration isopleth map.

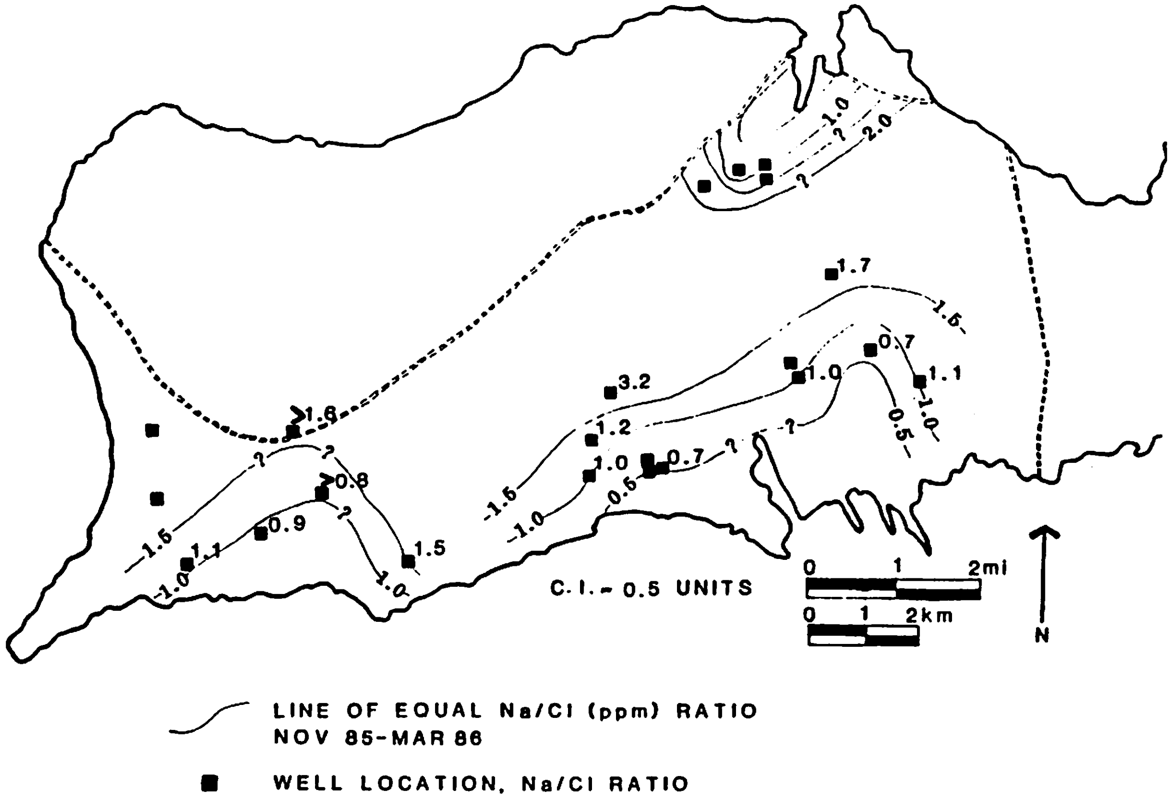

Figure 7. Sodium/Chloride (Na/Cl) ratio isopleth map.

Mixing Curves

Mixing curves were plotted for several elements using values for rainwater and seawater as the end members of the curve. Chloride was generally used as the independent variable, and was assumed to behave conservatively. For waters of low ionic strength, this assumption should be quite accurate. For the sake of simplicity, literature values of seawater constituents were used (Drever, 1982), and the rainwater was assumed to contain no dissolved solids. No change in the conclusions are caused by the inclusion of actual analyses of St. Croix rainwater and seawater (Appendix).

Sodium plotted consistently in excess of values expected if the chemistry of the groundwater were a simple function of mixing fresh water and seawater. In most cases, the excess averaged more than 100 ppm Na greater than would be predicted for a mixed water of comparable chloride content (Fig. 8).

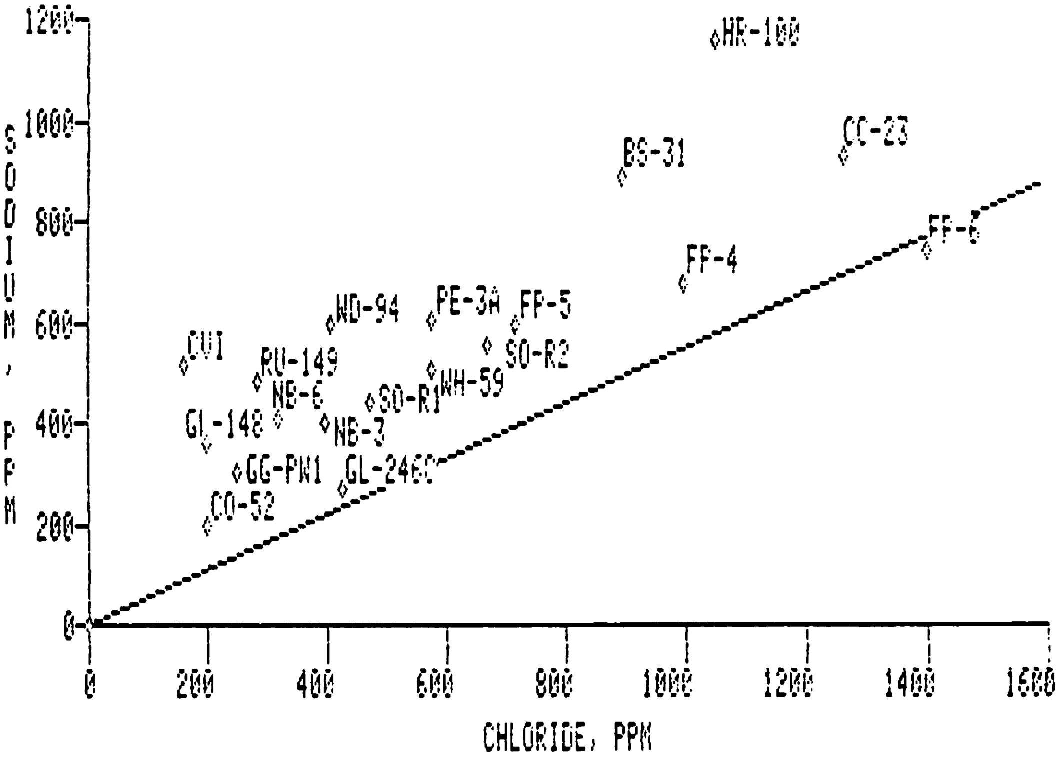

Figure 8. Freshwater mixing curve: sodium vs. chloride.

Salinity (dissolved solids) plots consistently in excess of the mixing curve, but with a high correlation to total chloride content (Fig. 9). When combined with the behavior of the dissolved constituents mentioned below, this suggests a net contribution of dissolved constituents to the groundwater through interaction with aquifer materials. Previously published data showed similar trends (Fig. 10).

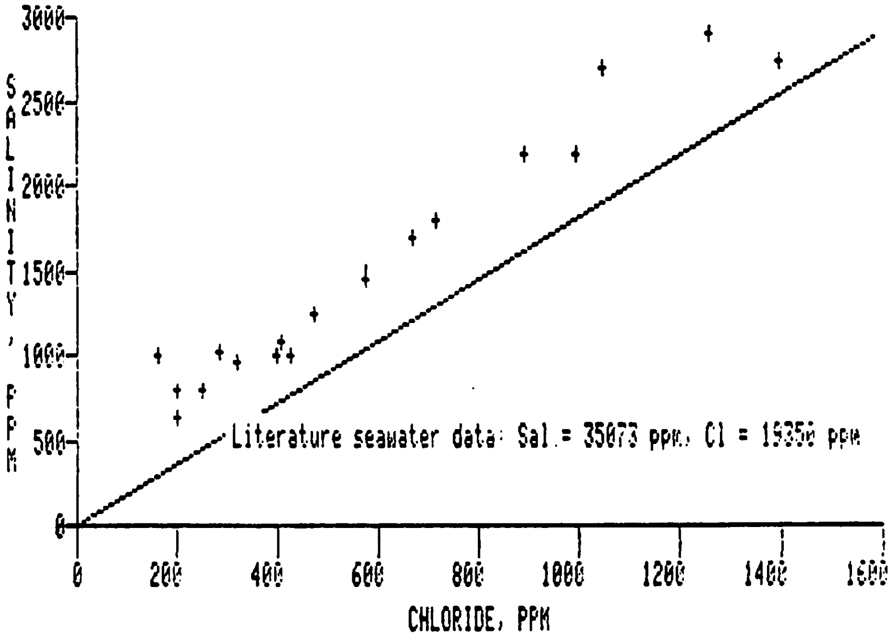

Figure 9. Seawater mixing curve: dissolved solids vs chloride.

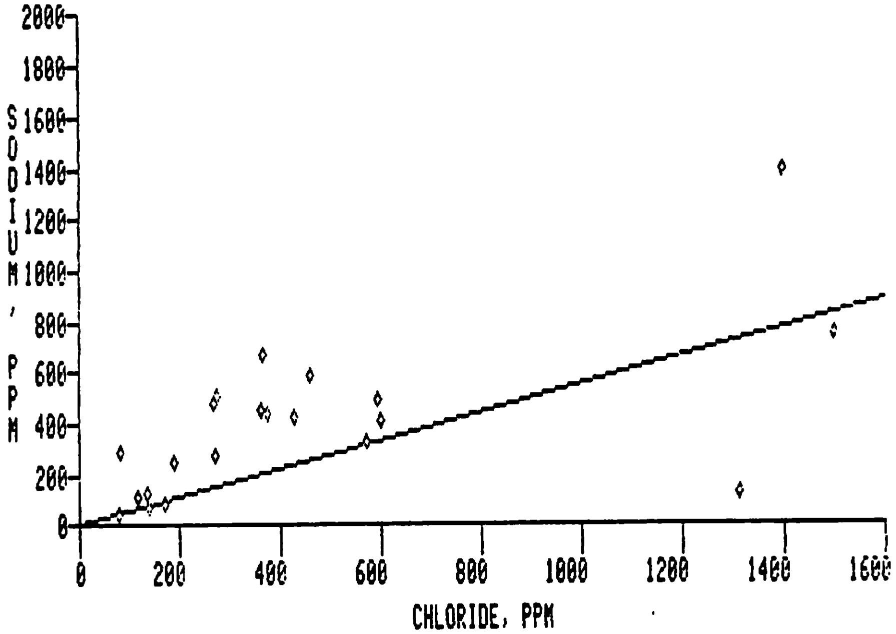

Figure 10. Seawater/freshwater mixing curve: sodium vs. chloride (data from published reports).

In contrast, potassium consistently fell below theoretical mixing values when plotted against both chloride and sodium (Fig. 11, 12). Both sodium and potassium are highly mobile and form extremely soluble minerals on evaporation. It is unlikely that concentrations of either element would be modified by evaporative precipitation as in the Hardie-Eugster model (Hardie and Eugster, 1970), by evaporative precipitation and re-solution by rainwater, or by biological processes.

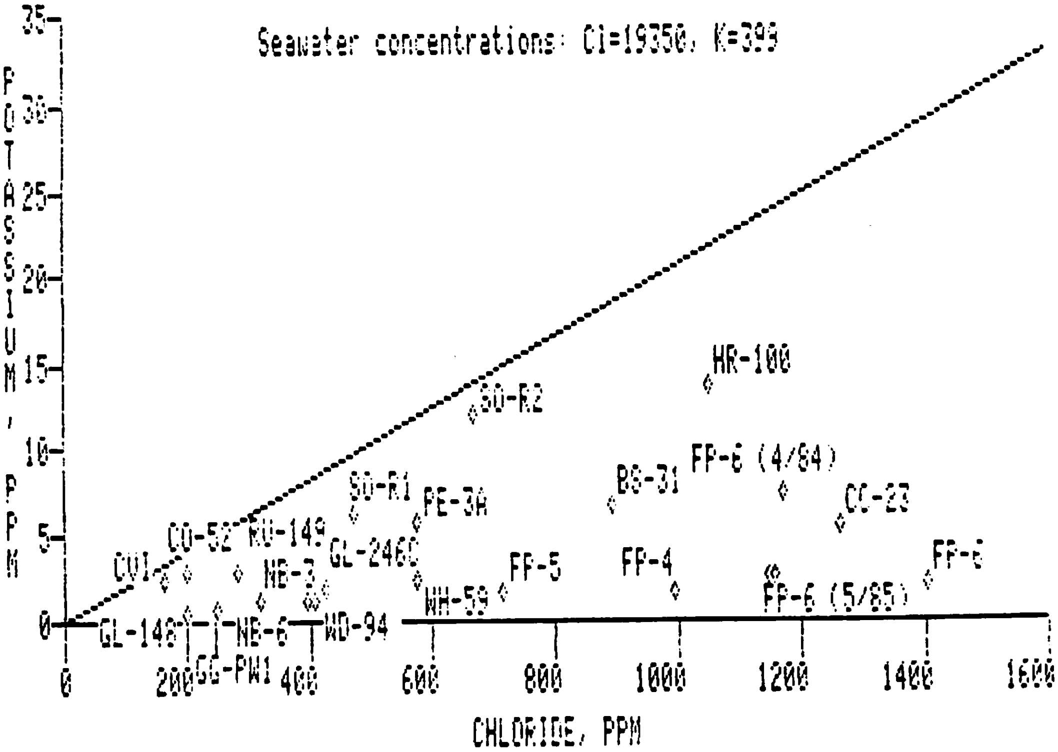

Figure 11. Seawater mixing curve: potassium vs. chloride.

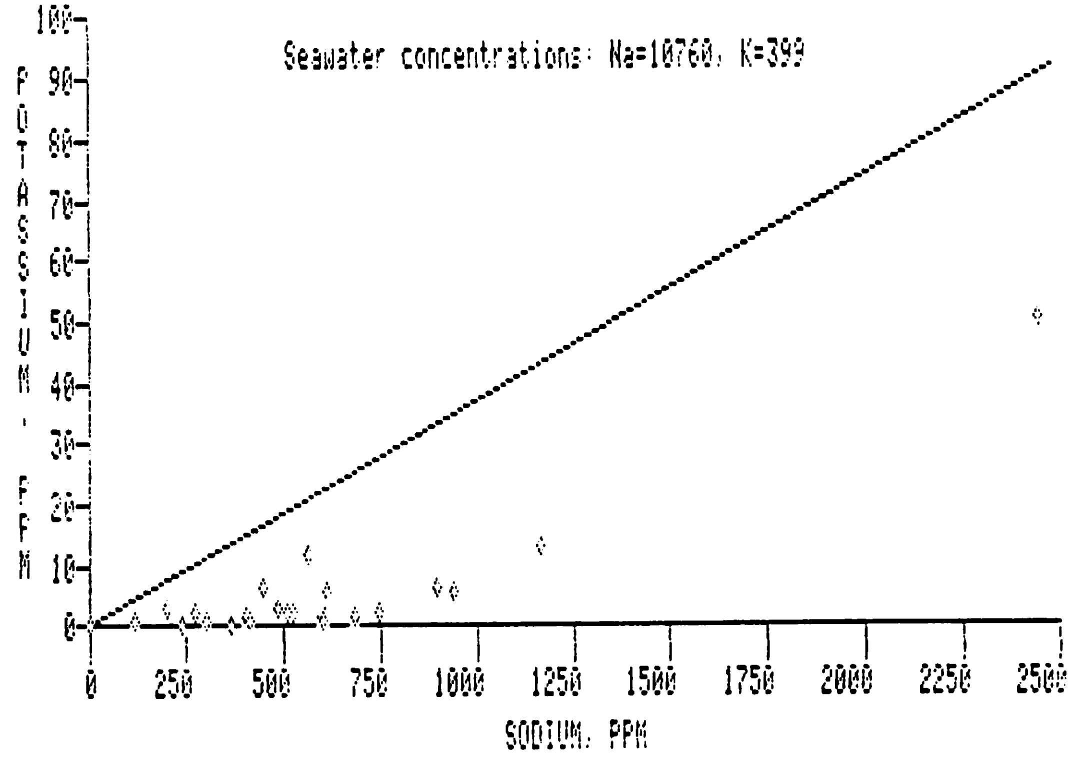

Figure 12. Seawater mixing curve: potassium vs. sodium.

Both calcium and alkalinity show up in the groundwater well in excess of a rainwater/seawater mixing curve (Figs. 13, 14). This is to be expected in a carbonate aquifer. Magnesium values form a scatter plot around the mixing line when plotted against chloride (Fig. 15), and shows no consistent trend.

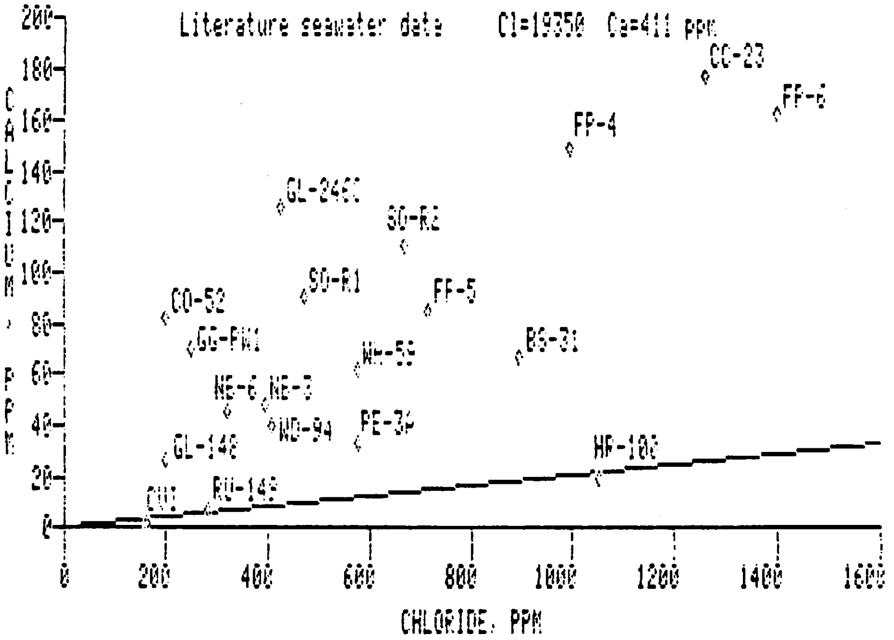

Figure 13. Seawater mixing curve: calcium vs. chloride.

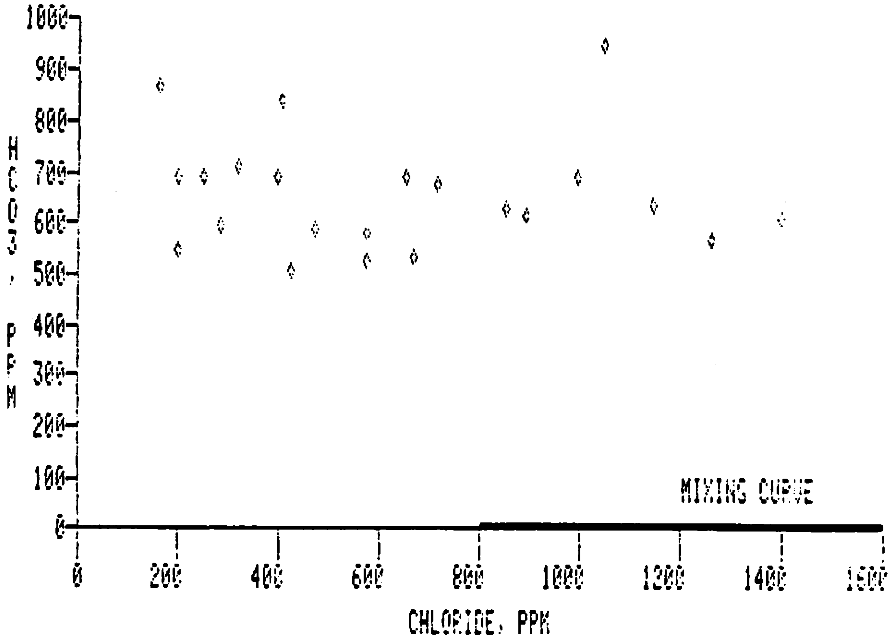

Figure 14. Seawater mixing curve: alkalinity vs. chloride.

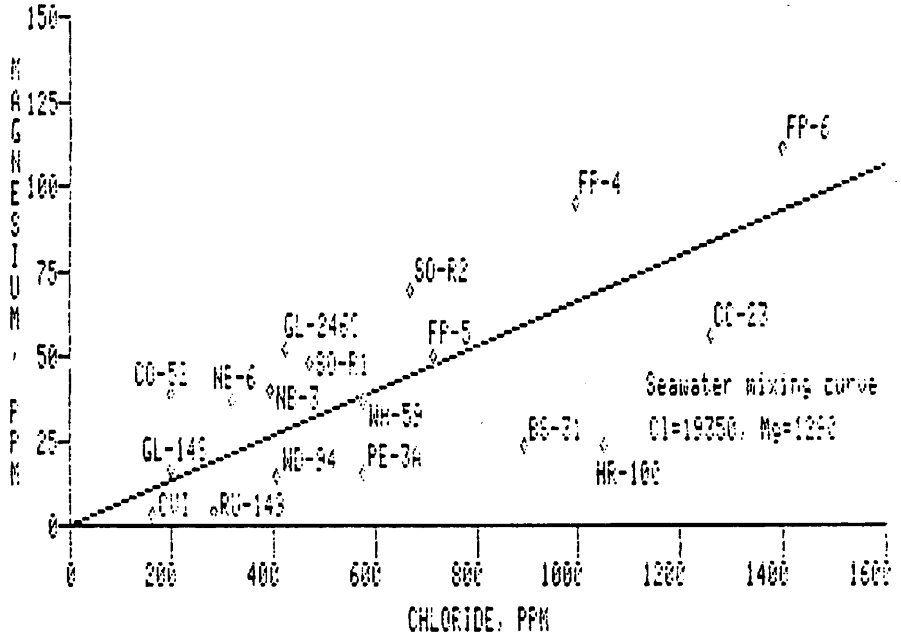

Figure 15. Seawater mixing curve: magnesium vs. chloride.

Chloride Content vs. Depth

Robison (1972) showed a marked relationship between the altitude of the water column and the chloride content of the groundwater. The plot showed an inflection point close to sea level where chloride contents increased rapidly with depth (Fig. 4). This type of plot assumes that groundwater enters the well column uniformly between the water table and the bottom of the well (Robison, 1972). A similar plot from our data does not show nearly as clear a relationship (Fig. 16).

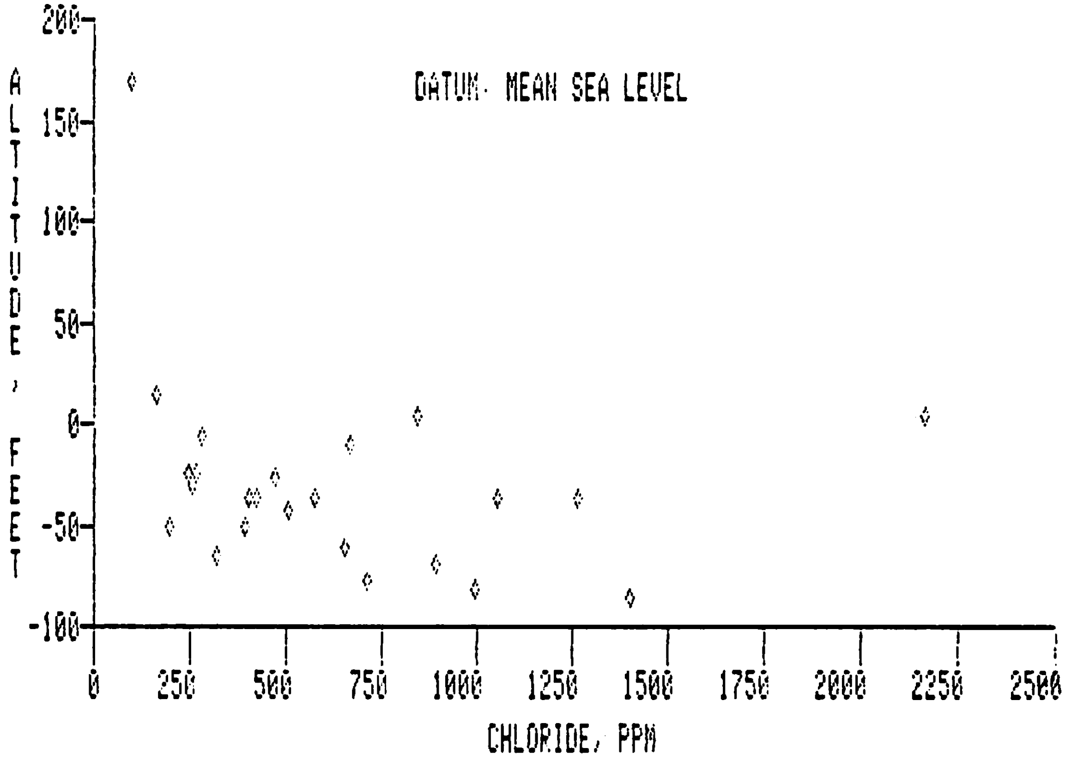

Figure 16. Well altitude vs. chloride (data from this report).

There are several differences between the two plots: our data were plotted as elevations of well bottoms rather than as average water-column heights, and our data base is smaller than that of Robison (1972) and does not include as many wells in the 0 to +100 ft msl range. The different procedure used in measuring water-column altitude is not significant since this would only change the relative position of the curve's inflection point. The smaller size of our data set, however, may be responsible for the less clear correlation between well altitude and chloride content, and the lack of connection between the wells with bottom depth below sea level and the wells significantly above sea level.

Based on our data alone, the correlation between chloride content and depth is not nearly as strong as Robison (1972) implies; there is a wide range of chloride values in groundwater from any given well altitude. The majority of wells in this study have bottom elevations between mean sea level and -100 feet. Regardless of the interpretation, high dissolved salt content should be expected with well altitudes close to, or below sea level.

Trace Elements

The trace elements analyzed were all below recommended concentration limits as set by the federal government, with the exception of an iron analysis from the Fairplain well field and manganese values from two private wells (Appendix). The rest of the trace metal analyses show very low values and in many cases are below the detection limits of the analytical technique (Appendix). No anomalously high values for barium were recorded, despite values in excess of the EPA regulations found by Geraughty and Miller (1983b) in the Barren Spot well field.

It should be noted that the recommended concentration limits for iron and manganese were set to minimize problems associated with stains and precipitates in household use rather than problems associated with human health (Freeze and Cherry, 1979). Both iron and manganese are necessary minerals in human nutrition. The possibility exists that at least part of the high iron levels in the FP-6 well were due to the steel casing of the well. However, the private wells showing elevated manganese levels were cased with PVC.

Chemical Modeling

Seven samples were modeled for speciation by the PHREEQE program (Parkhurst et al., 1980), showing a range of saturated phases in the well waters tested. The groundwater was calculated to be oversaturated with respect to quartz in all samples modeled, and chalcedony was calculated to be oversaturated in all wells tested except well PE-3A (Table 1). The groundwater was calculated to be supersaturated with respect to calcite in only three of the well waters modeled: BS-31, CO-52, and FP-6. Similarly, the groundwater was calculated to be supersaturated with respect to dolomite in NB-6, CO-52 and FP-6. It is interesting to note that in well NB-6, the groundwater is simultaneously oversaturated with respect to dolomite and undersaturated with respect to calcite. Other phases calculated to be supersaturated in the groundwaters modeled include gibbsite, kaolinite, barite, hematite, goethite and $Fe(OH)_3$ (Table 1).

TABLE 1

CHEMICAL MODELING RESULTS

WELL	COLL. DATE	SUPERSATURATED PHASES
BS-31	11/25/85	CALCITE, BARITE, CHALCEDONY, QUARTZ
CO-52	03/14/86	CALCITE, DOLOMITE, CHALCEDONY, QUARTZ, GIBBSITE, KAOLINITE
FP-6	11/26/85	CALCITE, DOLOMITE, BARITE, CHALCEDONY, QUARTZ, HEMATITE, GOETHITE, $Fe(OH)_3$
GL-148	03/20/86	CHALCEDONY, QUARTZ, GIBBSITE, KAOLINITE
NB-6	12/07/85	DOLOMITE, CHALCEDONY, QUARTZ, HEMATITE, GOETHITE, $Fe(OH)_3$
PE-3A	03/18/86	QUARTZ, GIBBSITE, KAOLINITE
SO-R1	03/16/86	CHALCEDONY, QUARTZ

DISCUSSION

Water Quality

Most of the groundwaters sampled exceeded EPA limits for Cl and dissolved solids, and several exceeded the EPA limits for sulfate. The Recommended Concentration Limits for these constituents, however, are primarily based on taste and aesthetic considerations, rather than direct problems with human health (Freeze and Cherry, 1979). Sodium, however ranged from 99 to 2445 mg/L in the samples collected. No EPA limits have been set for sodium presumably because of the wide concentration ranges of the element in public water supplies (M. Simms, Louisiana State University, pers. comm., 1986). However several states have established advisory levels of 20 mg/L for persons with cardiac- and blood pressure-related diet restrictions (Geraughty and Miller, 1983b).

The average concentration of sodium in waters sampled for this report was 578 mg/L, or more than 20 times the 20 mg/L advisory level mentioned above. For the sake of comparison, some breakfast cereals contain approximately 300 mg of sodium per serving, and an ounce of potato chips might contain around 200 mg. A more detailed discussion of health-related problems can be found in Geraughty and Miller Inc. (1983a and b).

The distribution of the more highly mineralized groundwaters is shown in Figures 5 and 6; these zones are concentrated along the coast-lines of the island. The areas of high mineralization are found on the south coast industrial zone near Martin Marietta, in the river basin in the Salt River and Concordia areas, and in the estates close to the shoreline south of Fredericksted. For the most part, these areas correspond closely to the areas of high chloride and dissolved solids discussed by Geraughty and Miller (1983a).

Both Jordan (1975) and Robison (1972) discuss a zone of highly mineralized groundwater extending inland parallel to the mountains of the northside range and in areas close to the carbonate highlands. These highly mineralized areas were not found in this study, nor were they found by Geraughty and Miller (1983a). Jordan (1975) mentions dissolved solids in excess of 20,000 mg/L in these areas and suggested that they were the result of highly saline connate waters from the Kingshill Limestone. Although large areas were not sampled in this study, it is difficult to believe that such areas would not have been found in either the

Geraughty and Miller (1983a) study or this one. Assuming that no analytical errors account for the high dissolved solid groundwaters, it is difficult to believe that mixing with highly saline formation waters would be restricted to discrete areas of the marls, and that those areas would be so short-lived. We feel a better explanation lies in seawater contamination due to over pumpage.

Mineralization of groundwater

Analyses of St. Croix groundwater show a consistent excess in dissolved solids relative to a mixing curve of fresh water and seawater (Fig. 9). This excess of dissolved solids is produced by an increase in most of the major groundwater constituents relative to chloride (Figs. 8 - 15) except potassium. In particular, the ratio of sodium to chloride increases rapidly inland despite the fact that absolute quantities of both elements decrease in the same direction (Figs. 5, 6, 7). Potassium is the only major constituent that falls below the seawater mixing curve when plotted against both chloride and sodium.

Several explanations of the chemistry of St. Croix groundwater have been suggested:

1) Concentration of rainwater through evapotranspiration.

2) Precipitation and re-solution of salts in the soil zone.

The first two explanations, concentration of rainwater and the precipitation/dissolution of salts in the soil zone are somewhat related, and difficult to distinguish chemically. Dissolved constituents of seawater are taken into the atmosphere as aerosols or salt crystals, and are directly deposited in the soils or accompany rainfall. The dissolved constituents are concentrated by evaporation and transpiration, leaving the remaining groundwater more concentrated with respect to the minerals in solution, or alternately, by precipitating salts which are then re-dissolved by the next influx of rainfall.

The net result of these processes is an increase in the dissolved constituents in shallow groundwater relative to rainwater. Both Jordan (1975) and Robison (1972) cite these processes as being important sources of the mineralization of shallow groundwater and estimate that the rainwater has been concentrated 30 times to contain the amount of chloride found in shallow groundwater. Although this process probably does occur on a highly evaporative island such as St. Croix, it does not explain the change in ionic ratios relative to seawater that are found in St. Croix groundwater.

3) Solution of aquifer materials by rain and groundwater.

Dissolution of aquifer minerals is a process by which groundwater reacts with the minerals of the aquifer, dissolving the rock and altering the composition of both the groundwater and the rock. In the case of carbonate aquifers, much dissolution of the rock material can occur because of the undersaturated nature of the rainwater and the rapid dissolution kinetics of carbonate minerals. In a similar manner, groundwater oversaturated with respect to mineral phases can further alter its chemistry by the precipitation of minerals along its flow path.

4) Cation exchange.

In cation exchange, clay minerals will take up cations from solution in exchange for bound cations already occupying exchange sites (Drever, 1982). This is an equilibrium process and is affected by the concentration of ions in solution, including the pH, the radius of hydration of cations in solution, and the types of minerals in the aquifer. By this process, a groundwater could change the relative quantities of ions in solution by reaction with aquifer materials.

5) Ionic diffusion.

Ionic diffusion is the process of migration of ions through a fluid in response to a chemical concentration gradient. This process does not include mass transport of materials by processes such as convection and water flow.

6) Mixing with "connate" waters.

The term "connate water" refers to the water trapped in the aquifer during deposition of the sediments. As such, the water would reflect the chemistry of the seawater at the time the rocks were deposited. In actual usage, the term is confusing and somewhat ambiguous, since it is difficult to distinguish waters that represent original seawater from those that have been heavily altered through interaction with rock material (Drever, 1982). We would prefer the use of the term "formation water". By mixing relatively fresh groundwater with highly mineralized formation water, the resulting water would be intermediate in composition.

7) Mixing with seawater.

The process of mixing seawater with fresher ground waters is an obvious one on small oceanic islands such as St. Croix, and would result in a groundwater of intermediate composition. If this process takes place with no competing processes, the ionic ratios of the groundwater should fall on the mixing curve between the two end-member waters.

Regarding the most likely mechanisms for the formation of St. Croix groundwater, we offer the following observations:

1) The chemistry of the groundwaters is complex, and is not strictly the result of simple mixing of fresh water and seawater.

2) The chloride content and dissolved solids content increase rapidly toward the coast, indicating that interaction between groundwater and seawater is important.

3) Despite the increase in chloride content toward the coast, the increase in Na/Cl ratios away from the coast indicates that the groundwater gains significant quantities of dissolved material from the aquifer.

We suggest that the chemistry of the groundwater is best explained by a combination of several processes, of which reaction with the aquifer and mixing with seawater are the most important on a regional scale. With the present information we cannot eliminate any single process, but we feel that there is adequate information to indicate the relative importance of several.

The concentration of rainwater through evapotranspiration and the precipitation and re-dissolution of salts derived from sea spray are discussed in detail in Robison (1972), Jordan (1975) and in Black, Crow and Eidsness (1976). We feel that this is a less important process in the production of the bulk chemistry of the groundwater than the reports listed above imply.

The concentration of rainwater to the extent mentioned in Robison (1972) could explain an increase in chloride, but would not alter the ratio between sodium and chloride. Sodium, potassium and chloride salts are extremely soluble, and do not precipitate until salinities well in excess of seawater are reached. Similarly, the salts formed through the evaporation of sea spray would re-dissolve with added rainfall, and would not alter the sodium/chloride or potassium/chloride ratios. The concentration of rainwater to the extent suggested by Robison (1972) produces a groundwater with a chloride concentration of 210 mg/L. Less than 12 percent of the samples collected for this report had chloride contents that could be explained by concentration only to this extent.

Reaction with the minerals in the Kingshill Limestone aquifer is an important source of dissolved solids in St. Croix groundwater, and is understated in Cederstrom (1950), Robison (1972) and Jordan (1975), among others. Mineral reactions in this case may include cation exchange, mineral alteration and mineral dissolution. These processes could include the replacement of sodium in exchange sites on clays by potassium and calcium; mineral transitions such as smectite to illite, or albite to smectite; and the dissolution of volcanoclastics and carbonates. All the components mentioned above exist in significant if not abundant quantities in the Kingshill Limestone. Gerhard et al. (1978) measured insoluble residues in Kingshill Limestone strata ranging from less than 5% to over 90%. Common non-carbonate constituents in the Kingshill Limestone include feldspars, clay minerals, hornblende, quartz and lithic clasts.

It is not possible at this point to prove the existence of specific reactions in the aquifer/groundwater system. However, the previously mentioned processes provide the best explanation for the loss of potassium and the uptake of sodium, silica, calcium and bicarbonate by the groundwater, as well as provide the best explanation for the increase in the sodium to chloride ratio away from the shoreline. This latter point indicates a change in dominance of diagenetically controlled groundwater inland as opposed to the seawater-controlled groundwater chemistry close to the shoreline.

The increase in chloride, sodium, and salinity values close to the coast indicates an increase in the control of seawater chemistry on the groundwater. Similarly, the ratio of sodium to chloride approaches that of seawater in wells close to the coastline. We interpret this to mean that mixing with seawater progressively overprints diagenetic effects in the more highly mineralized coastal wells.

The effect of ionic diffusion in this process is difficult to assess due to lack of information on the flow rates of St. Croix groundwater and the difficulty of securing reliable information of salinity changes with depth. However, because the St. Croix carbonate aquifers are layered, presumably restricting vertical flow (Black, Crow and Eidsness, 1976; Gill and Hubbard, 1986), and the Jealousy Formation clays presumably restrict seawater incursion from below, the effects of vertical ionic diffusion are probably minimal.

The presence of "connate" fluids can neither be proven nor disproven at this point. However, since the Jealousy formation clays are over 1400 feet thick (Cederstrom, 1950), and presumably overlie noncompressable Cretaceous basement rock, the suggestion of formation waters derived from compacting clays (Robison, 1972) is not without merit. At this point, our data give no suggestion of anomalous zones of higher salinities caused by mixing with highly altered formation waters. In addition, the layered nature of the aquifer would presumably restrict the upward migration of Jealousy Formation fluids in the same manner that they would restrict vertical seawater intrusion.

Chemical modeling

Minerals calculated to be oversaturated with respect to St. Croix groundwaters at various locations include calcite, dolomite, barite, quartz, chalcedony, kaolinite, hematite, goethite, $Fe(OH)_3$ and gibbsite. This assemblage of minerals is further evidence of extensive interaction of silicate minerals in the aquifer system. The preponderance of quartz and chalcedony indicate the possibility of silica precipitation in aquifer rocks.

Oversaturation with respect to aluminosilicates such as kaolinite and gibbsite in three of the seven samples modeled corresponds with wells in two areas of high siliciclastic content (CO-52, GL-148) and one well in an area where the mineralogy is less known (PE-3A). Authigenic clay minerals are found in the Kingshill Limestone (Gill and Hubbard, 1986). The geochemical modeling calculations indicate that St. Croix groundwater is capable of producing certain clay minerals under the present chemical conditions.

An interesting observation is that only three of the seven samples modeled were calculated to be oversaturated with respect to calcite. In this instance, St. Croix groundwaters are apparently reaching saturation with silicate phases before saturation is reached with carbonates. In part, this is no doubt due to the high solubilities of the carbonates and the very low solubilities of quartz and its polymorphs in neutral to slightly acidic waters. However, the samples of water saturated with respect to calcite all lie close to the coast in areas of higher salinity. The saturation with respect to calcite is probably explained by mixing with seawater.

The sample modeled from the Negro Bay well field was saturated with respect to dolomite, but undersaturated with respect to calcite, conditions considered to be ideal for the formation of dolomitic rock. Dolomite is present in the aquifer system within three kilometers of the sampled well (Gill and Hubbard, 1986), at roughly the same distance from the coast. More modeling is necessary to determine whether mixing-zone dolomitization is viable on a regional scale on St. Croix today. Mixing-zone dolomitization is one of several explanations for the formation of dolomite in the carbonate strata of St. Croix.

The samples calculated to be saturated with respect to iron-bearing phases such as hematite and goethite both came from public wells equipped with steel casing (Wells NB-6 and FP-6). We feel that contamination from the steel casing is possible in this instance.

Summary

The major sources of groundwater mineralization on St. Croix are seawater mixing and diagenetic interactions in the aquifer. In this case, diagenetic interactions include cation exchange, mineral transformation and dissolution of aquifer minerals. Concentration of rainwater through evapo-transpiration has been cited as an important source of groundwater mineralization by several authors. However, the levels of mineralization produced by this process could also be explained by incorporation of aerosols and salt spray into the groundwater, and in any case do not explain the generally higher levels of dissolved constituents found in St. Croix groundwaters nor the relative proportions of those constituents.

Chemical modeling of the groundwaters shows a dominance of saturated silicate phases rather than carbonate phases in the groundwater. The majority of wells sampled yield groundwater still undersaturated with respect to calcite. Those wells oversaturated with respect to calcite lie near the coastline, suggesting the influence of seawater mixing rather than dissolution of aquifer carbonates. One well sample showed simultaneous undersaturation with calcite and supersaturation with respect to dolomite. Simultaneous supersatuation of dolomite and undersaturation of calcite has been invoked as an important prerequisite of mixed-water dolomitization. More samples need to be modeled to see whether these conditions are regionally extensive.

Almost all the well water samples exceeded EPA recommended limits for chloride and dissolved solids. Several of those analyzed for sulfate also exceeded EPA limits. Since the limits for chloride, dissolved solids and sulfate are set primarily on the basis of water taste and esthetics, whether these levels are objectionable depends on intended water use. The levels of sodium in the groundwater were very high, with groundwater sodium evidently being produced by water-rock reactions in levels above those expected from strict mixing processes. The sodium levels are a point of potential concern from a health standpoint.

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APPENDIX

RESULTS OF CHEMICAL ANALYSES

Key to data tables on subsequent pages

EPA M. P. C.: Maximum Permissible Concentration

EPA R. C. L.: Recommended Concentration Limit

-- : Data not available

<DL : Below detection limit

>RNG : Over range of calibration

APPENDIX-CHEMICAL ANALYSES

WELL NAME	COLL. DATE	LOCATION	OWNER	SOURCE
EPA M. P. C.*	--	--	--	Freeze and Cherry (1979)
EPA R. C. L.**	--	--	--	
Detection Limit	--	--	--	--
BS-31	Nov 25 85	Barren Spot wellfield, #31	VI Govt	--
BS-31	May 19 85	Barren Spot wellfield, #31	VI Govt	--
BS-3A	May 19 85	Barren Spot wellfield, #3A	VI Govt	--
BS-8	Apr 4 84	Barren Spot wellfield, #8	VI Govt	--
CA-109	Mar 8 86	Carlton, Plot 109	J. Stout	--
CA-15	Mar 12 86	Carlton, Plot 15	B. Rezende	--
CC-23	Mar 21 86	Castle Coakley, Plot 23	L. Satomayor	--
CO-1	Apr 4 84	Concordia wellfield, #1	VI Govt	--
CO-52	Mar 14 86	Concordia, Plot 52	F. Malloy	--
CVI	Mar 12 86	College of the VI	CVI	--
FP-4	Nov 27 85	Fairplain wellfield, #4	VI Govt	--
FP-5	Nov 27 85	Fairplain wellfield, #5	VI Govt	--
FP-6	Apr 4 84	Fairplain wellfield, #6	VI Govt	--
FP-6	May 15 85	Fairplain wellfield, #6	VI Govt	--
FP-6	May 19 85	Fairplain wellfield, #6	VI Govt	--
FP-6	Nov 26 85	Fairplain wellfield, #6	VI Govt	--
FP-8	Nov 27 85	Fairplain wellfield, #8	VI Govt	--
GG-PW1	Apr 4 84	Golden Grove wellfield, #PW1	VI Govt	--
GG-PW1	Dec 9 85	Golden Grove wellfield, #PW1	VI Govt	--
GL-148	Mar 20 86	Glynn, Plot 148	L. Williams	--
GL-246C	Mar 14 86	Glynn, Plot 246C	Dr. Williams	--
HR-100	Mar 10 86	Hannahs Rest, Plot 100	C. George	--
LG-1	Apr 4 84	La Grange wellfield, #1	VI Govt	--
MH-35	Mar 10 86	Mars Hill, Plot 35	Tony's Laundromat	--
NB-3	Nov 29 85	Negro Bay wellfield, #3	VI Govt	--
NB-6	Dec 7 85	Negro Bay wellfield, #6	VI Govt	--
PE-3A	Mar 18 86	Pearl, Plot 3A	M. Maneilly	--
Rainwater	Mar 13 86	East End, St. Croix	--	--
RU-149	Mar 18 86	Ruby, Plot 149	S. Smith	--
Seawater	Mar 86	Tague Bay, St. Croix	--	--
Seawater-avg.	--	--	--	Drever (1982)
SO-R1	Mar 16 86	Solitude Remainder, Well 1	R. Roebuck	--
SO-R2	Mar 16 86	Solitude Remainder, Well 2	R. Roebuck	--
WD-94	Mar 7 86	Williams Delight, Plot 94	D. McLean	--
WH-59	Mar 12 86	Whim, Plot 59	R. Jackson Jr.	--

* Maximum Permissible Concentration, US EPA

** Recommended Concentration Limit, US EPA

Specific conductivity

from conductance meter

APPENDIX-CHEMICAL ANALYSES

WELL NAME	COLL. DATE	TEMP (C)	pH	(amb.temp) (umho/cm) SPEC COND	(conduct.) (ppm) SALINITY	(sum, ppm) SOLIDS	as CaCO3 (ppm) HARDNESS
EPA M. P. C.*	--	--	--	--	--	--	--
EPA R. C. L.**	--	--	--	--	500	500	--
Detection Limit	--	--	--	--	--	--	--
BS-31	Nov 25 85	26.7	7.13	4110	2200	2492	266
BS-31	May 19 85	27.4	7.05	4150	2100	--	--
BS-3A	May 19 85	27.5	7.27	3330	1900	--	--
BS-8	Apr 4 84	--	--	--	--	--	--
CA-109	Mar 8 86	29.1	6.95	822	250	--	265
CA-15	Mar 12 86	27.3	7.20	1327	1270	--	175
CC-23	Mar 21 86	27.3	6.80	5500	2900	--	679
CO-1	Apr 4 84	--	--	--	--	--	--
CO-52	Mar 14 86	32.3	6.91	1558	650	856	367
CVI	Mar 12 86	29.0	7.97	2110	1000	--	22
FP-4	Nov 27 85	28.0	7.01	4610	2200	2547	763
FP-5	Nov 27 85	29.0	6.96	3550	1800	2027	421
FP-6	Apr 4 84	--	--	--	--	--	--
FP-6	May 15 85	28.2	6.87	4690	--	--	--
FP-6	May 19 85	27.3	6.88	4650	2500	--	--
FP-6	Nov 26 85	28.1	6.96	5100	2750	2969	866
FP-8	Nov 27 85	27.4	7.06	3280	--	--	407
GG-PW1	Apr 4 84	--	--	--	--	--	--
GG-PW1	Dec 9 85	27.3	6.67	1903	800	1082	175
GL-148	Mar 20 86	27.4	7.20	1805	800	--	138
GL-246C	Mar 14 86	27.4	6.72	2102	1000	1211	531
HR-100	Mar 10 86	27.5	7.38	5100	2700	--	150
LG-1	Apr 4 84	--	--	--	--	--	--
MH-35	Mar 10 86	30.8	7.32	12750	6500	--	600
NB-3	Nov 29 85	27.3	7.05	2203	1000	1376	285
NB-6	Dec 7 85	27.1	6.99	2103	967	1285	266
PE-3A	Mar 18 86	30.4	7.12	3075	1500	--	150
Rainwater	Mar 13 86	--	5.13	--	--	--	2
RU-149	Mar 18 86	26.8	7.68	2107	1033	--	37
Seawater	Mar 86	--	--	--	--	--	6657
Seawater-avg.	--	--	8.15	--	--	35016	6322
SO-R1	Mar 16 86	28.4	6.76	2655	1250	1504	426
SO-R2	Mar 16 86	28.2	6.71	3420	1700	--	564
WD-94	Mar 7 86	28.2	7.09	2300	1100	1636	162
WH-59	Mar 12 86	29.6	7.16	2997	1450	--	309

* Maximum Permissible Concentration, US EPA
** Recommended Concentration Limit, US EPA

APPENDIX-CHEMICAL ANALYSES MAJORS --- in order of decreasing concentration in seawater

WELL NAME	COLL. DATE	Cl (mg/l)	Na (ppm)	SO4 (mg/l)	Mg (ppm)	Ca (ppm)	K (ppm)
EPA M. P. C.*	--	--	--	--	--	--	--
EPA R. C. L.**	--	250	--	250	--	--	--
Detection Limit	--	--	.25	--	.002	.002	1.0
BS-31	Nov 25 85	894	896	272	23.9	66.7	6.7
BS-31	May 19 85	853	825	266	--	--	5.6
BS-3A	May 19 85	654	739	208	--	--	4.0
BS-8	Apr 4 84	846	860	268	--	--	.5
CA-109	Mar 8 86	<150	121	37	30.6	55.6	.8
CA-15	Mar 12 86	<150	235	61	15.1	45.2	<DL
CC-23	Mar 21 86	1263	937	--	56.6	178.0	5.6
CO-1	Apr 4 84	507	401	155	--	--	4.2
CO-52	Mar 14 86	199	201	59	39.0	82.7	3.0
CVI	Mar 12 86	162	522	--	3.7	2.7	2.4
FP-4	Nov 27 85	996	683	248	94.9	149.5	1.7
FP-5	Nov 27 85	714	598	207	50.5	85.5	1.9
FP-6	Apr 4 84	1173	703	180	--	--	7.4
FP-6	May 15 85	1146	689	254	--	--	2.7
FP-6	May 19 85	1157	697	228	--	--	2.7
FP-6	Nov 26 85	1402	744	208	112.1	162.0	2.3
FP-8	Nov 27 85	--	604	211	49.8	80.9	2.0
GG-PW1	Apr 4 84	269	302	102	--	--	<DL
GG-PW1	Dec 9 85	248	304	99	>RNG	69.6	.8
GL-148	Mar 20 86	199	367	--	17.1	27.0	.6
GL-246C	Mar 14 86	425	271	50	52.6	126.1	2.1
HR-100	Mar 10 86	1052	1165	--	24.2	20.2	13.6
LG-1	Apr 4 84	259	99	--	--	--	<DL
MH-35	Mar 10 86	--	2445	--	104.2	68.6	51.0
NB-3	Nov 29 85	395	403	103	40.4	47.7	1.4
NB-6	Dec 7 85	319	413	78	36.8	45.9	1.3
PE-3A	Mar 18 86	575	610	--	16.1	33.6	5.8
Rainwater	Mar 13 86	--	<DL	--	.4	<DL	<DL
RU-149	Mar 18 86	282	486	--	4.6	7.4	3.0
Seawater	Mar 86	--	12029	--	1370.0	414.0	402.0
Seawater-avg.	--	19350	10760	2710	1290.0	411.0	399.0
SO-R1	Mar 16 86	470	447	119	48.4	90.8	6.4
SO-R2	Mar 16 86	669	560	--	69.7	110.9	12.1
WD-94	Mar 7 86	406	599	154	14.9	40.2	1.3
WH-59	Mar 12 86	575	510	--	37.3	62.2	2.6

* Maximum Permissible Concentration, US EPA
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APPENDIX-CHEMICAL ANALYSES

		Alkalinity				
WELL NAME	COLL. DATE	HCO3 (ppm)	CO3 (ppm)	Sr (ppm)	Si (ppm)	SiO2 (ppm)
EPA M. P. C.*	--	--	--	--	--	--
EPA R. C. L.**	--	--	--	--	--	--
Detection Limit	--	--	--	.0025	.14	.096
BS-31	Nov 25 85	617	--	1.58	12.9	27.6
BS-31	May 19 85	626	--	1.59	--	--
BS-3A	May 19 85	693	--	.77	--	--
BS-8	Apr 4 84	--	--	1.72	--	--
CA-109	Mar 8 86	532	--	.43	>RNG	>RNG
CA-15	Mar 12 86	534	--	.22	17.0	36.4
CC-23	Mar 21 86	567	--	2.26	11.4	24.4
CO-1	Apr 4 84	--	--	3.12	--	--
CO-52	Mar 14 86	551	--	1.00	>RNG	>RNG
CVI	Mar 12 86	866	--	.28	19.8	42.4
FP-4	Nov 27 85	690	--	--	15.8	33.8
FP-5	Nov 27 85	676	--	--	17.3	37.0
FP-6	Apr 4 84	--	--	1.94	--	--
FP-6	May 15 85	636	--	1.93	--	--
FP-6	May 19 85	--	--	1.87	--	--
FP-6	Nov 26 85	609	--	1.95	17.3	37.0
FP-8	Nov 27 85	828	--	1.17	20.0	42.8
GG-PW1	Apr 4 84	--	--	.73	--	--
GG-PW1	Dec 9 85	690	--	.69	9.2	19.7
GL-148	Mar 20 86	688	--	.25	>RNG	>RNG
GL-246C	Mar 14 86	504	--	.54	16.2	34.7
HR-100	Mar 10 86	949	--	.36	13.5	28.9
LG-1	Apr 4 84	--	--	.68	--	--
MH-35	Mar 10 86	--	--	1.12	13.0	27.8
NB-3	Nov 29 85	693	--	.51	20.1	43.0
NB-6	Dec 7 85	710	--	.48	19.1	40.9
PE-3A	Mar 18 86	582	--	.50	9.6	20.5
Rainwater	Mar 13 86	<DL	--	<DL	.2	<DL
RU-149	Mar 18 86	595	--	.01	9.1	19.5
Seawater	Mar 86	--	--	6.75	--	--
Seawater-avg.	--	142	18	8.00	--	--
SO-R1	Mar 16 86	586	--	.83	15.4	32.9
SO-R2	Mar 16 86	535	--	1.18	15.0	32.1
WD-94	Mar 7 86	841	--	.28	3.0	6.4
WH-59	Mar 12 86	528	--	.77	14.6	31.2

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APPENDIX-CHEMICAL ANALYSES MINORS -- in alphabetical order by chemical symbol

WELL NAME	COLL. DATE	Al (ppm)	Ba (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)
EPA M. P. C.*	--	--	1.00	.01	--	.05	--
EPA R. C. L.**	--	--	--	--	--	--	1
Detection Limit	--	.1	.001	.01	.03	.025	.01
BS-31	Nov 25 85	<DL	.048	<DL	<DL	<DL	<DL
BS-31	May 19 85	--	--	--	--	--	--
BS-3A	May 19 85	--	--	--	--	--	--
BS-8	Apr 4 84	--	--	--	--	--	--
CA-109	Mar 8 86	<DL	.035	<DL	<DL	<DL	<DL
CA-15	Mar 12 86	<DL	<DL	<DL	<DL	<DL	<DL
CC-23	Mar 21 86	<DL	.036	<DL	<DL	<DL	<DL
CO-1	Apr 4 84	--	--	--	--	--	--
CO-52	Mar 14 86	<DL	.042	<DL	<DL	<DL	<DL
CVI	Mar 12 86	<DL	<DL	<DL	<DL	<DL	<DL
FP-4	Nov 27 85	<DL	.067	<DL	<DL	<DL	<DL
FP-5	Nov 27 85	<DL	.050	<DL	<DL	<DL	<DL
FP-6	Apr 4 84	--	--	--	--	--	--
FP-6	May 15 85	--	--	--	--	--	--
FP-6	May 19 85	--	--	--	--	--	--
FP-6	Nov 26 85	<DL	.064	<DL	<DL	<DL	<DL
FP-8	Nov 27 85	<DL	.042	<DL	<DL	<DL	<DL
GG-PW1	Apr 4 84	--	--	--	--	--	--
GG-PW1	Dec 9 85	<DL	.044	<DL	<DL	<DL	<DL
GL-148	Mar 20 86	<DL	.040	<DL	<DL	<DL	<DL
GL-246C	Mar 14 86	<DL	.038	<DL	<DL	<DL	<DL
HR-100	Mar 10 86	<DL	.033	<DL	<DL	<DL	<DL
LG-1	Apr 4 84	--	--	--	--	--	--
MH-35	Mar 10 86	.1	.038	<DL	<DL	<DL	.064
NB-3	Nov 29 85	<DL	.041	<DL	<DL	<DL	<DL
NB-6	Dec 7 85	<DL	.037	<DL	<DL	<DL	<DL
PE-3A	Mar 18 86	<DL	.040	<DL	<DL	<DL	<DL
Rainwater	Mar 13 86	<DL	<DL	<DL	<DL	<DL	<DL
RU-149	Mar 18 86	<DL	.031	<DL	<DL	<DL	<DL
Seawater	Mar 86	--	<DL	<DL	<DL	<DL	<DL
Seawater-avg.	--	.002	.002	0.05	.00005	.0003	.0005
SO-R1	Mar 16 86	<DL	.061	<DL	<DL	<DL	<DL
SO-R2	Mar 16 86	<DL	.060	<DL	<DL	<DL	<DL
WD-94	Mar 7 86	<DL	.040	<DL	<DL	<DL	<DL
WH-59	Mar 12 86	<DL	.036	<DL	<DL	<DL	<DL

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APPENDIX-CHEMICAL ANALYSES

WELL NAME	COLL. DATE	Fe (ppm)	Mn (ppm)	Ni (ppm)	V (ppm)	Zn (ppm)	(Cat/An) CHG.BAL.
EPA M. P. C.*	--	--	--	--	--	--	--
EPA R. C. L.**	--	.3	.05	--	--	5	--
Detection Limit	--	.015	.0025	.05	.025	.005	--
BS-31	Nov 25 85	<DL	.004	<DL	<DL	<DL	1.08
BS-31	May 19 85	<DL	<DL	--	--	--	--
BS-3A	May 19 85	<DL	<DL	--	--	--	--
BS-8	Apr 4 84	<DL	<DL	--	--	--	--
CA-109	Mar 8 86	--	--	<DL	<DL	<DL	--
CA-15	Mar 12 86	<DL	<DL	<DL	<DL	<DL	--
CC-23	Mar 21 86	<DL	.057	<DL	<DL	.009	--
CO-1	Apr 4 84	<DL	<DL	--	--	--	--
CO-52	Mar 14 86	--	--	<DL	<DL	<DL	1.01
CVI	Mar 12 86	<DL	<DL	<DL	.358	<DL	--
FP-4	Nov 27 85	--	--	<DL	<DL	.013	1.00
FP-5	Nov 27 85	--	--	<DL	.028	<DL	.97
FP-6	Apr 4 84	.030	<DL	--	--	--	--
FP-6	May 15 85	.040	<DL	--	--	<DL	--
FP-6	May 19 85	<DL	<DL	--	--	<DL	--
FP-6	Nov 26 85	2.216	.061	<DL	<DL	<DL	.92
FP-8	Nov 27 85	<DL	.010	<DL	.035	<DL	--
GG-PW1	Apr 4 84	<DL	<DL	--	--	--	--
GG-PW1	Dec 9 85	--	--	<DL	<DL	<DL	.81
GL-148	Mar 20 86	<DL	<DL	<DL	<DL	<DL	--
GL-246C	Mar 14 86	<DL	<DL	<DL	<DL	<DL	.95
HR-100	Mar 10 86	<DL	.002	<DL	.070	.025	--
LG-1	Apr 4 84	<DL	<DL	--	--	--	--
MH-35	Mar 10 86	<DL	.016	<DL	<DL	<DL	--
NB-3	Nov 29 85	<DL	<DL	<DL	.033	.007	.93
NB-6	Dec 7 85	.154	.008	<DL	<DL	.051	1.04
PE-3A	Mar 18 86	<DL	<DL	<DL	<DL	<DL	--
Rainwater	Mar 13 86	--	--	<DL	.028	.073	--
RU-149	Mar 18 86	<DL	<DL	<DL	.040	<DL	--
Seawater	Mar 86	<DL	<DL	<DL	<DL	<DL	--
Seawater-avg.	--	.002	.0002	.0005	--	.002	1.00
SO-R1	Mar 16 86	<DL	<DL	<DL	<DL	<DL	1.09
SO-R2	Mar 16 86	<DL	<DL	<DL	<DL	.451	--
WD-94	Mar 7 86	<DL	<DL	<DL	<DL	.007	1.03
WH-59	Mar 12 86	.027	.009	<DL	<DL	<DL	--

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