WATER RESOURCES RESEARCH, VOL. 28, NO. 6, PAGES 1597–1604, JUNE 1992

Stable Isotopic Study of the Groundwater of the Martha Brae River Basin, Jamaica

K. K. ELLINS

Department of Geology, University of Florida, Gainesville

The hydrology of a small karst drainage basin in Jamaica, the Martha Brae River basin, was examined using stable isotopes. Variations in the isotopic composition of the groundwaters sampled and their positions relative to the local meteoric water line on a $\delta D/\delta^{18}O$ diagram permitted the identification of two distinct groundwater types. The isotopic data also provided evidence that the most productive portion of the aquifer is divided by a major fault, which impedes groundwater flow. Information regarding the mechanisms and elevation of recharge was inferred from the δD versus $\delta^{18}O$ relationships and differences in isotopic composition, respectively.

1. INTRODUCTION

1.1. *Background*

The ratios of the stable isotopes of oxygen, $^{18}O/^{16}O$, and hydrogen, D/H ($^2H/^1H$), carry information about the origin of the water and provide a method of identifying different sources of water. Variations in the isotopic composition of natural waters result from isotopic fractionation, which occurs primarily during evaporation and condensation. The extent to which water is depleted in the heavier isotopes, deuterium and oxygen 18, relative to the lighter isotopes, hydrogen and oxygen 16, is a function of temperature and the history of fractionation that has occurred previously [*Ehhalt et al.*, 1963; *Dansgaard*, 1964; *Eriksson*, 1967; *Fritz and Fontes*, 1980; *Drever*, 1982]. In drainage basins for which data are scarce, the analysis of stable isotopes provides an alternate means to study hydrology for they can be measured quickly, easily, and without much expense. In addition, they complement very effectively more traditional sources of hydrologic data and also provide information which is not available from other types of data.

Past efforts to evaluate the groundwater resources of the Martha Brae River in Jamaica have relied heavily on detailed geophysical prospecting. These methods are costly and time-consuming, particularly for a developing nation like Jamaica with limited monetary and technical resources. The primary objective of the stable isotopic hydrologic investigation of the Martha Brae River basin was to identify of different groundwater types, trace patterns of groundwater movement, and characterize recharge conditions. This work was part of a larger study of the hydrology of the Martha Brae River basin, the results of which are reported elsewhere [*Ellins*, 1988*a*, *b*; *Ellins et al.*, 1989].

1.2. *Previous Work*

A joint investigation of the water resources of the Martha Brae Basin was carried out by the Jamaican Water Resources Division in collaboration with the United Nations Development Programme (UNDP) and the Food and Agriculture Organization of the United Nations (FAO) between 1965 and 1967 in order to determine the amount of groundwater and surface flow available for irrigation and for the municipalities of Falmouth and Montego Bay [*UNDP/FAO*, 1971]. The results of the investigation confirmed the existence of large stores of groundwater [*UNDP/FAO*, 1971]. As a result of the recommendations of the UNDP/FAO study, a number of wells were established in the basin. In 1980, however, turbidity and bacteriological problems encountered in some of the wells prevented the attainment of the groundwater abstraction design rate. The situation prompted the government of Jamaica to focus renewed attention on understanding the hydrology of the basin. The services of the Canadian hydrologic consulting firm of MacLaren Engineers, Planners and Scientists, Incorporated, and Hydrocon, Incorporated, of Jamaica were engaged to review the findings and recommendations of the UNDP/FAO study in light of new data acquired by the Jamaican Water Resources Division and the National Water Commission of Jamaica between 1967 and 1980, to determine the sources and pathways of pollutants affecting water quality in the aquifer, and to recommend new well sites for development [*MacLaren Engineers, Planners and Scientists, Incorporated*, 1981]. This paper reports some of the findings of a study I conducted in the Martha Brae River basin during 1983–1985, which involved the application of stable isotopes in addressing some of the hydrologic problems of the basin.

2. STUDY AREA

The Martha Brae River basin is primarily a karst drainage basin located in the northwestern part of Jamaica, a Caribbean island of 11,400 km^2, which is characterized by a tropical marine climate [*Town Planning Department of the Ministry of Finance and Planning*, 1972]. The Martha Brae River basin encompasses 590 km^2 and may be divided into three subregions: the Cockpit Country, the Martha Brae Valley, and the Coastal Plain. The Martha Brae Valley (260 km^2), situated between the Cockpit Country and the narrow Coastal Plain, is the most important subregion for the storage of groundwater. It is essentially an east-west trending interior karst valley, which is bisected by a ridge of hills running north-south. The eastern portion of the Martha Brae Valley constitutes the floodplain of the Martha Brae River. The flatter western portion of the valley lacks surface drainage and is known as the Queen of Spain's Valley (47

Paper number 91WR02519.
0043-1397/92/91WR-02519$05.00

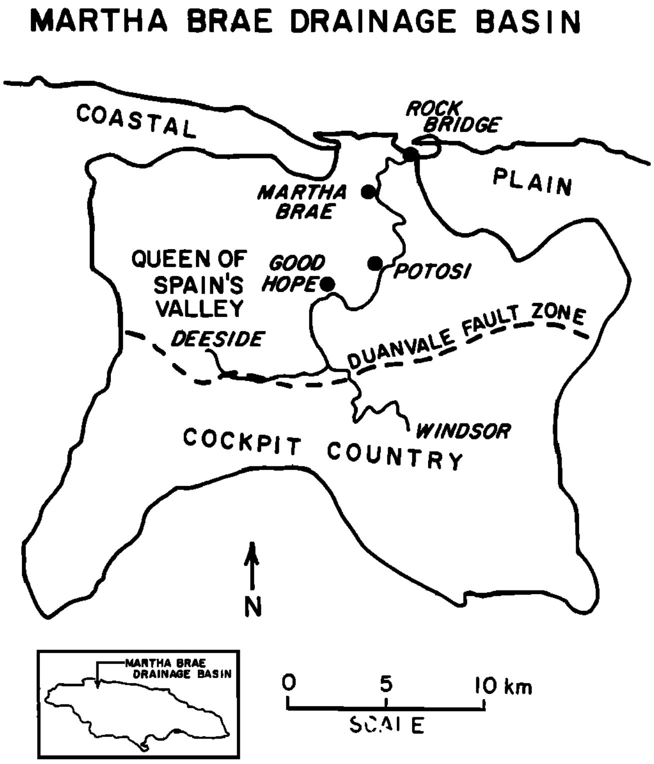

Fig. 1. Map of the Martha Brae River basin, showing the location of the Cockpit Country, Queen of Spain's Valley, Coastal Plain, and Martha Brae River.

km^2). In the course of the research efforts reported here, special emphasis was placed on understanding the groundwater regime of the Queen of Spain's valley since it is the island's second most important source of groundwater. Figure 1 shows the configuration and provinces of the Martha Brae River basin.

The most productive aquifer in the Martha Brae River Basin is the Tertiary White Limestone Formation (middle Eocene to lower Miocene). The original porosity of the limestone has been destroyed by recrystallization; consequently, its water-bearing capacity is characterized by a secondary permeability that has developed as a result of diagenetic processes and solution along joints or faults. In some areas, the White Limestone Formation attains a thickness in excess of 900 m [*Versey*, 1972]. Underlying the White Limestone Formation is the Yellow Limestone Formation, middle Eocene in age, which is composed of bioclastic and argillaceous limestones interbedded with calcarenous sandstones and clays. As a result of its high clay content, the Yellow Limestone is characterized by low permeability. Along the floodplain of the Martha Brae River and in some parts of the Queen of Spain's Valley, a thin blanket of Quaternary alluvium covers the White Limestone. Parallel to the coast, a ridge composed of seaward dipping chalks and limestones of the Montpelier Limestone Formation and younger carbonates (mid-Miocene and Pleistocene) rests upon the older recrystallized White Limestone [*Versey*, 1962; *UNDP/FAO*, 1971]. A map of the geology of the Martha Brae River basin is displayed in Figure 2. Numerous NW-SE or E-W trending faults related to a mid-Miocene period of uplift occur throughout the basin. These faults impede or act as preferred paths of groundwater flow [*UNDP/FAO*, 1971; *Versey*, 1972]. A major northwesterly trending fault, extending from Friendship through Wakefield and Gales Valley to Canaan, cuts through the alluvium covering the Queen of Spain's Valley in the Martha Brae River basin (refer to Figure 3). Earlier investigators have postulated that this fault, known as the Canaan-Friendship Fault, divides the limestone aquifer beneath the alluvium into two sections: the Hampden-Tilston block to the northeast of the fault line and the Deeside–Bunkers Hill block located to the southwest of the fault [*MacLaren Engineers, Planners, and Scientists, Incorporated*, 1981].

The average annual rainfall in the Martha Brae River basin varies from about 100 cm near the coast to 300 cm farther

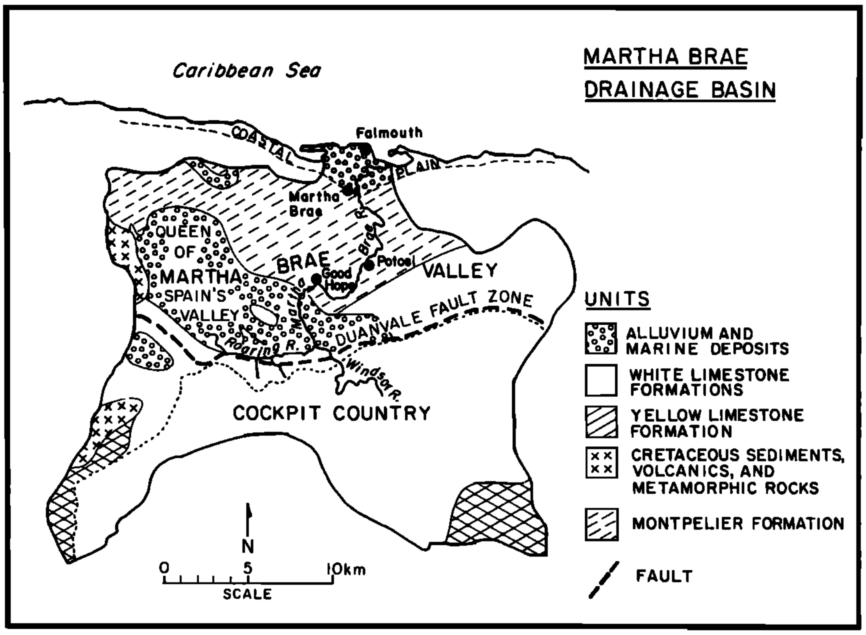

Fig. 2. Geologic map of the Martha Brae River basin.

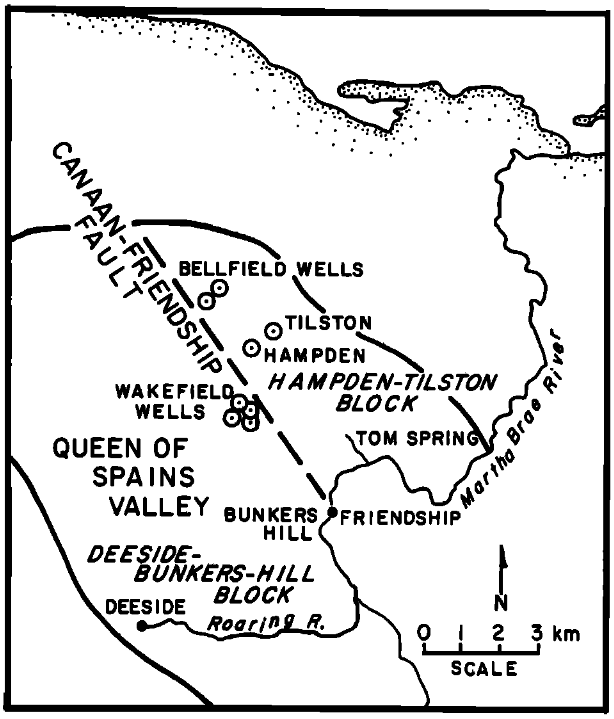

Fig. 3. Map of the Martha Brae Valley, showing locations of Wakefield and Hampden-Bellfield well fields, and the Canaan-Friendship Fault.

inland. Workers consider the Cockpit Country to be the primary recharge area for the groundwaters of the Martha Brae River Basin. One estimate attributes 69% of the total recharge to precipitation that accumulates in the Cockpit Country [*UNDP/FAO*, 1971]. Due to the action of infiltrating rainfall and corrosive runoff, an extensive underground hydrologic network of channels has been established in the hard, recrystallized units of the White Limestone beneath the surface of the Cockpit Country. Because of the steep hydraulic gradient in this area, however, there is little groundwater storage in the White Limestone aquifer in the Cockpit region. Instead, groundwater flows rapidly through the maze of conduits and collects in the units of the White Limestone Formation beneath the Martha Brae Valley [*Sweeting*, 1958; *Versey*, 1962, 1972; *Brown and Ford*, 1973; *White*, 1982]. Here, the underlying Yellow Limestone forms a barrier to the downward movement of water from the Martha Brae Valley at the base of the White Limestone aquifer [*UNDP/FAO*, 1971]. In addition, the northerly flow of groundwater from the Martha Brae Valley to the sea is impeded by the younger, less permeable carbonates of the coastal ridge. Besides retarding the discharge of water from the aquifer, the coastal ridge prevents seawater intrusion and helps to protect the quality of fresh groundwater [*UNDP/FAO*, 1971; *Versey*, 1972; *UNDP Department of Economic and Social Affairs*, 1976]. Although some groundwater stored in the White Limestone Formation is discharged into the Martha Brae River, significant stores remain in the Queen of Spain's Valley.

3. Methods

3.1. *Water Collection and Analysis*

Groundwater samples were collected from the all the active production wells of the Wakefield and Bellfield-Hamden well fields, and at the sources of many springs located within the Martha Brae River basin. Samples were collected in 1985 during October or November, at the end of the wet season, and in February or March, during the dry season. The samples were collected in 1-L polyethelene bottles in the field and transferred to 50-mL glass collection bottles in the laboratory to be stored for subsequent analysis.

Measurements of the ratio of $^{18}O/^{16}O$ in the equilibrated CO_2 were made on a VG Instruments Micromass 902 mass spectrometer at Columbia University's Lamont-Doherty Geological Observatory (LDGO). Samples were first treated with phosphoric acid and then equilibrated with CO_2 at 20°C using methods similar to those of *Epstein and Mayeda* [1953].

Deuterium analyses were carried out at LDGO and the Centre d'Etudes Nucleaires de Saclay (CEA) in France. Hydrogen in water was first reduced to hydrogen gas using a uranium furnace method similar to that established by *Epstein et al.* [1976]. The hydrogen produced was collected in accordance with the uranium pump procedures of *Friedman and Hardcastle* [1970]. The deuterium extraction system and methods used at LDGO are described in detail elsewhere [*White*, 1983]. Isotopic analyses were done on a Finnegan MAT 251 mass spectrometer at LDGO and on a modified Houston Instruments mass spectrometer with an automated water injection system at CEA. Corrections for $^3H^+$ ion production, which is collected with HD^+, are done automatically on both mass spectrometers.

Duplicate measurements on 22 samples carried out at LDGO and CEA had no significant systematic differences, indicating that the data sets are compatible and may be interpreted together without employing a correction factor for one of the data sets.

3.2. *Calibrations and Data Reporting*

Laboratory standards for deuterium analyses included Vienna standard mean ocean water (V.SMOW), and Lamont tap water 2 (W2). The reference used for the oxygen 18 analyses was North Atlantic deep water (NADW), whose $\delta^{18}O$ value has been established as −0.22‰ relative to SMOW through previous experimentation carried out at LDGO (R. G. Fairbanks, personal communication, 1985).

The D/H and $^{18}O/^{16}O$ isotopic ratios are expressed as delta values (δ) versus SMOW as follows:

$$\delta D‰_{\text{sample}} = \frac{D/H_{\text{sample}} - D/H_{\text{SMOW}}}{D/H_{\text{SMOW}}} \times 10^3$$

$$\delta^{18}O‰_{\text{sample}} = \frac{{}^{18}O/{}^{16}O_{\text{sample}} - {}^{18}O/{}^{16}O_{\text{SMOW}}}{{}^{18}O/{}^{16}O_{\text{SMOW}}} \times 10^3$$

3.3. *Accuracy*

The magnitude of the analytical error, which takes into account both sample preparation and mass spectrometry, is reflected in the reproducibility of measurements. On the basis of replica determinations, the experimental error associated with the δD measurements and the $\delta^{18}O$ measurements is ±1.7‰ and ±0.23‰, respectively.

TABLE 1. Stable Isotopic Composition of Groundwater in the Queen of Spain's Valley

Well Location	Date	δD, ‰	$\delta^{18}O$, ‰
	Wakefield Well Field		
Wakefield 1	Nov. 16, 1983	−9.4	−2.4
Wakefield 1	March 8, 1984	−8.8	−2.4
Wakefield 1	Sept. 27, 1984	−9.3	−2.3
Wakefield 3	Feb. 3, 1984	−9.5	−2.5
Wakefield 4	Feb. 3, 1984	−8.4	−2.5
Wakefield 2	Sept. 27, 1984	−10.4	−2.5
	Hampden-Bellfield Well Field		
Hampden 2	Nov. 16, 1983	−14.0	−3.1
Hampden 2	Feb. 3, 1984	−13.0	
Bellfield 2	March 8, 1984	−13.4	−3.8
Bellfield 2	Sept. 27, 1984	−13.8	−3.3

4. RESULTS AND DISCUSSION

4.1. *Isotopic Composition*

Two distinct groundwater types were identified in the White Limestone aquifer beneath the Queen of Spain's valley on the basis of deuterium content. One type represented the groundwaters of the Wakefield well field, located to the southwest of the Canaan-Friendship fault, while the other was associated with groundwaters of the Bellfield well field, which are to the northeast of the fault line. Groundwater from the Wakefield and Bellfield wells had average deuterium values of −9.1‰ and −13.5‰, respectively. These deuterium measurements provide clear evidence that the Canaan-Friendship Fault divides the limestone aquifer beneath the alluvium in the Queen of Spain's Valley into a northeast block (Hampden-Tilston block) and a southwest block (Deeside–Bunkers Hill block). Table 1 gives the stable isotopic composition of groundwater in the Queen of Spain's Valley. Figure 3 is a map of the Martha Brae Valley, showing the Canaan-Friendship Fault and the locations of Wakefield and Hampden-Bellfield well fields.

Deuterium data obtained during the rainy season in October 1984 for the Wakefield 2 well, 300 m to the south of the Friendship-Canaan Fault, however, suggest that there is some groundwater exchange across the Canaan-Friendship Fault. The October deuterium value of −10.4‰ for groundwater from the Wakefield 2 well was more depleted than groundwater from other Wakefield wells (refer to Table 1), indicating that the direction of groundwater flow across the fault is from the Hampden-Tilston block to the Deeside–Bunkers Hill block. During October 1984, the mean difference between the groundwater of the Deeside–Bunkers Hill block and the Hampden-Tilston block was about 4.5‰. Since the deuterium concentration of the groundwater from the Wakefield 2 well deviates from the average value of −9.4‰ that is representative of Deeside–Bunkers Hill groundwater by 1‰ and from the Hampden-Tilston waters by 3.5‰, it appears that the Wakefield 2 well tapped a mixture of approximately 75% Deeside–Bunkers Hill groundwater and 25% Hampden-Tilston groundwater at the time of sampling. Dye tracings, involving the injection of Rhodamine WT into a well in the Hampden-Tilston block of the aquifer, however, did not provide evidence of direct flow across the Friendship-Canaan Fault from the Hampden-Tilston block to the Deeside–Bunkers Hill block [*MacLaren Engineers, Planners and Scientists, Incorporated*, 1981]. This experiment was carried out under low groundwater conditions, however, while the deuterium data discussed here were representative of high groundwater conditions. Unfortunately, isotope data representative of low groundwater conditions were not available for comparison. Since the magnitude of the error associated with the δD measurements is ±1.7‰, additional geochemical, isotopic and dye tracing data are required to validate my interpretation.

4.2. *The δD Versus $\delta^{18}O$ Relationships*

When both deuterium and oxygen 18 data are available for the same sample, the values may be plotted on a δD versus $\delta^{18}O$ diagram and a trend line obtained by linear regression analysis. The trend line thus obtained may be interpreted in reference to the global meteoric water line (MWL) [*Craig*, 1961] or, if available, a local meteoric water line. (The MWL refers to a plot of the δD versus $\delta^{18}O$ values in precipitation.) The position of waters sampled along the MWL or within the space of the δD versus $\delta^{18}O$ plot reveals information about the conditions of recharge and also facilitates the recognition of different water types in a hydrologic system.

On the basis of such an approach, a meteoric origin for the groundwaters of the Martha Brae River basin was inferred. A plot of δD versus $\delta^{18}O$ for wells and springs of the Martha Brae drainage basin is presented in Figure 4. In general, the relationship between δD and $\delta^{18}O$ can be described by the expression, $\delta D‰ = 6.7\ \delta^{18}O + 7.5$ ($R = 0.88$). This trend is closer to the expression, $\delta D‰ = 6.17\ \delta 18O + 3.97$, which was developed by *Yurtsever* [1975] to describe the meteoric water line of tropical island stations included in the World Meteorological Organization/International Atomic Energy Agency precipitation sampling network, than the global MWL of $\delta D‰ = 8.0\ \delta^{18}O + 10$ [*Craig*, 1961].

Upon close examination of the data four measurements, designated by squares in Figure 5, seem anomalous. Of these, three fall above and one below the mean trend line. The anomalous measurements represent springs that form the headwaters of the Martha Brae River and Roaring River, the primary tributary to the Martha Brae, and groundwater collected from the Bellfield well field in March 1984. The springs correspond to the resurgence of rivers that originate in the mountainous interior of the island and traverse Cretaceous inliers of igneous and metamorphic rock before flowing underground once the contact with the White Limestone is reached. The offset from the mean trend line reflects variations in deuterium excess, defined as $d = \delta D - 8.8\ \delta^{18}O$ [*Dansgaard*, 1964]. This offset most likely represents indi-

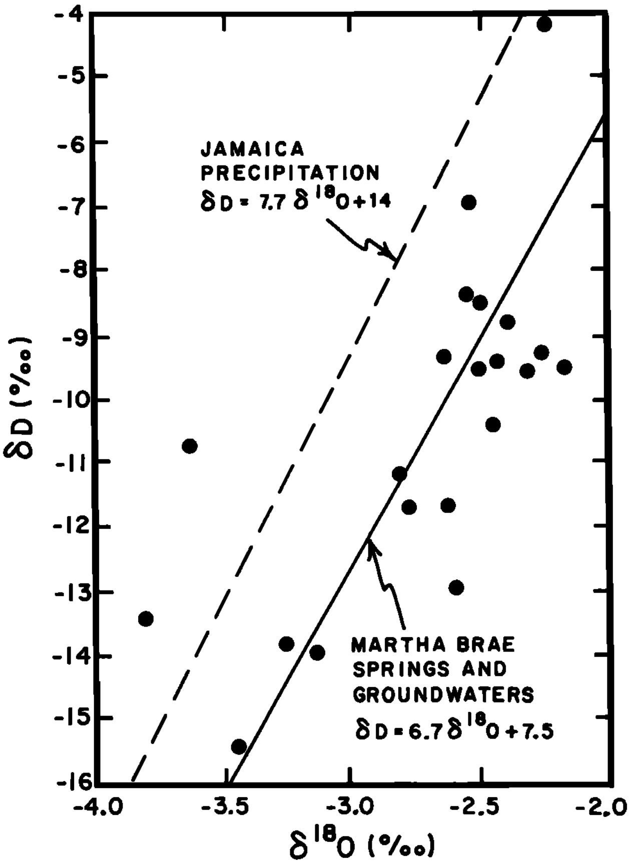

Fig. 4. Diagram of $\delta D/\delta^{18}O$ for springs and wells of the Martha Brae River basin.

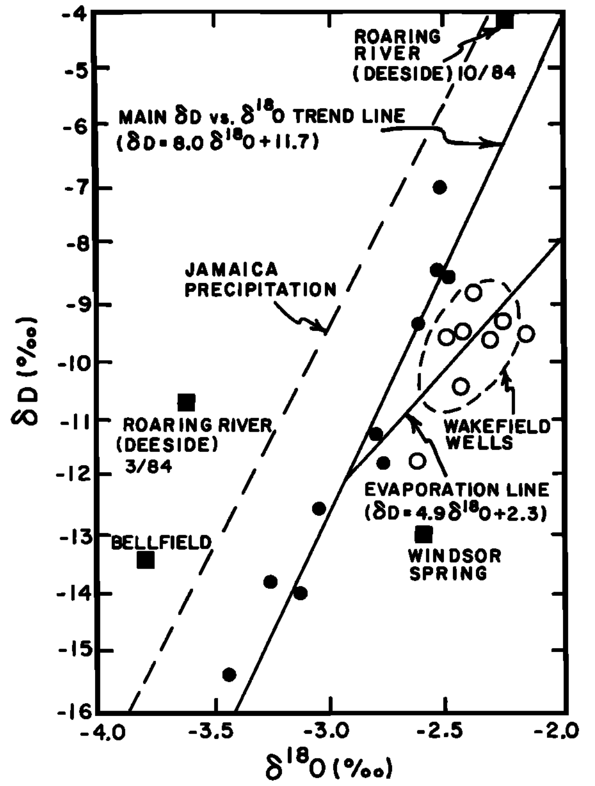

Fig. 5. Diagram of $\delta D/\delta^{18}O$ for different groundwater categories, showing mean precipitation value for Jamaican rain, 1983–1984 [*Ellins*, 1988*a*].

vidual storm events and thus implies a very short residence time for these waters.

Interestingly, there is also a cluster of measurements offset to the right of the mean trend line which appears to be representative of waters that have experienced evaporation. The data points of this group, designated by open circles in Figure 5, include all groundwaters of the Wakefield well field, one measurement from the Clarkstown well and one from the first of an important group of springs, known as the Potosi Boil, that rise in the bottom of the Martha Brae River. The deuterium values associated with these groundwaters range from −11.6‰ (Clarkstown) to −8.5‰ (Wakefield), most likely reflecting variations in the elevation of recharge. The δD versus $\delta^{18}O$ relationship that characterizes the group can be described by the expression, $\delta D‰ = 4.9\ \delta^{18}O + 2.3$ ($R = 0.85$). The low slope of the trend line, 4.9, falls within the range of 2–5 typically associated with evaporated waters.

The remaining springs and wells sampled in the Martha Brae River basin may be characterized by a δD versus $\delta^{18}O$ relationship of $\delta D‰ = 8.0\ \delta^{18}O + 11.7$ ($R = 0.93$), which can be compared with the local meteoric water line for the island: $\delta D‰ = 7.7\ \delta^{18}O + 14$ ($R = 0.90$) [*Ellins*, 1988*a*]. Deuterium values associated with these waters range from −15.4‰ to −8.4‰, again indicative of variations in the elevation of recharge. Included in these waters are the groundwaters of the Bellfield well field. Thus, the two groundwater types of the Queen of Spain's Valley that were identified on the basis of differences in deuterium content were further distinguished by their position relative to the MWL. The waters that constitute each groundwater type and their associated stable isotopic values are listed in Table 2.

From the δD versus $\delta^{18}O$ relationship that characterizes Deeside–Bunkers Hill groundwater ($\delta D‰ = 4.9\ \delta^{18}O + 2.3$), it was inferred that recharge to the Deeside–Bunkers Hill block of the limestone aquifer has experienced evaporation prior to storage. In comparison, the δD versus $\delta^{18}O$ relationship of the groundwater of the Hampden-Tilston block ($\delta D‰ = 8.0\ \delta^{18}O + 11.7$) did not suggest evaporation of the recharge. There are numerous surface ponds occupying clay-lined depressions that cover the land surface in the Deeside–Bunkers Hill area. These are separated from each other by outcrops of the White Limestone. In addition, there are also a large number of sinkholes present on the exposed limestone. Although the authors of previous studies have reported that there is no hydraulic continuity between the pond water and the underlying limestone aquifer, some have postulated that spillover from the ponds enters the limestone aquifer through active sinkholes during the rainy season when the ponds fill to overflowing [*MacLaren Engineers, Planners and Scientists, Incorporated*, 1981]. The isotopic data yielded by this study clearly confirm that the Deeside–Bunkers Hill subsection of the aquifer is recharged by partially evaporated water, giving credence to the spillover mechanism of recharge by partially evaporated pond water.

The land surface of the Hampden-Tilston area of the Queen of Spain's Valley, by contrast, is uniformly covered by alluvial deposits. Many clay-lined ponds are present in the layer of alluvium, but no open sinkholes [*MacLaren Engineers, Planners and Scientists, Incorporated*, 1981].

TABLE 2. Stable Isotopic Composition of Martha Brae River Basin Groundwaters

Source Sampled	Date	δD, ‰	δ^{18}O, ‰
	Group 1 (Anomalous)		
Roaring River at Deeside	Oct. 2, 1984	−10.6	−3.6
Bellfield 2 well	March 8, 1984	−13.4	−3.8
Roaring River at Deeside	March 8, 1984	−4.1	−2.2
Martha Brae at Windsor	March 14, 1984	−13.3	−2.6
	Group 2 (Evaporated)		
Clarkstown PEPL2 well	Sept. 27, 1984	−11.6	−2.6
Wakefield 2 well	Sept. 27, 1984	−10.4	−2.5
Coco Copse Spring (Potosi)	Oct. 1984	−9.5	−2.2
Wakefield 3 well	Feb. 3, 1984	−9.5	−2.5
Wakefield 1 well	Nov. 16, 1983	−9.4	−2.4
Wakefield 1 well	Sept. 27, 1984	−9.3	−2.3
Wakefield 1 well	March 8, 1984	−8.8	−2.4
Wakefield 4 well	Feb. 3, 1984	−8.4	−2.5
	Group 3		
Hampden 2 well	Nov. 16, 1983	−14.0	−3.1
Bellfield 2 well	Sept. 27, 1984	−13.8	−3.3
Manganiga Basin Head	Oct. 2, 1984	−9.3	−2.6
Manganiga Spring 2	Oct. 2, 1984	−8.3	−2.6
Martha Brae at Windsor	Oct. 1984	−11.2	−2.8
Morass Spring	Oct. 10, 1984	−15.4	−3.4
Tom Spring Source	Feb. 3, 1984	−11.6	−2.8

During the wet season as water levels rise, existing small ponds coalesce forming a few large ponds. During the dry season, the ponds recede as the water is evaporated. Thus, it is unlikely the recharge mechanism for the Hampden-Tilston block is infiltrating local precipitation or spillover from ponds.

4.3. *Isotopic Altitude Gradient and the Identification of Recharge Areas*

Studies involving the use of isotopes to define recharge areas are often based on the observation that the isotopic composition of precipitation varies as a function of altitude. Factors contributing to the relationship between isotopic content and altitude, referred to as the "altitude effect," are dependent on temperature. A complete discussion is beyond the scope of this paper. Briefly, during orographic precipitation, the cooling of water vapor in clouds as they rise over mountains results in increased depletion of the heavier isotopic species in precipitation with an increase in altitude.

Deuterium altitude gradients based on monthly composite samples of precipitation collected at three sampling stations located at different elevations have been established for the north coast of Jamaica [*Ellins*, 1988*a*]. The gradients developed correspond to three seasons: (1) a wet summer-autumn season (2.2‰ per 100 m); (2) a winter season with intermediate to low rainfall accumulations (1.8‰ per 100 m); and (3) a dry spring (0.9‰ per 100 m). Typical gradients reported in the literature range from about 1.2 to 4‰ per 100 m of elevation [*Fritz and Fontes*, 1980]. The interested reader is referred to *Ellins* [1988*a*] for a detailed discussion of these data. In this work, it is assumed that these gradients are valid for the entire north coast region of Jamaica and can be applied in a general way to waters of the Martha Brae River basin. Since most of the rainfall that recharges the aquifer falls in the wet summer-autumn season, the deuterium altitude gradient for that season was used to obtain a rough approximation of the difference in the mean elevations of the recharge areas corresponding to the two groundwater types occurring in the Queen of Spain's Valley.

The average δD value of −9.2‰ for Deeside–Bunkers Hill waters corresponds to an average elevation of recharge of approximately 300 m, assuming a mean residence time of one year. In fact, the groundwater is probably a mixture of water that originated in the Cockpit Country at higher elevations and recharge derived from local precipitation in the Deeside–Bunkers Hill area, which is approximately 150 m in elevation. The recharge mechanism for this fraction of groundwater in the Deeside–Bunkers Hill subsection of the aquifer was discussed in the previous section. The average δD value of −13.6‰ for Hampden-Tillston groundwaters suggests that the recharge area is about 200 m higher than the catchment for the Deeside–Bunkers Hill water, again assuming a groundwater residence time of at least one year. The lack of variation of the stable isotopic values of the groundwater from the Wakefield, Hampden, and Bellfield wells probably reflects the integration and mixing of recharge from the different seasons, and supports my assumptions regarding residence time. Based on the topography of the drainage basin and groundwater flow directions, which are shown in Figure 6, the most likely recharge sites for groundwater of the Hampden-Tillston limestone block is the Cockpit Country in the southwest and an upland area in the northwest of the Martha Brae River basin.

5. SUMMARY AND CONCLUSIONS

Variations in the isotopic composition of the groundwaters the Martha Brae River basin sampled and their positions relative to the local meteoric water line on a $\delta D/\delta^{18}O$ diagram permitted the identification of two distinct groundwater types in White Limestone aquifer underlying the Queen of Spain's Valley. The isotopic data also provided strong evidence supporting the contention that the Canaan-Friendship Fault divides the limestone aquifer beneath the

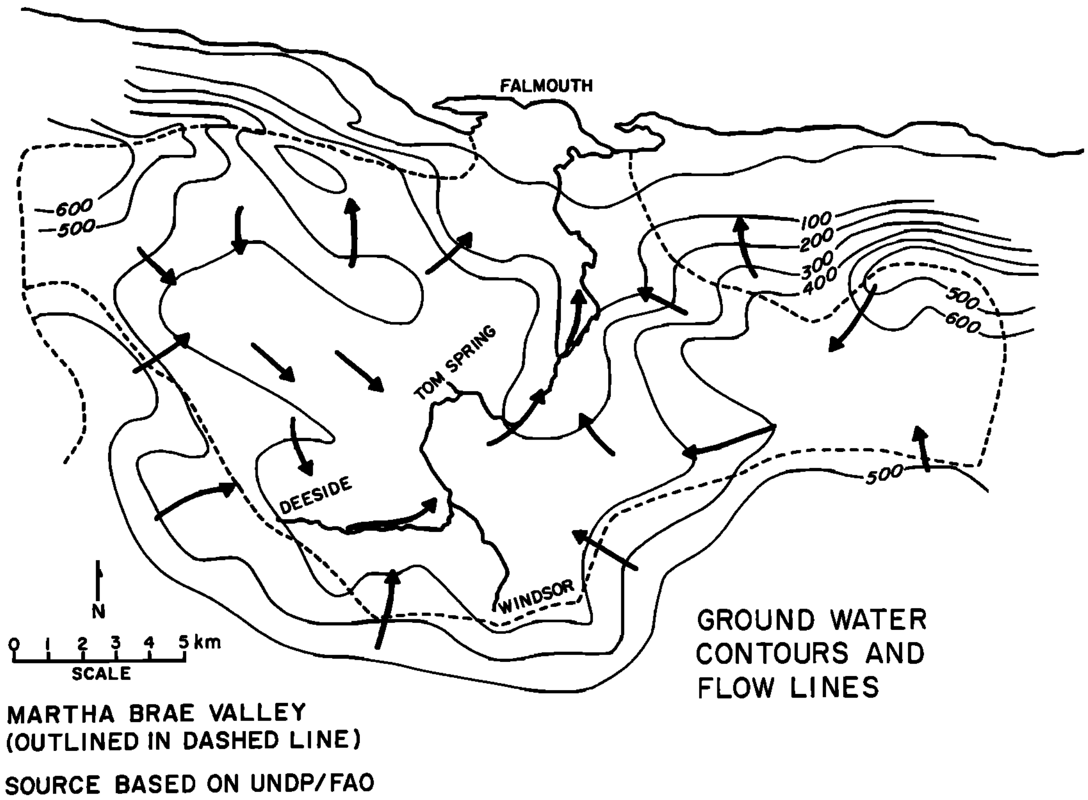

Fig. 6. Groundwater flow directions in the Martha Brae River basin.

alluvium in the Queen of Spain's Valley into a northeast block (Hampden-Tilston block) and a southwest block (Deeside–Bunkers Hill block), across which there may be limited groundwater exchange.

Information regarding the mechanism of recharge to the Deeside–Bunkers Hill subsection of the aquifer was inferred from the δD versus δ^{18}O relationship that characterized the groundwater of the Wakefield wells. These isotopic data clearly confirm that partially evaporated water, which spills over from the numerous surface ponds in the area during the rainy season when they overflow, replenishes the aquifer via active sinkholes in the karst.

Estimates regarding the elevation of recharge of the two groundwater types in the Queen of Spain's Valley were based on differences in deuterium composition and interpreted in reference to deuterium altitude gradients previously established for Jamaican north coast precipitation. On the basis of this approach, the Deeside–Bunkers Hill groundwaters sampled during this investigation appeared to be a mixture of water that originated in the Cockpit Country at higher elevations and recharge derived from local precipitation, which was collected in lakes prior to recharge. The data also indicate that the elevation of the recharge area of the Hampden-Tillston groundwaters was about 200 m higher than the catchment for the Deeside–Bunkers Hill water. The mean δD content of the Hampden and Bellfield wells indicated that groundwater in the Hampden-Tilston subsection of the aquifer was replenished by precipitation that accumulated at higher elevations. Patterns of groundwater flow suggest the Cockpit Country in the southwestern part of the Martha Brae River basin and an upland area in the northwestern part of the basin as probable sources.

Acknowledgments. The work described in this paper was partially funded by NSF grant EAIR-8305927. The author gratefully acknowledges the guidance of Jim White and is thankful for his assistance in obtaining the deuterium analyses at CEA.

References

Brown, M. C., and D. C. Ford, Caves and groundwater patterns in a tropical karst environment: Jamaica, West Indies, *Am. J. Sci.*, *273*, 622–633, 1973.

Craig, H., Isotopic variations in meteoric waters, *Science*, *133*, 1702–1703, 1961.

Dansgaard, W., Stable isotopes in precipitation, *Tellus*, *16*, 436–468, 1964.

Drever, J. I., *The Geochemistry of Natural Waters*, Prentice-Hall, Englewood Cliffs, N. J., 1982.

Ehhalt, D., K. Knott, J. F. Nagel, and J. C. Vogel, Deuterium and oxygen 18 in rainwater, *J. Geophys. Res.*, *68*, 3775–3780, 1963.

Ellins, K. K., Isotope hydrology of karst drainage basins in Jamaica and Puerto Rico, Ph.D. thesis, Columbia Univ., New York, 1988*a*.

Ellins, K. K., Isotope hydrology of the Martha Brae River basin in Jamaica (abstract), *Eos Trans. AGU*, *69*(44), 1194, 1988*b*.

Ellins, K. K., H. J. Simpson, and G. Mathieu, A study of surface discharge fluctuations in the Martha Brae River in Jamaica, using ^{222}Rn (abstract), *Eos Trans. AGU*, *70*(15), 334, 1989.

Epstein, S., and T. K. Mayeda, Variations of the ^{18}O/^{16}O ratio in natural waters, *Geochim. Cosmochim. Acta*, *4*, 213, 1953.

Epstein, S., C. J. Yapp, and J. H. Hall, The determination of the D/H ratio of non-exchangeable hydrogen in cellulose extracted from aquatic and land plants, *Earth Planet. Sci. Lett.*, *30*, 241–251, 1976.

Eriksson, E., Isotopes in hydrometeorology, in *Isotopes in Hydrology*, pp. 21–33, International Atomic Energy Agency, Vienna, 1967.

Friedman, I., and K. Hardcastle, A new technique for pumping hydrogen gas, *Geochim. Cosmochim. Acta*, *34*, 125–126, 1970.

Fritz, P., and J. C. Fontes, *Handbook of Environmental Isotope Geochemistry*, vol. 1, Elsevier Scientific, New York, 1980.

MacLaren Engineers, Planners and Scientists, Incorporated, The Queen of Spains Valley wellfield in the Martha Brae River basin, Trelawny, Jamaica, report, Toronto, Ont., 1981.

Sweeting, M. M., The karstlands of Jamaica, *Geogr. J.*, *124*, 184–199, 1958.

Town Planning Department of the Ministry of Finance and Planning, *The National Atlas of Jamaica*, Government Printing Office, Kingston, Jamaica, 1972.

United Nations Development Programme (UNDP) Department of Economic and Social Affairs, *Groundwater in the Western Hemisphere, Nat. Resour./Water Ser.*, vol. 4, Rome, 1976.

UNDP Food and Agriculture Organization (FAO), Appraisal report of the Martha Brae Valley, Trelawny, Rome, 1971.

Versey, H. R., Older Tertiary limestones, Synopsis of the Geology of Jamaica, edited by V. A. Zans, *Bull. Jam. Geol. Surv.*, *4*, 24–34, 1962.

Versey, H. R., Karst of Jamaica, in *Karst: Important Karst Regions of the Northern Hemisphere*, edited by M. Herak and V. T. Stringfield, Elsevier Scientific, New York, 1972.

White, J. W. C., The climatic significance of D/H ratios in white pines in the northeastern United States, Ph.D. thesis, Columbia Univ., New York, 1983.

White, M., Groundwater movement and storage in karstic limestone aquifers of Jamaica, paper presented at UNESCO International Hydrological Programme International Workshop on Karst Hydrology of the Caribbean Region, Havana, Cuba, Dec. 5–12, 1982.

Yurtsever, Y., Worldwide survey of stable isotopes in precipitation, report, 40 pp., Sect. on Isot. Hydrol., Int. At. Energy Agency, Vienna, Nov. 1975.

K. K. Ellins, Department of Geology, 1112 Turlington Hall, University of Florida, Gainesville, FL 32611.

(Received June 26, 1990;
revised September 23, 1991;
accepted September 27, 1991.)