Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer

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[1] The hydrology and geochemistry of groundwater in tropical island aquifers, such as on Barbados, are significantly influenced by tropical climatic conditions. Recharge to these aquifers is the product of regional and local climate patterns that control rainfall. Oxygen isotopes can be used to estimate the amount and timing of recharge on these islands because seasonal fluctuations of rainwater oxygen isotopic compositions are related to the amount of rainfall. This study shows that estimates of average annual recharge to the limestone aquifer on Barbados vary widely, displaying a more direct relationship to the distribution of rainfall throughout each year than to total annual rainfall. Recharge estimates are higher during years when rainfall is concentrated in the peak wet season months than during years when rainfall is more evenly distributed throughout the year. The El Niño-Southern Oscillation appears to be partially responsible for these rainfall and recharge fluctuations. Knowledge of interannual variation of recharge and processes responsible is important because recharge variation must be considered when setting groundwater management policies related to groundwater availability. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 1836 Hydrology: Hydrologic budget (1655); 1854 Hydrology: Precipitation (3354); 1884 Hydrology: Water supply; *KEYWORDS:* hydrogeology, recharge, island aquifers, Barbados, ENSO

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1. Introduction

[2] Small, unconfined aquifers, such as those that occur on small limestone islands, are characterized by groundwater residence times of years to tens of years. Because of the short groundwater residence time, groundwater availability in these aquifers is sensitive to short- and long-term climatic fluctuations that influence the amount of recharge. Consequently, it is vital that we understand recharge processes and interannual variations of recharge amounts. Additionally, the short groundwater residence times makes water quality in these aquifers susceptible to the effects of seawater intrusion, which in turn is related largely to fluctuations in recharge.

[3] The primary aim of this paper is to investigate (1) the processes by which recharge occurs in a limestone island aquifer, specifically the Pleistocene limestone aquifer on Barbados, and (2) interannual variation of recharge over the past 30 years. It has been shown that recharge to the limestone aquifer on Barbados is primarily influenced by runoff along dry valleys that produces discrete recharge by rapid infiltration through karst shafts or sinkholes that occur along the sides of the dry valleys [*Jones et al.*, 2000]. Comparison of oxygen isotopic compositions of groundwater and rainwater on Barbados indicates that there is also a rainfall threshold that must be exceeded before recharge takes place [*Jones et al.*, 2000]. This threshold coincides with the minimum rainfall required for the generation of runoff. The spatial distribution of recharge is a function of the spatial distribution of karst features that are sites of discrete recharge. Seasonal and interannual variations of recharge may be functions of the seasonal distribution of rainfall and interannual variations of rainfall, respectively. Seasonal distribution of rainfall on Barbados produces recharge during the wettest months of each year [*Jones et al.*, 2000]. Interannual variations of rainfall on Barbados may be influenced by phenomena such as the El Niño-Southern Oscillation (ENSO). This must be considered as a factor influencing interannual variations of both rainfall and recharge amounts on Barbados.

2. Climate

[4] Average annual rainfall on Barbados varies from about 1000 mm yr^{-1} at the extreme northern and southeastern margins of the island to more than 2000 mm yr^{-1} at the center of the island (Figure 1). On Barbados, the wet season extends from June to December with rainfall reaching a peak in August through October. Wet season rainfall accounts for approximately 60% of average annual rainfall.

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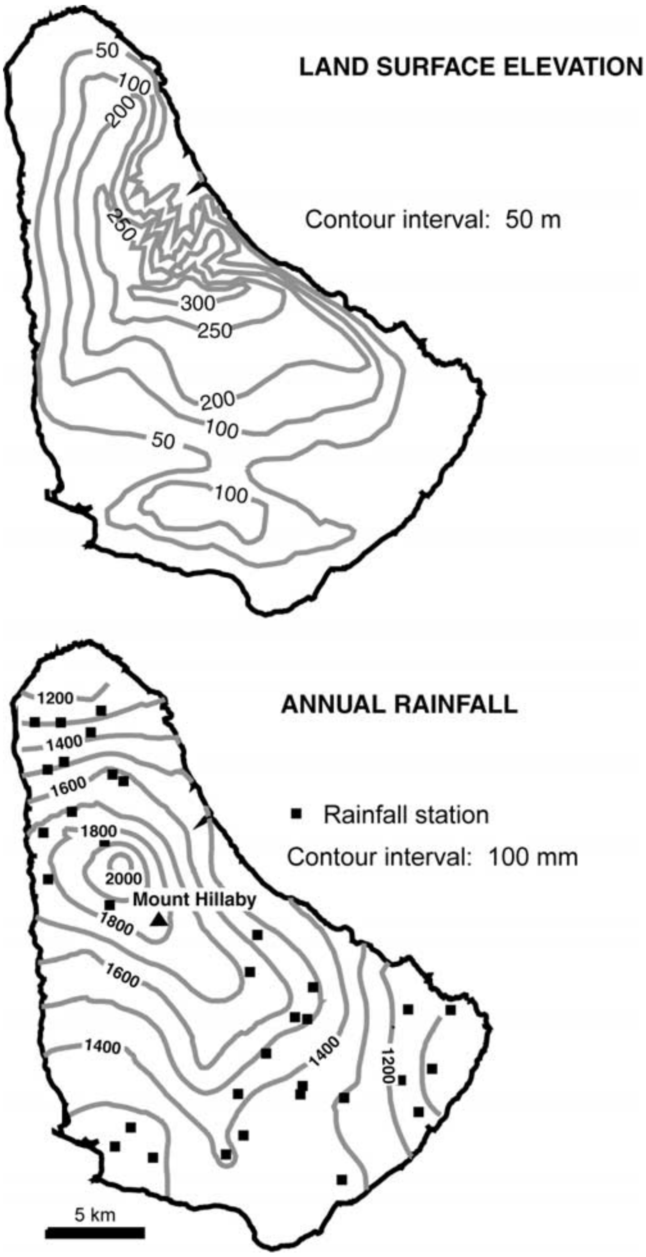

Figure 1. The distribution of annual rainfall (1992) on Barbados. Total annual rainfall is highest at the center of the island. Unpublished rainfall data obtained from the Caribbean Institute of Meteorology and Hydrology.

Dry season rainfall is associated with local convection due to moist air flowing over the heated island [*Malkus*, 1963]. During the wet season, in addition to local convection effects, rainfall occurs due to the combined effects of moisture associated with (1) tropical weather systems, such as tropical depressions and hurricanes, and (2) the proximity of the Intertropical Convergence Zone (ITCZ) [*Falkland*, 1991; *Reading et al.*, 1995]. The spatial distribution of rainfall varies seasonally. The highest rainfall occurs at the center of the island and on the western, leeward side of the island during the dry and wet seasons, respectively (Figure 2). Orographic effects that normally produce enhanced rainfall on windward slopes apparently do not play a major role in influencing the rainfall distribution on Barbados [*Reading et al.*, 1995].

3. Geology

3.1. Pleistocene Limestone

[5] The Pleistocene limestone aquifer of Barbados is composed of the Pleistocene coral reef limestone, up to 100 m thick, that covers about 85% of the island (Figure 3). The Pleistocene limestone overlies Tertiary-age rocks of the upper Scotland Formation and Oceanics Group.

[6] In response to continuous uplift, the coral reefs developed outward from the center of the island, forming

Figure 2. Wet season rainfall is highest on the western, leeward side of Barbados, especially at the peak of the wet season. Dry season rainfall is heaviest at the center of the island. Unpublished rainfall data obtained from the Caribbean Institute of Meteorology and Hydrology.

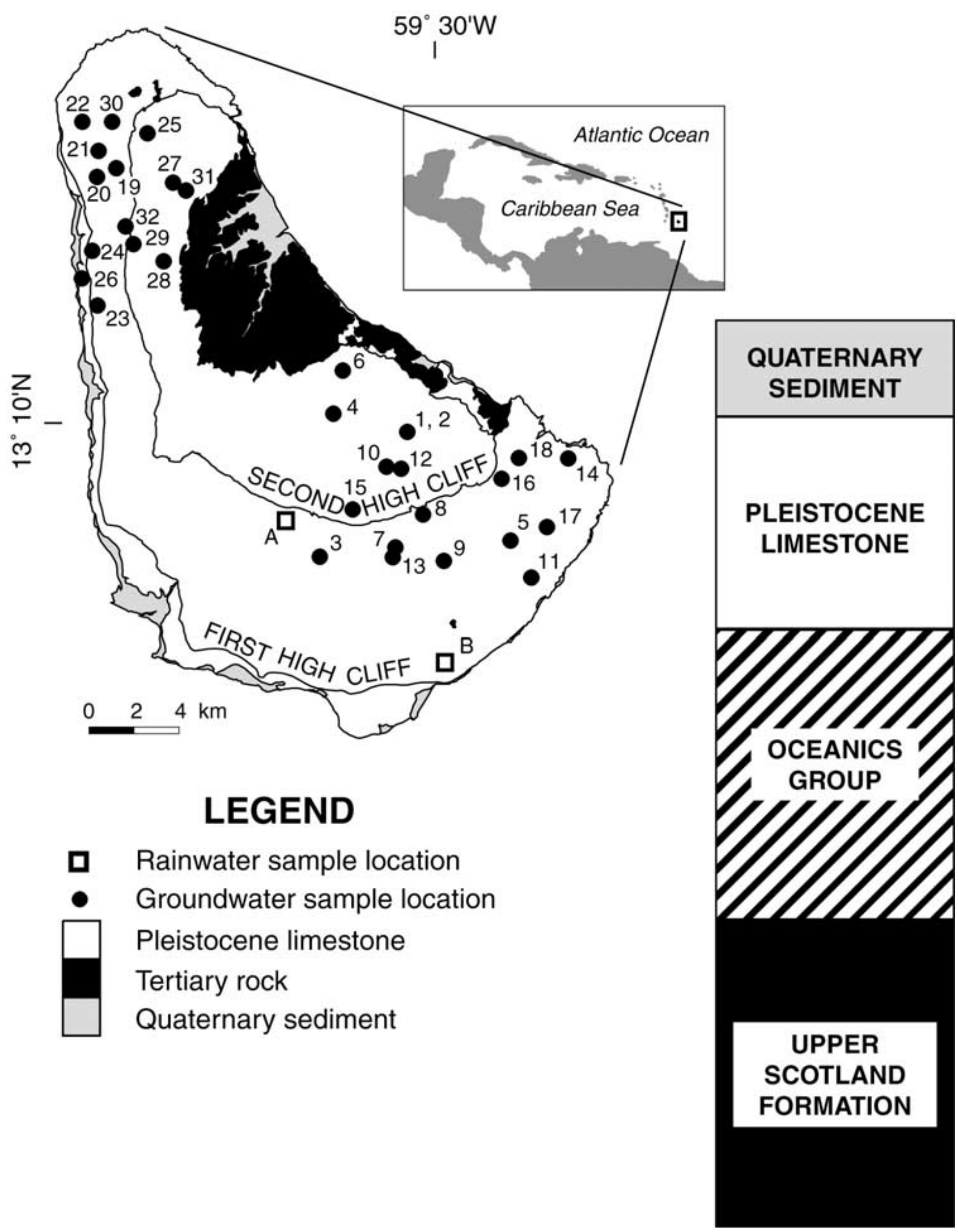

Figure 3. Geologic map of Barbados. The Pleistocene limestone that composes the aquifer occurs in the northern, western, and southern portions of the island. The Second High Cliff is approximately 30 m high and has been identified as a major site for discrete recharge to the underlying aquifer. The Tertiary rock outcrop is composed of the Oceanics Group and upper Scotland Formation. Adapted from Directorate of Overseas Surveys 1:50,000 geologic map (1983).

terraces. There are three main groups of terraces separated by the First and Second High Cliffs. The Second High Cliff is about 30 m high and occurs at an elevation of approximately 100 m. The Second High Cliff is highly karstified with the frequent occurrence of dry valleys and caves and consequently is the site of a large amount of discrete recharge to the aquifer. This spatial distribution of recharge has been confirmed by comparison of oxygen isotopic compositions of rainwater and groundwater [*Jones et al.*, 2000]. Recharge to this aquifer is facilitated by high limestone porosity of 20–60%, averaging 45%, and a specific yield of 12.5–15% [*Senn*, 1946; *Tullstrom*, 1964]. Recharge to this aquifer takes the form of diffuse and discrete infiltration through the soil and underlying limestone, processes that will be discussed in more detail below. Groundwater flows outward from the elevated parts of the aquifer and discharges primarily along the coast. This coastal discharge varies both spatially and seasonally, with higher discharge rates during the wet season [*Lewis*, 1985, 1987].

3.2. Upper Scotland Formation

[7] The upper Scotland Formation is composed of deep-sea deposits of sand with interbedded clay. These rocks potentially form an aquifer that directly underlies the Pleistocene limestone in parts of northern and eastern Barbados [*Senn*, 1946; *Speed*, 1981]. Little is known of the potential for the upper Scotland Formation as an aquifer

because few, if any, wells penetrate it. This is due to the adequate groundwater supply from the overlying Pleistocene aquifer and the well construction methods used on the island. Most wells on Barbados are hand-dug wells, constructed more than 100 years ago [*Senn*, 1946]. These wells are typically vertical shafts about 2–3 m in diameter that were dug until the water table was encountered. In some cases, horizontal shafts are constructed perpendicular to the hydraulic gradient to increase well yields. Well depths are limited by the base of Pleistocene limestone in upland areas and the thickness of the freshwater lens in coastal areas.

3.3. Oceanics Group

[8] The Oceanics Group in most areas separates the Pleistocene limestone from the upper Scotland Formation. This group is composed of low-permeability deep-sea deposits of clay and marl. The Oceanics Group forms an aquitard at the base of the Pleistocene limestone aquifer [*Senn*, 1946]. In upland areas of Barbados, most wells are dug to the top of the Oceanics Group to maximize saturated thickness. At the highest elevations where the saturated zone is very thin, a few wells have been dug into underlying Oceanics Group rock. These wells take advantage of the very low permeability of the Oceanics rock to form cisterns that collect water flowing along the Pleistocene-Oceanics contact. On Barbados, there is only one well known to obtain water from the Oceanics Group. This well is located in an area in southern Barbados where the Oceanics Group crops out and is highly jointed [*Senn*, 1946].

4. Hydrogeology

[9] The Pleistocene limestone aquifer is divided into two hydrologic zones, referred to as the Stream- and Sheet-water zones, depending on whether the aquitard lies above or below sea level, respectively (Figure 4). The Stream-water zone constitutes the bulk of the areal extent of the aquifer with the freshwater lenses of the Sheet-water zone primarily occurring within 1–2 km of the coast. In addition to hydrologic zones, the aquifer is subdivided into groundwater catchments [*Stanley Associates Engineering Ltd.*, 1978a]. These groundwater catchments are defined based on our knowledge of the topography of the aquifer base. It is assumed that the topography of the top of the aquitard controls groundwater flow paths in the aquifer. Consequently, ridges in the topography of the top of the aquitard form hydrologic divides.

4.1. Stream-Water Zone

[10] The Stream-water zone forms the upland portions of the aquifer. The term "Stream water" refers to the occurrence of underground streams in this portion of the aquifer. In the Stream-water zone, groundwater forms a thin layer, a few meters thick, at the base of the Pleistocene limestone where groundwater flows along the top of the underlying aquitard [*Senn*, 1946]. At some locations, groundwater flows through underground streams that incise the aquitard [*Harris*, 1971]. The topography of the top of the aquitard controls the groundwater flow paths and hydraulic gradients.

[11] Water level variations in wells in the Stream-water zone have been reported at several locations in the aquifer [*Senn*, 1946]. These water level fluctuations are typically seasonal fluctuations of less than 1 m but may be as much as 7 m [*Senn*, 1946]. The relatively large water level fluctuations are associated with (1) sinkhole depressions (sites 8, 10, and 19; Figure 3); (2) depressions in the topography of the aquitard (site 3); and (3) known underground streams (site 2 [*Senn*, 1946]). One can infer that these relatively large water level fluctuations are due to mounding of the water table during periods of recharge: (1) adjacent to points of discrete recharge; (2) where groundwater flow paths converge; and (3) due to water from underground streams infiltrating into the surrounding aquifer rock.

4.2. Sheet-Water Zone

[12] The Sheet-water zone occurs where the top of the basal aquitard lies below sea level. Consequently, groundwater occurs in freshwater lenses. In this part of the aquifer, the water table lies close to sea level [*Senn*, 1946]. Water level variations in the Sheet-water zone are typically due to tidal effects, especially near the coast. Water level fluctuations observed near the landward margin of this zone are attributed to large influxes of groundwater from the Stream-water zone [*Senn*, 1946; *Stanley Associates Engineering Ltd.*, 1978b]. Water level data for the period 1965–1971 from the southwestern parts of island show that minimum water levels generally coincide with the dry season (Figure 5). Water levels may rise up to 0.75 m above the average water level in response to above average monthly rainfall during the wet season [*Stanley Associates Engineering Ltd.*, 1978b]. Water levels may rise gradually in response to the cumulative effects of a long wet season (e.g., 1966) or rapidly in response to exceptionally wet months (e.g., October 1970). Generally, the water table will gradually return to average water levels over a period of 6–12 months [*Stanley Associates Engineering Ltd.*, 1978b]. There is little apparent response of water levels to rainfall during years with average or below-average rainfall.

[13] The Ghyben-Herzberg Principle [*Baydon-Ghyben*, 1888; *Herzberg*, 1901] suggests that fluctuations in Sheet-water zone water levels would be accompanied by fluctuations in the thickness of the freshwater lens. The freshwater lens on Barbados is 10–25 m thick [*Stanley Associates Engineering Ltd.*, 1978a]. Seasonal fluctuation in water levels would be accompanied by fluctuations in freshwater lens thickness. The freshwater lens and the mixing zone separating the freshwater from seawater are thickest toward the end of the wet season in response to recharge and thinnest by the end of the dry season [*Steinen et al.*, 1978; *Stanley Associates Engineering Ltd.*, 1978a].

5. Recharge

5.1. Infiltration Rates: Diffuse Recharge

[14] Variations in soil permeability may play a role in recharge to the Pleistocene limestone aquifer (Figure 6). Barbados soils are typically less than 2 m thick and become less permeable with depth [*Vernon and Carroll*, 1965]. Soils occurring above the Second High Cliff tend to have the highest permeabilities, with measured infiltration rates greater than 250 mm h^{-1} [*Tullstrom*, 1964]. Soils that occur below the Second High Cliff, at elevations below 100 m, tend to be less permeable, with measured infiltration rates of

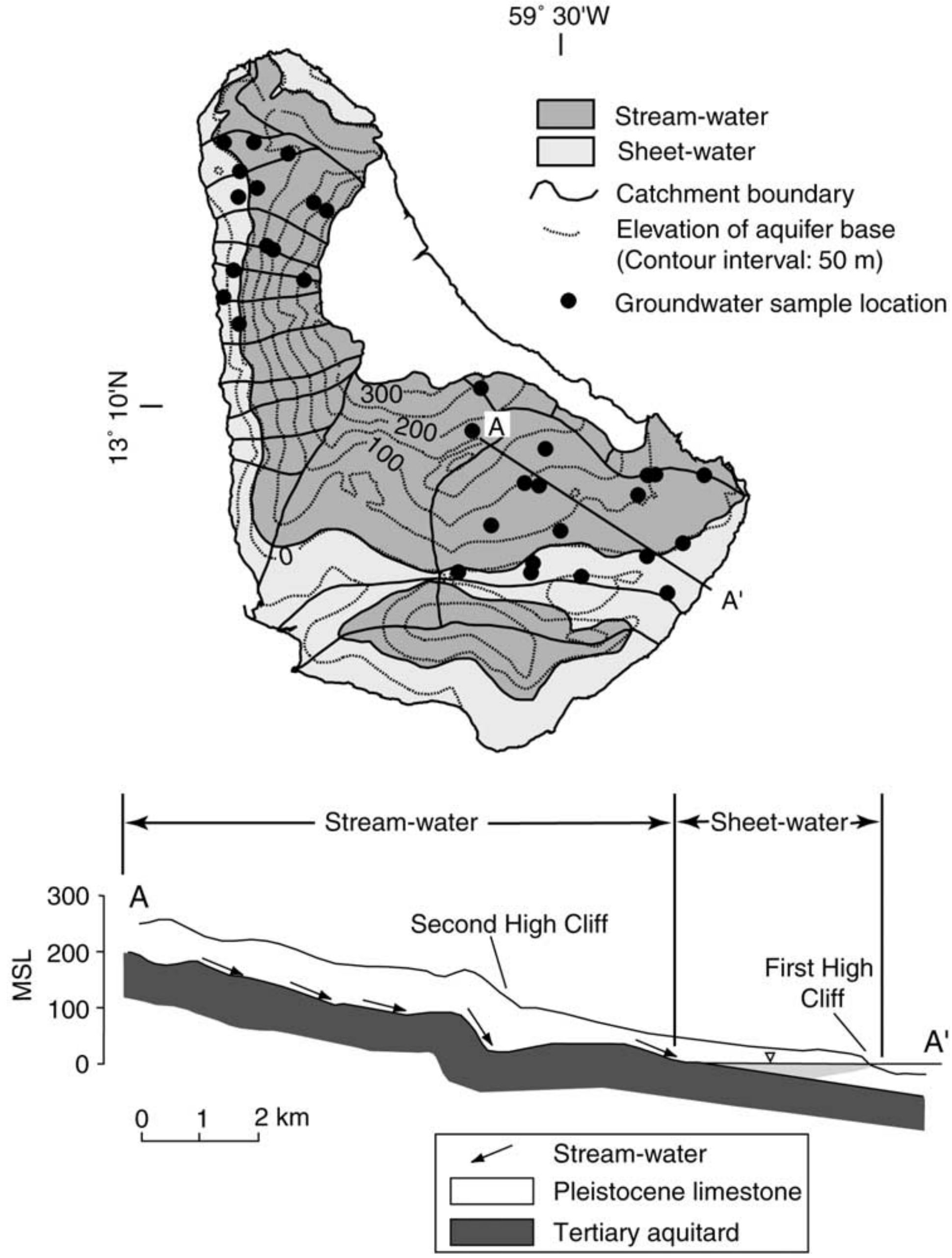

Figure 4. Hydrogeologic map of Barbados. The Pleistocene limestone aquifer is divided into several groundwater catchments due to the topography of the Pleistocene-Tertiary contact. The contours shown indicate the elevation of the base of the Pleistocene limestone. Adapted from *Stanley Associates Engineering Ltd.* [1978b] and *Barbados Ministry of Health et al.* [1991].

12.5–250 mm h^{-1}, but are mostly about 50 mm h^{-1} [*Tullstrom*, 1964]. These infiltration rates most likely represent infiltration through sugar cane fields that are tilled at 4- to 5-year intervals [*Tullstrom*, 1964]. The lowest soil permeabilities occur along topographic valley axes and in some sinkholes. The Pleistocene limestone is much more permeable than the overlying soils, with measured infiltration rates of 700–70,000 mm h^{-1} [*Tullstrom*, 1964; *Smart and Ketterling*, 1997].

[15] Barbados soils are typically composed of 60–70% clay [*Vernon and Carroll*, 1965]. Differences in soil infiltration rates can be attributed to differences in age and clay mineralogy. Weathering over time converts smectitic clays to kaolinite in soil environments. The soils that occur at lower elevations on Barbados are younger and have undergone less alteration than older soils [*Vernon and Carroll*, 1965]. Consequently, the predominant clay mineral present in these soils is smectite and their lower permeabilities are likely the result of the shrink-swell properties of smectite. Older soils occurring at higher elevations contain increasing amounts of kaolinite [*Vernon and Carroll*, 1965; *Beaven and Dumbleton*, 1966].

5.2. Karst Features: Discrete Recharge

[16] Dry valleys and sinkholes are the most obvious karst features that occur on Barbados (Figure 7). In

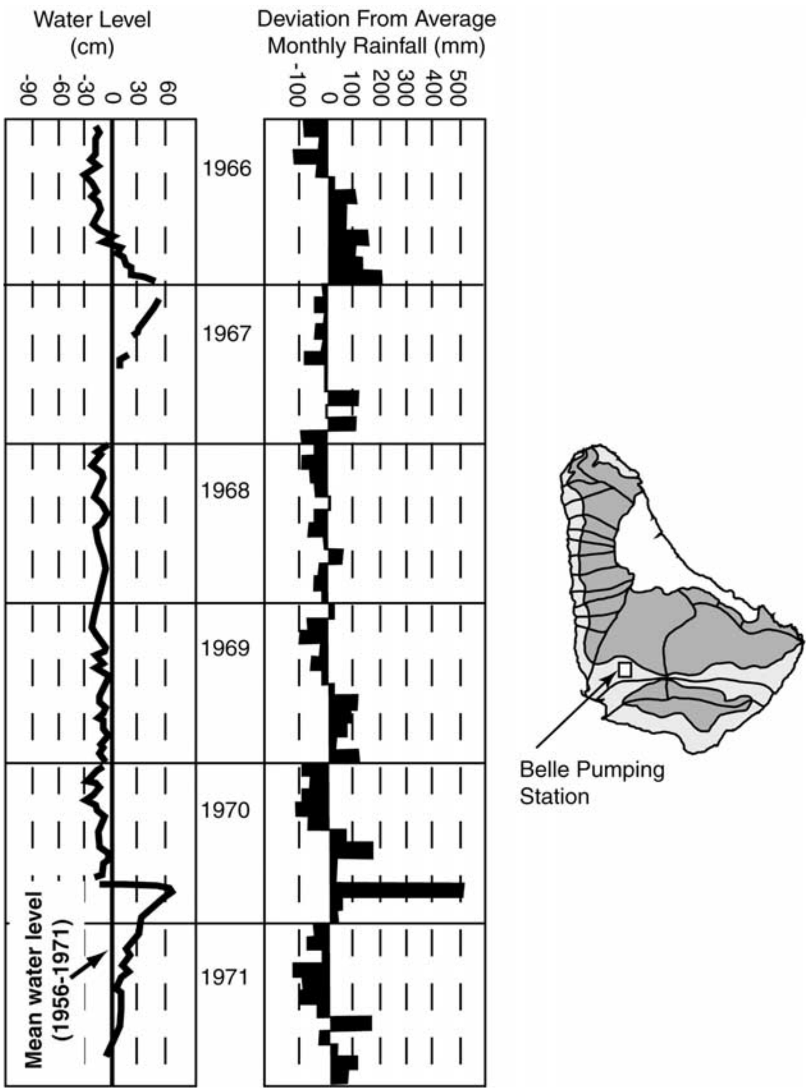

Figure 5. Water level fluctuations in the Sheet-water zone in response to rainfall observed at the Belle Pumping Station during the period 1966–1971. Adapted from *Stanley Associates Engineering Ltd.* [1978b].

addition to the less obvious karst features, such as caves, these are potential sites of discrete recharge to the underlying aquifer.

[17] Dry valleys on Barbados take the form of relatively narrow gullies that seem to be more numerous in areas characterized by moderate to steep slopes [*Day*, 1983]. These valleys are usually dry except along the west coast, where they intersect the water table [*Fermor*, 1972]. Runoff through the dry valleys only occurs for brief periods of time and is associated with heavy rainfall. It has been suggested that runoff is generated by rainfall rates exceeding 75–100 mm d^{-1} [*Tullstrom*, 1964]. It should be noted that these rainfall rates are anecdotal because there are no stream gages on Barbados and therefore it was not based on actual measurements. Surface runoff to the sea is only possible along the western and northern coasts of Barbados. Elsewhere, dry valleys disappear at lower elevations. Consequently, runoff generally either recharges the aquifer or is taken up by evapotranspiration. Surface water discharge on Barbados is very low and has been estimated to be less than 1% of average annual rainfall [*Stanley Associates Engineering Ltd.*, 1978a].

[18] The mean sinkhole density in western Barbados is 9.47 km^{-2}, and the sinkhole density is highest at elevations of 100–150 m [*Day*, 1983] (Figure 8). This elevation range coincides with the Second High Cliff. There is little evidence of structural control on the orientations of sinkhole depressions axes [*Day*, 1983]. On Barbados, sinkhole and dry valley development seem to be competitive [*Day*, 1983]. This is most apparent in western Barbados where some areas are characterized by the frequent occurrence of dry valleys and absence of sinkholes. High sinkhole densities tend to occur in areas where dry valleys are not well developed. These areas tend to be characterized by low relief. Similarly, dry valleys tend to be more numerous in areas characterized by relatively high relief. This can be explained by the effects of runoff and infiltration, factors that control the development of dry valleys and sinkholes, respectively [*Day*, 1983]. Infiltration dominates over runoff in areas characterized by low relief, and vice versa in high-

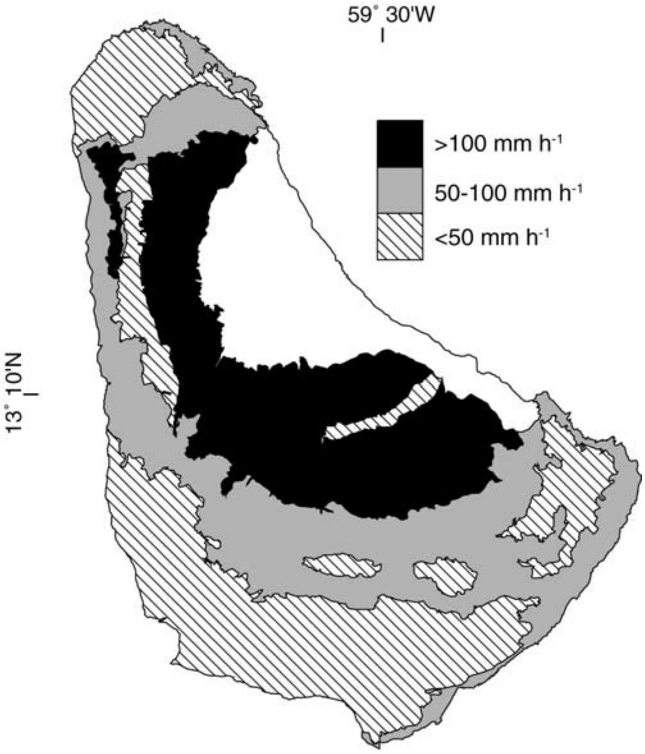

Figure 6. The infiltration rates of soils developed over the Pleistocene limestone aquifer. Barbados soil infiltration rates tend to increase with elevation. The most permeable soils occur above the Second High Cliff. Adapted from *Vernon and Carroll* [1965] and *Tullstrom* [1964].

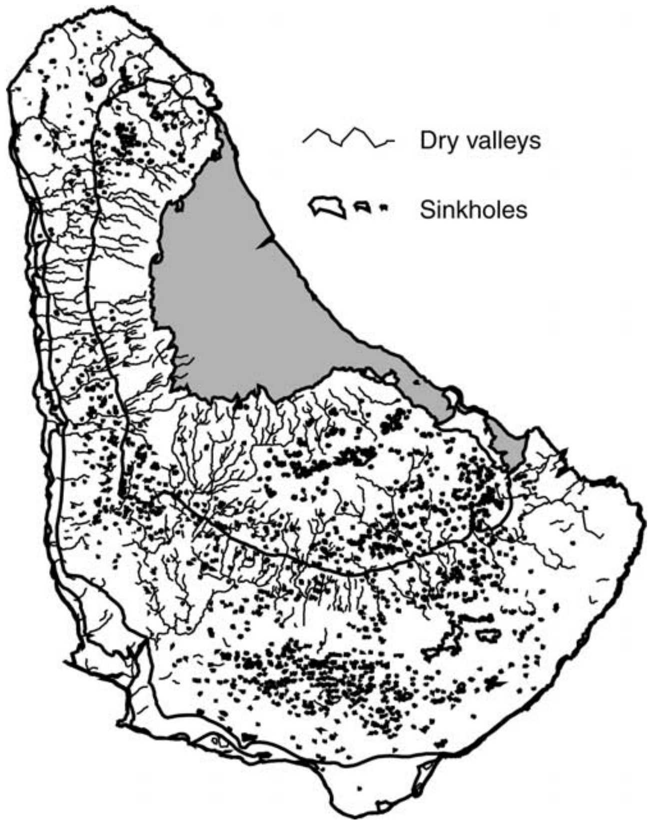

Figure 7. The major karst features on Barbados take the form of dry valleys on moderate to steep slopes and sinkhole depressions in flat areas, especially adjacent to the Second High Cliff. Adapted from Directorate of Overseas Surveys 1:10,000 topographic map series. Shaded area represents outcrop of Tertiary rocks.

relief areas. Consequently, sinkholes and dry valleys preferentially form in areas characterized by low relief and steeper slopes, respectively.

[19] Sinkholes on Barbados can be divided into two subpopulations. These subpopulations are (1) relatively large interfluvial sinkholes that occur between dry valleys, and (2) relatively small karst shafts occurring within the dry valleys [*Day*, 1983]. The karst shafts have greater potential as conduits for recharge to the aquifer than the larger interfluvial sinkholes. This is the case because interfluvial sinkholes are frequently filled with very low permeability soils that reduce their ability to transmit infiltrating water without ponding and extensive losses to evapotranspiration. On the other hand, the karst shafts that occur on the sides of dry valleys can potentially transmit large volumes of water to the aquifer during the brief periods of runoff [*Jones et al.*, 2000].

5.3. Recharge Processes

[20] Recharge to the Pleistocene limestone aquifer can take place by diffuse infiltration through the soil or by discrete infiltration through drainage wells, dry valleys, and some sinkholes. Infiltration tests and field observations on Barbados indicate that water residence times in the vadose zone range from several minutes to a few days for water infiltrating through sinkholes or drainage wells [*Smart and Ketterling*, 1997; B. J. Mwansa and L. Barker, Unpublished report on hydrogeological survey and pollution study of Harrison's Cave, 27 pp., 1996]. Residence times associated with diffuse infiltration are believed to be much longer,

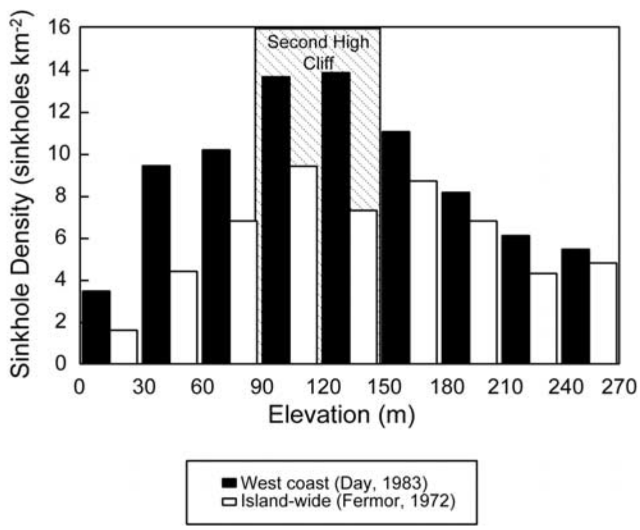

Figure 8. Studies by *Fermor* [1972] and *Day* [1983] indicate that the sinkhole density on Barbados reaches a maximum at elevations adjacent to the Second High Cliff. These elevations coincide with the low relief areas at the top and base of the Second High Cliff.

ranging from days to several months [*Senn*, 1946]. This conclusion was reached based on observed responses to rainfall in caves where a flow rate response is observed within hours of a large rainfall event followed by a second smaller response weeks or months later [*Senn*, 1946]. The first flow response is associated with rapid discrete infiltration, while the second response is related to slower diffuse infiltration. Diffuse recharge is most likely to occur where soil infiltration rates are highest (e.g., above the Second High Cliff). Pleistocene limestone is frequently exposed at the surface in dry valleys, especially where these valleys cut through the Second High Cliff forming narrow, deep channels. Small caves or karstic shafts along the sides of these dry valleys potentially act as vertical conduits for water to infiltrate directly into the limestone and rapidly recharge the aquifer. This process is only possible when there is sufficient rainfall to generate runoff along these dry valleys. Drainage wells constructed with the aim of preventing flooding of agricultural fields provide man-made conduits for recharge during periods of heavy rainfall and are also potential sources of groundwater contamination [*Smart and Ketterling*, 1997; *Jones*, 2002].

5.4. Estimated Recharge Rates

[21] Seasonal fluctuations in rainwater $\delta^{18}O$ values have made it possible for the first time to infer recharge seasonality and estimate the amounts of recharge on Barbados by comparing the isotopic compositions of groundwater and rainwater [*Jones et al.*, 2000]. The results of this study indicate that most recharge (1) is rapid, (2) takes place only during the wettest 1–3 months of each year, and (3) is 15–20% of average annual rainfall above the Second High Cliff, increasing to 25–30% at lower elevations. The higher recharge rates at lower elevations likely occur in response to discrete infiltration of large volumes of water through the highly permeable limestone [*Jones et al.*, 2000]. Recharge estimates based on groundwater constituents such as oxygen isotopes and dissolved chloride (1) have fewer uncertainties, (2) have the advantage of providing insight into the spatial and seasonal distribution of recharge to the aquifer, (3) are less affected by groundwater withdrawal, and (4) require fewer field measurements than recharge estimates based on direct measurement of hydrologic parameters [*Jones et al.*, 2000]. An advantage of the application of oxygen isotopes over chloride is that oxygen isotopes can be used to estimate recharge in both coastal and inland portions of the aquifer [*Jones et al.*, 2000].

5.5. Interannual Recharge Variations

[22] Interannual variations of recharge have been estimated based on the relationship between the average groundwater $\delta^{18}O$ value on Barbados and rainwater $\delta^{18}O$ values [*Jones et al.*, 2000]. This method of estimating recharge on Barbados infers that recharge only occurs during months with more than 195 mm of rainfall. This is because this method is based on mass balance and assumes that the groundwater oxygen isotopic composition is the weighted average of the rainwater that actually recharges the water table. The average groundwater oxygen isotopic composition on Barbados (−3.0‰) is equivalent to an average rainwater composition comprising only rainwater associated with monthly rainfall exceeding 195 mm. The 195 mm rainfall threshold represents minimum conditions that will

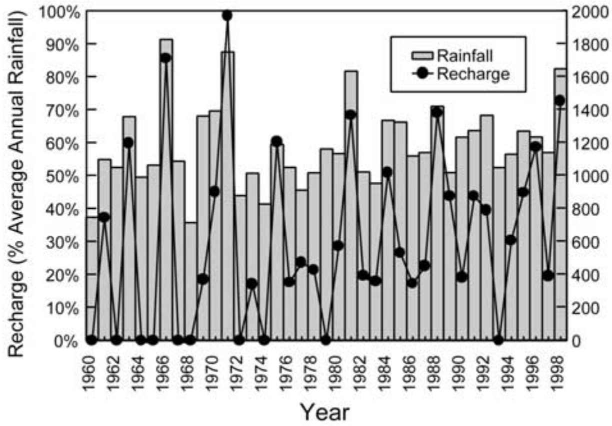

Figure 9. Interannual variation of recharge on Barbados responds more to the distribution of rainfall throughout the year than total annual rainfall. Consequently, years with very similar amounts of rainfall, for example, 1961 and 1962, may have significantly different recharge estimates.

result in recharge to the aquifer as a result of runoff to karst features. The amount of rainfall that will generate runoff in any specific rainfall event will vary with soil moisture, such that runoff and therefore recharge are more likely to occur when soil moisture is high. Recharge may thus be the product of multiple small rainfall events or a single large rainfall event. Monthly rainfall less than 195 mm is likely to be taken up by evaporation and transpiration and thus make an insignificant contribution to recharge. Recharge estimates for 1960–1998 fall within the range 0–99% of average annual rainfall with an average of 30% (Figure 9). These recharge estimates therefore are a measure of the proportion of rainfall during each year that occurs during months with more than 195 mm of rainfall. The variation of recharge over time is therefore related more to the distribution of rainfall throughout a given year than variations in total annual rainfall. For example, there was apparently much more recharge during 1994 (30%) than 1993 (0%), despite approximately equal amounts of rainfall during the respective years. This occurs because the amount of recharge is apparently higher when rainfall is concentrated in a few months of the year, usually the peak wet season months of August, September, and October. The conditions conducive to recharge usually occur during 1 month per year but may occur during as many as 3 months [*Jones et al.*, 2000].

6. Relationship Between Recharge and ENSO

[23] The phenomena of El Niño-Southern Oscillation (ENSO) is known to affect climatic conditions throughout the world. El Niño occurs when the cold Peruvian Current along the west coast of South America is periodically replaced by a weak warm ocean current [*Bigg*, 1990]. This phenomenon is closely associated with changes in upper atmospheric circulation that occur due to fluctuations of barometric pressures between the eastern and western South Pacific, known as the Southern Oscillation. The Southern Oscillation is caused by interannual sea surface temperature variations in the tropical Pacific Ocean [*Philander*, 1990; *Quinn et al.*, 1987]. These climatic fluctuations occur every 2–7 years [*Bigg*, 1990].

[24] ENSO potentially has an impact on hydrogeology by influencing variations of the spatial and temporal distribution of rainfall. In the western Atlantic, the onset of ENSO typically results in the development of fewer tropical weather systems, such as hurricanes, tropical depressions, and other tropical disturbances [*Gray*, 1984]. Tropical weather systems are less frequent during moderate to strong ENSO episodes because increased upper tropospheric westerly winds over the Caribbean basin and equatorial Atlantic enhance vertical shear and consequently inhibit their development [*Gray*, 1984; *Reading*, 1990]. These weather systems are partially responsible for rainfall on islands like Barbados, especially during the peak wet season months (August–October), which coincide with the peak of the hurricane season. ENSO therefore results in less rainfall and reduces the likelihood that recharge will occur. The development of tropical weather systems, however, is also influenced by other factors such as sea surface temperature and equatorial stratospheric winds [*Gray*, 1984; *Reading*, 1990]. This complicates the relationship between the development of tropical weather systems and ENSO [*Reading*, 1990]. Consequently, the correlation between the frequency of Atlantic tropical weather systems and El Niño-La Niña episodes is weak [*Reading*, 1990]. The onset of La Niña episodes has the opposite climatic effect to El Niño and results in more frequent development of tropical weather systems. Consequently, La Niña episodes result in more rainfall and a greater probability of recharge on Barbados.

[25] The multivariate ENSO Index (MEI) is a means of measuring the strength of ENSO episodes based on six variables: (1) sea level pressure; (2) zonal component of surface wind; (3) meridional component of surface wind; (4) sea surface temperature; (5) surface air temperature; and (6) total cloudiness fraction of the sky [*Wolter and Timlin*, 1993]. Positive MEI values represent El Niño episodes, whereas negative values represent La Niña episodes [*Wolter and Timlin*, 1993]. Annual MEI values fluctuate in response to cycles of El Niño-La Niña episodes (Figure 10). Generally, estimated annual recharge increases as the MEI values decrease, such that annual MEI minima coincide approximately with the highest recharge estimates. This relationship can be attributed to the effects of ENSO on the frequency of tropical weather systems. Little recharge takes place during El Niño years when wet season rainfall is suppressed, while much more recharge takes place associated with La Niña episodes when peak wet season rainfall is enhanced. There are periods, however, for example, the early 1960s and late 1970s, when the relationship between average annual MEI and recharge estimates is not apparent. The apparent relationship between average annual MEI and annual recharge can only be used qualitatively to predict periods of relatively high or low recharge because the correlation between annual MEI values and the magnitude of recharge is not statistically significant. This can be attributed to the weak correlation between tropical weather system development and ENSO episodes. This weak correlation is likely due to the influence of other lesser factors, such as the North Atlantic Oscillation, a discussion of which is beyond the scope of this paper.

[26] Monthly MEI values have been compared to the frequency at which the monthly rainfall threshold of 195 mm is exceeded for recharge to occur. These data suggest that when monthly MEI values are at or near minimum values, potential recharge episodes occur most frequently, 2–4 months per year, on Barbados. The number of months per year with rainfall exceeding 195 mm plays a role in determining the amount of recharge. Consequently, years with higher recharge episode frequencies will potentially have more recharge.

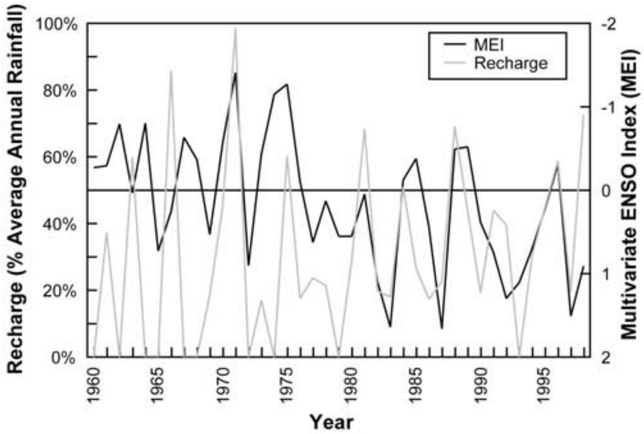

Figure 10. Interannual variations of recharge on Barbados display a general inverse relationship with ENSO. This apparent relationship is not statistically significant. This is likely due to the multiple conflicting factors, such as sea surface temperature and wind patterns at different altitudes. These factors influence the interannual variations in the frequency of tropical weather systems and thus indirectly influence the amount of rainfall and recharge on Barbados.

7. Conclusions

[27] The Pleistocene limestone aquifer of Barbados is a composite limestone island aquifer composed of Pleistocene coral reef limestone underlain by a deep-sea sedimentary aquitard. Groundwater flow paths in this aquifer are controlled by the topography of the top of the aquitard. Interannual variation of estimated recharge to the Pleistocene limestone aquifer generally fluctuates in response to ENSO. This interannual variation shows how recharge to the aquifer has fluctuated over time and is therefore a general indicator of how climatic conditions may influence recharge in the future. However, the relationship between recharge and ENSO on Barbados is complicated by other factors that also influence interannual variations of rainfall and therefore recharge.

[28] Knowledge of interannual variation of recharge and processes responsible for these variations has important implications for groundwater management because (1) it allow us to use climate predictions to qualitatively predict groundwater recharge variations; and (2) these recharge variations must be taken into account when setting strategies to determine groundwater availability in the aquifer.

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