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Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico and Guam

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Abstract

The hydrology and geochemistry of groundwater in tropical island aquifers, such as Barbados, Guam and Puerto Rico, 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.

The karst aquifers on Barbados, Guam and Puerto Rico have similar rainwater and groundwater oxygen isotopic compositions. Comparison of groundwater and rainwater oxygen isotopic compositions in the three aquifers indicates that: (1) recharge occurs by rapid infiltration with little evaporation prior to recharge; and (2) recharge is associated with similar monthly rainfall thresholds of 190–200 mm. These rainfall thresholds are remarkably similar for three aquifers in different geographic locations. Differences between the spatial variations of groundwater oxygen isotopic compositions on Barbados and Puerto Rico can be attributed to the more complex groundwater flow system on Puerto Rico. The surprising similarities of hydrologic conditions under which recharge will take place can be attributed to similarities in climate and geologic conditions, such as soils and limestone bedrock, that exist on the three islands. We therefore speculate that similar recharge-rainfall thresholds may be observed in other tropical karst aquifers.

Keywords: Hydrogeology; Recharge; Island aquifers; Barbados; Puerto Rico; Guam

1. Introduction

A recharge threshold is the rainfall required for recharge to an aquifer. This concept is most applicable to tropical karst aquifers where recharge is dominated by discrete infiltration through karst features, such as sinkholes and dry valleys. Discrete infiltration requires enough rainfall to generate runoff to transport water to the karst features (Jones et al., 2000). Without such transport, it is likely that the rainwater will be taken up by evapotranspiration.

Island aquifers, especially limestone aquifers, are the primary sources of potable water for the islands' inhabitants. These aquifers are usually relatively

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small, unconfined and characterized by groundwater residence times of years to tens of years. Consequently, these aquifers are fragile systems that respond rapidly to natural and anthropogenic processes. Groundwater quantities in these aquifers usually respond to short- and long-term climatic fluctuations that influence the amount of recharge and therefore the amount of groundwater available for use. Consequently, it is vital that we understand processes influencing recharge to these aquifers.

Limestone island aquifers are generally characterized by: (1) fresh meteoric water, seawater or a mixture of the two; (2) hydraulic heads affected by sea-level fluctuations, such as tides; and (3) aquifer rock that is more permeable than the underlying basement rock (Vacher, 1997). Limestone island aquifers have been classified based on the characteristics of limestone islands. These categories include coral reef islands which are subdivided into atolls, modern reefs, Quaternary reef islands, uplifted atolls, composite islands, and eolianite islands (Vacher, 1997). Large islands, like Puerto Rico, are not included in this classification system. Composite islands, like Barbados and Guam, are limestone islands composed of permeable limestone overlying relatively impermeable non-carbonate rocks that form an aquitard (Vacher, 1997). This aquitard comprises deep-sea sedimentary rocks in the case of Barbados and volcanic rocks on Guam. On composite limestone islands, freshwater lenses occur where the base of the limestone dips below sea level. Consequently, these limestone aquifers can be subdivided into two hydrologic zones with the intersection of the limestone base and sea level forming the boundary between the zones. Composite aquifers display characteristics that are similar to unconfined aquifers on larger islands or continents, such as Puerto Rico. Similar to unconfined coastal continental aquifers, groundwater flow in composite island aquifers is primarily influenced by stratigraphy. In these aquifers, sea-level fluctuations have an impact only on groundwater flow near the coast. In other words, composite island aquifers and unconfined coastal continental aquifers meet only the first and third of the three characteristics of limestone island aquifers discussed above.

The primary aim of this research is to investigate how conditions that result in recharge vary among different limestone aquifers. Understanding of the hydrologic conditions that produce recharge provides us with a method of predicting the seasonal and interannual variations of recharge to an aquifer, issues of vital importance to management of the groundwater resources. It has been shown that recharge to the limestone aquifer on Barbados is influenced primarily by the occurrence of runoff (Jones et al., 2000). Runoff along dry valleys produces discrete recharge by rapid infiltration through karst shafts or sinkholes that occur along the sides of the dry valleys. Comparison of oxygen isotopic compositions of groundwater and rainwater on Barbados indicates a rainfall threshold that must be exceeded before recharge takes place (Jones et al., 2000). This is possible because in tropical climates the oxygen isotopic composition of rainwater is controlled primarily by the amount effect. The amount effect is the inverse relationship between rainwater $\delta^{18}O$ values and the amount of rainfall (Dansgaard, 1964). The aim of this study is to investigate how these thresholds vary from island to island.

The same methods used on Barbados to determine recharge thresholds are used on Guam and Puerto Rico in this study with the aim of determining whether the rainfall thresholds vary from island to island. The three islands are characterized by similar tropical climates and limestone geology. The much higher rainfall on Guam, however, may produce a different rainfall threshold for recharge and higher recharge rates than on the other two islands. The similarity between the climate of Puerto Rico and Barbados suggests that rainfall thresholds may be similar.

2. Pleistocene limestone aquifer of Barbados

2.1. Climate

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 (Fig. 1). The wet season extends from June to December and reaches a peak in August–October. Wet season rainfall accounts for approximately 60% of average annual rainfall. Dry season rainfall is associated with local convection due to moist air flowing over

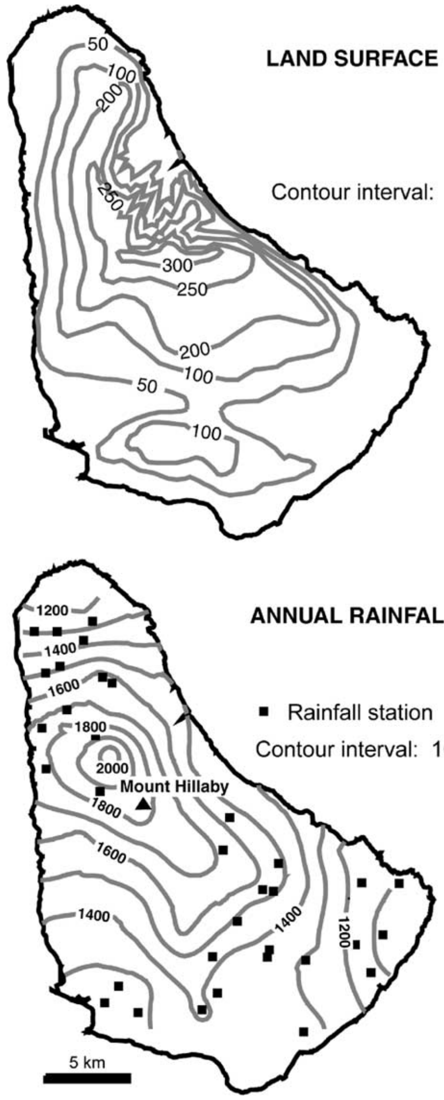

Fig. 1. The distribution of annual rainfall (1992) on Barbados. Total annual rainfall is highest at the center of the island. Unpublished rainfall data from the Caribbean Institute of Meteorology and Hydrology.

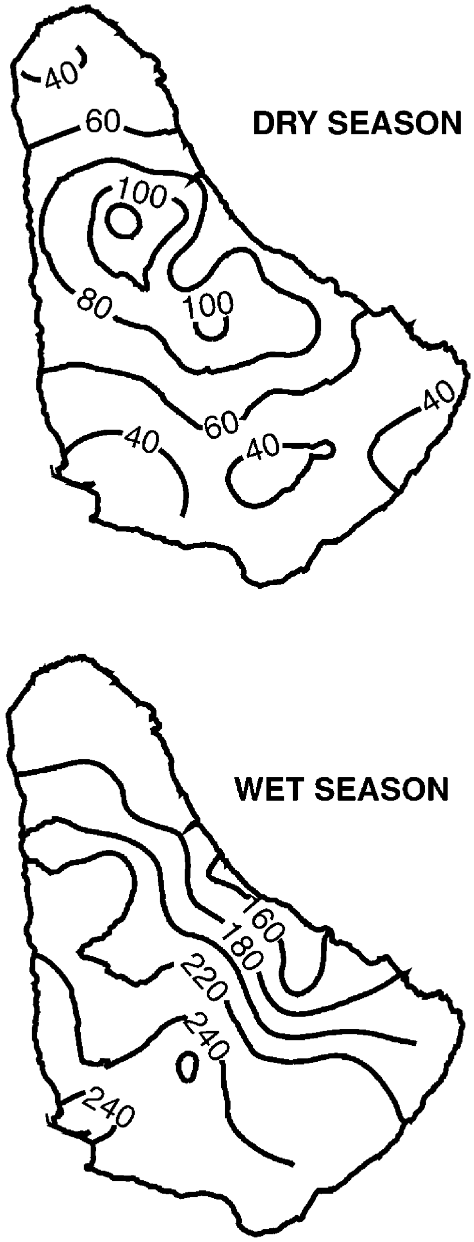

Fig. 2. Seasonal variation the spatial distribution of monthly rainfall (mm) on Barbados. Wet season rainfall is highest on the western, leeward side of Barbados, especially at the peak of the wet season. Dry season rainfall is heaviest at the center of the island. Unpublished rainfall data from the Caribbean Institute of Meteorology and Hydrology.

the heated island (Malkus, 1963). In addition to local convection effects, wet season 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 (Falkland, 1991; Reading et al., 1995). Rainfall distribution varies seasonally with highest rainfall occurring at the center of the island during dry season months and on the western, leeward side of the island during the wet season (Fig. 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, which has a maximum elevation of 340 m (Reading et al., 1995).

2.2. Geology and hydrogeology

The Pleistocene limestone aquifer of Barbados is composed of the Pleistocene coral reef limestone that covers about 85% of the island and overlies Tertiary-age rocks of the upper Scotland Formation and Oceanics Group (Fig. 3). The Pleistocene limestone is up to 100 m thick and is characterized by porosity of 20–60%, averaging 45%, and a specific yield of 12.5–15% (Senn, 1946; Tullstrom, 1964). The coral reefs developed outwards from the center of the island

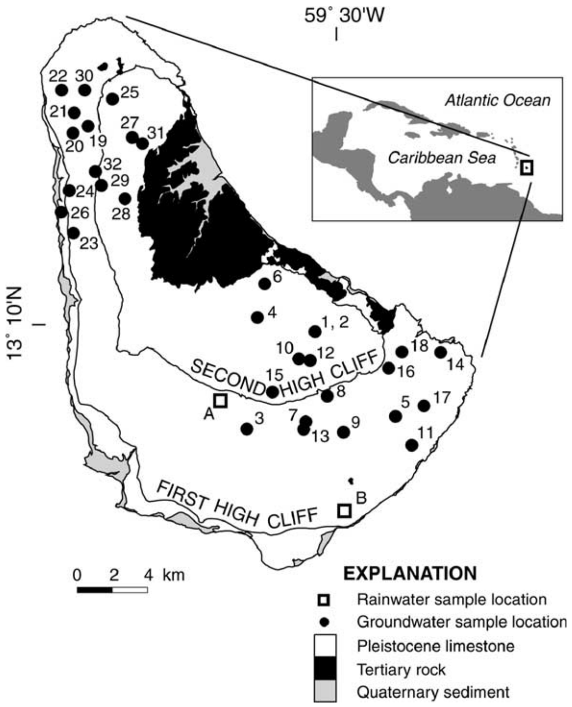

Fig. 3. Geologic map of Barbados. The Pleistocene limestone that comprises the aquifer occurs in the northern, western and southern portions of the island. The Second High Cliff is approximately 30 m high and has been identified as a major site for discrete recharge to the underlying aquifer (Jones et al., 2000). Adapted from Directorate of Overseas Surveys 1:50,000 geologic map (1983).

forming terraces in response to continuous uplift. 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 frequent dry valleys and caves, and consequently is an important site for discrete recharge, as is seen from comparison of oxygen isotopic compositions of rainwater and groundwater (Jones et al., 2000). 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).

2.3. Recharge processes

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-time in the vadose zone ranges from several minutes to a few days for water infiltrating through sinkholes or drainage wells (Mwansa and Barker, 1996; Smart and Ketterling, 1997). Residence times associated with diffuse infiltration are believed to be much longer, ranging from days to several months (Senn, 1946). This conclusion is based on observed responses to rainfall in caves where a flow rate response was 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 attributable to rapid discrete infiltration, and the second response is related to slower diffuse infiltration. Diffuse recharge is most likely to occur above the Second High Cliff where soil infiltration rates are highest. The Pleistocene limestone is often exposed at the surface in dry valleys, especially where these valleys cut through the Second High Cliff forming deep, narrow channels. Small caves or karstic shafts along the sides of these dry valleys are potential conduits for water to infiltrate directly into the limestone and rapidly recharge the aquifer. This process is possible only 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).

2.4. Estimated recharge rates

Seasonal fluctuations of 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). This is possible because of the inverse relationship between rainwater $\delta^{18}O$ values and the amount of rainfall on tropical islands, such as Barbados. The seasonality of recharge is inferred because groundwater $\delta^{18}O$ values are typically skewed towards wet season rainwater $\delta^{18}O$ values. Recharge amounts are estimated based on the assumption that the groundwater oxygen isotopic composition is the weighted average of rainwater that actually infiltrates to the water table. In this method of determining recharge, available rainwater oxygen isotopic data is used to determine conditions that will satisfy this assumption (Jones et al., 2000).

The unique results of this study indicate that most recharge: (1) is rapid; (2) takes place only during the wettest 1–3 months of each year, but only when monthly rainfall exceeds 195 mm; 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 (Jones et al., 2000) and dissolved Cl (Vacher and Ayers, 1980): (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 Cl is that oxygen isotopes can be used to estimate recharge in both coastal and inland portions of the aquifer (Jones et al., 2000).

3. The limestone aquifer of northern Puerto Rico

Puerto Rico is a relatively large tropical island composed of limestone flanking a volcanic core (Fig. 4). In this paper, discussion of the hydrogeology of Puerto Rico is restricted to the north coast of Puerto Rico where limestone aquifers are better developed, with emphasis on the unconfined aquifer. The unconfined limestone aquifer of north Puerto Rico, rather than the underlying confined aquifer, was selected for comparison with the Barbados aquifer because it displays more similarities to limestone aquifers that occur on small limestone islands.

3.1. Climate

Puerto Rico has a humid tropical climate. Average annual rainfall along the north coast varies

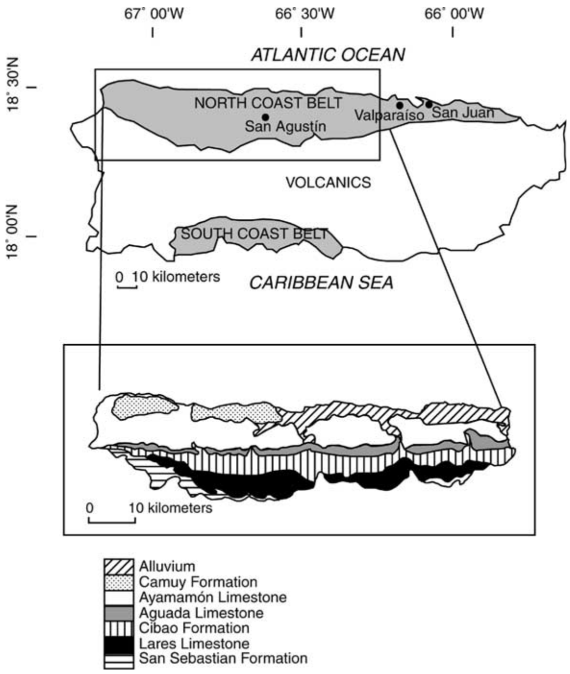

Fig. 4. Limestone on Puerto Rico primarily occurs in belts along the northern and southern coasts of the island flanking the volcanic core. Rainwater data used in this study was collected at Isla Verde, San Juan (IAEA/WMO, 1998), and at San Agustín and Valparaíso (Rodríguez-Martínez, 1997). Groundwater samples were collected throughout the North Coast Belt west of Valparaíso. Adapted from Giusti, (1978).

from about 1500 mm yr^{-1} along the coast to about 2500 mm yr^{-1} inland. There is less rainfall on the leeward southern coast. The dry season occurs from December to March or April, and the wet season generally occurs from June through November reaching a peak from August through November. The wettest months are usually September and October. About 60% of annual rainfall occurs during the wet season. Unlike Barbados, Puerto Rico is a mountainous island with elevations in excess of 1000 m. The spatial distribution of rainfall on the island is indicative of orographic effects (Reading et al., 1995).

3.2. Geology and hydrogeology

The limestone aquifers of Puerto Rico are composed of Oligocene to Miocene limestone (Fig. 4); (Giusti, 1978). This limestone forms wedges that thicken seaward and overlie Cretaceous and Tertiary volcanic rocks (Fig. 5). The limestone is subdivided into seven formations, the San Sebastián Formation, Lares Limestone, Mucarabones Sand, Cibao Formation, Aguada Limestone, Aymamón Limestone, and Camuy Limestone. The limestones of northern Puerto Rico are highly karstified (Giusti, 1978). Karstification takes the form of sinkholes and other solution features in the east, and karst hills and rivers

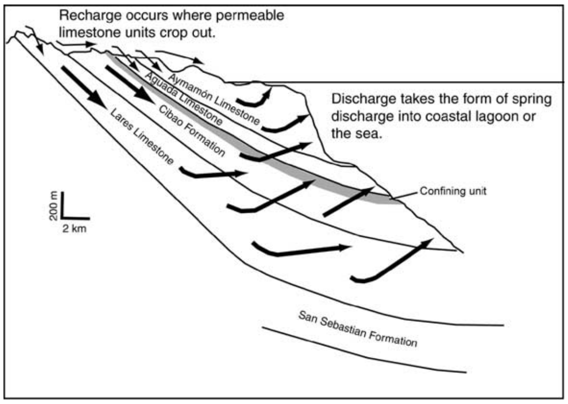

Fig. 5. Cross-section of limestone aquifers of northern Puerto Rico. The aquifer system of northern Puerto Rico is composed of two aquifers, an unconfined aquifer composed of the Aymamón Limestone and Aguada Limestone, and an underlying confined aquifer composed of part of the Cibao Formation and the Lares Limestone. The confining unit separating the two aquifers occurs in the upper part of the Cibao Formation. Adapted from Giusti, (1978).

that flow partly underground in the west. The karst hill topography that occurs on Puerto Rico does not occur on Barbados.

There are two limestone aquifers in northern Puerto Rico, an unconfined aquifer that occurs in the Miocene limestones of the Aymamón and Aguada Formations, and a confined aquifer in the underlying Oligocene limestones of the Cibao and Lares Formations (Giusti, 1978). The two aquifers are separated by lower-permeability units that occur at the top of the Cibao Formation (Rodríguez-Martínez, 1995). Recharge to the aquifer takes the form of infiltration from perennial and intermittent streams and rivers, and sinkholes that may be more than 30 m deep. The streams and rivers commonly have channels that disappear underground and reappear a few kilometers downstream. In northern Puerto Rico groundwater generally flows downdip, towards the north (Fig. 5). The saturated thickness of the unconfined aquifer is 100–300 m (Rodríguez-Martínez, 1995). Freshwater lenses occur along the coast and may extend several kilometers inland (Rodríguez-Martínez, 1995). Groundwater discharge takes place primarily along the coast in the form of seepage into the sea or coastal swamps and lagoons (Giusti, 1978). Groundwater residence times in the aquifer are unknown. Groundwater flow through the aquifer is highly controlled by fractures, especially in the outcrop areas (Rodríguez-Martínez, 1997).

3.3. Recharge processes

The available $\delta^{18}O$ and δD data for northern Puerto Rico indicate spatial and temporal variations in rainwater and groundwater compositions. The $\delta^{18}O$ values of rainwater collected at several locations in northern Puerto Rico have a relatively large range of −5 to +1‰ (Fig. 6); (Rodríguez-Martínez, 1997; IAEA/WMO, 1998). These data are monthly composite samples collected from 1968 through 1973 in San Juan (IAEA/WMO, 1998) and at different stations located in north-central and northwestern Puerto Rico from 1993 through 1995 (Rodríguez-Martínez, 1997). The range represents seasonal fluctuations similar to those observed on Barbados (Jones et al., 2000). During the wet season, rainwater compositions have lower $\delta^{18}O$ values than the dry season (Fig. 7). This indicates that seasonal fluctuation of rainwater $\delta^{18}O$

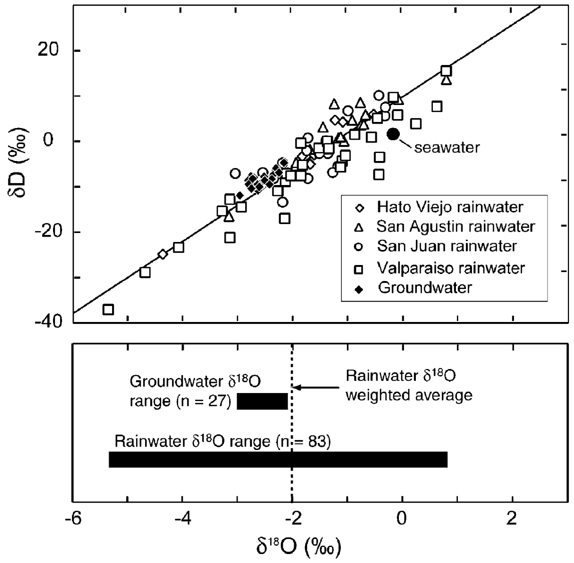

Fig. 6. The $\delta^{18}O$–δD compositions of rainwater and groundwater associated with the limestone aquifers of northern Puerto Rico. Data from Rodríguez-Martínez, (1997); IAEA/WMO, (1998).

values is related to the amount of rainfall (Fig. 8). Groundwater $\delta^{18}O$ values in the unconfined limestone aquifer of northern Puerto Rico display a relatively narrow range of compositions of −3 to −2‰. Both groundwater and rainwater compositions lie along the Global Meteoric Water Line (GMWL). Groundwater $\delta^{18}O$ values tend to be more negative towards the north and display no apparent temporal trends (Rodríguez-Martínez, 1997).

Groundwater oxygen isotopic data from Rodríguez-Martínez (1997) and monthly rainwater data from the Global Network for Isotopes in Precipitation (GNIP) database for San Juan, Puerto Rico (IAEA/WMO, 1998) were compared using methods similar to Jones et al. (2000). In this method, the rainwater data was used to balance following equation

$$[\Sigma_n(\delta^{18}O_{\text{rainwater}} \times P_{\text{month}})]/\Sigma_n P_{\text{month}} = \delta^{18}O_{\text{groundwater}} \quad (1)$$

where, n is the number of individual months taken from the entire data set used in the weighted average; $\delta^{18}O_{\text{groundwater}}$ is the oxygen isotopic composition of groundwater; $\delta^{18}O_{\text{rainwater}}$ is the oxygen isotopic composition of rainwater (i.e. individual GNIP analyses); P_{month}, monthly rainfall for month (mm).

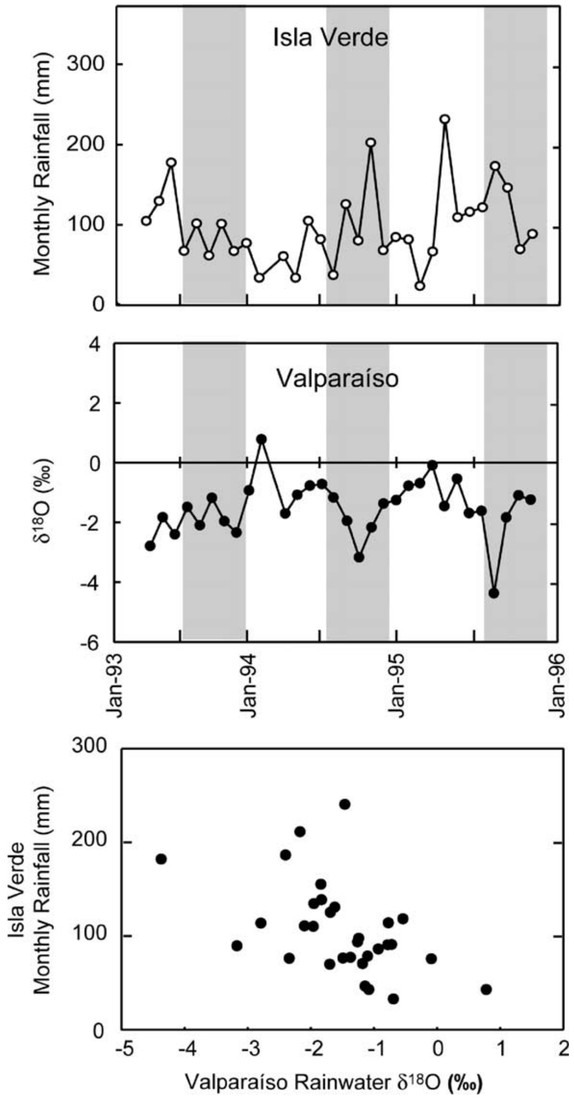

Fig. 7. Seasonal variations of rainwater oxygen isotopic compositions on Puerto Rico (1993–94). Rainwater $\delta^{18}O$ values are lower during peak wet season months (August to October). The gray shading indicates the peak wet season months. Based on data from Rodríguez-Martínez, (1997).

This determines the weighted average $\delta^{18}O$ value of the rainwater that contributes to recharge. The average groundwater composition in northern Puerto Rico is equivalent to the weighted average of monthly rainfall exceeding 190 mm. This suggests that on

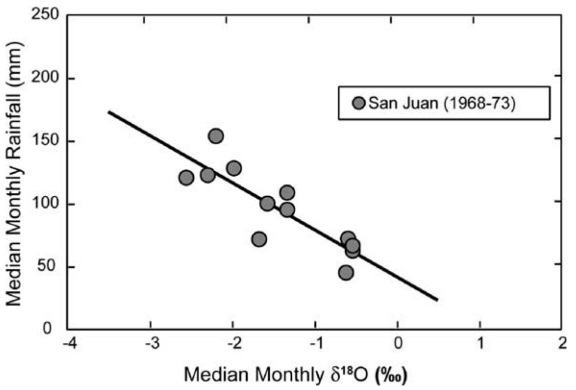

Fig. 8. The relationship between median monthly rainwater $\delta^{18}O$ values and median monthly rainfall for San Juan, Puerto Rico. Based on 1968–1973 data from GNIP (IAEA/WMO, 1998).

Puerto Rico, recharge to the limestone aquifer is associated with months having rainfall exceeding 190 mm. This rainfall threshold is essentially the same as the rainfall threshold of 195 mm calculated for Barbados. The coincidence of groundwater compositions with the GMWL suggests that losses due to evaporation prior to recharge are small.

4. The limestone aquifer of northern Guam

Guam is an island with size, climate and geology similar to Barbados. The limestone aquifer of northern Guam shares similar characteristics to the Pleistocene limestone aquifer on Barbados. These islands comprise subaerially exposed portions of submarine ridges. In both aquifers, the limestone aquifer rock is underlain by low-permeability Tertiary rocks that form an aquitard.

4.1. Climate

The climate of northern Guam is similar to Barbados. However, Guam is more humid with annual rainfall of 2200–2500 mm. Like Barbados, about 60–70% of annual rainfall occurs during a wet season that extends from July through November (Ward et al., 1965; Mink and Vacher, 1997).

4.2. Geology and hydrogeology

Miocene to Pleistocene coral reef limestone occurs in the northern half of the island forming a plateau with elevations ranging from 180 m in the north to 30 m in the south (Fig. 9). The limestone overlies Tertiary-age volcanic rock. In most areas, the contact between coral reef limestone and the volcanic rock lies below sea level (Ward et al., 1965). Limestone deposition starting during the Miocene centered around volcanic highs and developed outwards from these centers in response to uplift (Mink and Vacher, 1997).

The hydrology of northern Guam is dominated by subsurface flow. There are no perennial streams, and any surface runoff that occurs is short-lived and quickly infiltrates through sinkholes or dry valleys (Ward, 1961; Ward et al., 1965; Mink and Vacher, 1997). The limestone aquifer is composed primarily of freshwater lenses that occur where the base of the limestone lies below sea level (Mink and Vacher, 1997). Little groundwater occurs where the base of limestone lies above sea level. The aquifer rock has

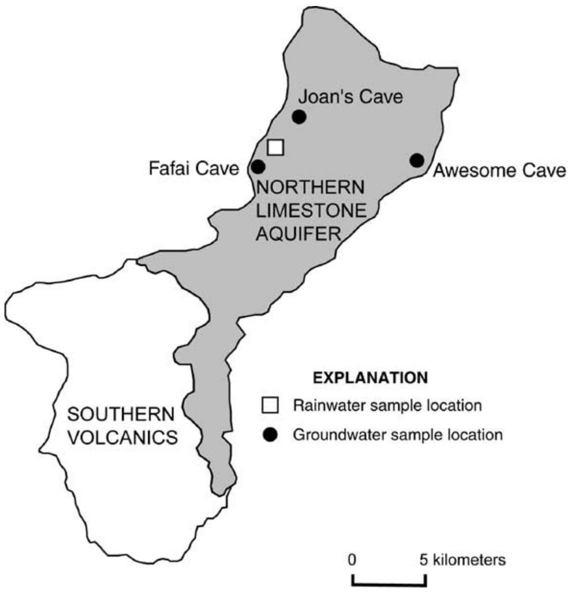

Fig. 9. Limestone on Guam primarily occurs on the northern portion of the island. For this study, groundwater samples were collected at three locations on the island. The rainwater data used in this study was collected as part of the GNIP project 1961–1977 (IAEA/WMO, 1998. The groundwater samples were collected by Ivan Gill. Adapted from Ward et al. (1965).

an average porosity of 10–25% (Mink and Vacher, 1997). The freshwater lens on Guam is up to 30 m thick. Groundwater flow generally takes the form of macro-porous-media flow (Barner, 1997). Groundwater flow rates have been measured at 6–15 m d^{-1} (Barner, 1997; Mink and Vacher, 1997). Estimated groundwater residence times for this aquifer are 5 years or less (Barner, 1997). Numerous dry valleys and sinkholes in limestone act as conduits for recharge to the aquifer (Ward, 1961; Ward et al., 1965; Mink and Vacher, 1997). Groundwater discharge from the freshwater lens may be diffuse flow or discrete flow taking the form of perennial springs and seeps along the coast (Ward et al., 1965; Jenson et al., 1997). Recharge estimates based on water-balance and groundwater and rainwater Cl concentrations indicate recharge to the limestone aquifer of approximately 60% of annual rainfall on Guam (Mink and Vacher, 1997). This estimate is similar to the 67% recharge estimate of Jocson et al. (2002) that was based on differences between daily rainfall and pan evaporation. Water-level responses in Guam wells indicate that the residence-time of infiltrating water in the vadose zone is a function of rainfall intensity and relative saturation (Jocson et al., 2002).

4.3. Recharge processes

The $\delta^{18}O$ values of rainwater collected in northern Guam as part of the GNIP project have a relatively large range of −9 to +2‰ (Fig. 10); (IAEA/WMO, 1998). These data represent monthly composite samples collected from 1962 through 1966 and 1973 through 1977 (IAEA/WMO, 1998). This range represents seasonal fluctuations similar to those observed on Barbados (Jones et al., 2000). During the wet season, rainwater compositions have lower $\delta^{18}O$ values than the dry season (Fig. 10). This seasonal fluctuation of rainwater $\delta^{18}O$ values is related to the amount of rainfall (Fig. 11). As part of this study, three groundwater samples were collected on Guam (Fig. 9). These groundwater samples display a relatively narrow range of $\delta^{18}O$ values of −6.7, −6.1, and −5.1‰, respectively. Both groundwater and rainwater compositions lie along the GMWL (Fig. 12). This indicates

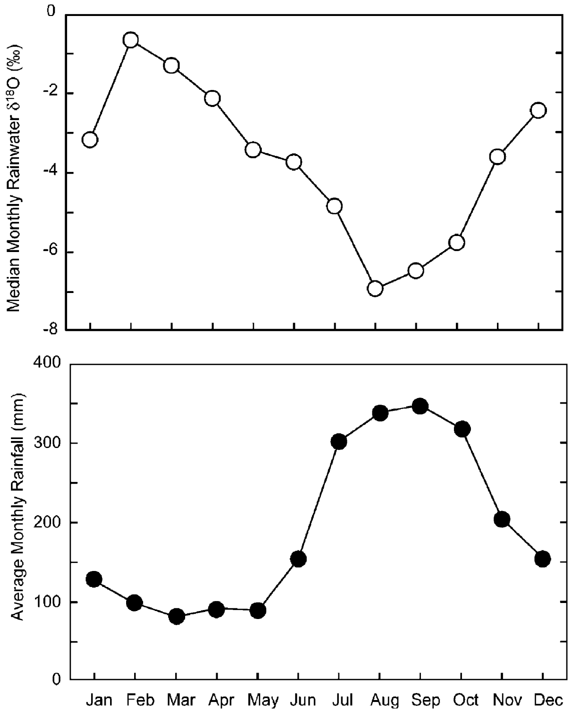

Fig. 10. Seasonal variations of rainwater oxygen isotopic compositions on Guam (1961–1977). Rainwater $\delta^{18}O$ values are lower during peak wet season months (July through October). Based on data from IAEA/WMO, (1998).

negligible effects of rainwater evaporation prior to recharge.

Comparison of groundwater and rainwater $\delta^{18}O$ values can be used to estimate recharge at specific sites or for the overall aquifer (Jones et al., 2000). This determines the weighted average $\delta^{18}O$ value of the rainwater that contributes to recharge. By applying this method to the Guam groundwater samples, recharge estimates for the three sample locations in northern Guam fall within the range of 70–100% of average annual rainfall. This method also indicates that recharge will take place associated with monthly rainfall exceeding 200 mm, a rainfall threshold remarkably similar to rainfall thresholds of 190 and 195 mm for Puerto Rico and Barbados, respectively (Table 1). The rainfall threshold of Guam normally occurs during the wet season months of July through November (Fig. 10). This indicates that the recharge period on Guam is about 5 months, much longer than on Barbados (one month) and would explain the high estimated recharge rates.

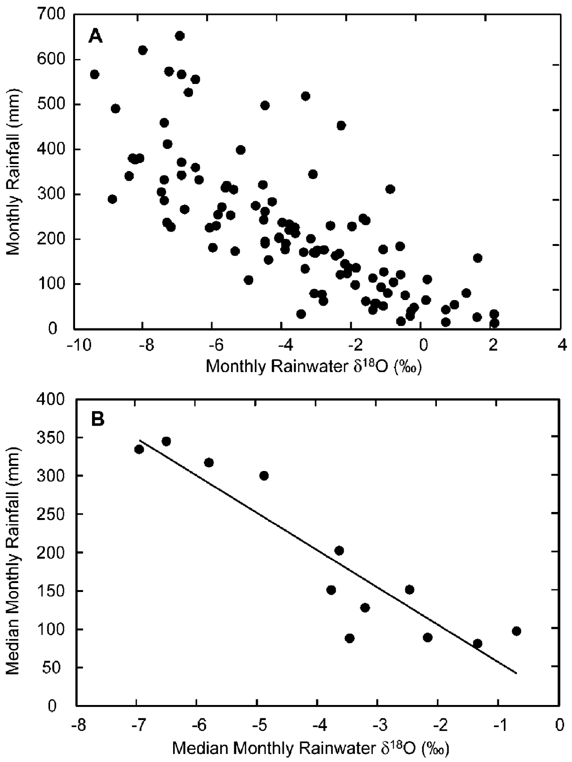

Fig. 11. The oxygen isotopic composition of Guam rainwater varies as a function of the amount of rainfall.

5. Discussion

Oxygen isotopes in Barbados groundwater and rainwater can be used to estimate recharge and indicate recharge seasonality and spatial distribution (Jones et al., 2000). This can be achieved because on Barbados the oxygen isotopic composition of rainwater is influenced primarily by the amount of rainfall. This results in seasonal fluctuations of rainwater composition that allow us to infer the recharge seasonality. Similar relationships between rainfall amounts and rainwater oxygen isotopic compositions are observed on Puerto Rico and Guam (Fig. 13). This relationship does not exist on subtropical or temperate islands, such as Bermuda (Fig. 13). Barbados, Puerto Rico and Guam are all characterized by tropical climates with distinct wet and dry seasons and a narrow temperature range. These conditions produce a relatively wide range of rainwater $\delta^{18}O$ values that

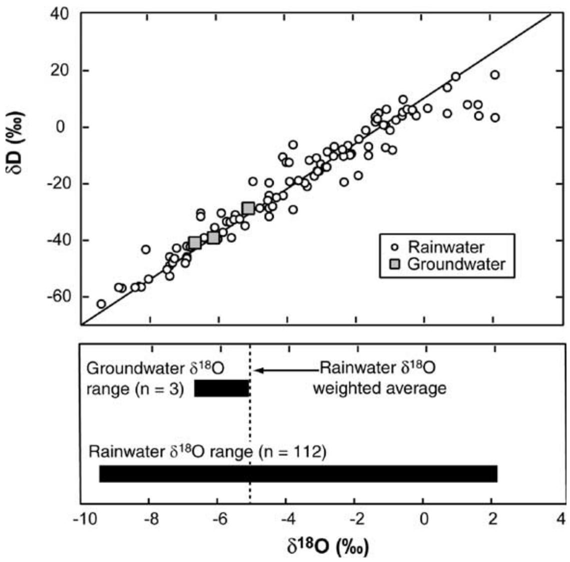

Fig. 12. The $\delta^{18}O$–δD compositions of rainwater and groundwater associated with the limestone aquifers of northern Guam. Rainwater data from IAEA/WMO, (1998).

represent seasonal fluctuations. On the other hand, the temperate climate and almost uniform distribution of rainfall on Bermuda produce no apparent relationship between rainfall and rainwater oxygen isotopic compositions. Consequently, it may not be possible to use groundwater and rainwater oxygen isotopes to estimate recharge in temperate climates. It may still be possible to use oxygen isotopes to constrain the seasonal distribution of recharge in temperate climates where there is a relationship between rainwater oxygen isotopic compositions and either temperature or rainfall. Due to the complex climate of Bermuda, rainwater $\delta^{18}O$ values display neither seasonal fluctuations nor statistically significant relationships ($r^2 = 0.03$) with either temperature or rainfall. Consequently, oxygen isotopes cannot be used to estimate the amount of recharge nor to constrain the seasonality of recharge on Bermuda.

The unconfined limestone aquifer of northern Puerto Rico displays some similarities to much smaller composite island aquifers, such as the limestone aquifers of Barbados and Guam. The most obvious similarity is the restriction of freshwater lenses to coastal areas due to the presence of an underlying aquitard. There are major differences,

Table 1
Comparison of the climates, groundwater and rainwater oxygen isotopic compositions, and rainfall recharge thresholds on Barbados, Guam and Puerto Rico

Aquifer	Barbados	Guam	Northern Puerto Rico
Latitude	13.25°N	13.5°N	18.5°N
Average annual rainfall	1,500 mm	2,400 mm	2,000 mm
Wet season months	June to December	July to November	June to November
Rainwater $\delta^{18}O$	-9 to $+5$‰ ($n=244$)	-9 to $+2$‰ ($n=112$)	-5 to $+1$‰ ($n=45$)
Groundwater $\delta^{18}O$	-4 to -2‰ ($n=47$)	-7 to -5‰ ($n=3$)	-3 to -2‰ ($n=27$)
Rainfall recharge threshold	195 mm	200 mm	190 mm
Aquifer rock age	Pleistocene	Miocene	Oligocene to Miocene

however, between the unconfined aquifer on Puerto Rico and composite island aquifers because the Puerto Rican aquifer is: (1) much larger and thicker than most island aquifers and will consequently have much longer groundwater flow-paths and residence-times; and (2) a more complex flow system displaying significant lateral and vertical flow components, as well as interaction with the underlying confined aquifer. Comparison of the limestone aquifers on Barbados, Guam and Puerto Rico show many similarities. They are karst aquifers characterized by diffuse recharge through soil and limestone and discrete recharge through karst features. Recharge on Barbados and Puerto Rico is associated with the peak of the wet season, while, on Guam, conditions conducive for recharge typically occur

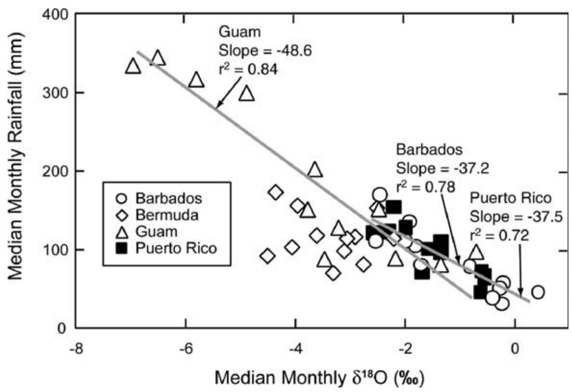

Fig. 13. Similar relationships between rainfall and rainwater $\delta^{18}O$ values exist on tropical islands, e.g. Barbados, Guam and Puerto Rico. This relationship apparently does not occur on Bermuda, an island with a temperate climate. This relationship has implications for whether rainwater oxygen isotopes can be used as a tool to estimate recharge amounts, seasonality and spatial distribution. Based on data from IAEA/WMO (1998).

throughout the wet season (Jones et al., 2000). However, the limestone aquifer on Puerto Rico is much larger and has a more complex flow system characterized by multiple permeable layers and recharge and discharge zones.

Oxygen isotopic compositions of rainwater collected on Barbados, Guam and at low elevations on Puerto Rico display similar $\delta^{18}O$ values that lie within ranges of -9 to $+5$‰, -9 to $+2$‰ and -6 to $+3$‰ on Barbados, Guam and Puerto Rico, respectively (Table 1). The slightly wider ranges of values on Barbados and Guam can be attributed to much longer periods of record of approximately 30 and 16 years, respectively, compared to six years on Puerto Rico. Rainwater $\delta^{18}O$ values are generally lower on Guam than on the other two islands because of higher rainfall (Fig. 13). By the amount effect, higher rainfall produces lower $\delta^{18}O$ values (Dansgaard, 1964). This produces lower groundwater $\delta^{18}O$ values on Guam (-7 to -5‰) than on Puerto Rico and Barbados.

The apparently similar rainwater oxygen isotopic compositions on Barbados and Puerto Rico produce similar groundwater compositions in the respective aquifers. These groundwater oxygen isotopic compositions lie within ranges of -3 to -2‰ and -4.5 to -2‰ on Puerto Rico and Barbados, respectively. Despite the similarities in groundwater and rainwater compositions on Barbados and Puerto Rico, the two aquifers display differences in spatial variations of groundwater oxygen isotopic compositions. In northern Puerto Rico, groundwaters are characterized by lower $\delta^{18}O$ values at lower elevations while the opposite trend occurs on Barbados (Rodríguez-Martínez, 1997; Jones et al., 2000). On Barbados, higher groundwater $\delta^{18}O$ values are attributed to enhanced recharge at lower elevations (Jones et al., 2000). The limestone aquifer of northern Puerto Rico is more complex and consequently the spatial variations of groundwater oxygen isotopic compositions on Puerto Rico do not reflect the spatial distribution of recharge. Oxygen isotopic compositions of groundwater reflect cumulative recharge to the aquifer. Consequently, lower recharge rates at high elevations coupled with high recharge rates at low elevations will result in the progressively higher groundwater $\delta^{18}O$ values along flow paths observed on Barbados. High recharge rates at higher elevations coupled with low recharge rates at low elevations will produce relatively uniform groundwater $\delta^{18}O$ values throughout the aquifer. This occurs because large volumes of recharge water from high elevations dominate groundwater compositions throughout the aquifer. Alternatively, lower groundwater $\delta^{18}O$ values at lower elevations in northern Puerto Rico have been attributed to inter-aquifer flow (Rodríguez-Martínez, 1997). This inter-aquifer flow may reflect upward flow of groundwater characterized by low $\delta^{18}O$ values from the underlying confined aquifer. These low groundwater $\delta^{18}O$ values may reflect: (1) recharge when climatic conditions and rainwater isotopic compositions differed from the present; or (2) groundwater recharge taking place at high elevations, where rainwater is characterized by lower $\delta^{18}O$ values. Further research is required to explain the spatial distribution of groundwater oxygen isotopic compositions on Puerto Rico using rainfall and rainwater data from stations that are close to the groundwater sample sites and therefore representative of actual recharge water compositions.

Conditions for the occurrence of recharge inferred from comparison of rainwater and groundwater oxygen isotopic compositions in the respective aquifers are surprisingly similar on all three islands. The relationship between average groundwater $\delta^{18}O$ values and rainwater oxygen isotopic compositions indicate that in all three aquifers: (1) recharge requires monthly rainfall in excess of 190–200 mm (Table 1); and (2) there is little evaporation of infiltrating water prior to recharge. The similarity among the rainfall thresholds that must be exceeded before recharge occurs suggests similarities in the factors, such as soil permeability, that influence the occurrence of runoff. The narrow range of rainfall thresholds is unexpected because one would expect significant variability from island to island due to variation of average annual rainfall among the three islands. However, when one considers that all three islands studied in this investigation are characterized by similar tropical climates and parent rocks, it should not be surprising to find similar soil types with similar hydraulic properties (Buol et al., 1989; Fitzpatrick, 1995). One can speculate that the rainfall thresholds observed on Barbados, Guam and Puerto Rico may occur in many tropical karst aquifers. To test this hypothesis, other studies may be conducted on other tropical islands. These studies should include comparisons of groundwater and rainwater oxygen isotopic compositions, as well as investigations of relationships between rainfall and surface runoff.

6. Conclusions

The limestone aquifers of northern Puerto Rico and Guam display some similarities to the aquifer on Barbados. However, the limestone aquifer of northern Puerto Rico has significant differences due to its much larger size and more complex flow system. The similar climatic and geologic characteristics of Barbados, Guam and Puerto Rico produce similar relationships between rainwater and groundwater oxygen isotopic compositions that allow us to determine the seasonal distribution of recharge and the rainfall thresholds that must be exceeded before recharge occurs. These rainfall thresholds indicate that recharge on Barbados and Puerto Rico is associated only with the peak wet season months while the more humid climate of Guam results in recharge throughout the wet season, as well as during some dry season months. Consequently, estimated recharge rates on Guam are much higher (70–100% of average annual rainfall) than recharge estimates on Barbados (15–25%). The narrow range of rainfall thresholds of 190–200 mm per month found for all three limestone aquifers studied is surprising. These results indicate that similar conditions are required in order for runoff, the prerequisite for discrete recharge, to occur. This narrow range may be attributable to the similar climate and geology that produce soils with similar hydraulic properties in all of these settings.

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