Use of environmental tracers (tritium^{3}H and SF$_6$) to improve knowledge of aquifer storage capacity, residence time and sustainability in the crystalline rock island aquifer of Tobago, West Indies.

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Abstract

Understanding the residence time, flow velocities and storage volumes in fractured rock aquifers is essential for assessing the sustainable use of groundwater in island aquifer systems. Environmental tracers such as tritium (^{3}H) and sulfur hexafluoride (SF$_6$) that enter the aquifer systems through natural hydrological processes are effectively used to quantify the "apparent age" of young groundwater (<60 years) to calculate these aquifer characteristics. The island of Tobago is predominantly a fractured rock aquifer system that contains groundwater sub-basins that produce between 100 to 1000% more than their calculated recharge. In this study, we analyzed ten samples from groundwater wells throughout the island for environmental tracers to establish the apparent age of the groundwater. We then estimate the active flux and storage volume of the aquifer. The ^{3}H results of ten wells throughout the island range from 0.02-0.60 TU. The groundwater samples to the south of the island possess more pre-modern groundwater ages (older ages) compared to samples in the north of the island. These tritium values reveal age ranges between 18 to 60 plus years This suggests that fractures create flow paths oriented towards the southern parts of the basin that enabled the transport of groundwater across significant topographic boundaries and watershed divides. Additionally, the data may support that southern wells are connected to isolated old sources of groundwater. SF$_6$ values range between 0.91 to 7.97 (part per trillion volume) with interpreted age range of between 18 to 39 years. Both tracers support the original hypothesis that longer residence time waters are located to the south of the island except for three SF$_6$ samples which are believed to be affected by excess air.

Key words: Fractured rock aquifers, environmental tracers, apparent age.

1. Introduction

Severe droughts in the Caribbean such as the "Pan Caribbean Drought" of 2013 to 2016 led to increased water shortages throughout the region (Herrera et al., 2018). This phenomenon has urgently increased the necessity of the Caribbean islands to understand their water resources and practice sustainable use. Small islands are more susceptible to groundwater shortages because of their limited surface area catchment sizes and storage capacities, and are at higher risk for water supplies to be affected by pollution and overuse (Herrera et al., 2018), (Karnauskas et al., 2016), (Schneider & Kruse, 2003). Climate models predict that projected precipitation will be reduced in the region leading to longer dry seasons, further stressing Surface and groundwater resources (Karmalkar et al., 2013).

Fractured bedrock aquifers have been shown to be reliable sources of potable water which can store and sometimes transport large quantities of groundwater (Gustafson & Krásný, 1994). These aquifers, as contrasted to porous media aquifer systems, present a myriad of challenges since fractures may possess an array of hydrologic conductivities, storage capacities and flow velocities (Enemark et al., 2019),(Morin & Savage, 2003), (Earnest & Boutt, 2014). Therefore, the assessment of these water deposits require the use of multiple methods of analysis (Shapiro et al., 2017), (Bense et al., 2013). Furthermore, an agglomerate of fractures and faults may transport and mix groundwater at various transit times and distances, some of which defy surficial groundwater divides or topographical boundaries (Earnest & Boutt, 2014), (Genereux & Jordan, 2006).

The island of Tobago contains a geologically complex aquifer system that is predominantly igneous and metamorphic rocks. There are small sedimentary deposits scattered throughout the island and a carbonate platform in the southern region which overlays basaltic basement rocks. (Snoke et al., 2001) (Figure 1). The bedrock of Tobago also contains many fractures, faults and lineaments which are remnants of the active tectonic history of the region (Snoke et al., 2007).

A recent hydrological assessment of the islands fractured rock aquifer system (Boutt et al., 2021) used an integrated approach which included isotopic analysis, annual recharge

estimates and steady state groundwater modelling. They found that some groundwater catchments were over producing between 100 to 1000% of water compared to their local calculated recharge (Boutt et al., 2021), (Figure 2). These results raised new questions about this aquifer system: (1) what are the source or sources of this excess water? (2) what are the roles of the fractures and faults in this system in the transport of groundwater? (3) how will this aquifer react to changes in seasonal recharge?
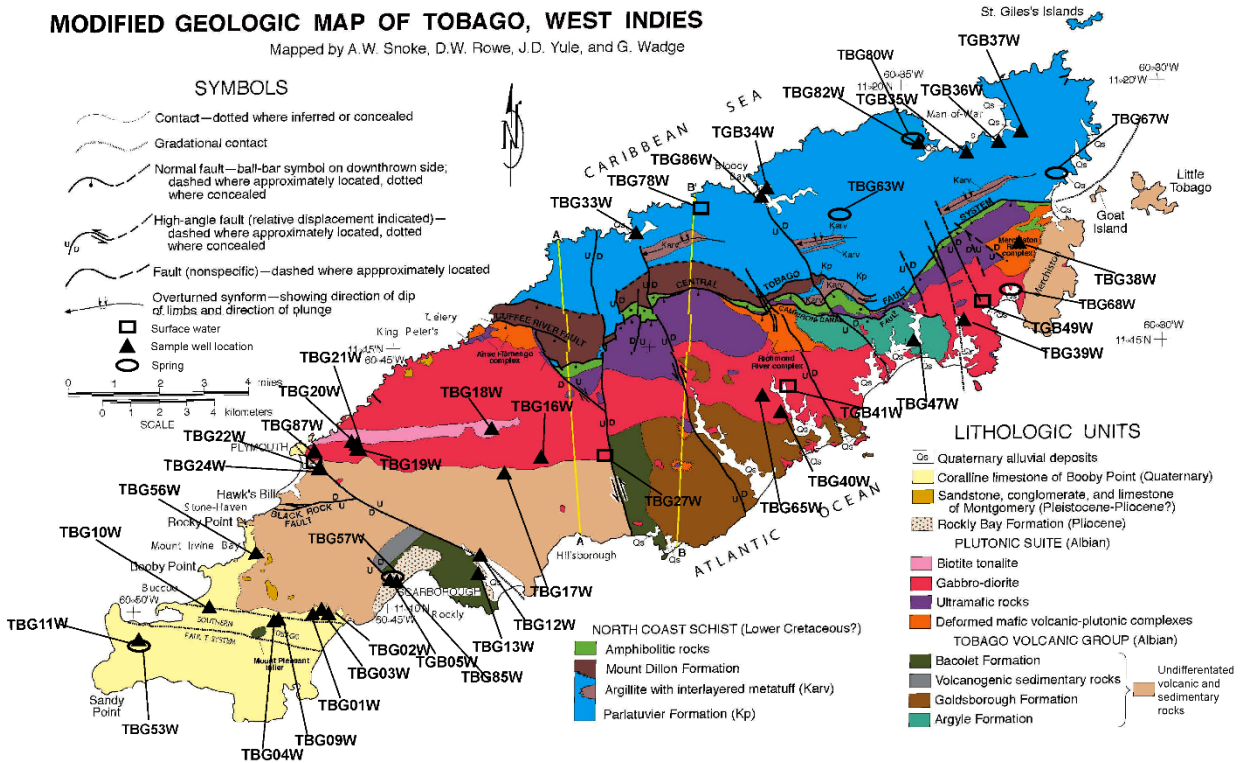

Figure 1. Modified Geological Map of Tobago from Snoke et al., 2001 showing sample locations of groundwater, surface water and springs, structural features, and lithological units.
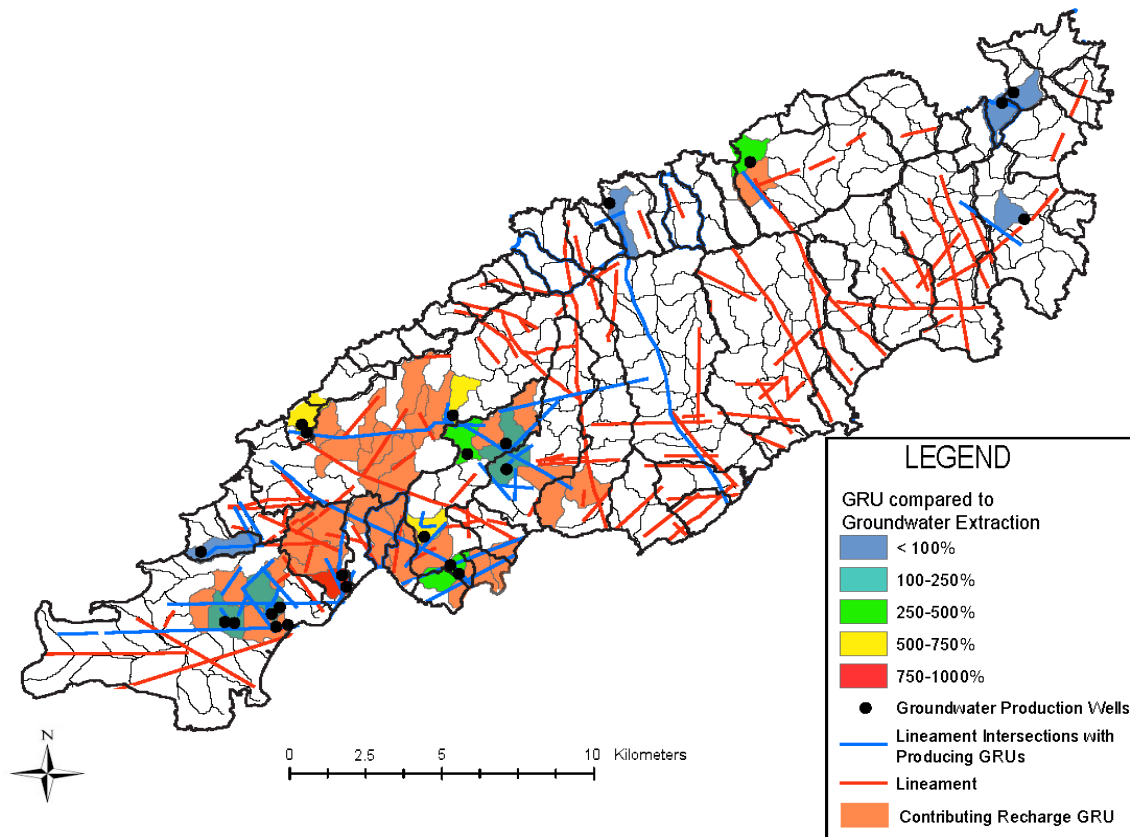
Figure 2. Map illustrating the relationship between total amount of in-place groundwater recharge units (GRU) compared to groundwater extraction in percentages from Boutt et al., 2021.

2. Aims and objectives.

The "apparent age" of groundwater in aquifer systems are a result of the characteristics of residence times. Therefore, longer travel times are attributed to longer distances water flow through these systems. We propose that the overproducing GRU's (Groundwater recharge units) on the island of Tobago are caused by the connectivity of these basins to longer flow-paths, thus resulting in water production beyond the local recharge conditions. If this is true, the groundwater in these basins will also reflect older "apparent ages".

The analysis of Tobago's groundwater "apparent age" using environmental tracers' tritium (^{3}H) and sulfur hexafluoride (SF_6) measurements aims to prove that the groundwater in the southern region of the island is older than the groundwater in the north. Additionally, the "apparent age" will be used as groundwater residence times to calculate storage volume, effective porosity, and groundwater velocity of the basins. This data will also be used in the

future to constrain a transient 3-dimensional groundwater model with projected precipitation values from the CORDEX climate model to the year 2046, to predict the change in storage in these basins on a monthly basis. The ability to quantify storage changes in these aquifer types is an essential tool that can be used to predict safe yields for groundwater extraction, thus promoting sustainable groundwater management.

3. Study Area

The islands Republic of Trinidad and Tobago are located northeast of Venezuela and are the last two islands of the Lesser Antilles. Tobago is the smaller of the two and is approximately 300 square kilometers, with its highest elevation in the Tobago Forest Reserve ~580 m above sea level (Boutt et al., 2021). The island contains a population size of 1.395 million people according to the World Bank in 2019 and is well known as a vacation destination.

3.1 Geology and Hydrogeology of the island

Tobago is predominantly composed of igneous and metamorphic rocks ranging from Mesozoic to Cenozoic in age: The North Coast Schist, the Tobago Volcanic Group and a Plutonic Suite (Speed & Smith-Horowitz, 1998), (Aitken et al., 2011), (Speed et al., 1993),& (Snoke et al., 2001). The sedimentary Holocene surficial deposits includes: limestone, sandstones, fossiliferous clays and gravels that represent archives of sea-level changes (Figure 1), (Snoke et al., 2001). The island's geographical location near the South-American Plate and Caribbean Boundaries has created multiple deformation events which formed N-S to NW-SE and W-E faults (Snoke et al., 2007) (Boutt et al., 2021). Most of the aquifers on the island are not composed of porous Media (Hydrogeological Atlas of the Caribbean Islands and UNESCO et al., 1986), instead they contain saprolite covers ranging from 1 – 8 m deep and faults and fractures that provide storage and preferential flow paths (Boutt et al., 2021). The production wells located in these igneous and metamorphic have historically shown to produce significant amounts of potable water. (Boutt et al., 2021).

The unconsolidated sedimentary deposits such as The Rockly Bay formation contains mixed layers of sand , gravel, and clay. The permeable layers in these deposits provide and transmit a moderate amount of recharge the fractured rocks below (Boutt et al., 2021). The carbonate to the south of the island has the lowest elevations above sea-level and is approximately 12m thick.

This deposit contains some areas of high secondary porosity, but the base of this unit is 10 m below sea-level making it susceptible to sea water intrusions.

3.2 Hydrology of Tobago

Tobago has a tropical climate and the air masses that provide precipitation are transported by The Atlantic Trade Winds from the north/northeast direction. There are two distinct seasons: the wet season from June to December, and the dry season January to May. A 50-year record of precipitation from 16 stations that were >95% complete was used to calculate the monthly average precipitation on the island (Boutt et al., 2021). Precipitation amount/ intensity varies due to orographic effect caused by the elevation of the mountain ridge (580 m), and surficial flow is radial in direction from the middle elevated ridge region of the island (Boutt et al., 2021). During the dry season the maximum rainfall is recorded in March as ~40 mm, and the wet season the maximum rainfall was recorded in November as ~300 mm (Boutt et al., 2021). The annual mean precipitation on the island is approximately ~1900 mm and the terrain is affected by high evapotranspiration ~ 1200 mm/year, and annual mean stream discharge ~ 380 mm/year (Boutt et al., 2021). There are many rivers and streams on the island, and there flow intensities are reflective of the seasonal changes, with lower flows during the dry season (Boutt et al., 2021).

4. Methodology

4.1 Tritium as a tracer for groundwater age determination.

Tritium (^{3}H) is a radioactive isotope with a half-life of 12.43 years and is a reliable tracer for the dating of young waters < 60 years old (Kendall et al., 2014). Tritium concentrations are measured in tritium units where (1 TU equals 1 ^{3}H atom in 10^{18} atoms of hydrogen). Before the initiation of nuclear testing in 1953, the tritium concentration in the atmosphere ranged between 2-8 TU, however, after the advent of nuclear testing the concentration spiked in the atmosphere between 1953 to 1964 (Kendall et al., 2014). There are still many unknowns about the amount of tritium pre-1952, however, it has been calculated that waters before this event contained a maximum tritium concentration between 0.1 to 0.4 TU (Kendall et al., 2014). Water after this

period contain increased tritium, which allows it to be utilized as a chemical marker for water age calculation. We decided to use this method of young groundwater age dating because tritium is one of the most reliable tracers for young groundwaters.

4.2 Sulfur hexafluoride as method for groundwater age determination.

Sulfur Hexafluoride (SF_6) is also used to age date water <50 years old and aid to resolve the extent of mixing in groundwaters (Gooddy et al., 2006). SF_6 is a gas commonly used in the production of electrical switches and metal casting processes because of its inert characteristics (Solomon, D.K., T.E . Gilmore, B. Kimball, 2015), (Darling et al., 2012). Long-term monitoring of this gas in the atmosphere shows it is increasing at a rate of 7% per year which dissolves in precipitation making its way into groundwater and is a reliable tool in the calculation of groundwater age and water flow paths (Solomon, D.K., T.E . Gilmore, B. Kimball, 2015), (Darling et al., 2012). There is also a small percentage of SF_6 that is introduced into the atmosphere and groundwater through terrigenic processes like the weathering of mineral fluorite and volcanic activity (Solomon, D.K., T.E . Gilmore, B. Kimball, 2015).

4.3 Sampling Procedure

Ten wells throughout the island were chosen for environmental tracers' tritium analysis and sulfur hexafluoride analysis (TBG85W, TBG16W, TBG20W, TBG03W, TBG37W, TBG18W, TBG12W, TBG04W, TBG38W and TBG88W) (Figure 5). Tritium samples were collected from access points delivered from municipal large diameter water supply wells in 1L high density polyethylene (HDPE) bottles, while the samples SF_6 were collected 1L plastic coated, amber glass bottles with a polyseal cone lined cap. The samples were collected by displacement of water method using copper tubing and a metal bucket to prevent contamination from atmospheric gases.

4.4 Laboratory Techniques/ Analytical Procedure

Tritium and SF_6 were analyzed at the University of Utah Noble Gas Laboratory. Tritium concentrations were determined through helium ingrowth, where waters are degassed in a stainless-steel flask and given approximately six months of time to decay, and then measured by

a Mass Analyzer (Model 215-50 Magnetic Sector Mass Spectrometer). The SF_6 samples were analyzed by gas chromatography. The instrument is calibrated to bulk air standards (a referenced air sample from Niwot Ridge, Colorado (Climate Monitoring and Diagnostics Laboratory (CMDL) and methods described in (Dutay et al., 2002), (Bullister et al., 2006),(E. Busenberg & Plummer, 2000).

4.5 Groundwater apparent age dating using tritium.

Groundwater dating using tritium requires historical tritium precipitation data for the calculation of natural background tritium levels. This data also allows assumptions to be made so that sample ages can be grouped as modern, mixed or premodern groundwater (Lindsey et al., 2019). Historical or current measurements of tritium in Trinidad and Tobago do not exist, so monthly tritium precipitation data between 1964 to 1991 from the island of Barbados was used to represent tritium levels for Tobago due to its geographical and climatic proximity. This data was acquired from the International Association of Atomic Energy Agency (IAEA) and essential for our interpretation of the well samples since tritium concentration in precipitation decreases towards the equator (Chatterjee et al., 2019). The monthly precipitation data was then converted to the annual average which ranged in values between 1 to 154 TU's and is represented by the black dashed line in Figure 5a. Each annual average annual tritium was then decayed to 2019 using the below equation.

Tritium (^3H): $N = N_0 e^{-\lambda t}$ or $ln = ln\ N_0 e^{-\lambda t.}$ Equation 1.

Where N is the number of atoms N_0 number of tritium atoms at time zero, t is the time in years, λ is equal to ln (2)/ t1/2, and t1/2 equal to 12.43 years. The equation of the line from the exponential curve was used to calculate the tritium precipitation projected to year 2019 (Figure 5a), (red dash line). The lowest tritium precipitation level from Barbados precipitation raw data was 1.87 TU, however the lowest value from the exponential curve was 1.37 TU. We decided to use the value (1.37 TU) to represent the background tritium level in the atmosphere that is created by natural nuclear reactions in the upper atmosphere. It was also assumed to be the modern water threshold meaning all groundwater tritium samples above this amount are modern groundwater (Figure 4a).

4.6 Groundwater apparent age dating using Sulfur hexafluoride.

The sulfur hexafluoride analysis was preformed using the methods described in (Eurybiades Busenberg & Plummer, 2008) (air curve revised in 2011), and equations discussed in (Maiss & Levin, 1994). In summary, SF_6 concentrations were tabulated using the approximate value of 1ml excess air from the sample bottle, atmospheric recharge temperature of 24 ˚C, well elevation (m) asl. The resulting values are seen in Table 2 as the uncorrected values and corrected values. The recharge year and apparent age were then calculated using the Piston Flow Model.

4.7 The use of "apparent age" in storage volume, effective porosity, and flow velocity calculations.

The apparent age can be used to assess the important characteristics of aquifers such as the total water volume, effective porosity (n_e), and flow velocities of basins and GRUs by the manipulation of the residence time equation (Equation 2 to 5), with the addition of aquifer thickness (well depth), basin and GRU flux and area data from Boutt et al., 2021. Please note these quantities were calculated for both the GRU and basins (Table 4).

Residence time (τ) = $\dfrac{\text{Volume of water } (V_w)}{\text{Flux } (Q)}$ Equation 2.

Volume of water (V_w) = $\tau * Q$

Equation 3.

Effective porosity (n_e)= V_w / V_a Equation 4.

Groundwater velocity = Distance to the top of the basin/ τ Equation 5.

The apparent age is substituted as the residence time and the flux is represented by the steady state model result groundwater recharge fluxes from Boutt et al., 2021. These inputs allow the calculation of the amount in the basin and GRU reservoirs (Table 4).

4.8 Kriging prediction maps

Only 10 wells were sampled for environmental tracer analysis, so geostatistical analysis was used to create prediction maps to show possible age values for the rest of the island (Figure 10 a & b). The kriging tool in ArcGIS was used to interpolate age values throughout the entire island for both ^{3}H and SF_6. Please note two control points were added to the tritium data near TBG20W, because the program treated the highest value (>60 years) as an outlier without them.

5. Results
5.1 Tritium

To establish the concentration of premodern groundwater, we need to constrain the historical tritium concentration in the input (precipitation). As mentioned earlier, tritium in precipitation has never been measured in Trinidad and Tobago, however we had access to, and used Barbados precipitation tritium measurements for our age calculations. The precipitation tritium data is fit to an exponential function because the equation could be used to project tritium levels in the atmosphere for dates after 1991 which is needed for our analysis. The lowest tritium value of (1.37 TU) is used as the background tritium amount in precipitation in Tobago today, and it was also used to represent the atmospheric tritium value in Tobago precipitation before nuclear testing 1953 (Figure 4) (Lindsey et al., 2019). We then decay that value to 2019 using Equation 1, which resulted in a tritium concentration of 0.05 TU, this value represents what precipitation tritium preatomic bomb would be in the year 2019 after decay. This value is also used as the premodern ground water threshold meaning all tritium values beneath that amount are premodern water therefore older than 60 years old (Figure 4).

The region in between the modern and premodern tritium groundwater values are considered mixed in composition. All of Tobago's groundwater tritium values range between 0.02 to 0.60 TU (yellow squares Figure 4) (Table 2). The results of the ten wells analyzed illustrates that there are a variety of age groups in the island's aquifer system.

The sample grouped in the orange rectangle could potentially have two ages since the orange rectangle connects to two locations on the red dashed decayed value line. These age values for those samples can be 12 to 22 years, or 32 to 42 years old (TGB16W, TBG37W, TBG39W). The sample in the green circle (TBG03W, TBG04W, TBG12W, TBG18W, TGB85W and TBG88W) fall beneath the decay line which suggest that all these samples are older than 27 years. Finally, sample TBG20W is located beneath the premodern threshold line which indicates that this water is older than 60 years (purple circle).

The groundwater tritium results were then plotted spatially on the GRU comparison map with pie charts to represent the modern groundwater (orange segments) and premodern/ older water (black). This map further revealed that the older ground waters are located to the south of the island (Figure 4).
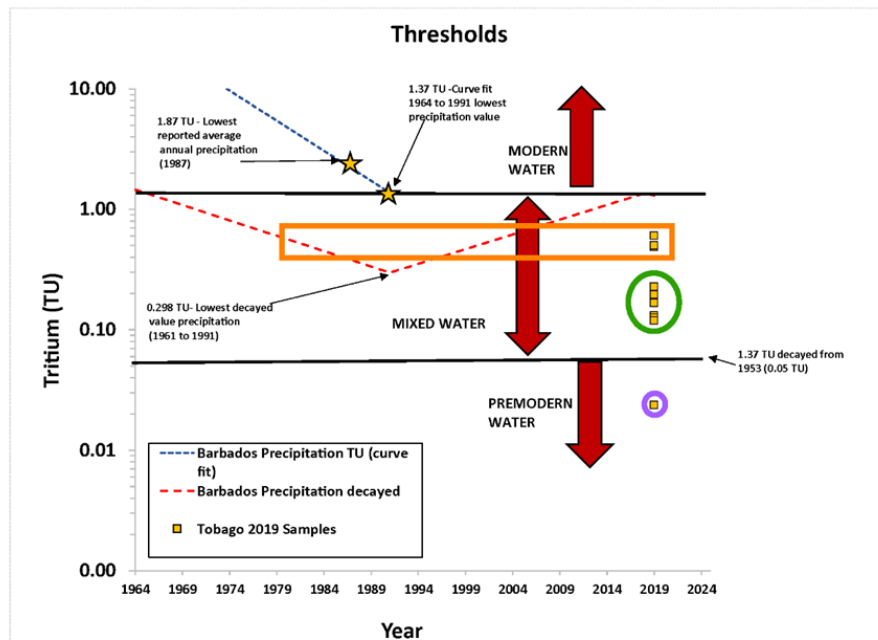

Figure 4. Tritium analysis of Tobago's groundwater using thresholds from Barbados historical precipitation tritium data.

Figure 5. Percent groundwater age represented in pie charts (grey represent premodern water and orange representing modern water) and GRU compared to groundwater extraction map.
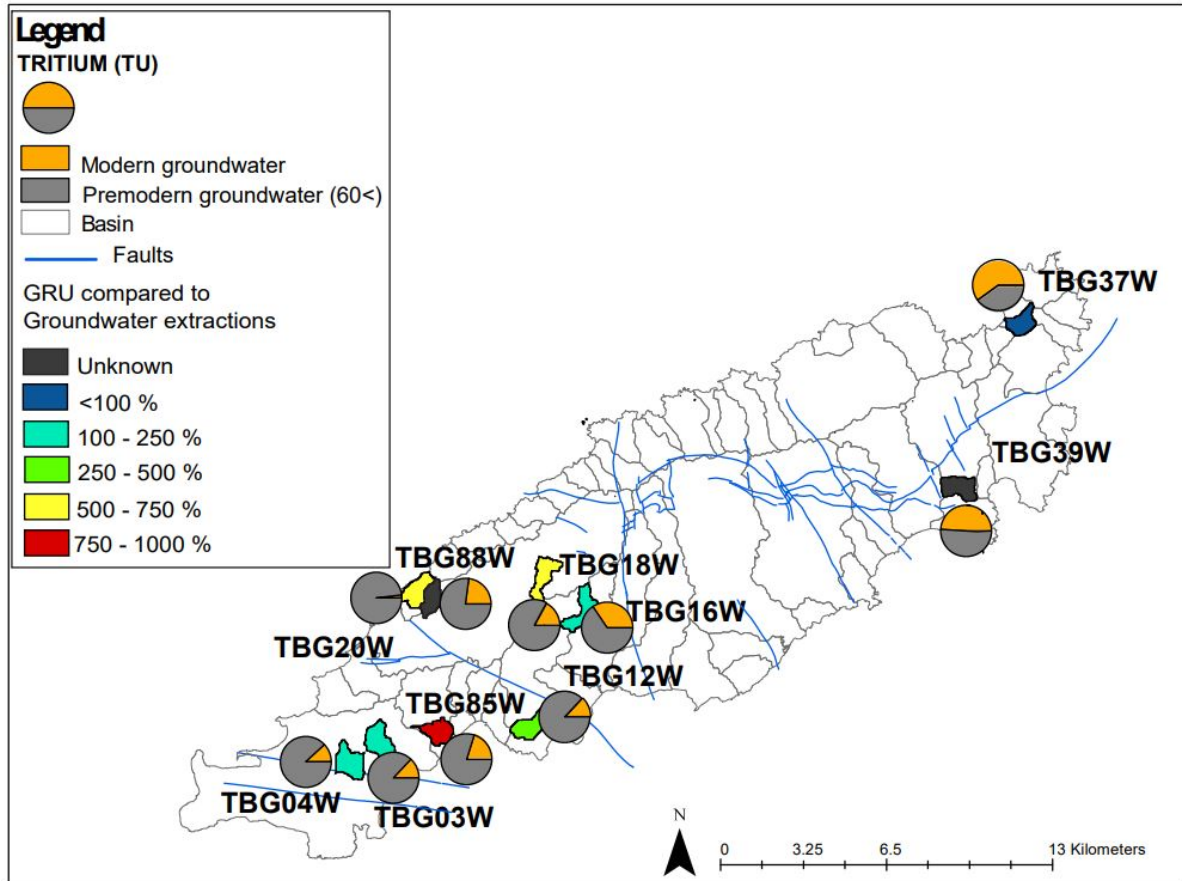

Table 1. Tritium and sulfur hexafluoride with analytical errors and uncorrected values.

Well ID	Tritium (TU)	^{3}H analytical error	SF_6 (pptv)	SF_6 uncorrected values
TBG85W	0.20	0.09	6.91	8.24
TBG16W	0.50	0.05	4.17	4.98
TBG20W	0.02	0.16	7.13	8.50
TBG03W	0.13	0.22	1.74	2.07
TBG37W	0.60	0.05	4.42	5.26
TBG18W	0.17	0.38	2.60	3.10
TBG12W	0.13	0.21	1.49	1.77
TBG04W	0.12	0.04	7.27	8.67
TBG39W	0.49	0.13	4.47	5.32
TBG88W	0.23	0.10	0.91	1.09

Table 2. SF_6 uncorrected and corrected values and 3H well samples ages.

Well ID	Piston flow model SF6 recharge year	Piston flow model SF6 recharge **uncorrected** age, years	Piston flow model SF6 recharge **corrected** age, years	Tritium age years
TBG85W	1989	10	31	>29
TBG16W	2000	21	21	>18
TBG20W	1983	9	37	>60
TBG03W	1988	32	32	>29
TBG37W	2001	20	20	>18
TBG18W	1993	28	28	>29
TBG12W	1986	33	33	>29
TBG04W	1985	9	34	>29
TBG39W	2002	18	18	>18
TBG88W	1981	39	39	>29

4.3 Sulfur hexafluoride

The sulfur hexafluoride results present a range of values between 0.91 and 7.27 Pptv with interpreted age ranges between 18 to 39 years (Table 1 & 2). Since this environmental tracer is increasing at a rate of 7% per year since the 1960's (Darling et al., 2012), we expect to see larger values for premodern waters and smaller values for young water. Unlike the tritium results SF_6 results show that both the oldest and youngest waters are in the southern region of the island, with the oldest water located in wells TBG03W, TBG12W and TBG88W, and youngest water are in wells TBG04W, TBG20W AND TBG085W (Table 2). Samples with larger concentrations of SF_6 contain between 2.4 to 2.85 Pptv less than the atmospheric level measured in mid-2018 (Figure 6).
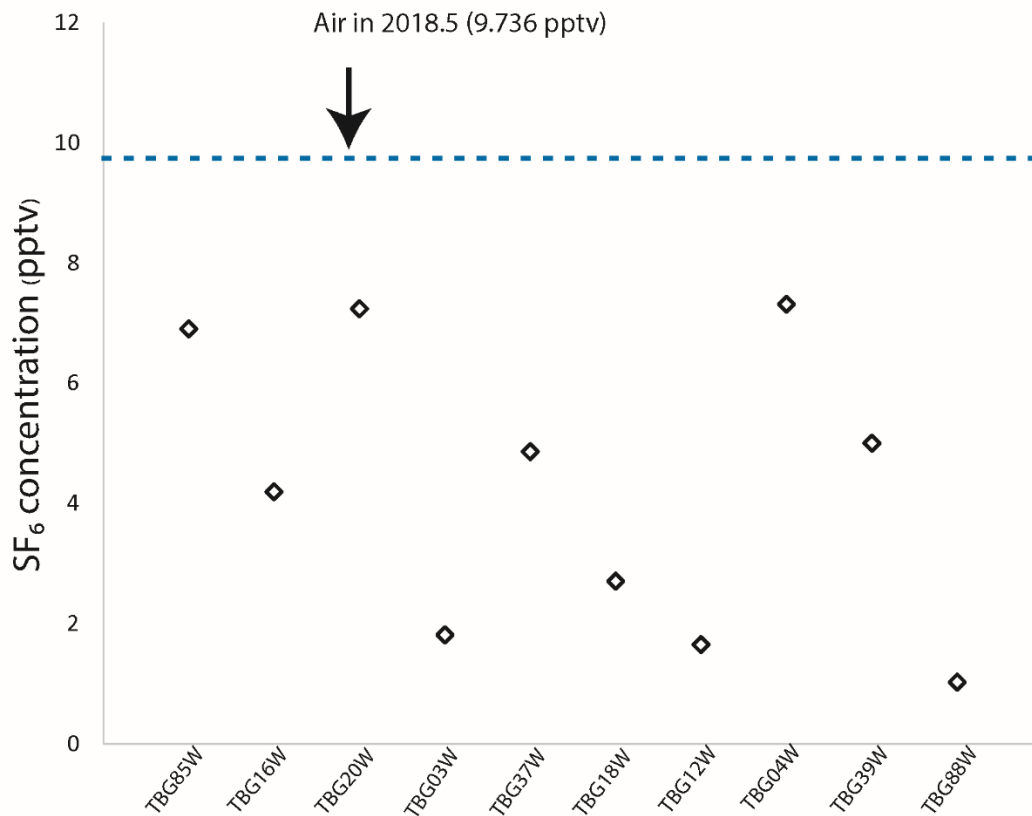
Figure 6. SF$_6$ water concentration per well location Pptv.

6. Discussion

The tritium results directly support the hypothesis that water sampled from wells in the southern region of the island contain more premodern water. The SF$_6$ data however, displayed mixed results, which is illustrated in Figure 6. When tritium and SF$_6$ is assessed in a bivariant plot we expect to see lower tritium and SF$_6$ to represent premodern water and the reverse for modern waters. Most of the environmental tracer results support the hypothesis that premodern water samples are located to the south of the island, except for three SF$_6$ samples (Figure 7). These values are considered very high, and the samples were expected to contain very little SF$_6$ because the tritium results show that they are some of the oldest waters in the island. We consider that these outliers contain "excess air" which is modern air dissolved in the groundwater

causing the large increases of SF_6 in the samples. Tritium results are considered to be more reliable because the hydrogen atom is part of the water molecule and its values are decay dependent (Hofmann et al., 2020). Therefore, if the SF_6 age values of these three wells were correct, then the ^3H values would also reflect younger ages. SF_6 can increase in groundwater through terrigenic sources (dissolution of fluorite and volcanism)(Solomon, D.K., T.E . Gilmore, B. Kimball, 2015),(E. Busenberg & Plummer, 2000),(Darling et al., 2012). Poulsen et al., 2020 showed higher SF_6 values in groundwater samples can originate from compressed air used in well installation or trapped air in the subsurface high recharge locations. Though methods to clearly distinguish between these two sources are still being developed, the SF_6 atmospheric concentration of the year that the wells were installed can be used to assess if the "excess air" was added to the system during the drilling. Other possible causes of "excess air" that has not been thoroughly studied is the effect of fracture rock aquifer wells that have histories of production above the safe yield thresholds. An analysis of the island's production wells, and their adjacent monitoring wells were completed, and it showed that these three wells were producing above their safe yields for some years in the past. The large drawdowns of these wells especially during dry periods could increase the amount of modern air in the fractures which can become trapped as the well water storage is replenished.

We used two methods to assess the corrections needed for the three SF_6 outliers. The first method was discussed by Pouslen et al., (2020), where the of SF_6 concentration in the atmosphere during the well installation year is used as the correction value (Figure 7 & Table 3). Please note that the installation year for TBG20W is not known, so we used the year the well production data record began in 2006. The result is seen in Figure 7 where the colored diamonds represent the wells with this correction.

We also calculated the approximate amount of excess air that needs to be subtracted from these samples to plot close to the linear fit line (Table 3). We subtracted between 15ml to 35ml of excess air from their measured results to fall within the expected range of correct values. The colored circles in Figure 7 shows where these samples will plot after the concentrations of the "excess air" is subtracted.

The ages of the tritium and the SF_6 results with an approximation of corrected values were plotted spatially and made visually comparable by bar graphs on a modified Snoke et al.,

(2001) geological map (Figure 8). The result implies that the wells in the southern region of the island contain the oldest groundwater.

Kriging statistical projection maps of both environmental tracers were created to calculate ground water ages throughout the island based on the results of the ten wells (Figure 10 a & 10 b). These interpolated results show similar trends of increases to the southwest of the island.

Tobago's groundwater tritium levels were also compared to groundwater tritium publications of other island aquifers at similar latitudinal locations (Figure 9),(Nelson et al., 2013),(Hofmann et al., 2020),(Hynek et al., 2017). The dates to which the samples in these studies were collected were all decayed to 2019. The results reflect similar value ranges however, Tobago's samples contain the lowest median and mean results suggesting that it has older water ages in general compared to all the other islands. It is also very significant due to the fact the Tobago is located the closest to the equator and its aquifer was expected to only contain younger groundwater.

The apparent age results of Tobago's groundwater also presented an opportunity to calculate other aquifer characteristics by substituting its values for the residence times for the groundwater in these wells. These calculations were completed with data from Boutt et al., 2021, which included of all the basin and GRU fluxes presented by their steady state model, as well as the GRU and basin volume and area measurements. We calculated aquifer storage volume size, flow velocity and effective porosity(specific yield) of the aquifer (Equations 2 to 5) (Table 4).

All the watershed volumes for these 10 wells are multiple orders of magnitude greater than the volume of water that can be contained in the GRU's (Table 4). Therefore, the production level can be maintained once there is consistent recharge. However, there are few wells with notable characteristics: Well TBG20W GRU and basin volumes are nearly proportional to each other (8,362,011 and 8,415,465 m^3 respectively). Since this is the only well in this highly producing GRU and it is already producing more than 99% of the watershed recharge, new wells should not be placed in this watershed or GRU. This well also possesses one of the smaller groundwater velocities compared to the other wells (0.30 km/yr), however the aquifer is very productive because both the GRU and the basin's high effective porosity increases flow capacity (0.160 and 0.136 respectively) (Table 4).

It must also be noted that the flow velocity has a direct correlation to the groundwater age in this aquifer. For example, wells with the most premodern waters possess the slowest velocities though there are smaller distances between the well and the top of their watersheds (TBG20W, TBG88W). These calculations provide preliminary insight into this aquifer systems which can be compared to groundwater models that are created for the island. They also provide tools to effectively manage of these watersheds especially during periods of droughts. Safe yield production level can now be more efficiently calculated, especially in changing climate scenarios. During severe drought periods the wells whose productions is supported by majority premodern water can be used at increased capacities.
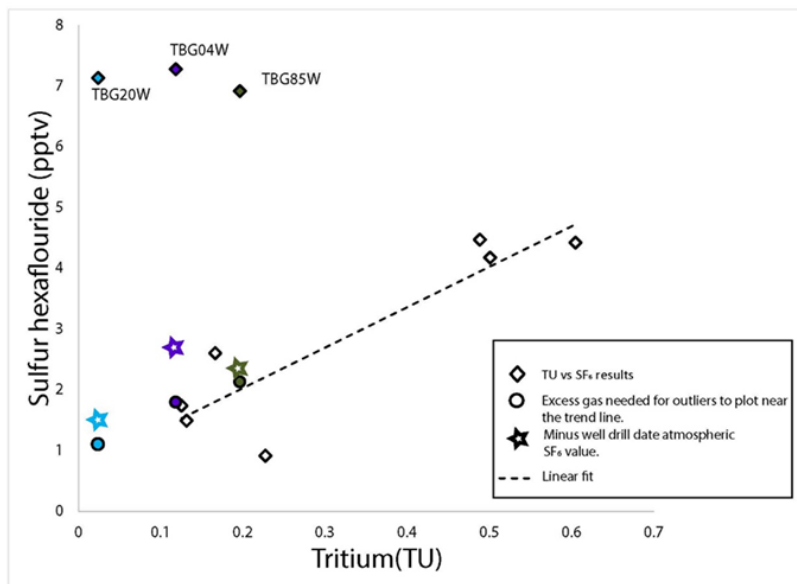

Figure 7. Bivariant plotting of SF_6 and ^3H showing the SF_6 outliers (colored diamonds). The linear fit was calculated excluding the outliers. Colored circles represent outliers corrected by the approximation of excess air, and colored stars represents the outliers corrected for excess air using the SF_6 concentration in the atmosphere during the year the wells were drilled.
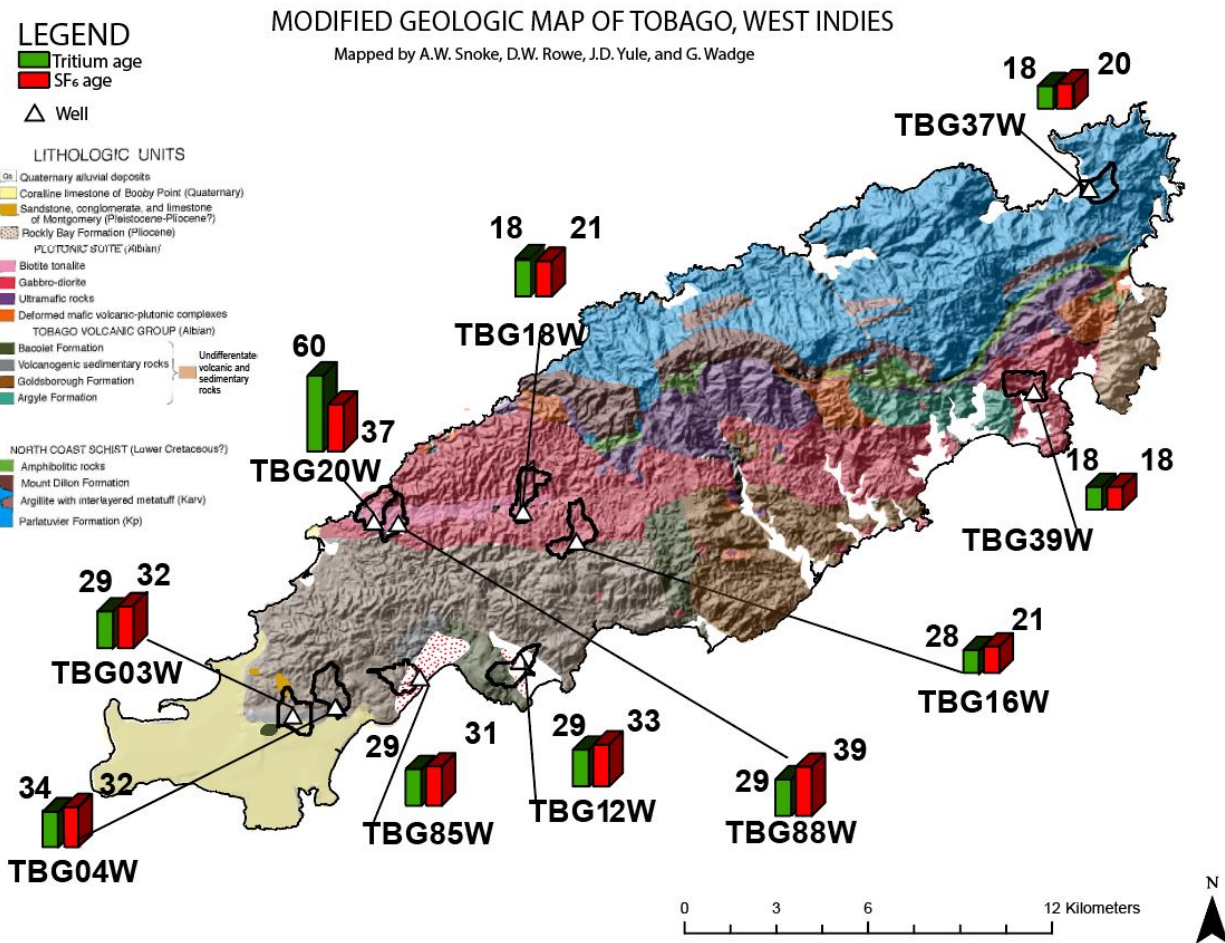
Figure 8. Modified geological map from Snoke et al., 2001 showing the locations and lithology of wells, and their age comparisons.
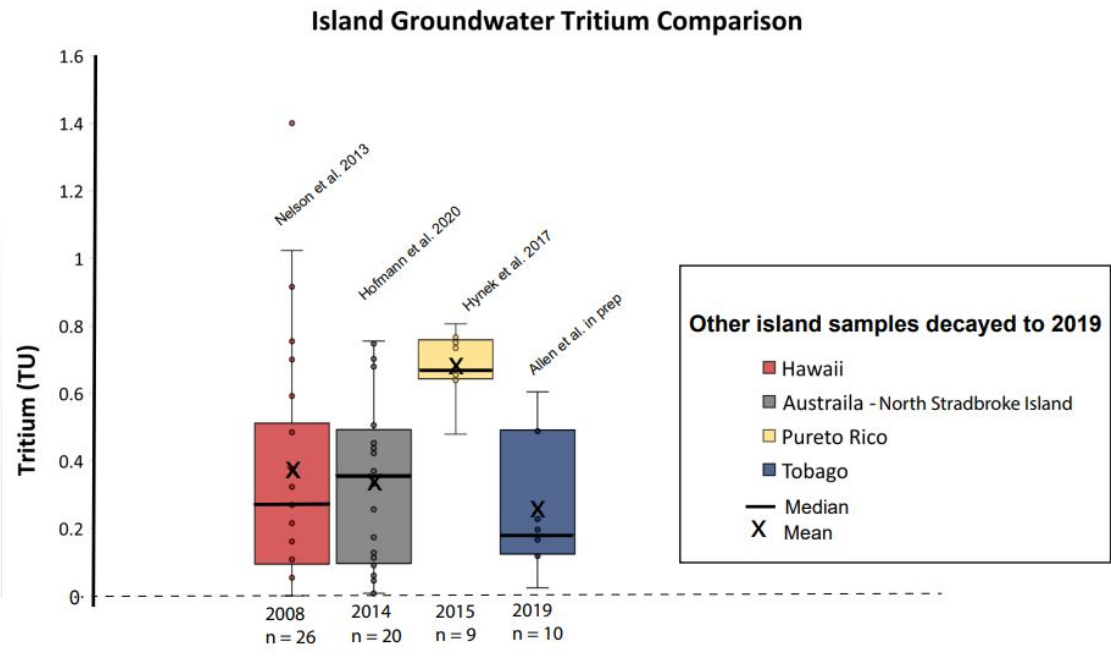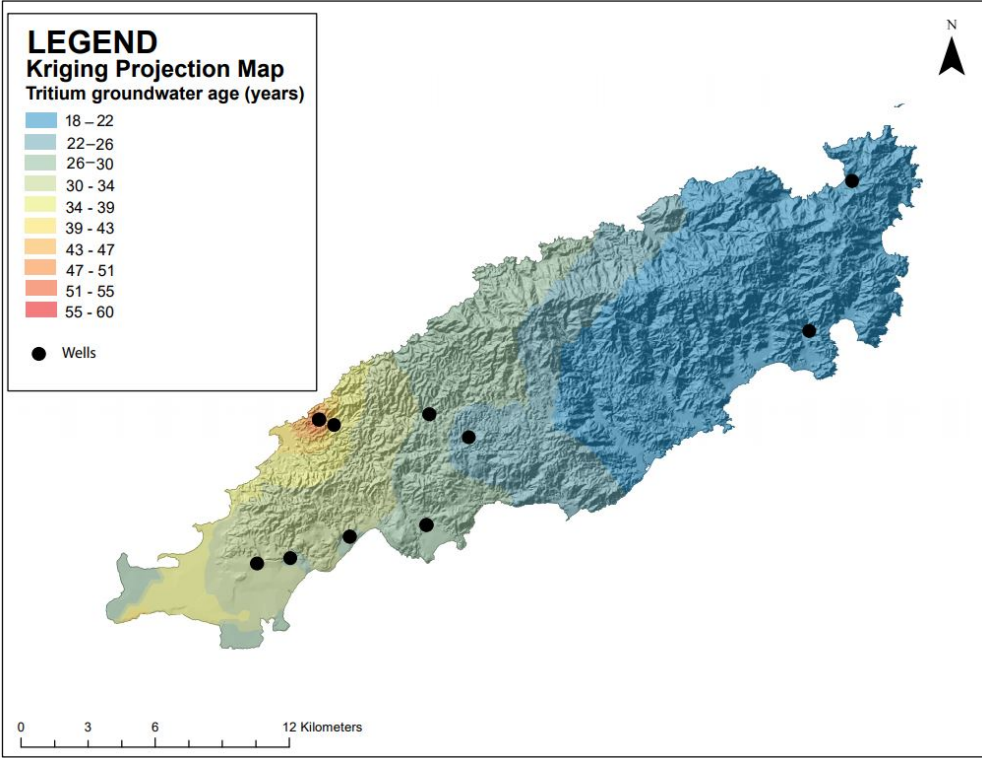
Figure 9. Tobago groundwater tritium results compared to other islands.

Figure 10. Kriging projections for both (a) tritium and (b) sulfur hexafluoride throughout Tobago.
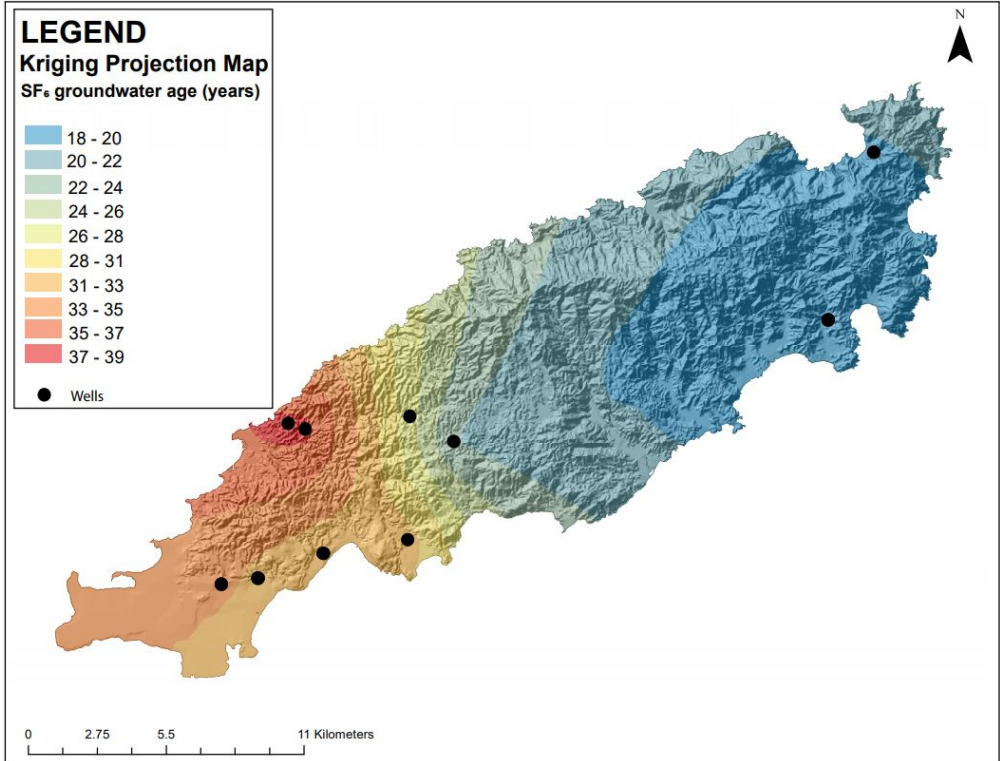
a

b

Table 3. SF$_6$ outlier's data with excess air calculations.

Well ID	Calculated SF$_6$ (pptv)	Approximated excess air amount	Minus approximated excess air	Well drill year	Amospheric SF$_6$ (pptv) Well drill year	Minus atmospheric SF$_6$ (pptv) Well drill year
TBG85W	6.91	15ml	2.13	2000	4.57	2.35
TBG04W	7.27	20ml	1.79	2000	4.57	2.71
TBG20W	7.13	35ml	1.10	2006	5.94	1.19

Table 4. Storage volume, effective porosity, and flow velocity calculations.

									Calculated							
Well ID	Aquifer Thickness ~Well Depth (m)	Residence Time (yrs)/ apparent age (t)	Area (km²) GRU	Area (km²) Basin	Volume of Aquifer GRU (km³) (V$_w$)	Volume of Aquifer Basin (km³)	FLUX (Q) m³/yr GRU Recharge	FLUX (Q) m³/yr Basin Recharge	V$_w$ (m³) GRU	V$_w$ (m³) BASIN	V$_w$ (km³) GRU	V$_w$ (km³) Basin	Effective Porosity (n$_e$) GRU	Effective Porosity (n$_e$) Basin	Distance. top of basin to well (km)	GW Velocity (km/yr)
TBG85W	109	29	0.86	5.3	0.09374	0.5777	108,920	1,141,304	3,158,686	33,097,806	0.003	0.033	0.034	0.067	59	2.03
TBG16W	243	20	1.23	11.7	0.29889	2.8431	232,959	1,942,960	4,659,183	38,859,199	0.005	0.039	0.016	0.014	37	1.85
TBG20W	100	60	0.76	0.9	0.076	0.09	139,367	140,258	8,362,011	8,415,465	0.008	0.008	0.110	0.094	18	0.30
TBG03W	100	32	1.31	30.3	0.131	3.03	487,735	7,906,118	15,607,524	252,995,776	0.016	0.253	0.119	0.083	37.5	1.17
TBG37W	100	18	0.92	2.4	0.092	0.24	160,179	401,350	2,883,226	7,224,295	0.003	0.007	0.031	0.030	27.5	1.53
TBG18W	100	29	0.98	32.9	0.098	3.29	122,591	5,569,915	3,555,147	161,527,546	0.004	0.162	0.036	0.049	58	2.00
TBG12W	187	33	0.86	11.7	0.16082	2.1879	131,688	1,942,960	4,345,720	64,117,679	0.004	0.064	0.027	0.029	12.5	0.38
TBG04W	123	34	1.24	30.3	0.15252	3.7269	403,297	7,906,118	13,712,084	268,808,013	0.014	0.269	0.090	0.072	67.5	1.99
TBG39W	182.88	18	0.81	14.6	0.1481328	2.670048	175,291	9,953,973	3,155,238	179,171,514	0.003	0.179	0.021	0.067	47	2.61
TBG88W	127.1	39	1.08	33.0	0.137268	4.1943	104,149	5,569,915	4,061,811	217,226,700	0.004	0.217	0.030	0.052	7.75	0.20

7. Conclusion

Ten wells were sampled for "apparent age" analysis of environmental tracers' tritium and sulfur hexafluoride. The age range of the tritium samples were between 18 to > 60 years old, while the SF_6 ranged between 18 and 39 years. Both methods suggest that the water in the southern region are older than waters in the north except for three SF_6 samples which are believed to be affected by "excess air" contamination. Therefore, caution should be made when interpreting this environmental tracer in a fracture rock system.

We calculated the effective porosities of both GRUs and basins, and it was found that the GRUs where TBG03W and TBG20W are located contain values like those of gravels. The most important revelation of these findings is that there are waters greater than 60 years old on such a small island, however it is still not known if this premodern water is being provided by a deep old groundwater source or longer flow paths.

This research can be improved by observing how this system reacts to changing climate scenarios over long periods of time. This can be achieved by annual environmental tracer testing and transient groundwater modelling. The results of which can aid in the safe yield production levels for individual wells and promote the sustainable use of this aquifer.

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