ORIGINAL ARTICLES

Grand Bahama Post-Hurricane Dorian: A Comparison of Fresh Water in Two Primary Wellfields

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Abstract

Freshwater lenses, a layer of fresh water that floats atop saline groundwater, are vulnerable sources of drinking water for small islands. The threats to freshwater lenses, and their recovery following catastrophic events, is not well-documented. Due to storm surge and flooding during Category 5 Hurricane Dorian in September 2019, the freshwater lenses of Grand Bahama were inundated with salt water, removing the freshwater source of drinking water for the island. This study builds on previous work to monitor the recovery of the freshwater lenses three years after the hurricane by assessing tidal lag, as well as stable isotopes in water (δ^2H and δ^{18}O), to understand the hydrologic characteristics of the freshwater lens in Grand Bahama. Results from electrical conductivity revealed that the tidal lag, or the time it takes for the tidal effect to be observed in groundwater, was approximately 2.5 hours on average. Through stable isotope analysis of precipitation samples, we determined a local meteoric water line of $\delta^2H = 8.2 * \delta^{18}O + 12.2$, which is close to the Global Meteoric Water Line. Groundwater samples did not show evidence of significant evaporation from precipitation. These results serve as baseline data for additional monitoring and recovery efforts on Grand Bahama.

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Introduction

Across small island nations, freshwater sources are often limited in quantity, limiting available drinking water. In The Bahamas, drinking water is typically sourced either from desalinated ocean water or groundwater (U.S. Army Corps of Engineers, 2004; Welsh & Bowleg, 2022). On islands where groundwater is used as the primary source, the water is withdrawn from the freshwater lens (FWL) that floats atop saline ocean water (Cant & Weech, 1986). FWLs are extremely vulnerable due to their limited supply, which is recharged solely from precipitation, and the potential to be heavily impacted by land-based contaminant sources and saltwater intrusion. Despite their fragile nature, many islands across the archipelago are heavily reliant on these FWLs to supply drinking water due to the economic and environmental burden of desalinating ocean water (Welsh & Bowleg, 2022).

Prior to Hurricane Dorian, Grand Bahama had the second most extensive freshwater resources of the Bahamian islands. The groundwater served as the only source of drinking water, with the depth of the FWL being up to 9 m in some regions (U.S. Army Corps of Engineers, 2004). The Grand Bahama Utility Company, the managers of the water supply for the island, established six wellfields, with two wellfields – known as Wellfield 1 (W1) and Wellfield 6 (W6) – providing approximately 95% of the drinking water for the island (Welsh et al., 2022).

On September 1-3, 2019, Hurricane Dorian passed over Grand Bahama and Abaco islands. Hurricane Dorian was classified as Category 5 with wind speeds up to 296 km/h, precipitation over 1 m, and flooding up to 6.4 m in some regions (Avila et al., 2020; Cerrai et al., 2020). The flooding caused destruction of the inland ecosystem and pine forests (Global Forest Watch, 2022; Welsh et al., 2022). Furthermore, the extensive flooding resulted in saline inundation of the primary freshwater supply wellfields, leading to an infiltration of saltwater into the freshwater lens, rendering the drinking water source unusable (Bahamas, Ministry of the Environment and Natural Resources, Forestry Unit, 2021).

After the receding of the flood in the wellfield, the utility company of Grand Bahama tried to remove the intruded saltwater from the freshwater lenses by intensive pumping from the wells within the wellfield (Grand Bahama Utility Company, personal communication, June 27, 2021). However, this did not lead to the intended effects and the water supply from these wellfields remained brackish (Welsh et al., 2022).

One potential approach for the recovery of freshwater lenses is the dilution of brackish groundwater by natural recharge from rain (Chaves, 2021). Groundwater monitoring and data collection are prerequisites for any effective management of groundwater resources, including groundwater quality, such as salinity, and groundwater resource availability (Bundesanstalt für Geowissenschaften und Rohstoffe, 2015). Livshitz (2020) stated that a groundwater monitoring plan is necessary for the implementation of effective future aquifer remediation efforts on Grand Bahama.

Within this work we aim to understand the potential for natural recovery of freshwater lenses in The Bahamas. Therefore, information about water characteristics before and after catastrophic events, including storm surges due to hurricanes, is necessary to identify the governing processes in the groundwater systems on the island. However, limited data exist within The Bahamas and small islands in general. To contribute to this body of knowledge, we started a long-term monitoring of the FWL water quality in the wellfields of Grand Bahama including temperature, electrical conductivity (EC), water levels, and stable water isotopes. The analysis of the groundwater monitoring data can also elucidate tidal influence on the dynamics of groundwater levels (GWLs) and hydraulic conductivity of groundwater, which can support the investigation of long-term trends (Singaraja et al., 2018). The evaluation of stable water isotopes in precipitation and groundwater can provide insight into groundwater sources and flow conditions (Leibundgut et al., 2009). Processes that interact with groundwater, such as recharge, flow and diffuse contamination, evapotranspiration, saltwater intrusion, and groundwater extraction, can be quantitatively described by analysing groundwater monitoring data (Nielsen, 1991).

Within this work, we present collected data from the years 2021-2022 and first findings of governing processes of the groundwater system on the island of Grand Bahama. We built our assessment on previous work in W1 and W6 (Welsh et al., 2022), providing important baseline data for the three years following Hurricane Dorian.

Study area

Grand Bahama is the northernmost major island within The Bahamas and located in a sub-tropical region. According to a past study by the U.S. Army Corps of Engineers (2004), annual precipitation is approximately 152.4 cm. The two primary wellfields that are used for drinking water, W1 and W6, were the areas of focus for this study. These wellfields are managed by Grand Bahama Utility Company. W1 is located in western Grand Bahama, in the northwest region of the capital city of Freeport within pine forest and urban land cover. W6 is located in western Grand Bahama to the northeast of the city of Freeport, with land cover consisting primarily of pine forest and some residences. Approximately 35% of the drinking water on the island was sourced from W1 and 60% was sourced from W6 prior to Hurricane Dorian (Welsh et al. 2022).

Methods

Two separate field campaigns were conducted as part of this study. The first involves the analysis of GWLs, EC, and temperature from April 2021 to August 2022. The second portion involved sampling for stable isotopes in water, which was conducted during two field visits, in January 2022 and May to June 2022.

To evaluate depth to groundwater, the non-governmental organisation IsraAID installed three groundwater monitoring wells in each of the two wellfields (MW-1A, MW-1B and MW-1P in W1 and MW-6A, MW-6B and MW-6P in W6; Figure 1). Since April 2021, data loggers have been installed in each of these monitoring wells to collect a variety of parameters including EC, GWL, and temperature. Tides cause short term fluctuations in these parameters (e.g., Wang et al., 2013). The depths of the data loggers in the wells were readjusted at the end of July and beginning of August 2021, separating the time series into time series one: April 2021-July 2021, and time series two August 2021-June 2022 and therefore data are not available for every month within the monitoring period.

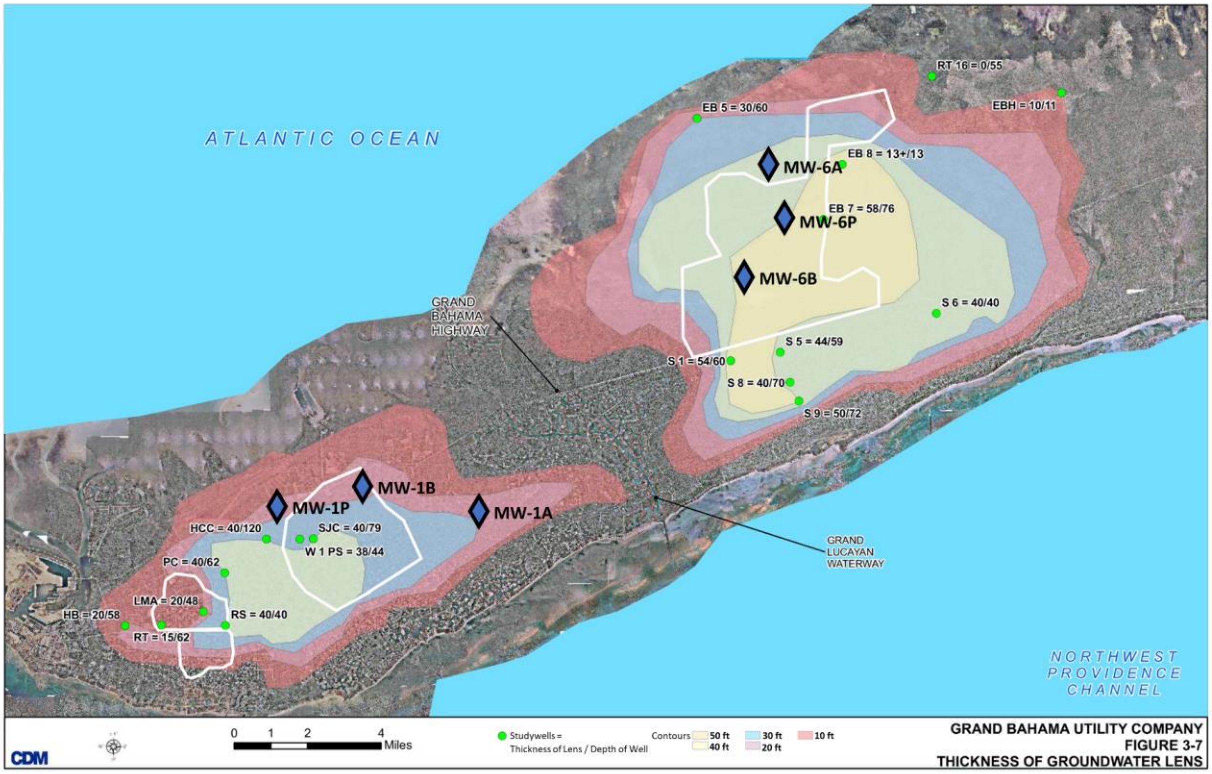
A statistical time series analysis was applied to the available data between April 2021 and June 2022 to monitor the salinity of the freshwater lenses over time. Precipitation and tidal data, obtained from the National Oceanic and Atmospheric Administration (2022, 2023), were correlated with the groundwater monitoring data to identify factors influencing salinity.

Cyclical components, such as tides, in the groundwater monitoring data were identified and quantified using a cross-correlation analysis, which is applicable to time series with equidistant data points and is a validated method in hydrogeology (Merkel & Planer-Friedrich, 2003), and applicable to the analysis of karst hydrological systems (Denić-Jukić et al., 2020). When a significant cross-correlation is present, the time-lag of the reaction of one data series to the next can be determined. In this study, the time-lag was calculated between the tidal fluctuations and changes in groundwater, measured as EC, as well as the fluctuations in GWL. The tidal lag (TL) is defined in Equation 1,

$$TL = T - T_0 \qquad (1)$$

where TL is the time it takes for the high (or low) tide to arrive in the groundwater from the coastline, T is the time that the peak is registered in the groundwater, and T_0 is the time when high/low tide hits the coast (Jiao & Post, 2019).

Figure 1 *Location of Monitoring Wells and Fresh Water Lens on Grand Bahama*



Note: Location of monitoring wells (MW) on Grand Bahama and freshwater lens (FWL) thickness (adapted from CDM, 2011). The three monitoring wells in Wellfield 1 are MW-1A, MW-1B, and MW-1P, and the three monitoring wells in Wellfield 6 are MW-6A, MW-6B, MW-6P.

The effect of the tides on EC and the GWL was analysed. Approximately two high and two low tides occur each day. Coastal tides propagate in the subsurface and reach the freshwater lens after a certain time, called the tidal lag, depending on the subsurface conditions, causing a groundwater tide at the peak of the GWL. The tide predictions were interpolated between the available high and low tide values and hourly tidal values were retrieved, to perform the cross-correlation analysis between tidal and monitoring data. These interpolated hourly tidal data were correlated with the original hourly monitoring data from the monitoring wells.

The seasonal effects on Grand Bahama are dominated by the wet and the dry season. Typically, the wet season lasts from the beginning of June to the end of November but can start early in May. The wet season coincides with the Atlantic Hurricane Season (United Nations Framework Convention on Climate Change, 2014). Seasonal effects were discussed together with the analysis of the monitoring data.

For stable isotope sampling, field campaigns were conducted to collect water samples. For groundwater, four wells were used from W1 and seven wells were used from W6. The wells within the wellfields are connected to spigots for Grand Bahama Utility Company access, and therefore to sample for isotopes the water was turned on and allowed to run for one minute to flush the pipes. Samplers rinsed the 5 mL sample bottles before collecting samples, and the bottles were sealed with Parafilm to prevent evaporation. Samples were stored in a cooler until returning from the field, at which time samples were placed in a refrigerator and stored at 5 ^{o}C until analysis.

Precipitation samples were collected for stable isotopes on an event-basis at one location in western Grand Bahama. A passive collector was used, consisting of a 10 cm diameter plastic funnel with a fine mesh placed atop the funnel to prevent contamination from debris. Plastic tubing connected the funnel to a 100 mL high-density polyethylene container. Samples were manually collected from the field immediately following storm events to avoid evaporation. A composite sample from the event was transferred to a 5 mL sample bottle and wrapped with Parafilm to avoid evaporation. Samples were immediately refrigerated at 5 ^{o}C until transported to the laboratory for analyses.

Stable isotope analyses of hydrogen (δ^2H) and oxygen (δ^{18}O) were conducted at the Washington State University Water and Environmental Research Laboratory in Palouse, Washington, USA using Los Gatos Research Water Isotope Analyzer IWA-45EP. Stable isotope compositions are presented in delta notation (‰, per mil) with the ratios (R) of ^{18}O/^{16}O and ^{2}H/^{1}H relative to Vienna Standard Mean Ocean Water (Dansgaard, 1964).

Using a simple linear regression between δ^{18}O and δ^2H ratios in precipitation, we calculated the Local Meteoric Water Line (LMWL) for the study site. In addition, we calculated d-excess for all samples to compare the proportions of δ^2H to δ^{18}O in water samples with the equation d-excess = $\delta^2H - 8 \times \delta^{18}O$ (Dansgaard, 1964).

Results

Influence of tides on electrical conductivity

For all monitoring wells, except for MW-6A, a significant correlation ($p \leq .05$) between the fluctuations of EC and tides was found (Table 1). The tidal lag is the time difference between the measured peak of EC in the FWL and the peak of the coastal tide and therefore the time it takes for the tidal effect to arrive in the groundwater. On average, the tidal lag was 2.5 hours (weighted by number of months), with a minimum of 1 hour (MW-1B, MW-1P, MW-6B) and a maximum of 5 hours (MW-1A). For the second time series of MW-1P, the cross-correlation analysis resulted in a lag value of -21 hours (Table 1). This negative value is difficult to explain and might indicate a stronger retardation (extending more than one tidal period) or coupling with other hydraulic/hydrochemical cycles.

The tidal lag of the EC was plotted against the direct distance of the monitoring wells to the coast for data from W1 and W6 (Figure 2). The average tidal lags of the monitoring wells (MWs) were inconsistent over the two time series, with a deviation of up to 2 hours per MW.

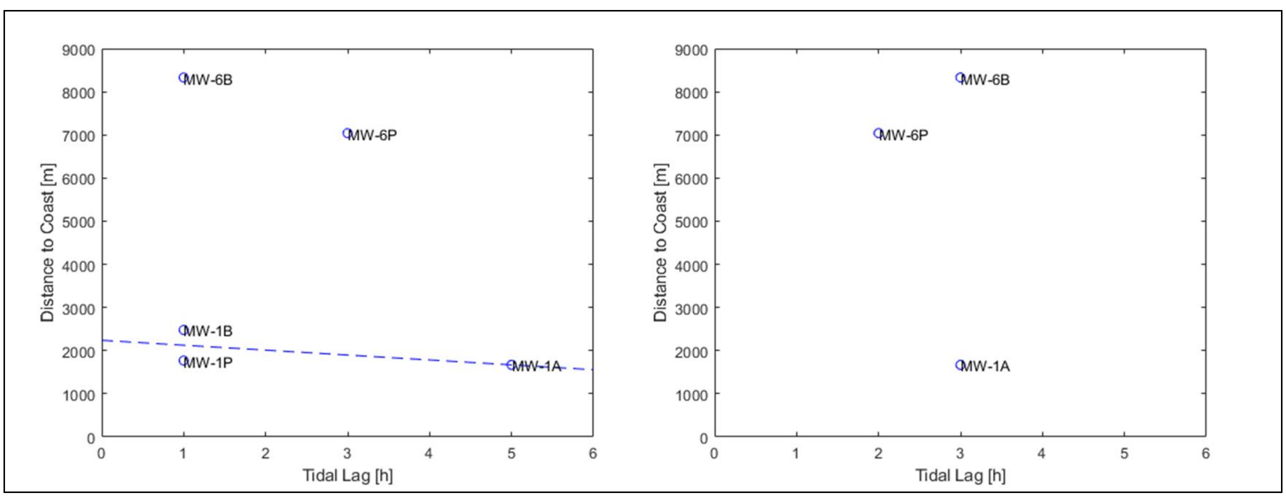
The tidal lag is illustrated for MW-6B in Figure 3, showing the tidal fluctuations in blue and the fluctuation of EC in orange. Results revealed that coastal tides create groundwater tides in the wellfields, leading to short-term EC fluctuations in a cyclical manner. We observed a significant correlation between tidal predictions and EC, as well as GWLs (not shown), in almost all monitoring wells (Table 1). Lateral saltwater intrusion by the tides causes cyclical fluctuations in EC with a time lag of an average of 2.5 hours. The areas close to the mixing zone were affected by the tide first, as seen in Figure 2 and Table 2.

Table 1 *Correlation Between Tidal Predictions and Electrical Conductivity in Monitoring Wells*

	Time Series One				Time Series Two									
EC & Tides	Apr 21	May 21	Jun 21	Jul 21	Aug 21	Sept 21	Oct 21	Nov 21	Dec 21	Jan 22	Feb 22	Mar 22	Apr 22	May 22	Jun 22
MW-1A				*r* = 0.5385 TL = 5h		*r* = 0.7148 TL = 3h									
MW-1B				*r* = 0.8878 TL = 1h											
MW-1P	*r* = 0.2498 TL = 1h				*r* = 0.6882 TL = -21h										
MW-6A			No correlation				No correlation								
MW-6B		*r* = 0.7314 TL = 1h					*r* = 0.1067 TL = 3h								
MW-6P	*r* = 0.3623 TL = 3h				*r* = 0.6385 TL = 2h										

Note: Correlation coefficient (*r*) and tidal lags (TL) in hours for electrical conductivity (EC) and tides for all six investigated wells, separated into the Times Series One (April 2021-July 2021) and Time Series Two (August 2021-June 202.). Months marked in blue indicate the wet season. Dark green indicates a strong correlation between tides and EC (r > 0.7), whereas lighter green indicates significant but lower correlation. Red indicates a significant negative correlation.

Figure 2 *Tidal lag, April-August 2021, and August 2021-June 2022*



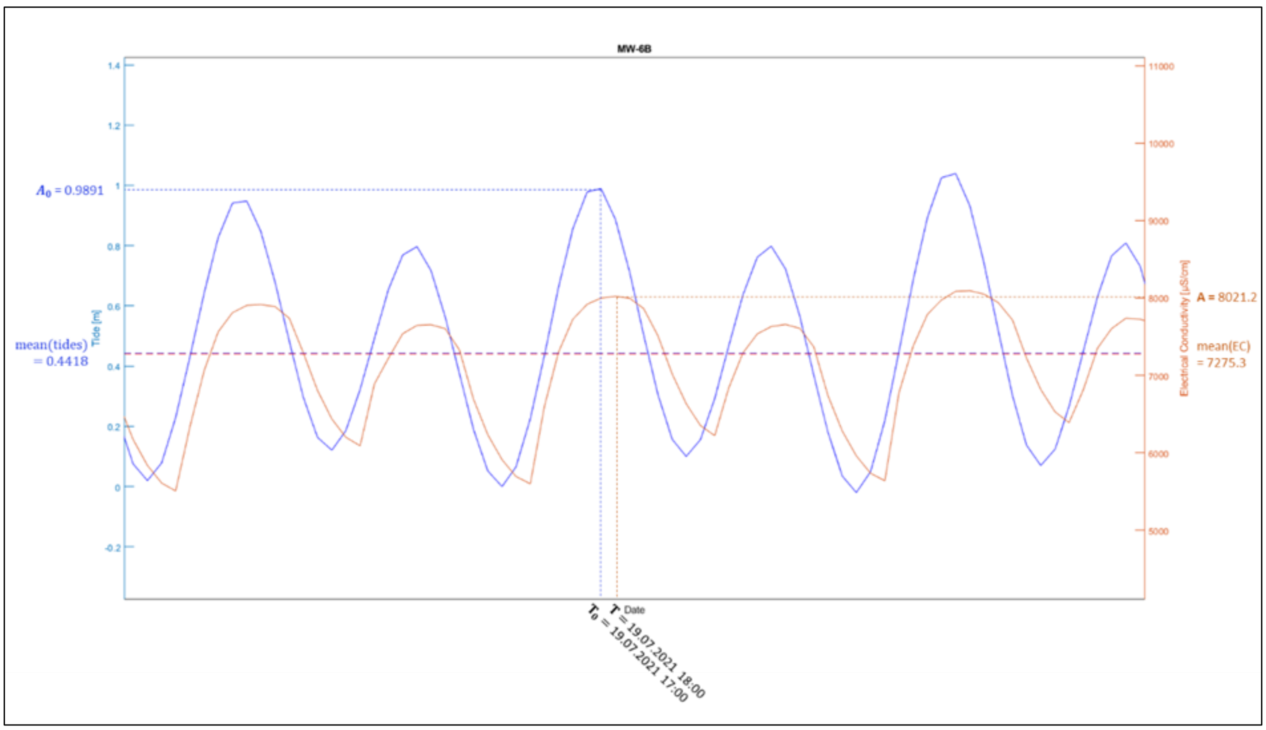
Note: Tidal lag, in hours, of electrical conductivity (EC) relative to distance from the coast for Time Series One (April-August 2021, left panel) and Time Series Two (August 2021-June 2022, right panel) for Wellfields 1 and 6. *Blue dashed line*: simple linear regression of average tidal lag values of Wellfield 1.

Correlation of groundwater level and electrical conductivity

EC and GWL are linked by several processes, such as saltwater intrusion (leading to increasing GWL and EC) or freshwater intrusion (leading to increasing GWL and decreasing EC due to dilution effects). On the other hand, a decreasing GWL might lead to a higher EC (lower water volume). The correlation analysis between GWL and EC is conducted on aggregated daily data, since the continuous fluctuations caused by the tides are eliminated in the daily mean values. However, the daily mean values of EC and GWL are approximations, as the average cycle time of the tides is 12 hours 25 minutes 14 seconds (not exactly 12 hours as assumed in the daily mean values). The maximum lag values of the cross-correlation analysis are 0 days for each time series of all MWs, which allows a direct correlation analysis without shifting the time series.

Table 2 shows correlations between GWL and EC for monitoring wells in W1 and W6. In W1, a predominantly positive correlation between EC and GWLs was found. An increasing groundwater level (GWL) with increasing EC may indicate that saltwater intrusion processes are dominant, including lateral tidal intrusion or upconing effects due to excessive pumping. For W6, correlations are negative. Increasing GWL with decreasing EC point towards predominant inflow ore recharge of freshwater to the aquifer, as further discussed below.

Figure 3 *Tidal Lag of Electrical Conductivity and Tidal Fluctuations in Monitoring Well MW-6B.*



Note: An example of the tidal lag of electrical conductivity (orange) and tidal fluctuations (blue) over time in well MW-6B. The mean values of tide and EC are indicated by the dashed lines.

Stable isotope sampling

A total of 12 precipitation samples were collected between May 18 and June 6, 2022. Based on δ^2H to $\delta^{18}O$ ratios in precipitation collected, the LMWL for Grand Bahama was calculated as $\delta^2H = 8.2 * \delta^{18}O + 12.2$ (see Figure 4). For groundwater sampling, one round of samples was collected during the January 2022 field campaign to collect one sample from each of the 11 groundwater wells. In the May-June field campaign, a total of 41 groundwater samples were collected from the 11 groundwater wells. As seen in a comparison of results between wellfields, W1 and W3 (Table 3), W1 revealed slightly more depleted values compared with W6. Precipitation and groundwater results are shown on Figure 4. The groundwater samples from both W1 and W6 plotted along the LMWL.

Table 2 *Correlations between GWL and EC for Monitoring Wells in Wellfield 1 and Wellfield 6.*

	Time Series One				Time Series Two										
GWL & EC	Apr 21	May 21	Jun 21	Jul 21	Aug 21	Sept 21	Oct 21	Nov 21	Dec 21	Jan 22	Feb 22	Mar 22	Apr 22	May 22	Jun 22
MW-1A			No correlation		r = 0.2366										
MW-1B			r = 0.8615												
MW-1P	r = 0.4445				r = -0.4341										
MW-6A			r = -0.5509				r = -0.7090								
MW-6B		r = -0.5601					r = -0.5466								
MW-6P	r = -0.3018				r = -0.4623										

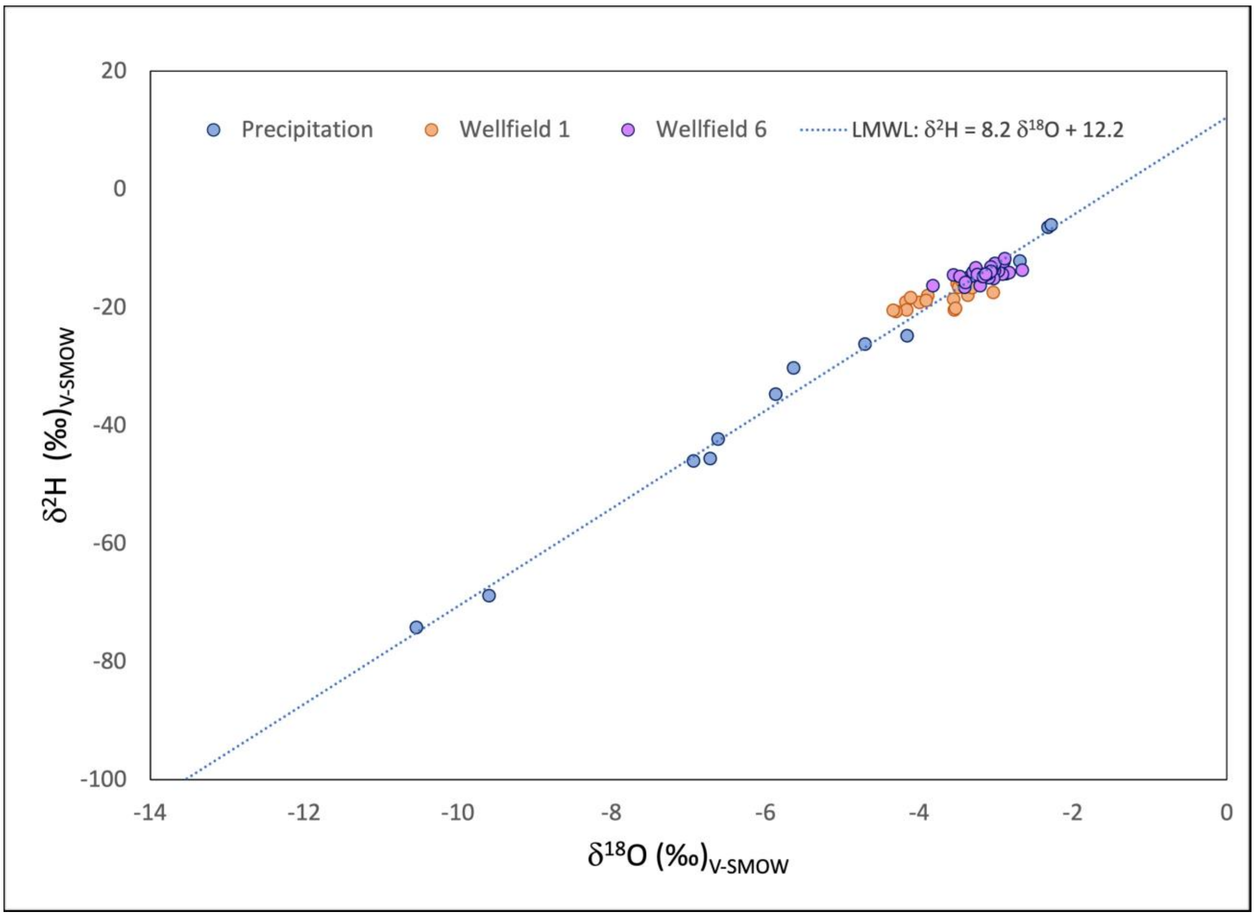
Note: Results of correlation analysis (r) for groundwater level (GWL) and electrical conductivity (EC). *Green*: significant negative correlation for Times Series One (April 2021-July 2021) and Time Series Two (August 2021-June 2022). *Red:* significant positive correlation, *Grey:* no correlation. *Months marked in blue*: wet season.

Table 3 *Comparison of Stable Isotopes Results between Wellfield 1 and Wellfield 6*

	δ^{18}O		δ^{2}H		d-excess	
	W1	**W6**	**W1**	**W6**	**W1**	**W6**
Average	-3.75‰	-3.28‰	-18.51‰	-14.99‰	11.45	11.27
Standard deviation	σ = 0.39	σ = 0.23	σ = 1.6	σ = 0.81	2.44	1.53
Minimum	-4.32‰	-3.82‰	-20.71‰	-16.60‰	6.80	9.15
Maximum	-3.04‰	-3.03‰	-15.61‰	-13.93‰	14.53	14.20

Note: Comparison of stable isotopes results between Wellfield 1 (W1) and Wellfield 6 (W6). n = 17 for W1 and 35 for W6

Figure 4 *Stable Isotopes in Groundwater at Wellfields 1 and 6, Freeport, Grand Bahama*



Note: Stable isotopes (δ18O and δ2H) for precipitation samples collected in May and June 2022 are shown in blue. The Local Meteoric Water Line (LMWL) for the region was calculated as δ2H = 8.2 * δ18O + 12.2 and is shown as a blue dashed line. Stable isotopes (δ18O and δ2H) for groundwater samples collected in May and June 2022 for Wellfields 1 (orange) and 6 (purple) are shown in comparison to precipitation samples (blue).

Discussion

Tidal analysis

Even though the magnitudes of daily EC fluctuations are very small, and daily averages of EC are somewhat constant over the monitoring period in the observed monitoring wells, the tidal influence on groundwater is significant. W1 is located in a more densely populated area with infrastructure and impervious surfaces, and the monitoring wells are located closer to the edges and mixing zone of the freshwater lens, favouring tidal influences. At W6, a negative correlation between EC and GWLs suggests that dilution processes, such as rainwater infiltration, are dominant in the area, with fewer impervious surfaces and open wells, potentially facilitating vertical freshwater intrusion after rainfall events.

As observed in this study, tidal lags show a tendency to decrease with depth in FWLs, i.e., the top and centre of the FWL are less responsive, as the areas closest to the mixing zone are affected by the tide first. The linear correlation of the tidal lag and distance to coast for the first time series was determined only for the wells in W1, which is counterintuitive as tidal lags decrease with increasing distance to coast (Table 1; Figure 1). Xun et al. (2006) found a linear increase in time lag with the distance from the coast. Similarly, Whitaker et al. (2023) found a reduction in tidal lag with decreasing distance from the north-east coast on Andros Island (Conch Sound), mostly fitting a linear trend. On Grand Bahama, this relation could not be reproduced, indicating that other factors have an influence on the EC fluctuations and that distance to the coast is not the primary factor for the tidal lag of EC. As the karstic subsurface is very heterogeneous, its structure and hydraulic properties, including hydraulic conductivity and porosity, seem to have a greater influence on the tidal lag than the direct distance to the coast. These investigations aimed at finding relations between groundwater monitoring data and tidal influences. The processes discussed are possible contributions, which are interacting with complex flow and transport processes in the subsurface.

The groundwater monitoring data collected represent a very short period for time series analysis, with less than one year of consistent data available for most of the monitoring wells due to the depth of the data logger being readjusted during the monitoring period. As Grand Bahama has a tropical monsoon climate with wet and dry seasons throughout the year, multi-year data series are necessary to detect long-term trends in aquifer salinity, otherwise seasonal effects dominate the variation in EC within the groundwater, which was shown for the collected groundwater monitoring data using statistical trend analysis (results not included in this study).

As the monitoring wells are located within active wellfields, it is assumed that pumping of groundwater from neighbouring wells directly affects the salinity and the GWL at the monitoring sites. Unfortunately, the authors of this paper have no data on the pumping schemes applied to the surrounding wells so that effects of pumping could not be included in this study. In particular, the monitoring wells in Wellfields 1 are located very close to active pumping wells (latest status early 2021), which could cause mixing processes as salinity levels increase even during the wet season. In a study combining 3D groundwater modelling with field-scale pumping tests, Stein et al. (2019) investigated the effects of pumping saline groundwater from a phreatic coastal aquifer. They found that parts of the freshwater aquifer that were impacted by salinization could be remediated and that this effect increases with higher pumping rates. In addition, when simultaneously pumping fresh groundwater further inland and saline groundwater from below the fresh-saline water interface, the freshening effect is less pronounced, and the salinity of the aquifer is more stable. In line with the modelling results, the field experiments revealed that the salinity in the observation wells decreases over the course of pumping. It was found that the pumping of saline groundwater does not salinize the aquifer and may even rehabilitate it by negating the effect of sea water intrusion. In the context of pumping saltwater from barrier wells for protecting production wells, Ozaki et al. (2021) investigated the effectiveness of such schemes. They have identified critical pump ratios for preventing saltwater intrusion to the production wells. John and Das (2021) analysed the relationship between decreasing GWLs and increasing EC values. For the studied aquifer they have found a positive correlation between GWL and EC, where the application of artificial recharge was recommended for mitigating salinization.

Stable Isotope Analysis

For precipitation samples, the LMWL of δ^2H = 8.2 * δ^{18}O + 12.2 is close to the Global Meteoric Water Line of δ^2H = 8.0 * δ^{18}O + 10 (Craig, 1961). However, the LMWL was derived from twelve samples collected during the rainy summer months, and additional sampling throughout the year would ensure the representativeness of the LMWL for the different seasons in the region. Groundwater samples plotted along the LMWL, indicating that the groundwater was not subjected to significant evaporative effects. These initial results suggest that W1 and W6 have slightly different signatures given the clustering of data for each wellfield along the LMWL. Given the geographic proximity of the two wellfields to each other and that precipitation is the main input into the FWL, the isotope ratios in precipitation are expected to be similar in the two regions. However, these results could suggest the existence of microclimate systems on the island, causing a more distinct signature if precipitation varies between the two wellfield regions. Additionally, groundwater level fluctuations influenced by tidal changes and the existence of the Grand Lucayan waterway could affect the groundwater movement and residence time of the FWL in those areas, resulting in different signatures. More data are necessary over a longer period of time to see whether these two regions show different signatures.

In this study, average d-excess values for 11.45‰ (W1) and 11.27‰ (W6), which were slightly higher than the global average. Previous high-frequency sampling in Nassau, New Providence during Hurricane Dorian in 2019 revealed average d-excess values of 12.14‰ (Welsh & Sanchez-Murillo, 2020). D-excess values that vary significantly from the global average of +10‰ can indicate a change in relative humidity from the source of precipitation, an increase or decrease in sea surface temperatures, or wind speeds in excess of 7 m/s, which affects evaporation (Jouzel et al., 2013). Given the proximity of the samples from the ocean, which provides source precipitation and reduces the rain-out effect, then these results are expected.

Conclusion

To our knowledge, the presented data are the first monitoring campaign in Grand Bahama and the first baseline data for stable isotopes in Grand Bahama. Additionally, information is lacking regarding the influence of tides on GWLs. Within this work, we present these results as baseline data for western Grand Bahama and to build understanding of the hydrologic processes influencing the freshwater lenses on the island. Data collection from individual monitoring wells provides local results that may not be representative of the larger surrounding area. Therefore, we do not interpret and generalise the results for the entire island.

Extensive monitoring, in terms of area coverage, are required to draw conclusions about the evolution of salinity in Grand Bahama's total groundwater resources. Here only initial relationships between tidal influences, EC, and GWL could be investigated. The inconsistency in trends between the different wellfields for tidal lag and correlation coefficient points towards different governing processes within the wellfields supported by the variations identified for the stable water isotopes between the two wellfields as well.

Further work is necessary to monitor stable isotopes in precipitation over a longer period of time to capture seasonal variations. Additionally, more data collected in both the freshwater lenses and precipitation will provide important information on the mean travel time for precipitation to the FWL, as well as the residence time with the FWL. However, these initial data serve as an important baseline for providing the first LMWL calculated in Grand Bahama. Moreover, eventually with additional data, calibrating and validating a groundwater model would be feasible to identify governing environmental processes in the wellfields. With such a model, sustainable groundwater management predictions would be possible to estimate natural recharge and safe yields from the wellfields.

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