The Vulnerability of Shallow Groundwater on a Small Tropical Indonesian Island

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Abstract

Small islands depend on rainwater as a source of water. Climate variability affects changes in groundwater chemistry on small islands. Pari Island is one such small island, located in Indonesia, with an area of 41.32 ha and a population of 1,441. This study aims to assess the vulnerability of groundwater quality to climate variability based on observations from Pari Island, including the influence of tourism on groundwater. The study used traditional hydrochemistry analysis methods (Piper, Durof, Scholler, and Gibb's diagrams), a questionnaire survey, and Standardized Precipitation Evapotranspiration Index (SPEI) analysis. The results indicate a strong correlation between SPEI-2 and the total dissolved solid content of groundwater, demonstrating that two-monthly interval precipitation has an impact on groundwater quality. The hydro chemical analysis of samples taken from dug wells shows that, geographically, the influence of climate variability on Pari Island weakened from west to east, corresponding to patterns related to the direction of the monsoon winds of tropical Indonesia. Increased tourism worsened groundwater vulnerability due to increased water demand and resultant wastewater load.

1. Introduction

Groundwater is a highly important resource needed for many human activities, especially in terms of meeting household requirements (Bhutiani et al., 2021). Typically, the availability of water on small islands is strongly controlled by the availability of rainwater and groundwater (Filho et al., 2020; Susilawaty et al., 2016). Groundwater availability is also closely related to climate variability (Barbieri et al., 2021; Grimm & Natori, 2006; Scalzitti et al., 2016); specifically, climate variability affects the time and magnitude of potential groundwater input (i.e., recharge), thus controlling its availability (Hughes et al., 2021). The limited catchment areas on small islands increase the vulnerability of groundwater to climate variability, an effect which is worsened by anthropogenic influences (Masood et al., 2021). However, the interactions between climate variability and anthropogenic influences on groundwater quality are complex (McGill et al., 2019).

Pari Island is part of the Thousand Islands Regency, which belongs to the regional part of the capital of Jakarta Province, Indonesia. Pari Island is the largest island of the Pari Island Cluster and represents the center of marine tourism in this island group (Cahyadi et al., 2018; Rustam et al., 2014). The water demands and waste generated on Pari Island has increased with its population; in addition, the development of tourism on Pari Island has also increased rapidly in the last 10 years, leading to mass tourism that has been detrimental to the island's ecosystem (Cahyadi et al., 2018; Hidayati et al., 2018). Although the tourism sector has improved the economic status of the local communities, it has also negatively affected water resources (Cappucci et al., 2020). The need for clean water continues to increase at the end of each week to meet the needs of homestays and catering. Furthermore, garbage production by tourists is double that of waste produced by local residents of Pari Island (Assa & Wibisono, 2020). In addition to garbage, the incidence of liquid waste is also increasing, as the island's sewage treatment infrastructure is still very underdeveloped. The combination of these environmental issues increases groundwater vulnerability and threatens the sustainability of water resources on Pari Island. Thus, studies relating to water resources, especially groundwater, are of particular importance in anticipating water scarcity in the future.

There have been several previous studies on ecosystem damage around Pari Island, such as the influence of benthic dinoflagellates on algal blooms in the waters of Pari Island (Thoha et al., 2020), an evaluation of benthic habitats in the waters of Pari Island using image data analysis (Anggoro et al., 2018), strategic development of mangrove ecosystem management using SWOT (Strengths, Weaknesses, Opportunities, Threats) and AHP (Analytical Hierarchy Process) methods (Cahyadi et al., 2018), an evaluation of ecological vulnerability (Farhan & Lim, 2012), the development of a payment for ecosystem services (PES) scheme for environmental protection (Hidayati et al., 2018), and ecotourism studies focused on conservation approaches (Leonard et al., 2020).

Previous water resource studies conducted on Pari Island include the effect of mean sea-level change on tourist sites (Candrasari et al., 2015), the application of SWOT methods for water resource management related to increased pressure from tourism activities (Sinulingga et al., 2015), and the quantitative prediction of water resource-carrying capacity requirements in the future (Marganingrum & Sudrajat, 2018). However, studies investigating groundwater vulnerability, especially those that focus on changes in groundwater quality regarding climate variability and pressure from tourism activities, remain limited. Thus, this paper analyzes the influence of climate variability, temperature, changes in groundwater chemistry, and pressure from tourism activities on the overall vulnerability of groundwater on Pari Island.

2. Materials And Methods

2.1 Material

The data used in this paper are primary data from field surveys and questionnaires, in addition to some secondary data comprising daily precipitation and temperature data recorded from January 1997 to June 2015, obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) of the Republic of Indonesia. Data downloaded from the Prediction of Worldwide Energy Resource (POWER) Project under the National Aeronautics and Space Administration (NASA) Applied Sciences Program (https://power.larc.nasa.gov/data-access-viewer/) were used as part of data preparation. The POWER Access Data were used to determine the average values at a resolution of 0.5° latitude and 0.5° longitude. The downloaded data span the period from January 1981 to December 2020 at two coordinates: 5.8573°S and 106.6184°E, located at the center of Pari island, and 6.1077°S and 106.8804°E, located at the BMKG Tanjungperiok marine weather station.

2.2 Methods

To analyze changes in water quality, field surveys and water sampling were conducted. Well water samples were collected from 11 well points for water sampling and 14 others well points for only in situ measurements. Measurements and sampling of well water were conducted at two different times (early June 2021 and mid-November 2021). The following parameters were measured for each sample: temperature, pH, electrical conductivity (EC), major element content (anion and cation), total dissolved solids (TDS), and total organic carbon (TOC). Temperature, pH, and EC were measured in situ using Horiba water checkers, while the other parameters were analyzed in the laboratory using the standard APHA-2005 method. The major elements measured include Na^+, K^+, Mg^{2+}, and Ca^{2+} (major cations) and Cl^-, $SO_4{}^{2-}$, and $HCO_3{}^-$ (major anions). The TDS concentration was measured using a gravimetric method. The TOC was analyzed based on the dry combustion method, performed on acidified samples at 850°C using an Elementar® TOC Analyzer. The carrier gas was air, with a flow rate of 200 mL/min and a pressure value between 1100–1300 mbar. To see the distribution of EC and pH values at the study area, the interpolation method was used with Surfer app version 8.01.

Further comparison of ion content ratios and other traditional hydro chemical analyses (Schoeller diagram, Piper Diagram, Durof Diagram, and Gibbs Diagram) were used to determine the water type, water and rock interactions, ion exchange processes, the provenance of salinity, and the changes of composition and concentration of groundwater contaminants (Thin et al., 2018; Tiwari et al., 2019).

To test the accuracy of the water chemistry data analysis, the charge balance error (CBE; or error in ionic balance (EIB)) technique was used (Equation 1). The data can be considered accurate if the CBE or EIB is approximately 5% (Adimalla et al., 2021; A. Cahyadi et al., 2017; Tiwari et al., 2019).

$$CBE = \left(\frac{\sum cations - \sum anions}{\sum cations + \sum anions}\right) * 100$$

1

This study collected data through questionnaire surveys. The census method was chosen, where each respondent represented a house inhabited by Pari Island residents. There were 317 respondents in this study divided into four groups by region. The questionnaire data were then processed using descriptive statistics.

The Standardized Precipitation Evapotranspiration Index (SPEI) approach was used to characterize dry and wet events. SPEI (Vicente-Serrano et al., 2010) is a climatic drought index used to assess anomalous dry and wet conditions based on monthly precipitation and temperature data. SPEI can depict the multi-scalar characteristics of dry and wet precipitation conditions, as well as temperature variability.

The daily precipitation and temperature data retrieved from the BMKG database had some gaps that needed to be filled. The filling process used multiple regression equations that were based on the existing data. The equations are as follows:

$$\hat{P}_{Pari} = 0.5760 \bullet P_{Tjp} + 0.3620 \bullet P_{PariPDA} - 0,$$

2

$$\hat{T}_{Pari} = 0.69179 \bullet T_{PariPDA} - 0.00204 \bullet P_{Pari} + 9.69139$$

3

where $\hat{P}_{Pari}$: predicted monthly precipitation of Pari island,

$\hat{T}_{Pari}$: predicted monthly temperature of Pari island,

P_{Tjp} ; monthly recorded precipitation data at BMKG Tanjungperiok station,

$P_{PariPDA}$: monthly precipitation of Pari island from POWER Data Access,

$T_{PariPDA}$: monthly temperature of Pari island from POWER Data Access, and

P_{Pari} : monthly precipitation of Pari island.

The selected predictor variables in Equations 2 and 3 are based on correlation strength between predicted variables (dependent variables) and predictor variables. The equations were tested on training data.

The SPEI utilizes the climatic water balance (i.e., precipitation minus potential evapotranspiration) for its calculations. All data were aggregated monthly. A simple temperature-based Thornthwaite method was used to estimate monthly potential evapotranspiration (Thornthwaite, 1948). The same approach was used when SPEI was first introduced (Beguería et al., 2014).

Timescales in SPEI reflect meteorological anomalies and their impacts on different water resources. On a small coral island such as Pari island, meteorological anomalies, rainwater storage, shallow wells, and near-surface soil moisture conditions for agriculture can be assessed over short timescales of 1–2 months. The three-month timescale reflects deep soil moisture and deep groundwater anomalies. The medium six-month timescale reflects seasonal dry or wet anomalies, and a timescale of 12 months reflects interannual variability.

3. Results

3.1 Study Area

The study location (Figure 1) is the entirety of Pari Island, which covers an area of 41.32 ha. In accordance with DKI Spatial Planning for the year 2030, the areal allocation of Pari Island is 50% for tourism, 40% for settlements, and 10% for research (DKI Jakarta Provincial Regulation Number 1 of 2012). The total population at the end of October 2021 was 1,441 people (Pari Island Village Data, 2021), a 30% increase compared to 2016 (Pari Island Village Data, 2016). The residents of Pari Island are concentrated in the middle of the island on its southeastern side and mostly live to the southwest and northeast of the pier.

Not all residents have their own wells — there are several communal wells from which each house drains water using individual pipes from the same well. Figure 2 shows the distribution of each well at which the water quality was measured. All samples (except W1 and W6) are used by residents only for bathing, washing, and toilet purposes. For drinking water and cooking needs, residents purchase water from the groundwater reverse osmosis (GWRO) well, installed by the government as a water supply, or bottled mineral water. The price of water from the GWRO well is 500 rupiahs per gallon, whereas mineral water costs 20,000 rupiahs per gallon. On average, every household buys GWRO water or bottled mineral water once a week (Figure 3).

3.2 Hydrogeochemical Analyses

Tables 1 and 2 show the results of well water quality measurements from Pari Island in early June 2021 and mid-November 2021, respectively. In June, the pH values ranged from 5.9–7.8, whereas they ranged from 7.3–8.2 in November. There were no significant differences in observed salinity between June and November. In contrast, there were marked differences in EC, which ranged from 193–1,280 uS/cm (average 540 uS/cm) in June, while the equivalent values in November ranged from 643–7,580 uS/cm (average 2,883 uS/cm).

Table 1
Groundwater quality analysis in June 2021.

Sample Code	pH	EC	Salinity	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	TDS
		uS/cm	%	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
W1	6.21	747	0.40	523.5	37.0	210.1	96.4	109.4	320.5	1299.8	677
W2	5.85	193	0.09	104.7	11.1	101.0	41.3	144.3	104.9	341.3	362
W3	6.17	224	0.10	142.5	12.7	97.0	43.8	113.9	70.0	397.7	379
W4	7.31	269	0.13	139.6	11.4	169.7	41.6	172.8	114.5	468.0	405
W5	7.62	329	0.16	209.4	5.3	157.6	58.3	145.1	91.6	605.2	439
W6	6.50	499	0.26	407.1	23.6	97.0	39.1	94.8	67.3	816.2	536
W7	6.72	544	0.02	10.2	1.3	101.0	6.3	109.5	16.5	150.0	562
W8	7.09	762	0.03	142.5	5.0	88.9	20.7	189.6	96.0	270.0	686
W9	7.13	1,280	0.05	81.4	11.9	109.1	20.1	135.0	62.8	232.1	981
W10	7.80	547	0.02	18.0	5.5	80.8	18.6	127.7	22.2	150.0	563
W15	7.64	547	0.02	9.6	0.3	40.4	12.8	66.0	3.7	75.0	563

Table 2
Groundwater quality analysis in November 2021.

Sample Code	pH	EC	Salinity	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	Hardness ($CaCO_3$)	TDS
		uS/cm	%	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
W1	7.50	7,580	0.41	681.7	105.5	303.0	145.0	300.6	361.5	1,796.5	1,489.9	6,607
W2	8.08	2,400	0.11	81.5	26.9	129.3	47.5	164.0	90.8	377.3	576.5	1,363
W3	7.89	2,800	0.13	133.4	33.4	125.2	52.3	193.2	108.7	453.3	584.3	1,668
W4	7.33	2,990	0.14	163.0	51.2	218.2	44.8	368.0	125.8	515.6	827.4	1,652
W5	7.64	4,790	0.24	102.3	48.6	222.2	65.7	198.4	125.8	638.4	925.3	2,819
W6	7.30	7,030	0.37	257.9	84.8	161.6	51.2	128.8	91.7	763.3	687.0	5,742
W7	7.83	643	0.02	9.2	2.6	125.2	21.9	277.6	36.8	120.2	459.3	501
W8	7.82	784	0.03	29.6	24.3	84.8	13.8	159.8	62.6	145.8	306.8	605
W9	7.78	1,260	0.05	123.0	25.6	113.1	15.3	263.2	78.2	240.3	396.3	864
W10	7.91	701	0.03	14.4	4.6	113.1	15.3	173.3	32.5	137.5	396.3	531
W15	8.17	735	0.03	18.5	1.3	105.0	15.5	161.5	15.4	150.0	373.4	584

The TDS concentrations measured at wells in the western part of the island were greater than those recorded from wells in the eastern part of the island. Notably, the TDS values in the western to central wells (W1 to W6) were not suitable for use as drinking water. In accordance with the 2001 Government Regulation of the Republic of Indonesia Number 82, the value of TDS should not exceed 1,000 mg/L. The value of TDS is positively correlated to EC, and thus the EC values of wells in the western region of Pari Island were higher than those in the central and eastern parts of Pari Island.

Figure 4 shows the results of interpolation of the EC value distribution in Pari Island. In June 2021, the peak EC value was recorded around the W8 well, which decreased toward the southwest and northeast. In November, the highest EC value was once again observed around the W8 well, however, the values in the southwest and northeast were higher than those observed in June. In November, the values of EC to the southwest were greater than those to the northeast. The pH and salinity values did not differ significantly between June and November 2021. In June, the pH was slightly acidic to alkaline, while the pH was neutral to alkaline in November. Figure 5 shows the distribution of pH values on Pari Island.

The major element concentrations presented in Tables 1 and 2 were also plotted as a Schoeller diagram (Figure 6). The abundance of cations in the groundwater at the study area was Na^+ > Ca^{2+} > Mg^{2+} > K^+, while the anion abundances are Cl^- > HCO_3^- > SO_4^{2+}. In general, the abundance of cations and anions was greater in November compared to June. The data shown in the Schoeller diagrams suggest that the water quality of dug wells located in the eastern region of Pari Island (W7–W15) have lower ion abundances than those in the western region of Pari Island.

In addition to analyzing the physical parameters and major elements in the groundwater, TOC analysis was performed for the 11 dug wells used in the study (Figure 7). TOC is a measure of organic matter content, which can be used as a parameter to evaluate water pollution (Lee et al., 2020). High TOC values imply lower dissolved oxygen (Al-Said et al., 2018), which further influences chemical reactions in the water (Sanz et al., 2021). The results of this analysis showed that groundwater from the west and middle areas (W1–W6, except W2) had higher TOC values than those in the east area (W7–W10).

3.3 Impact of Tourism

Tourism is a factor that can significantly increase the vulnerability of water resources. To date, marine tourism activities on Pari Island have developed significantly. Tourism on Pari Island began in 2010 with the opening of Pasir Perawan Beach by local residents as a tourist destination. The results of the questionnaire indicate that the beaches have become the main attraction for tourists visiting Pari Island (70% of respondents); the other principal attraction is the island’s natural beauty (28% of respondents).

The development of tourism on Pari Island has led to changes in resource use by residents, especially with regard to the resources demanded by their livelihoods. Approximately 29% of Pari Island residents work in the tourism sector as their main job (Figure 8a). However, some residents who work in the non-tourism sector also receive additional income from the tourism sector such as by providing homestays and catering services for tourists. This proportion of residents involved in tourism-related jobs continues to grow as the number of tourist visits increases. As many as 50% of respondents stated that the level of tourist density of Pari Island was “solid”, while as many as 10% stated that it was “very dense”. A total of 45% of respondents also stated that their residential homes are used for lodging or homestays for tourists.

The development of tourism on Pari Island has been proven to have had a positive impact on the socio-economic status of the people of Pari Island. The questionnaire results show that 58% of respondents stated that their income has increased due to the development of tourism (Figure 8b), while as many as 68% of respondents stated that their quality of life has improved due to tourism (Figure 8c). In addition, most respondents stated that unemployment has decreased with increasing activity in the tourism sector (Figure 8d).

In contrast, the increase in tourism activities has been accompanied by a decline in environmental quality. The interview results (Figure 9a) showed that many respondents felt that ecosystem conditions had worsened due to tourist activities (59% of respondents), low environmental awareness (13%), and irresponsible exploitation (4%). A total of 72% of respondents said that wastewater had increased due to tourist activities on Pari Island (Figure 7b). These results indicate tourism has had a negative influence on the island’s environmental conditions. In contrast, the island’s community feel that water resources on Pari Island are still quite safe — 55% of questionnaire respondents reported that water availability is was unaffected by tourism, while only 28% of respondents stated that the water availability was reduced due to tourism activities (Figure 9c).

In particular, Figure 9c suggests that the threat of tourist activities to water resources has not been fully realized by the Pari Island community. This is likely due to the provision of additional water supply from the GWRO well for cooking and drinking purposes as well as the availability of bottled mineral water used for drinking water.

3.3 Climate Variability

3.3.1 Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI graphs (Figure 10) illustrate the variability of several indices on various timescales during the period between 1980 and 2020. These indices reflect the anomaly intensity of dry and wet conditions, where positive values indicate wet conditions and negative values indicate dry conditions. These SPEI values can be used to define the intensity of the anomaly conditions (Table 3), based on the intensity classification system described by the Standardized Precipitation Index (Mckee et al., 1993). The SPEI graphs can also be used to characterize the magnitude of each dry or wet event by multiplying the corresponding intensity by the duration of the event, i.e., the number of months over which each dry or wet event occurs.

Table 3 Intensity classification of dry and wet conditions based on SPEI.

SPEI	Classification of dry	SPEI	Classification of wet
0 to -0.99	Mildly dry or near-normal	0 to +0.99	Mildly wet or near-normal
-1.00 to -1.49	Moderately dry	+1.00 to +1.49	Moderately wet
-1.50 to -1.99	Severely dry	+1.50 to +1.99	Very wet
≤ -2.00	Extremely dry	≥ +2.00	Extremely wet

In general, the SPEI shows continuous variations of dry and wet events. The potential evapotranspiration does not vary significantly on a yearly basis, and thus the index values mainly follow the variations in precipitation. Table 4 summarizes the number of occurrences of dry and wet events of specific intensities at various SPEI timescales. For example, for SPEI-3, 21 very-to-extreme intensity wet events occurred between 1981 and 2020, of which 12 events (60%) occurred in the second half of this period, i.e., between 2001 and 2020. This table clearly shows that high-intensity events were more frequent in the second half of this period than in the first half. SPEI-12 is an exception, where more severe and extreme dry events occurred in the first half-period than the second; however, the magnitude of both dry and wet events has increased over time (Figure 11). This may indicate that interannual variability supersedes seasonal variability in the second half of the period.

Table 4
Number of occurrences of wet and dry events based on multi-timescale SPEI on Pari island from 1981 to 2020.

Timescale	Intensity class	Index	Number of event occurrences in the full period (1981–2020)	Number of event occurrences in the 2nd half of the period (2001–2020)
SPEI-3	Very-to-extremely wet	≥ +1.5	21 times	12 times
	Extremely wet	≥ +2.0	3 times	3 times
	Severe-to-extremely dry	≤ -1.5	13 times	7 times
	Extremely dry	≤ -2.0	-	-
SPEI-6	Very-to-extremely wet	≥ +1.5	6 times	4 times
	Extremely wet	≥ +2.0	1 time	1 time
	Severe-to-extremely dry	≤ -1.5	12 times	7 times
	Extremely dry	≤ -2.0	-	-
SPEI-12	Very-to-extremely wet	≥ +1.5	3 times	3 times
	Extremely wet	≥ +2.0	1 time	1 time
	Severe-to-extremely dry	≤ -1.5	8 times	3 times
	Extremely dry	≤ -2.0	2 times	1 time

3.3.2 Extreme precipitation

Extreme intensity precipitation events on a small island commonly relate to the occurrence of storms and high waves. Flooding can occur when storms and high waves are superimposed with high tides. In addition to the potential for flood-related infrastructure and agricultural damage, freshwater lenses can rapidly become saline when overland seawater floods occur. Such seawater floods have previously been reported on Pari island.

A distribution curve of monthly precipitation shows that the top 5% of intense monthly precipitation events occur at precipitation levels in excess of 406.6 mm; these are considered to be extreme events (Figure 12). With reference to the monthly data, these extreme events occurred 25 times from 1981 to 2020, with about 72% of these extreme events occurring in the second half of the period (2001–2020). The frequency of these extreme events increased towards the end of the analyzed period.

4. Discussion

Changes in groundwater chemistry have an influence on water quality, which may represent a threat to human health (Snousy et al., 2021). Understanding the processes involved in such changes can help in the development of countermeasures against such occurrences.

Based on the plotted Durof diagrams (Figure 13), changes in water chemistry observed in the study area are due to the processes of ion mixing and simple dissolution (Ravikumar et al., 2015). These chemical changes cause typical changes in shallow groundwater in the study area. The mixing of ions results in ion exchange, which can be described by the relationship between concentrations, i.e., (Ca^{2+} + Mg^{2+})−(SO_4^{2-} + HCO_3^-) and (Na^+ + K^+)−Cl^- (Li et al., 2021), as well as chloro-alkaline indices (CAI) (Tiwari et al., 2019). The results of calculations using data from Tables 1 and 2 indicate that, regardless of when they were collected, all water samples from the dug wells had negative concentration relationship values with positive CAI. This suggests the withdrawal of Na^+ + K^+ ions and the release of Ca^{2+} and Mg^{2+} ions in the water samples from the dug wells; this process is referred to as reverse ion exchange (Li et al., 2021; Tiwari et al., 2019).

The CAI values were found to be consistent with the plotted Piper diagrams (Figure 14), which show that the well water facies at the study area are largely composed of mixed CaMgCl and primary or secondary saline water (Snousy et al., 2021). According to the classification of Gappuci et al. (2020), almost all wells in Pari Island cannot be categorized as freshwater; the sole exception is W7. Well W7 is located in the center of the island where the freshwater lens is thickest. In June 2021, the water quality in W7 was classified as secondary saline water; it was then reclassified to fresh water in November 2021. Dilution by rainwater probably improved the groundwater quality at well W7. The facies of other wells also shifted from primary saline water (NaCl) and secondary saline water (CaCl) in June to mixed water (CaMgCl) in November (Cappucci et al., 2020; Snousy et al., 2021).

In general, calcium is the dominant ion in freshwater, while magnesium is the dominant ion in seawater. Hence, the Mg^{2+}/Ca^{2+} ratio can be used as an important delineator between freshwater and seawater (Tiwari et al., 2019). Figure 15 shows that the ratio of Mg^{2+}/Ca^{2+} to Cl^- is less than 1 for all wells, with exception of well W1 in June 2021. This suggests that freshwater characteristics in the study area were stronger than those of seawater during both sampling periods. This may explain the assumption by Pari Island residents that their well water was either quite safe or did not change during that period. The ratio of Mg^{2+}/Ca^{2+} to Cl^- decreased in November 2021 compared to June 2021. This is consistent with the interpretation of the occurrence of a reverse ion exchange process, where the abundance of Ca^{2+} or rainwater dilution causes the Cl^- value to decrease.

Goddy and Hinsby (2008) found that the average TOC in natural groundwater was 2.7 mg C/L, while TOC levels in untreated domestic wastewater were reported between 80 and 260 mg/L (Metcalf and Eddy, 2003). The findings in this study as well as a consideration of the predominant local activities suggest that the groundwater in the study's sampling locations was affected by domestic sources.

Tables 1 and 2 show a significant increase in EC values in the dug wells in the western to central regions of Pari Island (W1–W6) in November 2021 compared to June 2021. In contrast, the increase in EC values was not significant in the central and eastern regions of Pari Island (W7–W15). Figure 16 presents the distributions of water samples from the study area as plotted on a Gibbs diagram and suggests that the EC increase is related to rock weathering and evaporation–crystallization processes. Before June 2021, the groundwater chemistry of the dug wells on Pari Island was controlled by rock weathering processes; subsequently, between June and November, this chemistry was controlled by the processes of evaporation or crystallization (Li et al., 2021; Tiwari et al., 2019). There is a positive relationship between EC and TDS, in which an increase in TDS concentration will result in further increases in EC value (Rebello et al., 2020; Rusydi, 2018).

Evaporation is among the major factors that influence the chemical composition of shallow groundwater (Richter and Kreitler in Nguyen et al., 2015). Evaporation reduces the water content, consequently increasing the concentration of the residual chemical constituents. This process can also explain the similar behavior observed in the TOC values, especially for samples from the west and middle of the island (except for sample W2). There is the possibility that the organic content in the groundwater was diluted by rainwater during the period June to November 2021.

Figure 17 shows the TOC values of seawater recorded in June and November. In June, seawater from the west coast had very high TOC levels compared to that of the central and east coast. This value is also extremely high compared to TOC levels in the Arabian Gulf (0.8–3.9 mg/L; Emara, 1998). Emara (1998) also noted a significant correlation between TOC values and the presence of petroleum hydrocarbons.

Salinity also influences the organic content in groundwater. Based on Piper diagrams, when the entire groundwater area consists of mixed water and primary and secondary saline water, tidal seawater intrusions can influence the organic content of the groundwater. The salinity may change the chemical composition in the water, thus decreasing its dissolved oxygen abundance and increasing its TOC (Al-Said et al., 2018).

In samples from the east of the study area (see Figure 7), the organic matter content of the groundwater did not decrease between June and November despite increasing groundwater dilution by rainwater; some TOC values in this area are even higher in November than those recorded in June. The seawater origin of the organic matter can be potentially disregarded as the TOC value in the eastern part of the study area (W13) in November is relatively low (Figure 17); other activities should be investigated as a source of the organic matter.

The analysis of climate variability indicates that there has been a trend of more frequent extreme precipitation events, suggesting that the frequency of seawater floods could increase. In this regard, the low-level areas in the west of Pari Island are likely to become more vulnerable in the future, contributing to the increased vulnerability of water resources of the island.

The SPEI results at different timescales show varying trends (Table 4). The short- and medium-timescale SPEI results (SPEI-3 and SPEI-6) indicate an increasing frequency of very-to-extremely or severe dry and wet events, as well as a clear increasing trend in both dry and wet event intensity. An increasing intensity of wet events is beneficial for the sustainability of water resources, while an increasing trend in dry events is disadvantageous for water resources. The magnitudes of dry events on both short and medium timescales have slightly decreased over time (Figure 9). The long-timescale SPEI (SPEI-12) data show an increasing trend of wet events and a decreasing trend of dry events. However, the magnitude of these dry events has increased, suggesting that the increased dry event magnitudes from interannual variations could supersede or counteract any benefits to water resources from the occurrences of wet events from monthly and seasonal variations.

Seasonal variations are widely reported to affect the salinity of groundwater of small islands (Barbieri et al., 2021; Canul-Macario et al., 2020; Giridharan et al., 2008; Heiss & Michael, 2014; Isa et al., 2014). Salt concentrations are typically higher during the dry season and lower when rainwater dilutes the concentrated groundwater during the wet season. However, climatic seasonality has been altered as a result of climate change, with the start of seasons becoming increasingly less predictable. The correlation between the TDS content of groundwater and the SPEI on Pari island is strongest for SPEI-2 (-0.87), suggesting that two-monthly interval precipitation events have the most significant impact on groundwater quality.

5. Conclusions

The chemical characteristics of shallow groundwater on Pari Island are strongly influenced by climate variability. The results of SPEI analysis suggest two-month interval precipitation events have the strongest influence on changes in groundwater quality in the study area. The recorded groundwater variability was stronger in the west area of the Pari island than in the east. Changes in water quality during extreme weather events will tend to increase groundwater vulnerability, particularly because groundwater has become the main source of water used to meet the daily needs of the island’s population. This vulnerability has worsened due to the pressure of tourism activities that increase water demand and pollution loads. To reduce groundwater vulnerability, improved awareness, waste management, and technology are required to better manage groundwater.

Declarations

Contributions

All authors have equal contributions to this article. **Dyah Marganingrum** contributed to the preparation of the manuscript and analysis of water chemistry; **Heru Santoso** contributed to the collection of climate data and analysis; **Diana Rahayuning Wulan** contributed to the collection of total organic carbon data and its analysis; **Yayat Sudrajat** contributed tothe mapping; **Eko Yulianto** contributed tothe correction of the article’s writing; **Triyono** and **Vera Bararah Barid**contributed to theimplementation of the surveys, including collection and processing of the data questionnaires.

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Funding Information and Conflicts of Interest

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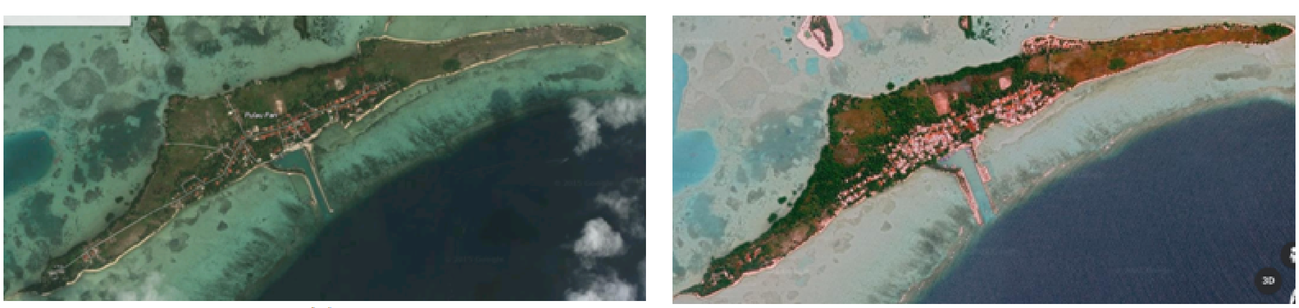
Figures



(a) (b)

Figure 1

Aerial imagery of Pari Island taken from Google Earth for the years (a)2015 and (b) 2021.

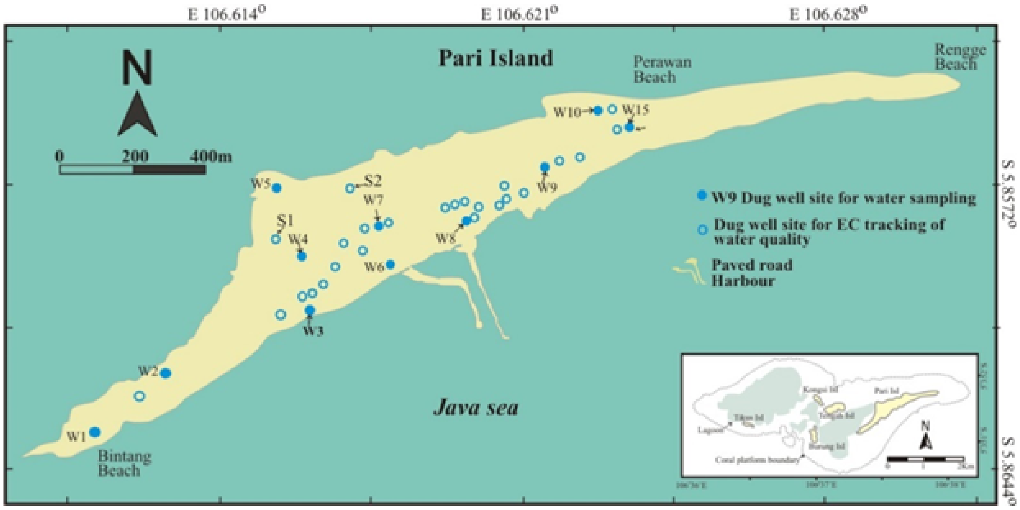


Figure 2

Map of Pari Island and dug well locations where water samples were collectedfor hydrochemical analysis.

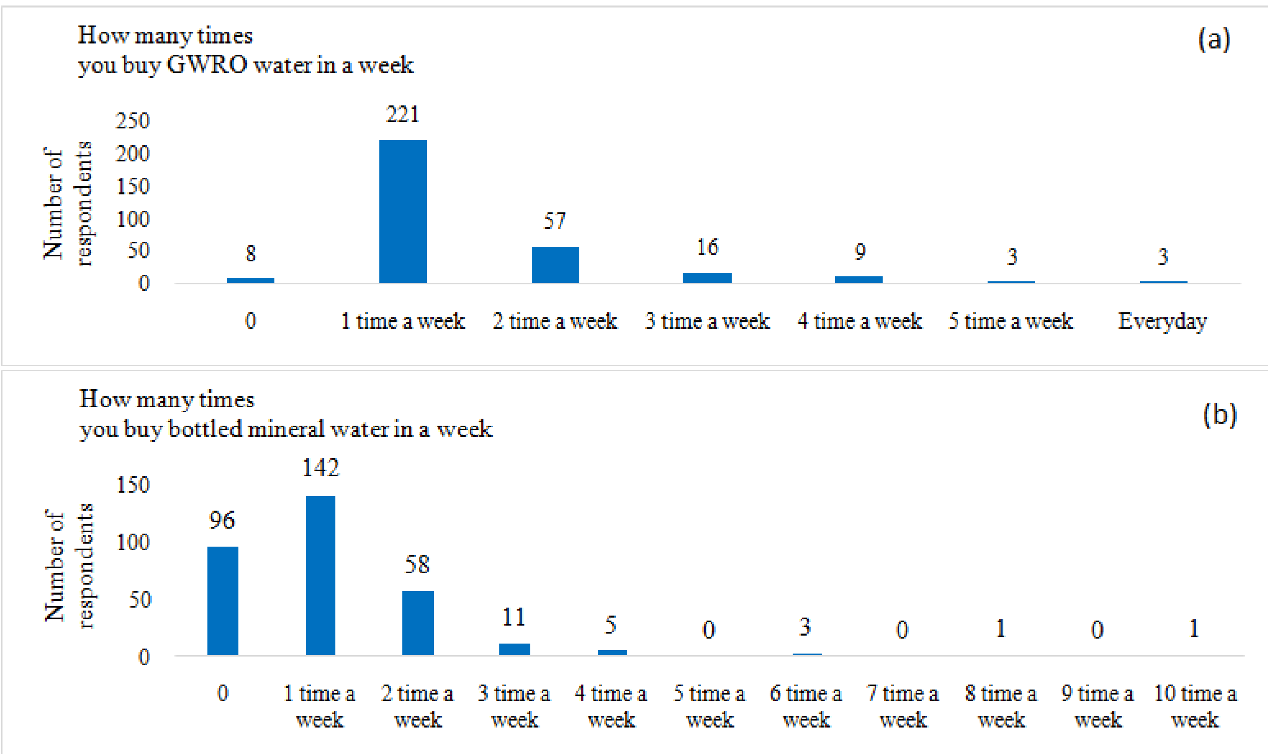


Figure 3

Weekly drinking water needs of residents categorized according to purchases from either a)the GWRO wellor b) bottled mineral water.

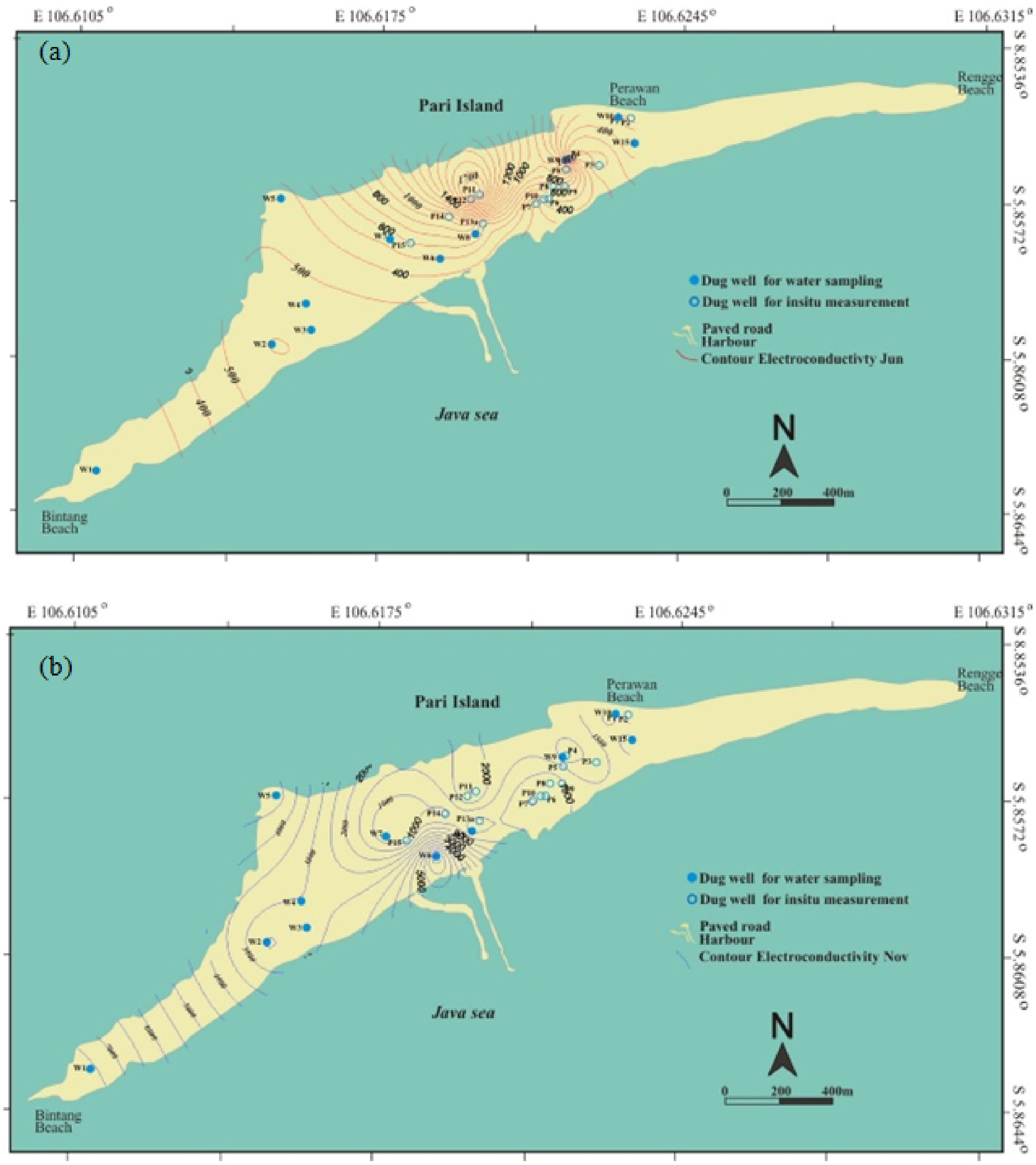
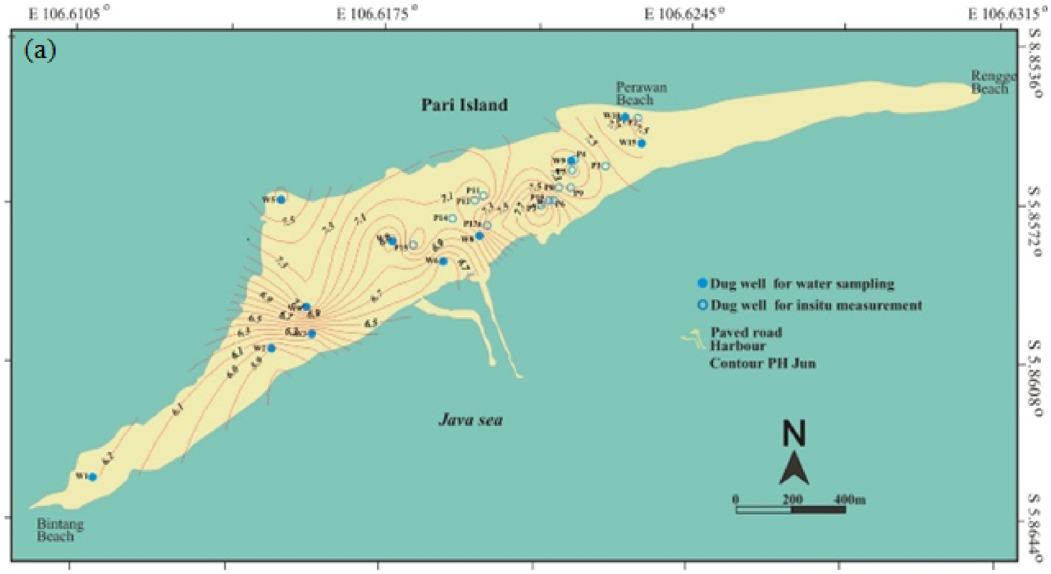


Figure 4

Electrical conductivity distribution onPari Island in (a) June 2021and (b)November 2021.



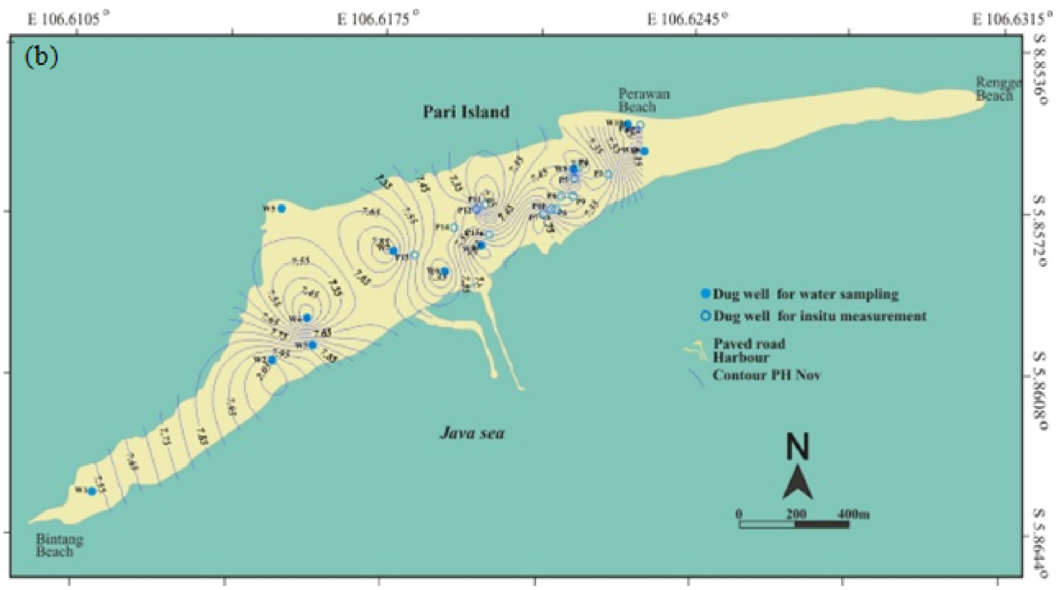


Figure 5

pH distribution on Pari Island in (a) June 2021and (b) November 2021.

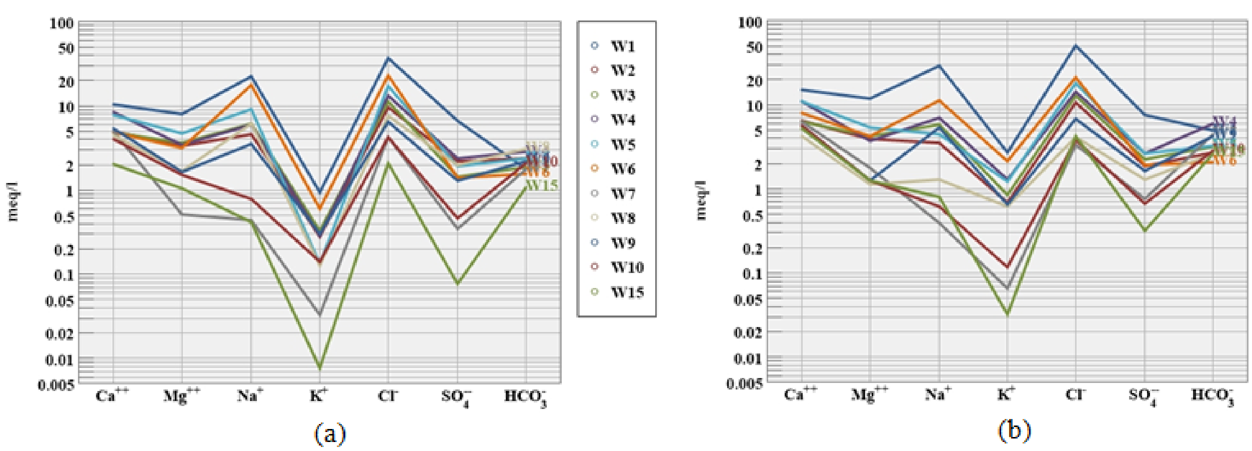


Figure 6

Schoeller diagramsshowingion concentration of Pari Island groundwater in (a) June 2021 and (b) November 2021.

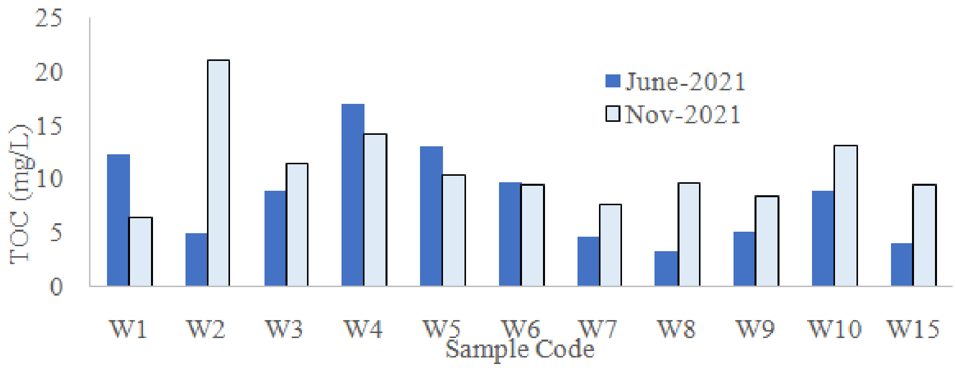


Figure 7

TOC of groundwater inJune 2021 and November 2021.

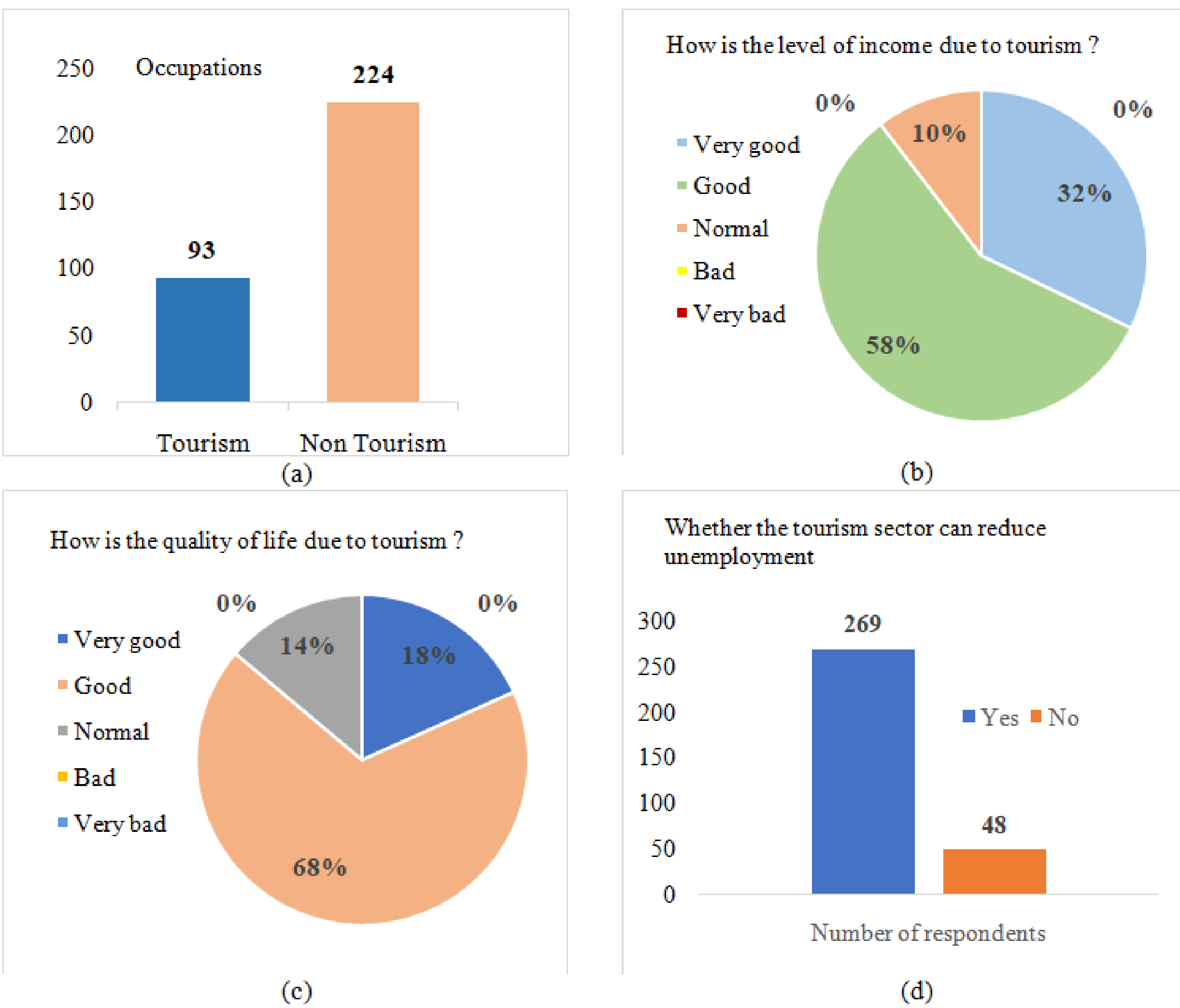


Figure 8

Questionnaire responses relating to the tourism sector and its influence on the economy of the people on Pari Island.

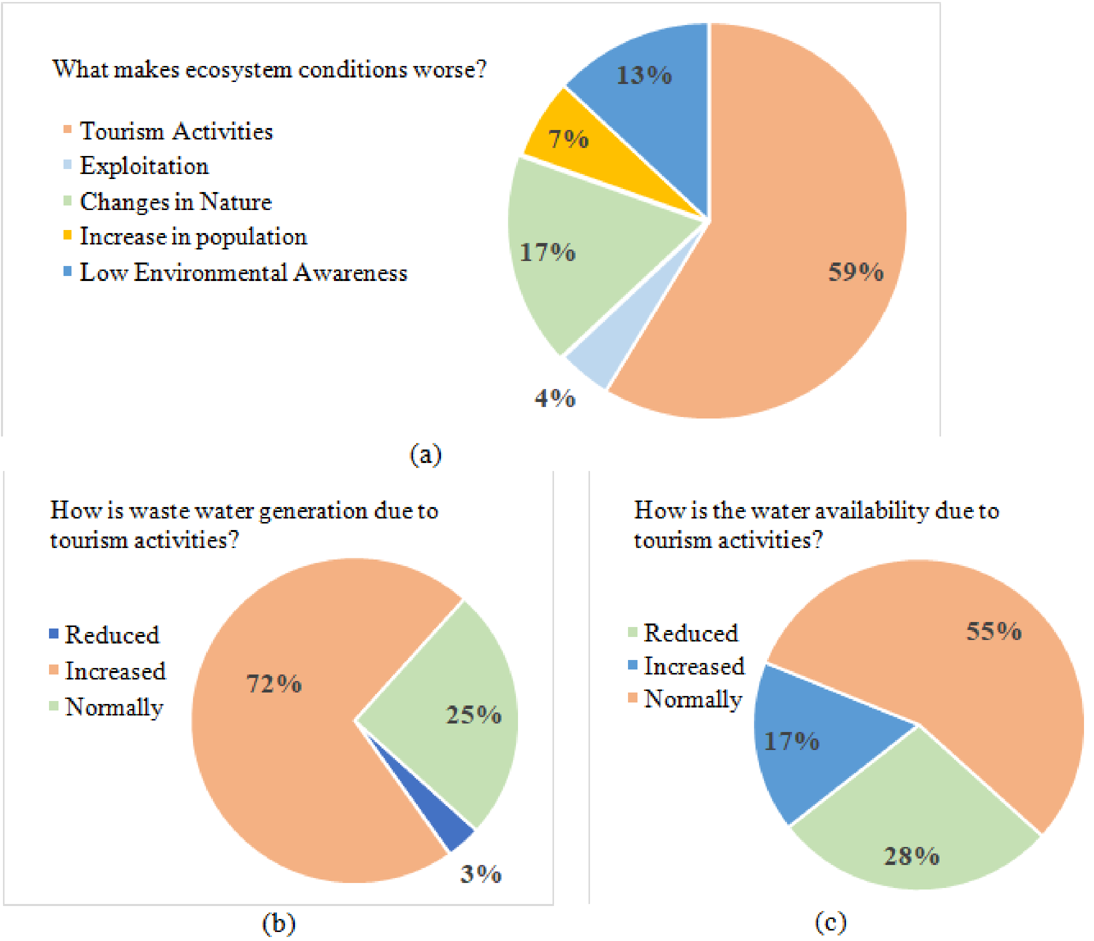


Figure 9

Questionnaire responses relating to impactsoftourist activities on water availability and the environment onPari Island.

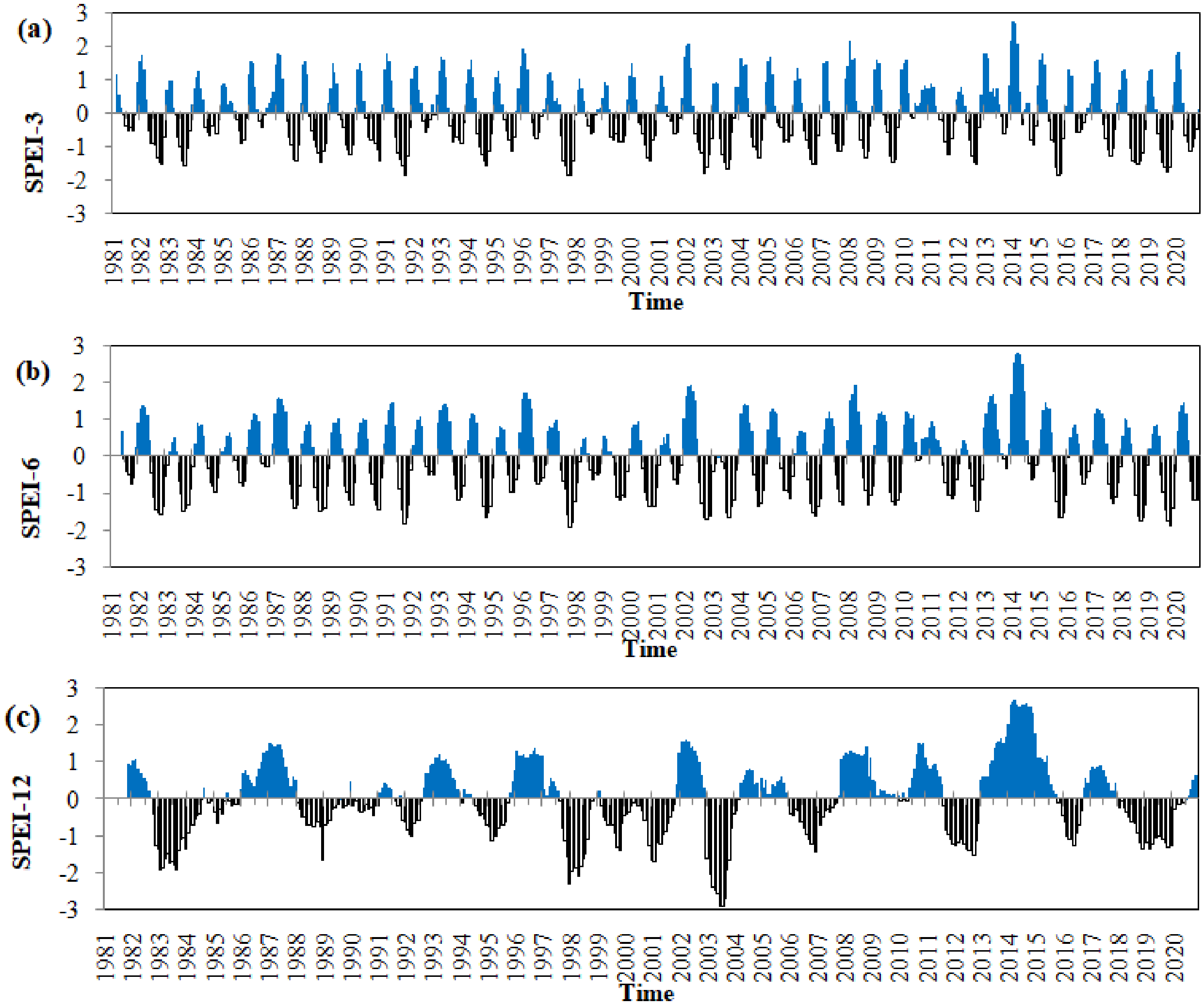


Figure 10

Graphs of Standardized Precipitation Evapotranspiration Index (SPEI) of 3-month timescale (a), 6-month timescale (b), and 12-month timescale (c) of Pari island for a period from 1981 to 2020.

Figure 11

Plots of strongest yearly magnitudes from (a) SPEI-3 and (b)SPEI-12.

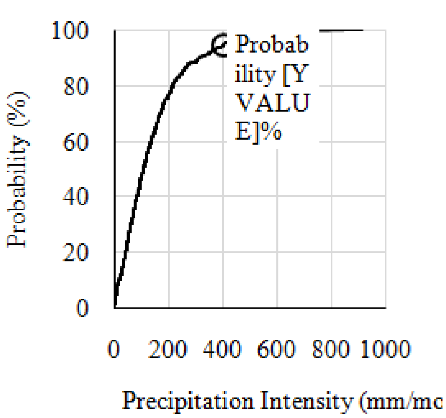


Figure 12

Distribution curve of precipitation intensity in the period from1981 to 2020.

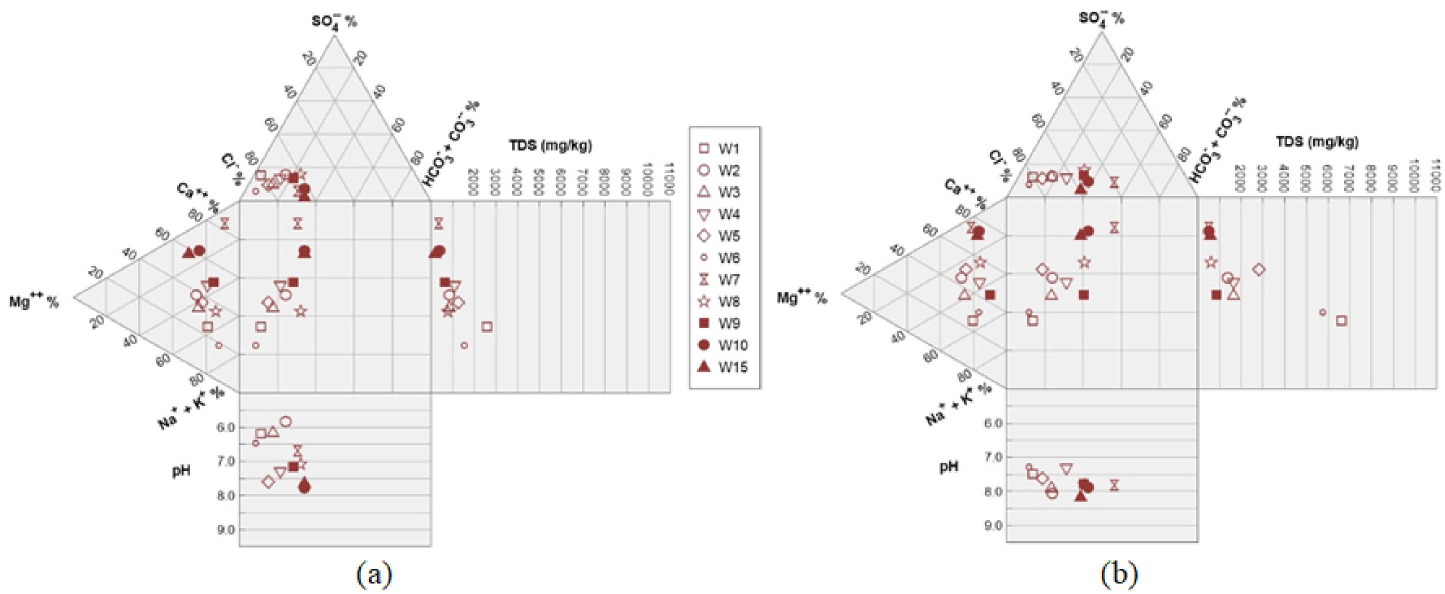


Figure 13

Durof diagrams showing the proportions of various ions, pH values, and TDS concentrations for the dug well water samples obtained in (a) June 2021 and (b) November 2021

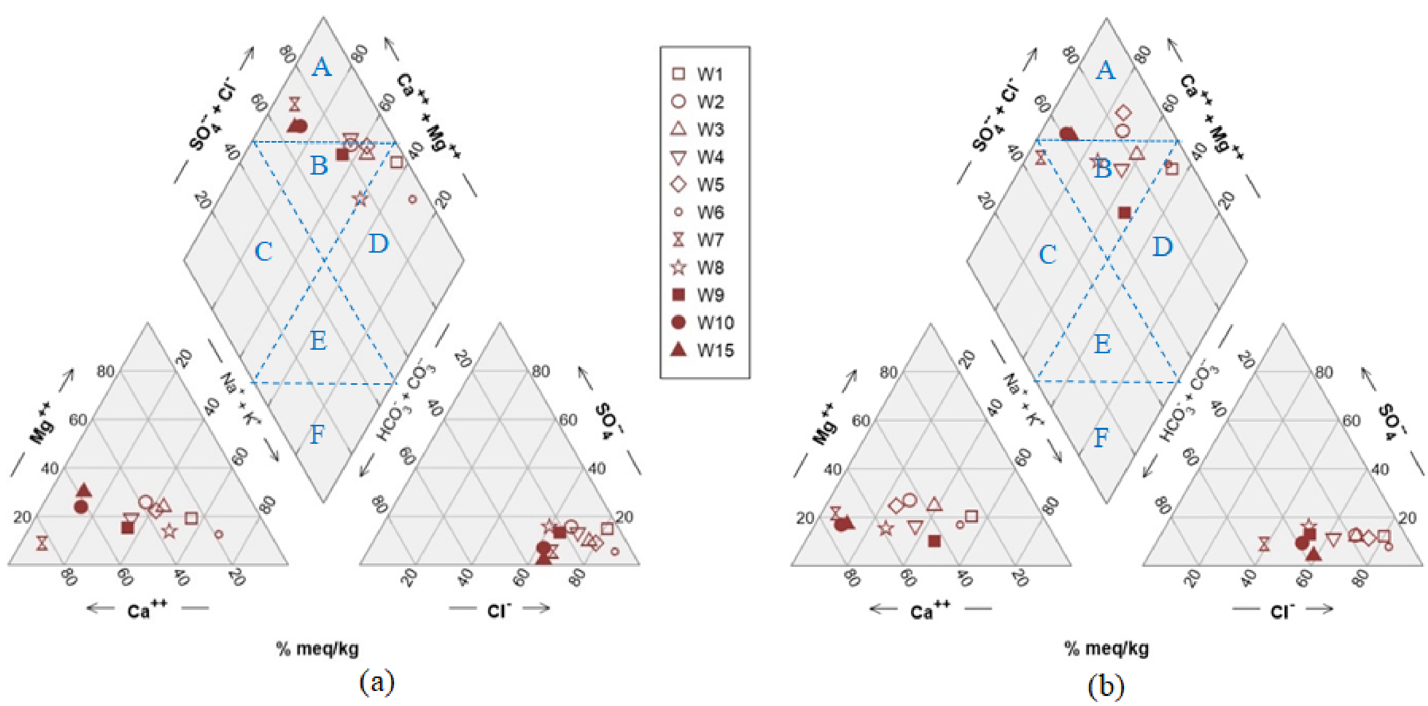


Figure 14

Piper diagram: (a) early June 2021 and (b) mid-November 2021.A:secondary saline water; B:mixed CaMgCl; C:freshwater $CaHCO_3$; D:primary saline water (NaCl); E:mixed $CaNaHCO_3$; F:Alkaline water ($NaHCO_3$)(Gappuci et al., 2020; Snousy et al., 2021).

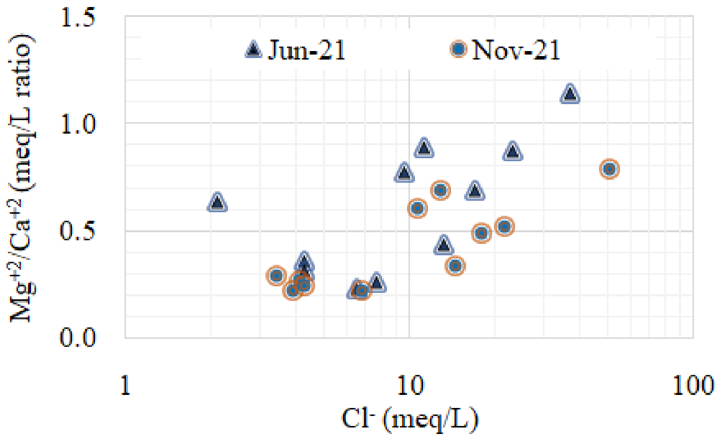


Figure 15

Ionic ratio diagramMg^{2+}/Ca^{2+} versusCl^{-}

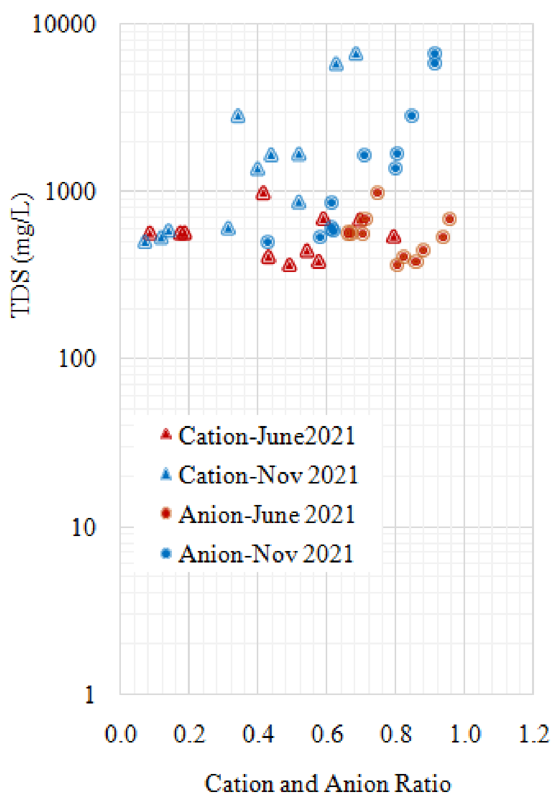


Figure 16

Gibbs diagram showing the geochemical processes controlling the evolution of groundwater geochemistry as well as data measured from the dug wells in June and November 2021.

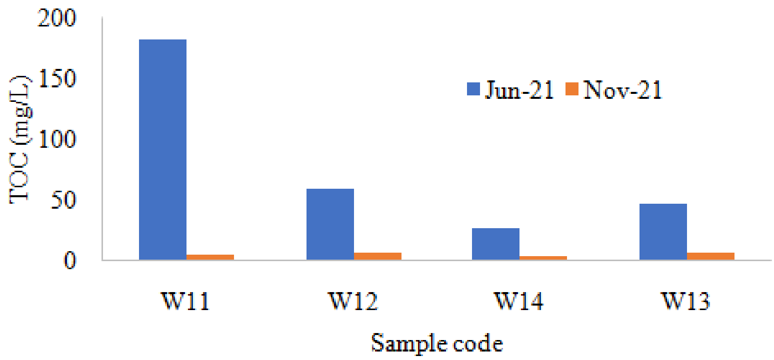


Figure 17

TOC values of seawater in June and November on the west coast (W11), central coast (W12, W14), and east coast (W13).