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Research, assessing and water quality change trends in the Holocene and Pleistocene layers to meet water supply requirements for the coastal area of Binh Thuan province, Vietnam

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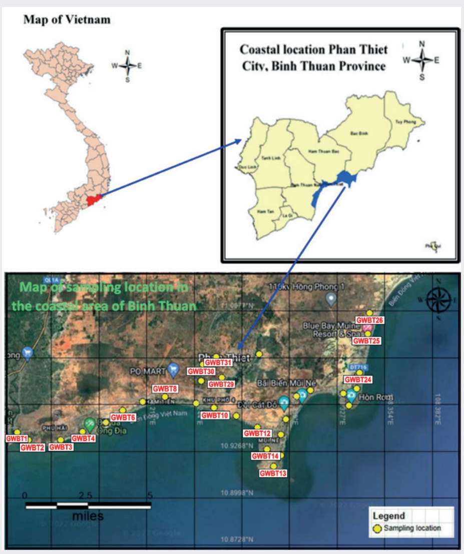
Abstract: The study conducted water sampling at 30 well locations in 3 aquifers with different water depths (X15 m, X24 m, X36 m) in the Holocene and Pleistocene aquifers in the coastal area of Binh Thuan province, Vietnam. Water quality index calculation methods, correlation analysis, and principal component analysis were applied. The results showed that the Groundwater Quality Index fluctuated at "Excellent", accounting for 18.61 %; "Good" accounts for 38.05 %; "Poor" accounts for 20.55 %; the remaining "Very Poor" and "Inappropriate" account for 22.79 %. The most "inappropriate" part is in Ham Thuan, Phan Thiet. Some well sites are not suitable for water supply. In the coastal area of Phan Thiet, the average chloride content during the year is higher than the allowed standard. During 3 years of monitoring, in the dry season, the highest chloride content was 478 mg.L^{-1} at sites GWBT16, GWBT20, and 521 mg.L^{-1} at GWBT24. The results of the principal component correlation analysis of water quality in the X15 m aquifer show a tendency to be more severely affected by high tides during the rainy season.

Key words: Binh Thuan province, correlation analysis, GWQI, Holocene aquifer, Pleistocene aquifer

Graphical abstract



Highlights

- People in the coastal area of Binh Thuan province, Vietnam, mainly use drilled well water, but due to prolonged heat and increased damage caused by climate change, the groundwater level in deep aquifers has decreased.
- There were 30 well locations in 3 aquifers with different depths (X15 m, X24 m, X36 m) sampled at the coastal area of Binh Thuan, Vietnam to conduct research.

1 Introduction

Most people in the coastal area of Binh Thuan province use drilled well water, but due to prolonged heat and increased damage from climate change, groundwater levels have decreased in deep aquifers. In addition, deeper wells contain a lot of salty water due to the influence of sedimentary history, craft village activities, the tradition of processing anchovies, and the fish sauce of residents over the years. Binh Thuan province's groundwater resources are divided into two porous aquifers, four aquifers and fissure aquifer zones, geological formations that are very poor in water or contain no water. The results of assessing exploitable reserves of groundwater in Binh Thuan province have shown that the distribution area of freshwater aquifers is about 4,080.7 km^2, with exploitable reserves of 652,290 m^3.day^{-1} (DOWR, 2017).

Currently, the exploitation of groundwater sources in the province has 29 projects, with a total flow of 14,210 m^3.day^{-1}.

In Binh Thuan, domestic water demand in the province is met by only 40 % from surface water; the rest is mostly exploited from groundwater sources, especially by hotels serving coastal tourists of the province (DOWR, 2021). Vietnam's geological structure is characterized by aquifers mainly found in tectonic rupture zones and karst, basalt, or sedimentary rocks. Groundwater in coastal areas is mainly exploited in porous and fractured aquifers (Thang, 1999). The porous aquifers of the Binh Thuan coastal area are formed in Quaternary unconsolidated sediments. These aquifers have the characteristics of laminar groundwater flow, changing with seasons and coastal dynamics. The source of additional water reserves for this aquifer is mainly water seepage from rainwater and runoff water from mountains and from other aquifers along the coast. The water reservoir thickness in these sediments can reach 5–10 m, even up to 25–30 m in some places, with hydraulic gradient usually small, about 0.005 to 0.01. The common thickness of aquifers is usually about 5–10 m (Viet, 2023). Fractured aquifers consist mainly of fractured rock masses of basalt formations and terrigenous sediments. The hydraulic characteristics of water flow in this aquifer represent a turbulent flow. One of the widely used and effective methods of assessing the groundwater quality is the Groundwater Quality Index (GWQI).

GWQI is a quantitative assessment method of the groundwater quality, expressed through a scale, which is an important parameter for zoning groundwater quality. The GWQI is widely used worldwide, calculation formula was developed to evaluate groundwater quality in Al Najaf City, Iraq (Brown et al., 1972). These authors used the World Health Organization's domestic allowable limit values to calculate the weights. The GWQI index is also widely used in the environmental field, such as for studying groundwater quality developments and evaluating environmental quality parameters in Bangladesh (Doza et al., 2016), Turkey (Varol et al., 2015), Egypt (Masoud et al., 2018), and Japan (Shrestha et al., 2007).

In Vietnam, the GWQI is still widely used in research to evaluate groundwater quality depending on use purposes and regions. A study of the GWQI index in groundwater in Ba Ria-Vung Tau used weighted values, based on the importance of the indicators and showed that in the dry season, it fluctuates in the range of 10–271, respectively, with water quality declining from "Good" to "Very Poor". For the rainy season, the GWQI index value is higher than in the dry season and ranges from 15–403, corresponding to a decline in water quality from "Good" to "Unsuitable" (Au et al., 2020). However, currently, there is no research using this method to evaluate groundwater quality in Holocene and Pleistocene sedimentary aquifers for coastal areas for tourism exploitation in Binh Thuan province, Vietnam. In addition, the correlation and relationship between the evolution of groundwater quality in these aquifers over time (rainy season, dry season) and space (high tide, low tide) have not been given due attention in this field, considering the current climate change situation.

The purpose of this study is to evaluate the current status of groundwater quality and consider its correlation in space and time to predict future developments. Based on the results, the study proposes timely solutions to ensure quality water supply to serve the province's coastal tourism development needs and the strategy to protect the water resources of the entire region.

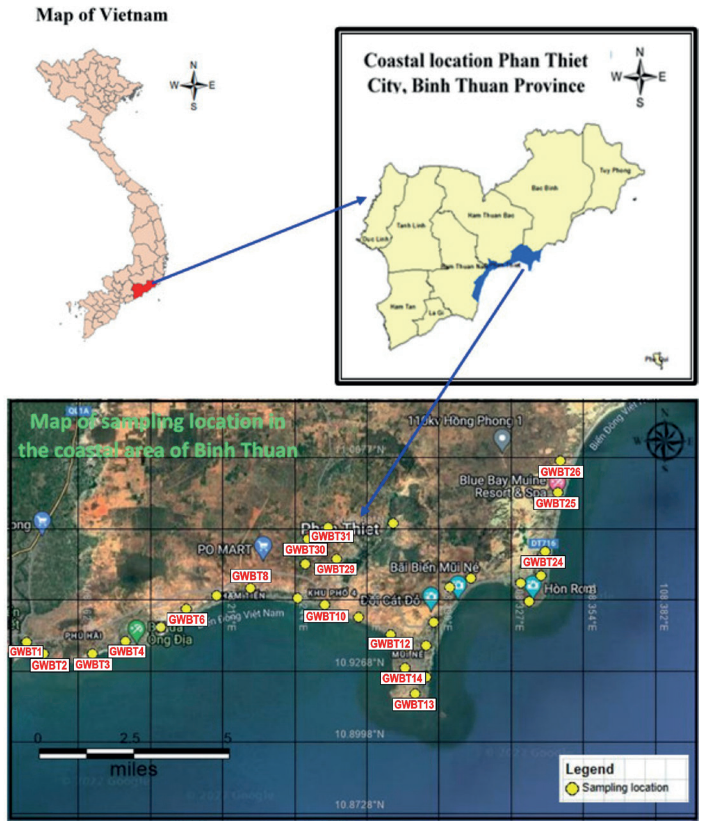


Fig. 1. Sampling area in Binh Thuan province.

Tab. 1
Site coordinates of studied wells

No.	Sampling site name	Coordinates		Water depth [m]	Aquifer	Stratigraphic characteristics
1	GWBT-1	N 10° 56′ 20.1″	E 108° 08′ 33.0″	10.120	X15 m	From the ground to a depth of 15 m, it contains mainly Holocene sediments, easily affecting the environment of recharge water sources. It is a shallow vascular layer, almost pressureless. The main composition of this aquifer includes small to medium-grained sand of white-grey color, containing ilmenite, the lower part contains grit, gravel, pebbles and a little clay powder.
2	GWBT-2	N 10° 56′ 00.7″	E 108° 08′ 54.5″	11.200		
3	GWBT-3	N 10° 55′ 58.0″	E 108° 10′ 01.7″	10.291		
4	GWBT-4	N 10° 56′ 14.8″	E 108° 10′ 46.0″	10.213		
5	GWBT-5	N 10° 56′ 34.4″	E 108° 11′ 36.4″	10.102		
6	GWBT-6	N 10° 56′ 51.1″	E 108° 12′ 05.5″	11.322		
7	GWBT-7	N 10° 57′ 20.2″	E 108° 12′ 52.3″	10.218		
8	GWBT-8	N 10° 57′ 31.5″	E 108° 13′ 37.8″	11.234		
9	GWBT-9	N 10° 57′ 16.1″	E 108° 14′ 42.4″	10.109		
10	GWBT-10	N 10° 57′ 07.0″	E 108° 15′ 19.9″	10.200		
11	GWBT-11	N 10° 56′ 49.1″	E 108° 16′ 07.0″	17.172	X24 m	From the ground to a depth of 24 m, it consists of Holocene sediments and Pleistocene sediments. The stratigraphy of this aquifer mainly consists of white-grey and yellow-grey sand, fine sand grains mixed with Holocene clay silt.
12	GWBT-12	N 10° 56′ 25.5″	E 108° 16′ 50.5″	18.968		
13	GWBT-13	N 10° 56′ 09.6″	E 108° 17′ 12.6″	17.110		
14	GWBT-14	N 10° 55′ 40.2″	E 108° 17′ 10.0″	18.218		
15	GWBT-15	N 10° 55′ 06.2″	E 108° 17′ 24.6″	17.549		
16	GWBT-16	N 10° 55′ 27.7″	E 108° 17′ 38.1″	17.222		
17	GWBT-17	N 10° 56′ 17.6″	E 108° 17′ 38.3″	17.306		
18	GWBT-18	N 10° 56′ 43.0″	E 108° 17′ 49.4″	18.813		
19	GWBT-19	N 10° 57′ 30.7″	E 108° 18′ 12.1″	18.109		
20	GWBT-20	N 10° 57′ 42.1″	E 108° 18′ 39.0″	18.287		
21	GWBT-21	N 10° 57′ 36.1″	E 108° 19′ 49.0″	24.251	X36 m	From the ground to a depth of 36 m, it is mainly Pleistocene sediments. The main stratigraphy of this aquifer consists of yellow-brown and red-brown sand, fine sand grains mixed with Pleistocene clay silt.
22	GWBT-22	N 10° 57′ 40.1″	E 108°20′06.2″	24.199		
23	GWBT-23	N 10° 57′ 47.6″	E 108° 20′ 16.0″	24.197		
24	GWBT-24	N 10° 58′ 16.5″	E 108° 20′ 23.9″	24.233		
25	GWBT-25	N 10° 59′ 33.6″	E 108° 20′ 39.7″	24.000		
26	GWBT-26	N 11° 00′ 09.1″	E 108° 20′ 50.2″	24.292		
27	GWBT-27	N 10° 58′ 58.7″	E 108° 16′ 54.6″	24.310		
28	GWBT-28	N 10° 58′ 06.8″	E 108° 15′ 35.6″	24.111		
29	GWBT-29	N 10° 58′ 00.9″	E 108° 14′ 53.8″	24.219		
30	GWBT-30	N 10° 58′ 34.8″	E 108° 14′ 56.6″	24.202		

2 Materials and Methods

2.1 Study area and investigative surveys

Holocene aquifers are shallow, close-to-ground aquifers that are easily contaminated directly from discharge sources. They are unpressurized aquifers, with a shallow water level that fluctuates seasonally and tidally, rising and falling twice a day with an amplitude ranging from 0.5–0.7 m. The aquifer in Holocene sediments (qh) of the entire Binh Thuan province is quite widely distributed, covering an area of about 710.5 km^2. The total thickness of Holocene sediments varies greatly from 5–50 m and include many different sources of replenishment. The main sources of additional water supply for these sediments are rainwater and permeable surface water. These sediments are composed of small- to medium-grained quartz sand, white grey in color, containing ilmenite. The lower part has gravel, and pebbles mixed with a little clay silt, with a thickness of 10–15 m (Phu et al., 2020a). This is the first aquifer to receive direct rainwater and discharge from residential areas and industrial zones.

Pleistocene sediments are mainly composed of marine, river-sea, and sediments. These sediments typically do not have a separate waterproof layer. The thickness of the Pleistocene sediment layer ranges from 2 to 25 m, commonly from 8 to 12 m. Their main composition includes sand mixed with silt-clay, silt-clay mixed with yellow sand, and white quartz sand, and the lower part has a thin layer of pebbles and gravel. The additional supply source for these sedimentary layers is direct rainwater infiltration (Phu et al., 2022a).

2.2 Sampling site and analysis method

Samples were taken at hotels and motels that had private wells drilled to serve tourists, along the coast of Binh Thuan province (Fig. 1). Coordinates and names of coded wells and different water extraction depths are presented in Tab. 1.

The study surveyed and took samples at 30 wells in both the rainy and dry seasons in three years 2021, 2022, and 2023. Using specialized machines, pH, dissolved oxygen (DO), electrical conductivity (EC), and oxidation-reduction potential (Eh) are measured on-site to determine the basic physicochemical characteristics of groundwater samples taken from drilling wells at various elevations that serve as domestic water sources for hotels. The depth of the wells surveyed in the study ranges from a minimum water level of 0.5 m to a maximum water level of 40 m. A total of 2 samples are required to be collected at each site. Sampling was conducted every 6 months, both during the dry and rainy season throughout the year. In Binh Thuan province, the rainy season extends from May to December, while the dry season lasts from January to April. The sampling work has been carried out during the period of 2019–2021. The groundwater sampling process follows the requirements specified in TCVN 6663 (ISO 5667) (Tab. 2).

Tab. 2

Analytical parameters and standards

No.	Parameter	Units	Standard and methods
1	pH	–	TCVN 6492:2011
2	TH	mg/L	TCVN 6224:1996
3	TDS	mg/L	TCVN 9462:2012 ASTM D5284-09
4	SO_4^{2-}	mg/L	SMEWW 5220C:2012
5	Cl^-	mg/L	TCVN 6194:1996
6	$N–NH_4^+$	mg/L	SMEWW 4500-NH_3.B&F:2012
7	$N–NO_3^-$	mg/L	SMEWW 4500-NO_3^-.E:2012
8	Cu^{2+}	mg/L	SMEWW 3113B:2012
9	Fe^{2+}	mg/L	SMEWW 3113B:2012
10	F^-	mg/L	SMEWW 3113B:2012
11	Coliforms	CFU/100 ml	TCVN 6187-2: 1996

A total of 360 water samples from the Holocene and Pleistocene aquifers in Binh Thuan coastal area were analysed for physicochemical parameters. The water sample was quickly analysed for 5 parameters at the sampling scene including temperature (°C), pH, desolved oxygen (DO), electrical conductivity (EC), oxygen reduction potential (ORP), whereas 10 parameters at the national lab and the Southern Institute of Environment and Circular Economy (IECES) including total hardness (TH), total dissolved solids (TDS), sulphate (SO_4^{2-}), ammonium as N (NH_4^+), nitrate as N (NO_3^-), iron (Fe^{2+}), chloride (Cl^-), copper (Cu^{2+}), fluoride (F^-) and coliform parameters.

2.3 GWQI calculation method

The Ground Water Quality Index (GWQI) is a useful tool for establishing water quality and indicating the overall impact of chemical composition on water quality. GWQI is a quantitative description method of water quality and usability, expressed through a scale, and is an important parameter for zoning groundwater quality (Varol et al., 2015). This study used Brown's (1972) basic arithmetic equations (Brown et al., 1972) to calculate the GWQI index. Limit values of water quality indicators are given in QCVN 09:2023/MONRE (National technical regulation on ground water quality in Vietnam). The groundwater quality assessment scale is shown in Tab. 3.

Tab. 3
Water quality assessment scale using GWQI value

GWQI value	Rating of water quality
< 25	Excellent
25–50	Good
51–75	Poor
76–100	Very poor
> 100	Unsuitable

The calculation steps are as follows:

i) Weight distribution (ωi) for each parameter based on their importance to groundwater quality,
ii) Calculate relative weight (Wi) using equation (1),
iii) Calculate the quality assessment scale (qi) for each indicator according to equation (2),
iv) Determine SIi for each indicator according to equation (3),
v) Each survey sample is calculated GWQI using equation (4).

$$W_i = \frac{\omega_i}{\sum_{i=1}^{n} \omega_i} \quad (1)$$

$$q_i = \frac{C_i}{S_i} \text{ x } 100 \quad (2)$$

$$SI_i = W_i \, x \, qi \quad (3)$$

$$GWQI = \sum_{i=1}^{n} SI_i \quad (4)$$

Where: ω_i is the weight of each indicator and n is the number of survey indicators; W_i is the relative weight of each indicator; q_i is used to evaluate quality based on each specific indicator; C_i is the concentration of each indicator in the water sample ($mg.L^{-1}$); and Si is the standard of each indicator ($mg.L^{-1}$), taken according to QCVN 09:2023/MONRE. After calculating, the study used the GWQI value table corresponding to the water quality assessment level to compare and evaluate as shown in Tab. 3.

2.4 Multivariate correlation analysis

The study conducted correlation analysis, correlation matrix, and r value to evaluate the significance of correlation between water quality parameters in two seasons. The correlation coefficient (r) is a statistical index that measures the correlation between two variables. The correlation coefficient ranges from –1 to 1. A correlation coefficient of 0 (or close to 0) means that the two variables are not related. On the contrary, if the coefficient is –1 or 1, it means the two variables have an absolute relationship. If the value of the correlation coefficient is negative ($r < 0$), it means that when value x increases, value y decreases (and vice versa, when value x decreases, value y increases); If the value of the correlation coefficient is positive ($r > 0$), it means that when value x increases, value y also increases, and when value x decreases, value y also decreases, respectively. The correlation coefficient (r) is only meaningful if and only if the observed significance level is < 0.05 (Tuan, 2014).

2.5 Principal Component Analysis (PCA)

The PCA method represents high-dimensional data on a space with orthogonal bases, meaning if we consider each basis in the new space as a variable then the image of the original data in this new space is represented, expressed through independent (linear) variables. The PCA method finds a new space with the criterion of trying to reflect as much of the original information as possible. This allows consideration of using only a small number of variables to explain the data (Tuan, 2014).

Finding PCs that are a function of original variables:

$$PC_k = \delta_{1k}X_1 + \delta_{2k}X_2 + \cdots + \delta_{pk}X_p \quad (5)$$

We have p correlated variables: X1, X2, …, Xp obtained from n subjects. We want to find a method of transformation of X (n x p) matrix such that:

$$Y=\delta_1 X_1 + \delta_2 X_2 + \cdots + \delta_p X_p \quad (6)$$

Where, Y (vector of k) is called “principal components”; δ (δ1, δ2, …, δp): vector of weights such that:

$$\delta_1^2 + \delta_2^2 + \cdots + \delta_p^2 = 1 \quad (7)$$

→ Maximize the variance of data (X).

Find δ so that:

$$var(\delta^T X)=\delta^T var(X)\delta \quad (8)$$

The matric C = var(X) is actually covariance of X_i

The variance of Y (PC) is called the eigenvalue. According to the Kaiser criterion, PCs with eigenvalues > 1 and the number of PCs with total variance explained between 50 % and 70 % were kept constant (Tuan, 2014).

2.6 Representation of analytical data

The calculation and statistical results were performed using Microsoft Excel software, and the results of correlation analysis and PCA analysis were processed using R4.2.0 programming language (http://cran.r- project.org).

3 Research results and discussion

3.1 Results of analysing coastal groundwater quality according to the GWQI index

The monitoring data of the two sampling periods were statistically calculated and shown in Tab. 4. Measurement results of some water quality parameters at the sampling sites. They are including temperature, pH, DO, EC, and

ORP reflected the basic physicochemical properties of the water sample at the time of sampling (Tab. 4).

Monitoring results have shown that the pH value of groundwater in the study area during sampling periods in the dry and rainy seasons in 2021, 2022, and 2023 are all within the allowable limits of QCVN 09:2023/MONRE (National technical regulation on groundwater quality in Vietnam). The difference and balance in the pH value of groundwater inside the aquifers is due to the composition of soil and rock or the water supplement environment.

In general, over the years surveyed, the pH in the rainy season is lower than in the dry season. Low pH values cause corrosion to plumbing systems and equipment, making them susceptible to wear and tear, causing waste of clean water. In addition, corrosive substances released from equipment and metal pipes such as lead, copper, iron, and zinc enter the water supply, affecting the health of water users in the area.

The water temperature also did not have a big difference between the two sampling periods, the smallest average temperature value was 25.5 °C and the largest was 28.3 °C. The redox potential (ORP) in the study area is mostly negative and ranges from –54 mV to –107 mV in the dry season, and from –38 to –123.5 mV in the rainy season. Thus, at most well sites, the water contains many antioxidants. The average EC conductivity represents a high amount of ions present in the water, indicating high salinity, in the dry season especially with quite high values from 306.7 $\mu S.cm^{-1}$ to 401.9 $\mu S.cm^{-1}$.

Based on the survey results at the sites of drilled and dug wells in the Holocene aquifer, it has been shown that the water has no pressure, the shallow water level varies

Tab. 4

Summary of average measurement results of some water quality parameters at the sampling sites

Quick measurement results of some water quality parameters in 2021										
Value	**Dry-season**					**Rainy-season**				
	Temper [°C]	**pH**	**DO [mg.L⁻¹]**	**ORP [mV]**	**EC [µS.cm⁻¹]**	**Temper [°C]**	**pH**	**DO [mg.L⁻¹]**	**ORP (mV)**	**EC [µS.cm⁻¹]**
QCVN 09:2023/ MONRE	–	5.5–8.5	–	–	–	–	5.5–8.5	–	–	–
Minimum	25.5	5.5	3.2	–330	7.5	20.4	4.9	3.3	–349	5.1
Maximun	27.8	7.6	5.2	116	673	25.6	7.2	3.9	102	73
Mean	26.7	6.5	4.2	–107	340.3	23.0	6.0	3.6	–123.5	39.1
Quick measurement results of some water quality parameters in 2022										
Value	**Dry-season**					**Rainy-season**				
	Temper [°C]	**pH**	**DO [mg.L⁻¹]**	**ORP [mV]**	**EC [µS.cm⁻¹]**	**Temper [°C]**	**pH**	**DO [mg.L⁻¹]**	**ORP [mV]**	**EC [µS.cm⁻¹]**
QCVN 09:2023/ MONRE	–	5.5–8.5	–	–	–	–	5.5–8.5	–	–	–
Minimum	27.1	5.2	2.6	–300	7.8	21.6	5.7	3.5	–309	5.6
Maximun	28.5	7.6	5.2	156	796	29.3	7.0	4.2	115	93
Mean	27.8	6.4	3.9	–72	401.9	25.5	5.8	3.9	–38	49.3
Quick measurement results of some water quality parameters in 2023										
Value	**Dry-season**					**Rainy-season**				
	Temper [°C]	**pH**	**DO [mg.L⁻¹]**	**ORP [mV]**	**EC [µS.cm⁻¹]**	**Temper [°C]**	**pH**	**DO [mg.L⁻¹]**	**ORP [mV]**	**EC [µS.cm⁻¹]**
QCVN 09:2023/ MONRE	–	5.5–8.5	–	–	–	–	5.5–8.5	–	–	–
Minimum	27.4	5.3	1.7	–250	6.7	24.3	5.4	2.5	–359	7.6
Maximun	29.2	7.7	4.1	142	606	28.3	7.8	4.0	176	113
Mean	28.3	6.5	2.9	–54	306.7	26.5	6.7	3.5	–91.5	60.3

Notes:“–”: Not regulated; “Temper”: temperature from m to 5.0 m. The flow rate at exposed points is Q_0 = 0.01–0.3 L.s^{-1}. The chemical composition in the Holocene sedimentary aquifer is a mixture of bicarbonate chloride and bicarbonate sodium chloride. Chloride (Cl^-) content varies greatly: 3.0–478.0 mg.L^{-1}. Particularly in Phan Thiet, total chloride salt varies from 4.0–478 mg.L^{-1}. In particular, in the coastal of Phan Thiet, the average chloride salt content of the well during the year is very high compared to standards such as GWBT16, GWBT17, GWBT18, GWBT19, GWBT20 in all 3 years, and it is high in the dry season (Specifically, in the dry season at low tide, in 2022 and 2023, the chloride content has a maximum value of 478 mg.L^{-1} (GWBT16 and GWBT20) and 521 mg.L^{-1} (GWBT24), respectively).

Monitoring data showed that groundwater parameters are affected by geochemical and geological conditions such as average TH and TDS in the groundwater in rainy season is lower than in the dry season. This result can be explained by dilution from precipitation water infiltration; In particular, it shows a sharp decrease in concentration between two seasons in open wells. The main source of supply for the Holocene aquifer is rainwater. The two-season water level fluctuation according to monitoring documents is AH = 0.3–0.4 m. Therefore, the water quality in this sediment is susceptible to external environmental influences and has a high possibility of salinity. If used for daily life and tourism needs, the study suggests it is necessary to obtain water from deeper aquifers.

The proportionality constant K is 0.295, it is determined based on QCVN 09:2023/MONRE for physicochemical parameters. The study has determined the influence weights of physicochemical parameters, the results are shown in Tab. 5.

Tab. 5

Weight of water quality parameters according to QCVN 09:2023/MONRE

Number	Parameter	Units	Weight
1	pH	–	0.0347
2	TH	mg.L^{-1}	0.0006
3	TDS	mg.L^{-1}	0.0002
4	SO_4^{2-}	mg.L^{-1}	0.0007
5	Cl^-	mg.L^{-1}	0.0012
6	$N\text{–}NH_4^+$	mg.L^{-1}	0.2950
7	$N\text{–}NO_3^-$	mg.L^{-1}	0.0197
8	Cu^{2+}	mg.L^{-1}	0.2950
9	Fe^{2+}	mg.L^{-1}	0.0590
10	F^-	mg.L^{-1}	0.2950
Total			1.0000

The average value for all three water depths and color spectrum according to the value scale of the GWQI index at coastal sampling sites in Binh Thuan in 2021, 2022 and 2023 is shown in Tab. 6.

According to the water quality assessment color scale of Tab. 3 and the average GWQI values of the 3 aquifers in Tab. 6, it shows that the coastal area of Binh Thuan province mostly has groundwater quality reaching "Excellent" to "Good". Of these, sites that reached levels of excellent, good, poor, very poor, and unsuitable are 18.61 %, 38.05 %, 20.55 %, 10.83 %, and 11.96 %, respectively. Visualization of groundwater quality rates on a rating scale using GWQI values is shown in Fig. 2.

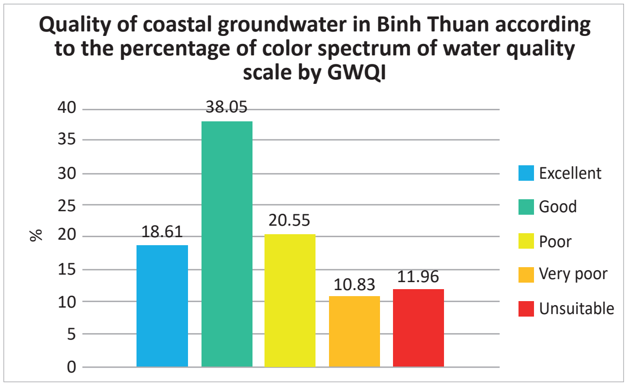


Fig. 2. Coastal groundwater quality in Binh Thuan, Vietnam, according to the percentage of color spectrum of water quality scale by GWQI index.

In general, the majority of water quality at points meets the requirements for water supply. However, it should be noted the decrease in the number of wells reaching the "Excellent" color scale in 2021, and the transition to the majority of the "Good" color scale in the following two years, 2022 and 2023. This shows that groundwater quality is deteriorating and decreasing in quality year by year. In addition, water quality that cannot be used to serve hotels, motels, or local activities ("Unsuitable" corresponds to the red color in the scale of Tab. 3) is concentrated at well sites: GWBT20, GWBT21, GWBT22, GWBT23, GWBT24, GWBT25, GWBT26, GWBT27, and GWBT28. These sites are located at the bay in the territory of Ham Tien and Phan Thiet of Binh Thuan province. Heterogeneity with increased permeability in aquifers is quite favorable for water flow replenishment in aquifers. However, these cracks are also favorable for saline intrusion and pollution from additional sources.

During the years surveyed, the water quality in the aquifers of Holocene and Pleistocene sediments was found to be contaminated by organic substances and high levels of Ammonium. This was attributed to the problem of

Tab. 6
Average GWQI index values and color spectra for all 3 water depths at groundwater sampling sites in the study area in 2022–2023

Site	2021				2022				2023			
	Dry season		Rainy season		Dry season		Rainy season		Dry season		Rainy season	
	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT	LT	HT
GWBT1	29	50	28	39	19	68	37	24	41	33	67	18
GWBT2	8	46	14	3	22	44	53	44	22	46	28	39
GWBT3	3	32	73	17	76	55	43	60	37	36	60	18
GWBT4	72	64	95	4	42	45	32	31	76	33	73	34
GWBT5	13	12	47	10	40	56	35	22	35	88	51	38
GWBT6	15	55	56	6	141	68	36	210	50	37	53	28
GWBT7	30	9	17	8	41	30	56	25	60	26	48	43
GWBT8	8	46	66	3	44	32	42	29	31	37	75	28
GWBT9 38 17			73	125	50	55	52	207	33	44	48	66
GWBT10	37	7	23	29	85	28	42	102	44	45	36	47
GWBT11	26	11	24	8	68	50	60	43	50	29	42	43
GWBT12	30	38	72	23	78	70	40	26	28	37	31	53
GWBT13	3	23	38	8	59	73	41	56	39	38	73	46
GWBT14	5	30	97	39	67	56	33	42	9	52	79	51
GWBT15	29	10	50	89	74	65	30	24	40	34	41	51
GWBT16	23	28	28	24	76	90	71	59	29	26	38	23
GWBT17	19	16	29	4	60	39	88	45	23	30	86	62
GWBT18	8	11	127	52	45	80	56	59	51	39	67	106
GWBT19	28	40	96	5	98	59	91	28	81	64	98	39
GWBT20	133	116	115	8	90	152	79	68	102	57	71	58
GWBT21	35	55	72	127	115	107	89	24	79	83	106	127
GWBT22	158	127	110	3	75	70	80	35	146	114	117	54
GWBT23	159	94	158	5	111	113	119	34	106	122	125	60
GWBT24	72	38	27	275	36	62	138	62	87	80	76	145
GWBT25	13	23	125	23	87	97	106	48	50	93	153	69
GWBT26	13	30	125	30	105	60	68	245	50	64	126	41
GWBT27	12	34	72	39	54	76	119	43	46	77	87	32
GWBT28	8	28	38	39	81	43	68	30	54	45	101	33
GWBT29	24	16	98	17	58	59	97	25	45	43	80	37
GWBT30	3	6	13	25	25	41	45	35	11	40	77	60

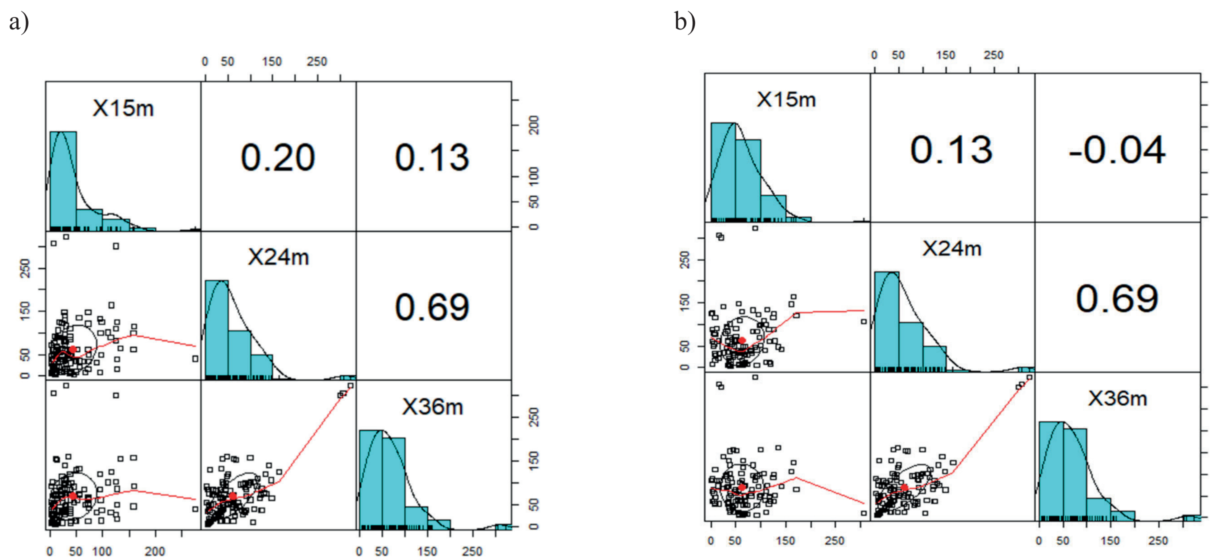
Note: LT-Low tide; HT-High tide

concentrated residential and tourist activities. According to Tab. 5, this factor has an influence weight of 0.2950. Besides, the location of Ham Tien Beach has the shape of a bay, easily concentrating pollutants, salt, and other substances that follow the ocean waves, creating layers of residue and sediment over time.

Results of correlation analysis between GWQI values at 30 well sites in space (high tide and low tide), and over time (dry season and rainy season) at 3 aquifers X15 m, X24 m, X36 m in 3 survey years 2021, 2022, and 2023 are shown in Fig. 3. Results indicate GWQI values at 30 well sites in space and time over 3 years surveyed at 3 levels. containing X15 m, X24 m, and X36 m are all correlated with each other; In particular, in 2021 and 2022, the water quality of the X24 m aquifer and the X36 m aquifer is quite strongly correlated (correlation coefficient r reaches 0.69).

3.2 Analysing the main components and trends of coastal groundwater quality in the province in the coming years

All monitoring sites with GWQI values in the three aquifers of Holocene and Pleistocene sediments surveyed, X15 m, X24 m, and X36 m have seasonal and tidal changes in sea level. We have predicted the evolution of the GWQI value of groundwater in these three aquifers and combined it with the results of correlation analysis in Fig. 4. The study performed principal component analysis. The results of data mining and extraction are shown in Fig. 4.



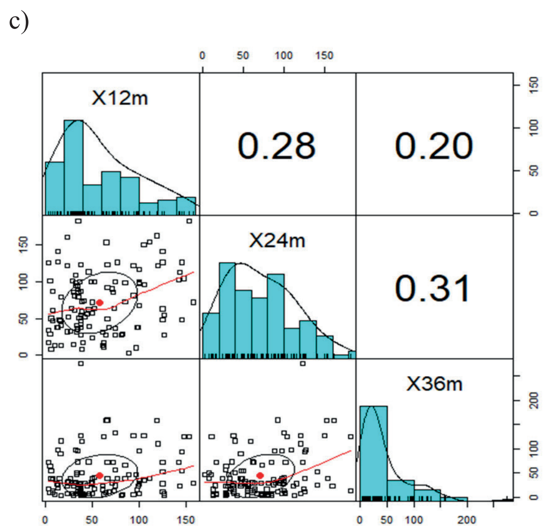


Fig. 3. Correlation matrix between GWQI values at 30 well sites in space and time over 3 years of survey:
a) 2021; b) 2022; c) 2023.

a)

```
> print(pc)
Standard deviations (1, .., p=3):
[1] 1.3273287 0.9656780 0.5528692

Rotation (n x k) = (3 x 3):
           PC1        PC2         PC3
X15m 0.2939663  0.9523077 -0.08181639
X24m 0.6835184 -0.1496143  0.71443556
X36m 0.6681215 -0.2659430 -0.69490137
> summary(pc)
Importance of components:
                          PC1    PC2    PC3
Standard deviation     1.3273 0.9657 0.5529
Proportion of Variance 0.5873 0.3108 0.1019
Cumulative Proportion  0.5873 0.8981 1.0000
```

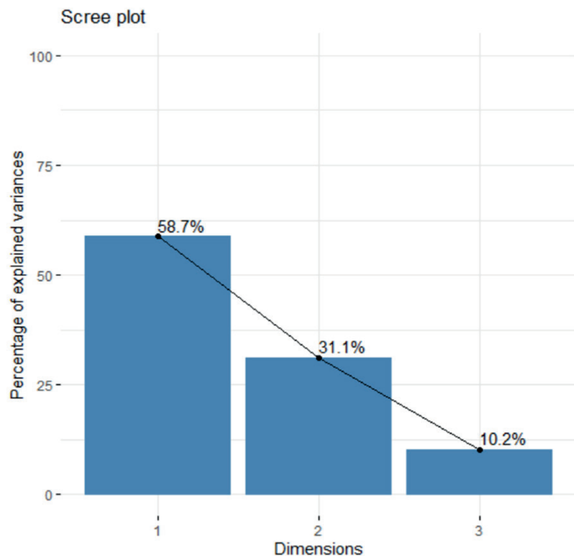
b)

```
> print(pc)
Standard deviations (1, .., p=3):
[1] 1.3021491 1.0071162 0.5386321

Rotation (n x k) = (3 x 3):
            PC1         PC2        PC3
X15m -0.0905821 -0.98201401 -0.1656604
X24m -0.7096697 -0.05305294  0.7025342
X36m -0.6986872  0.18120118 -0.6920999
> summary(pc)
Importance of components:
                          PC1    PC2     PC3
Standard deviation     1.3021 1.0071 0.53863
Proportion of Variance 0.5652 0.3381 0.09671
Cumulative Proportion  0.5652 0.9033 1.00000
```

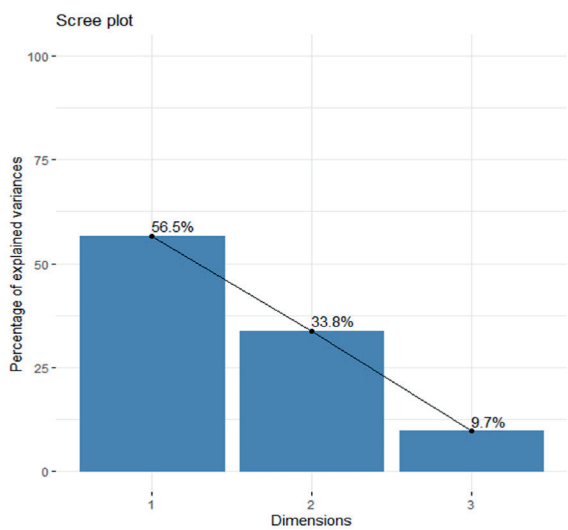
c)

```
> print(pc)
Standard deviations (1, .., p=3):
[1] 1.2357593 0.8968225 0.8176847

Rotation (n x k) = (3 x 3):
           PC1         PC2        PC3
X12m 0.5419293  0.76431805  0.3494718
X24m 0.6204177 -0.08333367 -0.7798316
X36m 0.5669166 -0.63943210  0.5193574
> summary(pc)
Importance of components:
                         PC1    PC2    PC3
Standard deviation     1.236 0.8968 0.8177
Proportion of Variance 0.509 0.2681 0.2229
Cumulative Proportion  0.509 0.7771 1.0000
```

d)



e)



f)

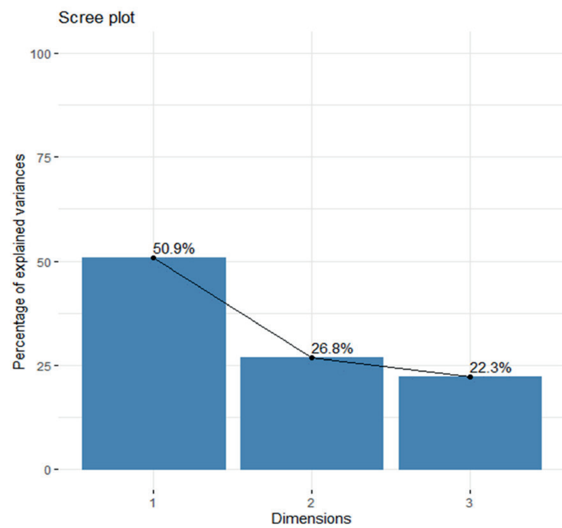


Fig. 4. Results of mining and extracting data of GWQI values at 30 well sites in space and time over the 3 years surveyed:
a) Principal component extraction results of GWQI values in 2021;
b) Principal component extraction results of GWQI values in 2022;
c) Principal component extraction results of GWQI values in 2023;
c) Screen plot chart in 2021;
d) Screen plot chart in 2022;
f) Screen plot chart in 2023.

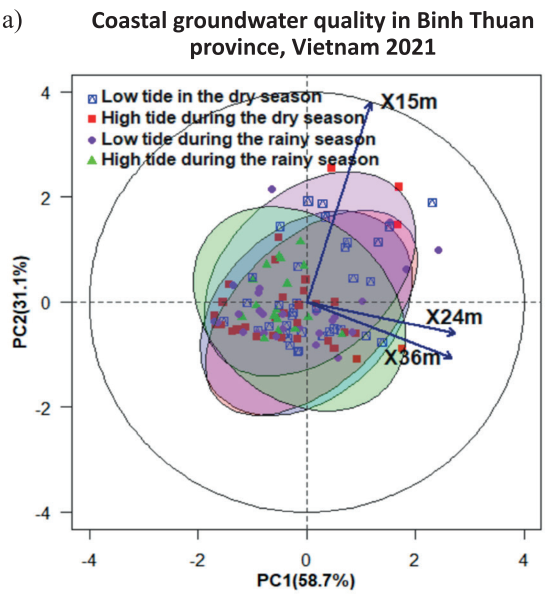
The results of mining and extracting principal components of GWQI values at 30 well sites in space and time during the 3 survey years 2021, 2022 and 2023 show:

i) In 2021 (Figs. 4a and 4d), the research has identified 3 main components including PC1 explains 58.7 % of the data variance, PC2 explains 31.1 % of the data variance and PC3 explains 10.2 % data variance. However, the study only selected PC1 and PC2 to analyse for forecasting because both of these components explained almost all of the data (reaching 89.81 %);

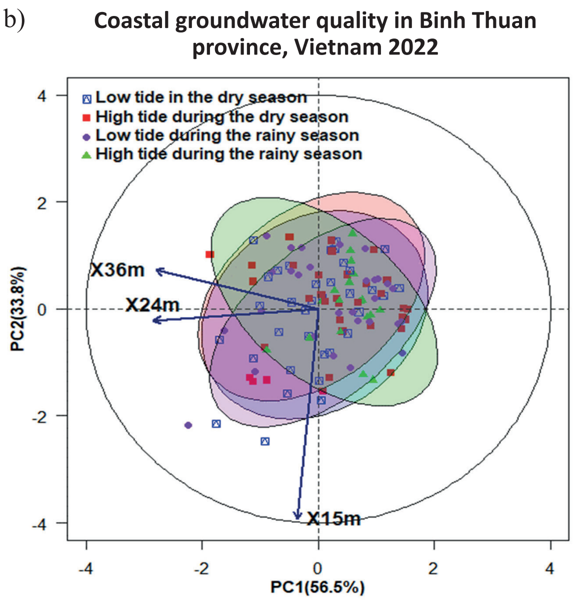
ii) In 2022 (Figs. 4b and 4e), the research has identified 3 main components including PC1 explains 56.5 % of data variance, PC2 explains 33.8 % of data variance and PC3 explains 9.7 % data variance. However, the study only selected PC1 and PC2 to analyze for forecasting because both of these components explained almost all of the data (reaching 77.71 %);

iii) In 2023, similarly (Figs. 4c and 4f), the study has identified 3 main components including PC1 explains 50.9 % of data variance, PC2 explains 26.8 % of data variance and PC3 explains covers 22.3 % of the data variance. However, the study only selected PC1 and PC2 to analyse for forecasting because both of these components explained almost all of the data (reaching 90.33 %).

a)



b)



c)

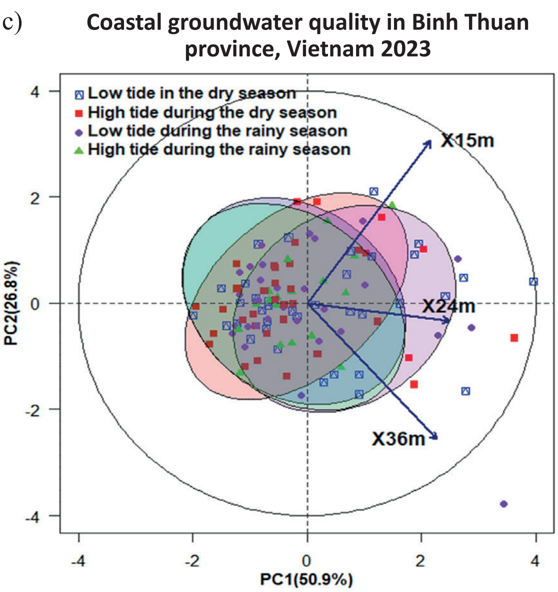


Fig. 5. Groundwater quality characteristics in 3 water depths X15 m, X24 m, and X36 m along the coast of Binh Thuan province during the 3 years surveyed: a) 2021; b) 2022; c) 2023.

The regression equation for the two components PC1 and PC2 according to the three water levels surveyed in 2021, 2022, and 2023 is presented in Tab. 7.

Tab. 7

Regression equation and regression coefficients for main components PC1 and PC2 in the 3 years surveyed

Year	Regression equation for two main components PC1 and PC2	
	PC1	PC2
2021	PC1 = 0.68*X24 m + 0.67*X36 m	PC2 = 0.95*X15 m
2022	PC1 = –0.7*X24 m – 0.69*X36 m	PC2 = –0.98*X15 m
2023	PC1 = 0.62*X24 m + 0.56*X36 m	PC2 = 0.76*X15 m

Notes:
– X15 m: GWQI value at 15m water depth,
– X24 m: GWQI value at 24m water depth,
– X36 m: GWQI value at 36m water depth.

Results of analysing groundwater quality characteristics in 3 water depths X15 m, X24 m, and X36 m coastal Binh Thuan province during 3 years of survey are shown in Fig. 5.

The results of data analysis from Fig.4 and Fig. 5 give the following conclusions: in 2021, the GWQI value of groundwater at the X15 m aquifer is greatly affected at high tide and in the rainy season (PC2) and the remaining 2 layers are both dependent on tide and season. For 2022, similar to the characteristics of 2021, the GWQI value of groundwater at the X15 m aquifer has been greatly affected by high Thuan province during 3 years of survey are shown in Fig. 5 tides, it all depends on the tide and the season. And in 2023, the GWQI value of groundwater at the high tide in the dry season.

3.3 Proposing solutions to prevent and develop coastal groundwater resources in Phan Thiet City, Binh Thuan province

3.3.1 Build water storage, do not allow water flows into the sea

This is a model that has been successfully applied in the world (Phu et al., 2024). When the rainy season comes, many areas of Binh Thuan province are flooded (Ham Thuan Bac district, Tanh Linh district). We have studied geology, geomorphology, hydrogeology, structure of aquifers to come up with a plan to build water storage (on the surface and under the ground).

3.3.2 Water replenishment for aquifers

Areas were selected based on the following conditions:

i) Determining permeability coefficient of the soil cover on the topographic surface in the selected areas for water storage;
ii) Checking the wetting ability of the unsaturated zone and check for the existence of tarnished areas in the unsaturated zone that may adversely affect the water quality;
iii) Checking the water transmission capacity of aquifers;
iv) Field investigation of geology, hydrogeology, geochemistry to select the distribution areas of surface sediments with high permeability coefficient in Binh Thuan. The results of field investigations on geology and hydrogeology of the coastal sand strip distributed from Phan Ri to Ham Tan – Binh Thuan have satisfied the above conditions. These are the suitable areas

The water replenishment for aquifers has been developed in several countries around the world. In Vietnam, the water replenishment for aquifers has been applied in some provinces in the Tay Nguyen area (Phu et al., 2022b). The reference to the literature and the combination of our research results are the basis for us to choose the appropriate positions. Water replenishment used the rainwater, applying of construction systems that add rainwater to the Holocene sediments (qh).

Rainwater is added to underground aquifers by the following manner:

Creating a rainwater reservoir at a site with a permeability coefficient of 2–7 m/day, rainwater will seep through the sand layers to the Holocene sediments (qh).

Collecting the rainwater in the drainage ditch and transporting it in a suitable location to add rainwater for the underground aquifer. Building underground storage tanks under buildings for rainwater collection and adding rainwater to the aquifer with wells. We recommend that it is necessary to design boreholes and an additional water by pumping to the Holocene sediments (qh) (Fig. 6).

3.3.3 The subsurface dam method

This method has been applied in some countries around the world such as India, and Japan (https://sswm.info/es/sswm-solutions-bop-markets/). In Vietnam, the subsurface dam model in the sand, the anti-water loss has been successfully built in My Thanh (Binh Thuan). The subsurface dam with soil cement – Bentonite is 370 m long, from 5 to 9.5 m deep, forming a cobblestone tank with a capacity of 200,000 m^3, guarantees My Thanh water factory 3 months of operation in the dry season (Dung et al., 2022).

This model is possible to extend to similar areas in the territory of Vietnam. In addition, it is possible to build a sand barrier dam at the foot of the coastwise dunes of Binh Thuan province. This sand barrier dam will keep rainwater present in the sand layer, preventing the infiltration of sea water into the land. In the dry season,

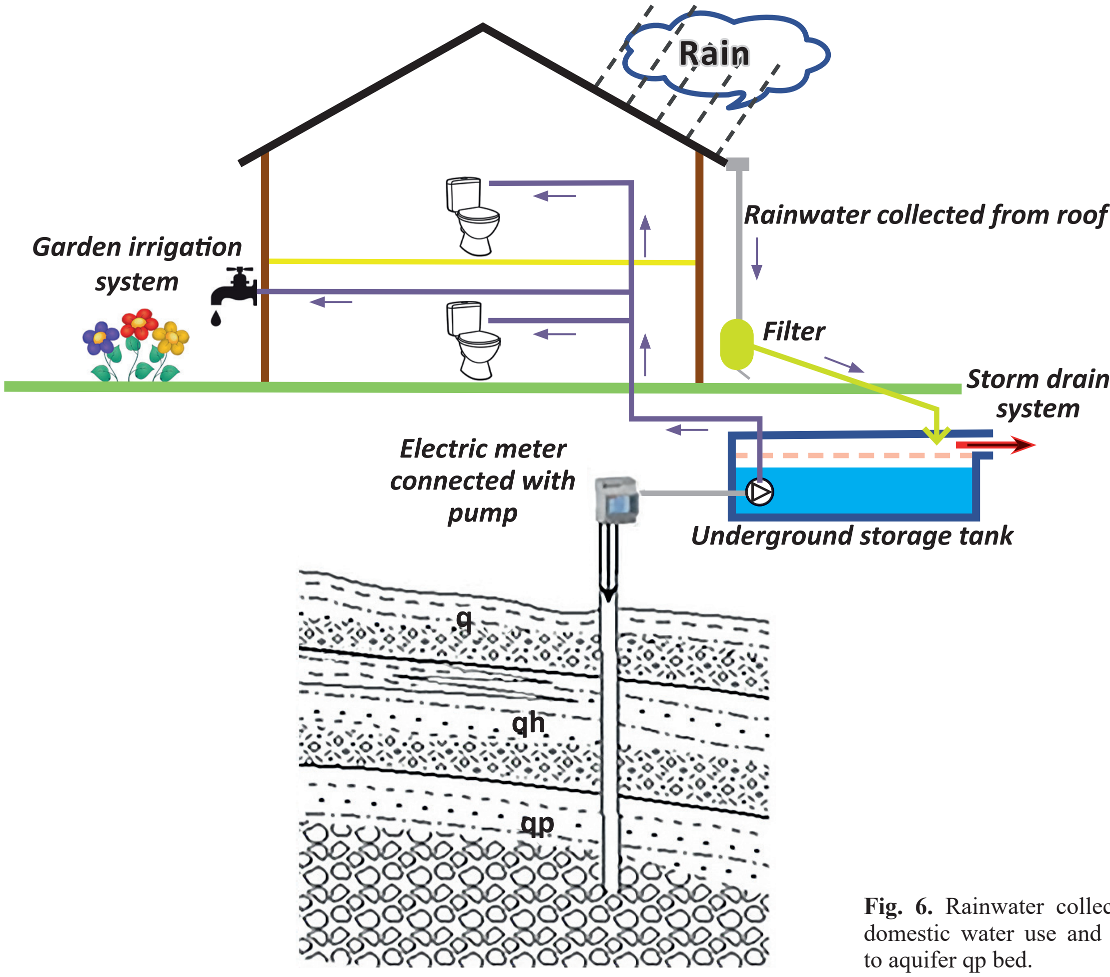


Fig. 6. Rainwater collection for domestic water use and addition to aquifer qp bed.

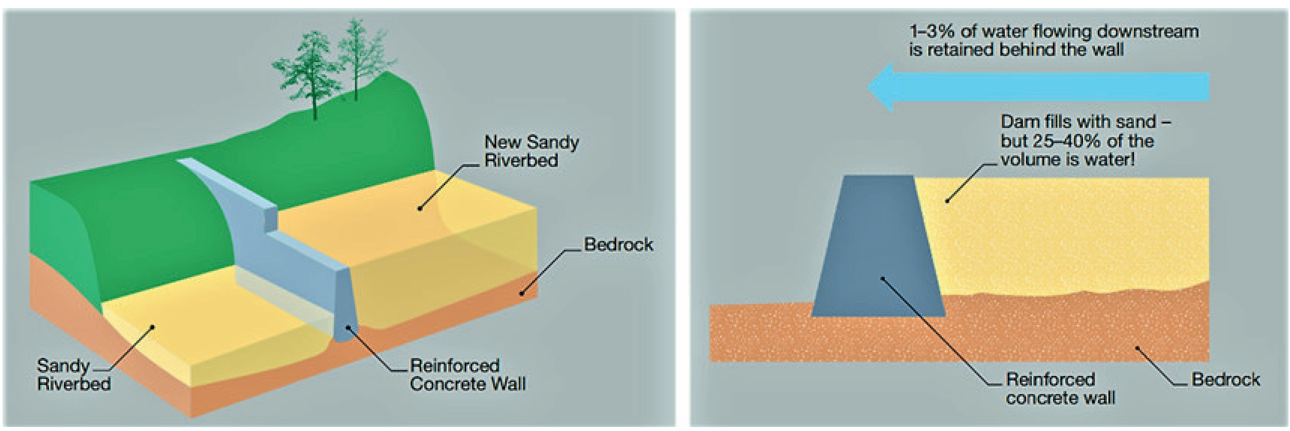


Fig. 7. Left: Schematic cross-section of a sand dam. Right: Sand accumulates until the dam is completely full of sand up to the spillway. Water is stored within the sand, protected and filtered, making up to 40 % of the total volume (Ryan et al., 2016).

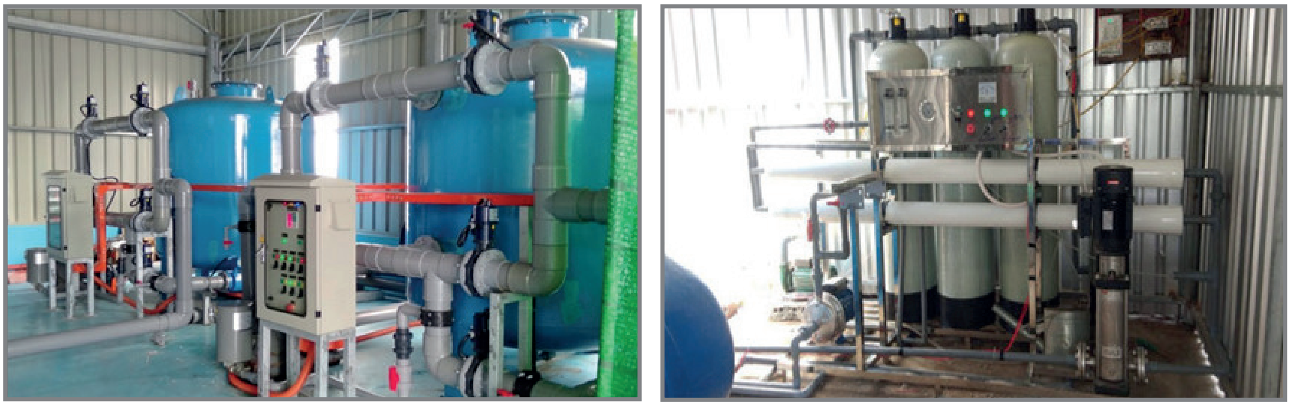


Fig. 8. Rainwater addition to aquifer qp.

Binh Thuan province is very short of water. The sand dam can be built for water storage. This model has been present in many countries around the world such as India, South Africa, and Kenya (Fig. 7).

3.3.4 Manufacturing seawater purifier

Vietnam has successfully made seawater purifier into freshwater with power reached 91 million liters of fresh water per day, named "Made in Vietnam". Vietnam has exported seawater purifiers to Saudi Arabia. We also made this device with power from 400 to 600 m^3/day (Phu et al., 2020b) (Fig. 8). Seawater purifier has been installed in Binh Thuan, Ben Tre, and Can Tho provinces. The disadvantage of this device is its high price.

Binh Thuan province has 7 groundwater aquifers. The authors' suggestions for minimizing water shortage have been applied in Binh Thuan province. The solutions are the use of a catchment area, simultaneous pumping rainwater into the qp aquifer, building underground dams, embanking sand dams and storing water, building a rainwater drainage system in the northwest-southeast direction, increasing the movement of water. Solutions for sustainable development of groundwater resources are not only beneficial for Binh Thuan province, but also can be applied well to other provinces in the territory of Vietnam. The authors' suggestions for minimizing water shortage, applied in Binh Thuan province, consist of the use of a catchment area and at the same time simultaneous pumping of rainwater into the qp aquifer, building underground dams, embanking sand dams and storing water, building a rainwater drainage system in the northwest-southeast direction, increasing the movement of water. Solutions for sustainable development of groundwater resources are not only beneficial for Binh Thuan province but also can be applied well to other provinces in the territory of Vietnam.

4 Conclusion

Research results have identified water quality trends in aquifers of Holocene and Pleistocene sediments along the coast of Binh Thuan province. The results of calculating the GWQI index and correlation analysis as well as principal component extraction analysis have shown changes in water quality in aquifers. This study also showed the decline in groundwater quality along Binh Thuan's coast in aquifers. In particular, wells in the Ham Tien area are declining more and more seriously, with some sites not meeting the requirements for water supply for domestic use or tourism in the area. Therefore, to supply water to this area, it is necessary to supplement or replace it with other water sources such as surface water, rainwater, treated seawater, or drill deep wells inland, which must have a safe radius of protection and a good drilling depth that meets the requirements of QCVN 09:2023/MONRE. The study has proposed a number of solutions to develop water resources to meet the daily living needs of the people and serve coastal tourists in Binh Thuan province, Vietnam.

References

Ahmad, A. B., 2014: Evaluation of Groundwater Quality Index for Drinking Purpose from some Villages Around Darbandikhan District. *Kurdistan Region-Science*, *7, 9, 34–41*. https://doi.org/10.9790/2380-07913441.

Au, N. H., Nhi, P. T. T., Vy, T. M. H., Hien, T. T., Hiep, T. N., Linh, L. K., Minh, T. B. & Ha, L. T. H., 2020: Application of Groundwater Quality Index (GWQI) and GIS in Groundwater Quality Zoning in the Pleistocene aquifer in Phu My Town, Ba Ria-Vung Tau province. *Science and Technology Development Journal – Science of the Earth & Environment, 4, 1, 149–161*. https://doi.org/10.32508/stdjsee.v4i1.525 (in Vietnamese).

Brown, R. M., Mcclelland, N. I., Deininger, R. A. & O'Connor, M. F, 1972: A Water Quality Index crashing the

Physiological Barrier. *Environmental Science Research*, *1, 173–182.*

DOWR, 2017: Department of Water Resources Management, http://dwrm.gov.vn/index.php?language=vi&nv=news&op=Hoat-dong-cua-dia-phuong/Binh-Thuan-se-duoc-quy-hoach-ve-tai-nguyen-nuoc-6511 (accessed August 9, 2023).

DOWR, 2021: Department of Water Resources, http://www.tongcucthuyloi.gov.vn/tin-tuc-su-kien/dam-bao-an-ninh-nguon-nuoc-kinh-6079 (accessed August 9, 2023).

Doza, M. B., Islam, A. R. M. T., Ahmed, F., Das, S., Saha, N. & Rahman, M. S., 2016: Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central Bangladesh. *Water Science, 30, 1, 19–40.* DOI:10.1016/j.wsj.2016.05.001.

Masoud, A. A., Horiny, M. M. E., Atwia, M. G., Gemail, K. S. & Koike, K., 2018: Assessment of groundwater and soil quality degradation using multivariate and geostatistical analyses, Dakhla Oasis, Egypt. *Journal of African Earth Sciences, 142, 64–81.* DOI:10.1016/j.jafrearsci.2018.03.009.

Phu, H. & Thao, H. T. P., 2020: Project report: "Planning for allocation and protection of groundwater resources in coastal sandy areas of Binh Thuan province". *Department of Natural Resources and Environment of Binh Thuan province.*

Phu, H., Do, N. T., Han, H. T. N. & Ha, T. T. M., 2022: Assessing surface water quality of main rivers in Binh Thuan province by WQI index and proposing solutions to protect water resources. *VN J. Hydrometeorol*., 13, 118–133. doi:10.36335/VNJHM.2022(13).

Shrestha, S. & Kazama, F., 2007: Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software, 22, 464–475.* DOI: 10.1016/j.envsoft.2006.02.001.

Thang, N. D., 1999: Geology and minerals in Phan Thiet and Gia Ray – Ba Ria newspaper groups. Explanation of geological maps at 1/200,000 scale. *Hanoi, Vietnam Department of Investigation and Inspection.*

Tuan, N. V., 2014: Data analysis with R. Publishing House General TP. *HCM, 145–148.*

Varol, S. & Davraz, A., 2015: Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). *Environmental Earth Sciences, 73, 4, 1725–1744.*

Viet, B. H., Binh, H. V. & Thanh, P. V., 2023: Hydrogeochemical characteristics and water quality in coastal areas of Binh Thuan province. Link: http://www.idm.gov.vn/nguon_luc/Xuat_ban/2006/A297/a38.htm (accessed August 9, 2023).

Výskum, hodnotenie a zmena trendov kvality vody v holocénnych a pleistocénnych vrstvách na splnenie požiadaviek na zásobovanie vodou v pobrežnej oblasti provincie Binh Thuan, Vietnam

V rámci výskumu na zabezpečenie zásobovania vodou v pobrežnej oblasti provincie Binh Thuan vo Vietname bol zrealizovaný odber vzoriek vody pomocou vrtov situovaných na 30 miestach a prestupujúcich 3 zvodnené vrstvy (generálne X15 m, X24 m, X36 m) v holocénnych a pleistocénnych vodonosných vrstvách.

Na spracovanie získaných údajov boli aplikované metódy výpočtu indexu kvality vody, korelačná analýza a analýza hlavných zložiek. Výsledky ukázali, že index kvality podzemnej vody sa pohyboval na úrovni „vynikajúca", čo predstavuje 18,61 %, „dobrá" 38,05 %, „zlá" 20,55 %, pričom kategórie „veľmi zlá" a „nevhodná" podzemná voda tvoria spolu 22,79 %. Najviac „nevhodná" podzemná voda je v oblastiach Ham Thuan a Phan Thiet, takže miestne studne nie sú vhodné na zásobovanie vodou. V pobrežnej oblasti Phan Thiet je priemerný obsah chloridov počas roka vyšší než povolený štandard. Počas 3 rokov sledovania bol v období sucha najvyšší obsah chloridov 478 mg . l^{-1} v oblasti vrtov GWBT16 a GWBT20 a 521 mg . l^{-1} vo vrte GWBT24. Výsledky korelačnej analýzy kvality vody vo vodonosnej vrstve X15 m ukazujú tendenciu k výraznejšiemu ovplyvňovaniu kvality vysokým prílivom a odlivom počas obdobia dažďov.

Autori navrhujú viaceré spôsoby riešenia nepriaznivej situácie: pumpovanie dažďovej vody do vodonosného horizontu (akviferu), budovanie podzemných a násypových pieskových hrádzí umožňujúcich cielený pohyb presakujúcej dažďovej vody a jej dlhodobé kumulovanie na požadovaných miestach.

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