Bulletin of the Geological Society of Malaysia, Volume 79, May 2025, pp. 45 - 56
DOI: https://doi.org/10.7186/bgsm79202506

Vulnerability assessment of coastal groundwater wells in Terengganu using TRUST Index

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Abstract: Coastal aquifers in Terengganu, Malaysia, face increasing challenges in groundwater quality and availability, necessitating a comprehensive assessment of their vulnerability. This study investigated groundwater vulnerability and susceptibility in the coastal region of Terengganu, Malaysia, where coastal aquifers face threats to groundwater quality and availability. A comprehensive groundwater vulnerability assessment was conducted using the TRUST Index. This index-based approach considers the lithology, river proximity, well usage, distance to the seashore, and well type. Field investigations were undertaken to obtain real-time measurements of well behavior. This included conducting constant-rate pumping tests on four private wells to gauge hydraulic conductivity. Consequently, flow rates were meticulously monitored throughout these tests, and water level measurements and physicochemical assessments were conducted over a 120-minute duration. Following this, the data was analyzed utilizing AQTESOLV software to determine the hydraulic conductivity, transmissivity, and storativity of the aquifer. The data from MW4, MW16, and MW20 collectively indicate favorable hydraulic characteristics, suggesting water movement within the aquifer, ranging from 4.02 m^3/day to 11.39 m^3/day. In contrast, MW7 displays an unexpectedly high discharge rate of 19.77 m^3/day, suggesting a highly permeable and efficient water-transmitting unconfined aquifer with limited water storage capacity. The vulnerability assessment classified the wells as Low, Moderate, and High vulnerability. Wells MW1, MW6, MW7, and MW20 were categorized as low vulnerability, indicating relatively secure groundwater quality and availability. Wells MW2, MW3, MW8, MW9, MW12, MW13, and MW14 were classified as moderately vulnerable, suggesting a moderate level of potential risk. Meanwhile, wells MW4, MW5, MW10, MW11, MW15, MW16, MW17, MW18, and MW19 were labeled as highly vulnerable, signifying a higher susceptibility to threats. The correlation matrix revealed insightful connections between hydrological and water quality parameters. The distance from the seashore is inversely correlated with salinity and specific conductance, signifying a reduced seawater water impact farther inland. Note that wells near rivers exhibit higher salinity, likely due to potential saltwater intrusion, emphasizing the importance of understanding these relationships in coastal aquifer systems. This study comprehensively assesses coastal groundwater vulnerability, behavior, and water quality. Its unique contributions lie in the meticulous hydraulic characterization and identification of unconventional well behavior. These findings emphasize the importance of considering temporal variations, local influences, and tailored management strategies for sustainable coastal groundwater resource utilization.

Keywords: Coastal aquifers, groundwater vulnerability, TRUST Index, hydraulic characteristics, groundwater quality

INTRODUCTION

Coastal groundwater wells serve as a crucial source of freshwater for many coastal communities, as their importance is growing in many coastal areas globally. However, the proximity of these wells to the ocean makes them vulnerable to various natural and anthropogenic hazards. Groundwater vulnerability refers to the susceptibility of groundwater to contamination with pollutants from various sources. Notably, coastal zones are particularly vulnerable to groundwater contamination due to their proximity to the ocean, which can lead to seawater intrusion and other sources of pollution (Aladejana *et al.,* 2021; Samsuddin Sah *et al.,* 2021; Zhang *et al.,* 2022). Furthermore, saltwater intrusion has been reported in several areas of Malaysia, including Kelantan (Kamal *et al.,* 2020), Kedah (Samsuddin Sah *et al.,* 2023), and Terengganu (Hairoma *et al.,* 2016; Lee *et al.,* 2017). The causes of saltwater intrusion are land use change and seawater intrusion caused by sea-level rise (Shamsuddin *et al.,* 2014; Lee *et al.,* 2017; Siang *et al.,* 2022). In addition, the threat posed by climate change can potentially exacerbate saltwater intrusion. An analysis conducted in the Terengganu Estuary by Lee *et al.* (2017) and Shamsuddin *et al.* (2014)

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

is a significant comparison worth mentioning. The study's findings indicated that between 1999 and 2000, evidence of saltwater intrusion was observed only at a distance of 5.27 km from the estuary mouth. Conversely, the present study by Siang *et al.* (2022) highlighted a distinct phenomenon during dry weather in the inter-monsoon period that leads to incoming tides, propelling coastal seawater further inland. This results in slightly saline water at monitoring stations situated at distances of 10.24 km and 9.43 km from the estuary mouth. Consequently, these factors negatively impact the quality and quantity of water resources, environment, and economic activities in the affected areas.

Groundwater vulnerability assessments can identify areas where groundwater is susceptible to contamination and determine the necessary actions to safeguard this vital resource. The DRASTIC method is commonly used to evaluate groundwater susceptibility to contamination (Barbulescu, 2020; Sarkar & Pal, 2021; Saranya & Saravanan, 2022). This method involves assigning a rating to each of the seven parameters, namely depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and conductivity. Correspondingly, these ratings are combined to produce an overall vulnerability score for each location. Previous research suggests that the DRASTIC technique may need to be calibrated and validated using field data to ensure accuracy, which can be a time-consuming and costly process (Alam *et al.,* 2014; Maleki *et al.,* 2023). A DRASTIC-LU was designed by Alam *et al.* (2014), which incorporated land use and land cover information to enhance the accuracy of the assessment of vulnerability studies. This study highlighted that different methods and approaches can be used to assess groundwater vulnerability, and it is crucial to select the most appropriate method for a particular study area. Recently, an integrated method of the DRASTIC index and the Z-number-Based Modeling (ZBM) approach in Iran conducted by Maleki *et al.* (2023) suggested that the ZBM performed better than the DRASTIC model and improved the quality of vulnerability zones. However, a study conducted in the Totko River Basin revealed that the DRASTIC and Analytic Hierarchy Process (AHP) methods could more accurately classify vulnerable zones.

Private wells serve various functions beyond household use, such as agricultural, industrial, and commercial irrigation. Many households in Terengganu, Malaysia, have installed private groundwater wells for domestic and agricultural purposes. However, limited research has been conducted on the threat of saltwater intrusion into freshwater resources in Terengganu. Research conducted by Lee *et al.* (2017) revealed that the utilization of private groundwater wells in the region has increased in recent years due to the high cost of the public water supply and concerns about the quality of treated water. In addition, this study revealed that groundwater is generally viewed as a dependable and affordable water source in the region, especially in areas where surface water sources may be limited or unreliable. According to Shamsuddin *et al.* (2014), increasing the frequency of coastal monitoring in Terengganu is crucial. This research revealed that the geophysical mapping of coastal aquifers demonstrates that rising sea levels due to climate change can lead to saltwater intrusion into the aquifers connected to the sea (Shamsuddin *et al.,* 2014). In addition, rising sea levels may increase saline water pressure, resulting in fresh/saline water boundary migration inland (Lola *et al.,* 2018). Hence, the main purpose of this study was to assess the susceptibility of groundwater in the coastal area of Terengganu. Groundwater susceptibility refers to the potential vulnerability of groundwater resources to contamination and depletion (Barbulescu, 2020; Rakib *et al.,* 2020). This is a critical concern, especially in coastal areas, where the interface between freshwater and seawater can lead to complex hydrogeological conditions. The groundwater vulnerability assessment in Terengganu employs the TRUST Index, a modified index-based method. The parameters integrated into the TRUST model encompass the type of lithology (T), proximity to the nearest river (R), well usage (U), distance to the seashore (S), and well type (T). This comprehensive approach systematically evaluated the susceptibility of groundwater in the region. These findings are expected to contribute to sustainable groundwater management practices, informed policy decisions, and improved regulation of groundwater use.

MATERIALS AND METHODS

Study area

The sampling site was located along the coastal belt in central Terengganu, specifically in Kuala Terengganu, Kuala Nerus, and Marang districts between latitudes 4°500″ N–5°30’0″ N and longitudes 103°0’0″ E–103°20’0″ E (Figure 1). Terengganu has a tropical climate with a wet season known as the Northeast monsoon (November – March) and a dry season known as the Southwest monsoon (April – September) (Kamaruddin *et al.,* 2021). Meanwhile, the temperature was relatively consistent, between 21°C and 32°C.

Methodology

A monitoring program was conducted from January 2021 to early 2022 despite COVID-19-related restrictions that limit the sampling period. The study encompassed the selection of twenty discrete sampling points strategically situated across eight distinct river basins: Sg Ibai, Sg Marang, Sg Mengabang Tok Jembal, Sg Merabang Pak Meras, Sg Merabang Telung, Sg Mercang, and Sg Terengganu (Figure 1). These points were selected based on tube well conditions, equipment availability, and site accessibility (Figure 2). Furthermore, the wells within the scope of the investigation were grouped into seven distinct categories: agricultural (one well), commercial (one well), educational facilities (two wells), industrial (one well), public (four wells),

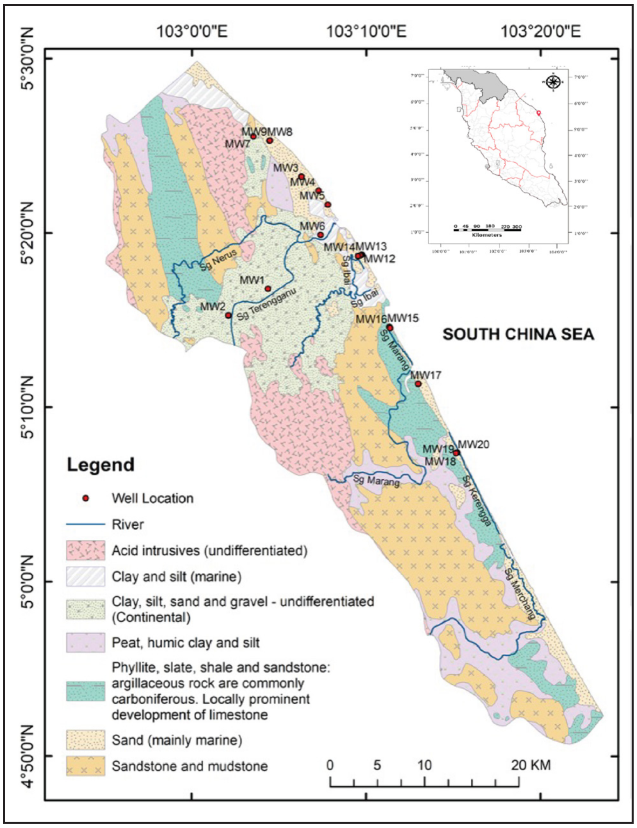

Figure 1: The geological map of the study area, encompassing the sampling wells.

religious (three wells), and residential (eight wells). The sampling procedure adhered to the guidelines published by the International Atomic Energy Agency (2015). The water level dip meter was employed to measure the water level. To facilitate in situ data collection, a YSI multiparameter sonde was utilized, enabling the measurement of crucial physicochemical parameters. This includes water level, pH, temperature, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Electrical Conductivity (EC), and salinity (Figure 3). These parameters are considered critical owing to their sensitivity to rapid fluctuations. Consequently, the distance from the sea and river was manually calculated using Geographic Information Systems (GIS) tools, and their respective values were determined.

A constant-rate pumping test was conducted for two to four hours at four specific sampling locations to study the impact of pumping on physicochemical characteristics. These locations were MW4, MW7, MW16, and MW20, which were selected for their relevance to this study. The pumping process employed a surface-water pump with a maximum flow rate of 1.5 m^3/hour and a 10-meter head. The exception was MW16, which used a submersible pump with a maximum flow rate of 1.8 m^3/hour. The flow rate was kept constant and monitored with a 90° v-notch. During the test, water level measurements were recorded at predetermined intervals, considering the test duration and timing of the data collection points. The YSI multiparameter probe was utilized to assess physicochemical characteristics during pumping. This assessment involved 18 measurements over 120 minutes, with intervals between successive measurements ranging from 5 to 10 minutes. The structured data-collection sequence commenced immediately after the start of the test. In addition, a high-frequency data collection approach was adopted during the initial stages due to the recognized tendency for rapid fluctuations within the first 10 minutes of pumping.

As the water table stabilized and reached equilibrium, the measurement intervals were gradually extended. The initial static water levels were established during these tests before pumping commenced, and the maximum drawdown values were recorded. To ensure consistent groundwater discharge and prevent abrupt fluctuations, the pumping rate was monitored continuously. The test execution was scheduled under favorable weather conditions, either in the morning or afternoon, when the environment was hot and sunny. This precaution was taken to prevent interference from rainwater, ensure accurate measurements, and avoid disturbances to the natural aquifer recharge process. Correspondingly, the AQTESOLV software was deployed to calculate parameters such as hydraulic conductivity, transmissivity, and storativity of the aquifer.

The conceptual framework

The TRUST index is a statistical tool used to predict the likelihood of finding groundwater at a specific location. The TRUST arithmetic index calculation product was then classified into three levels of vulnerability, as indicated in Equation 1. Note that the parameters used to build the TRUST model were lithology type, distance to the nearest river, well usage, distance to the seashore, and well type. The parameter with the largest impact on contamination is assigned a weight of ten, and fewer parameters are assigned one. Here, the range of parameter variables was divided into division ratings specific to the area under investigation based on the available geographical data. An importance rating was given to the range of each rating, with a higher rating indicating a larger effect on pollution. The TRUST method was applied to the groundwater vulnerability of the Terengganu coast to evaluate the impact of natural or anthropogenic contamination. Subsequently, groundwater is characterized by low vulnerability upstream and high vulnerability downstream, with strong vulnerability to saltwater intrusion in the coastal zone and proximity to nearby rivers:

$$\text{TRUST index} = \frac{W_T R_T + W_R R_R + W_U R_U + W_S R_S + W_T R_T}{15} \quad \text{(Equation 1)},$$

where

$W_T R_T$ is the product of weightage and rating for the T_1 parameter.
$W_R R_R$ is the product of weightage and rating for the R parameter.

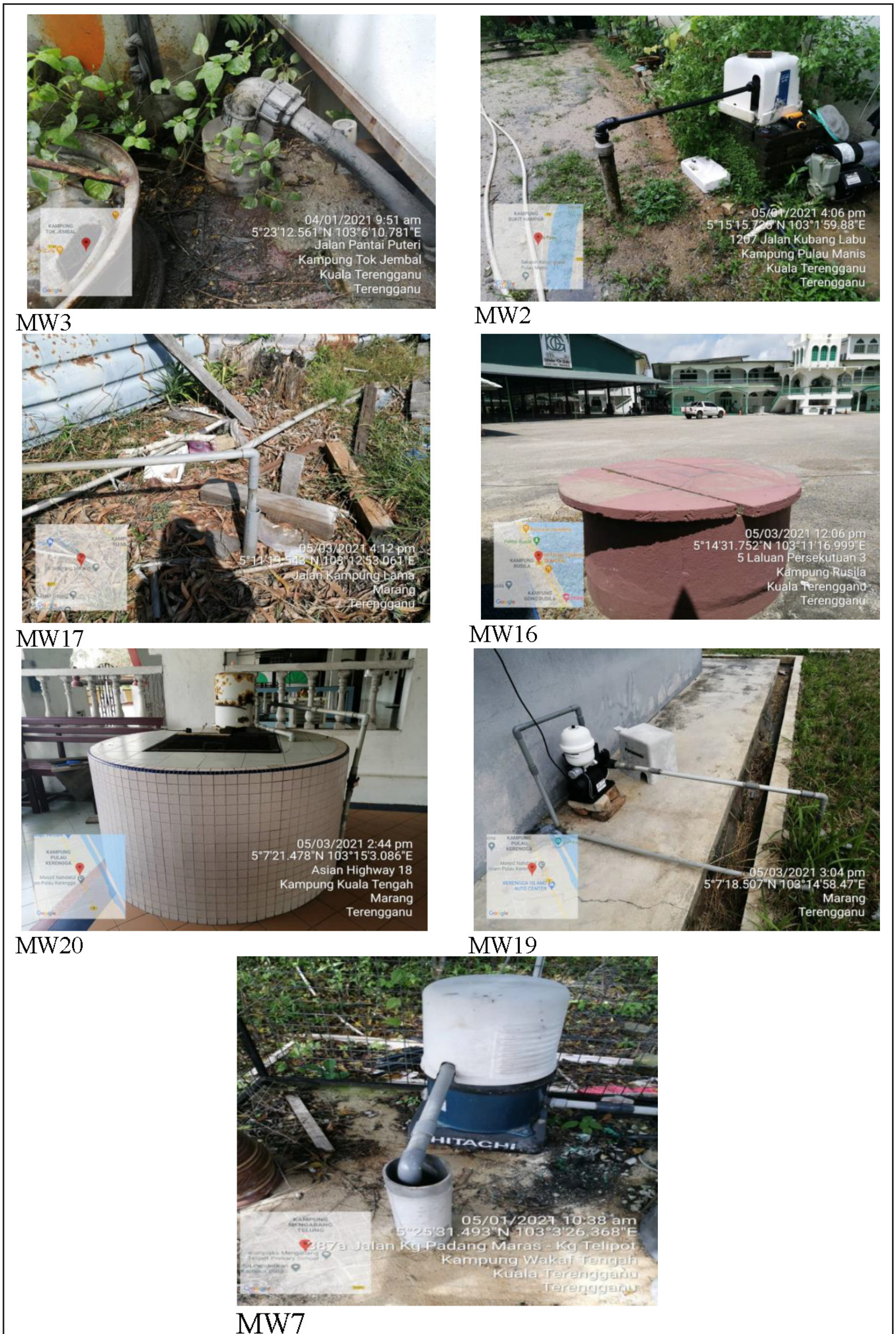

Figure 2: Type of wells in the study area.

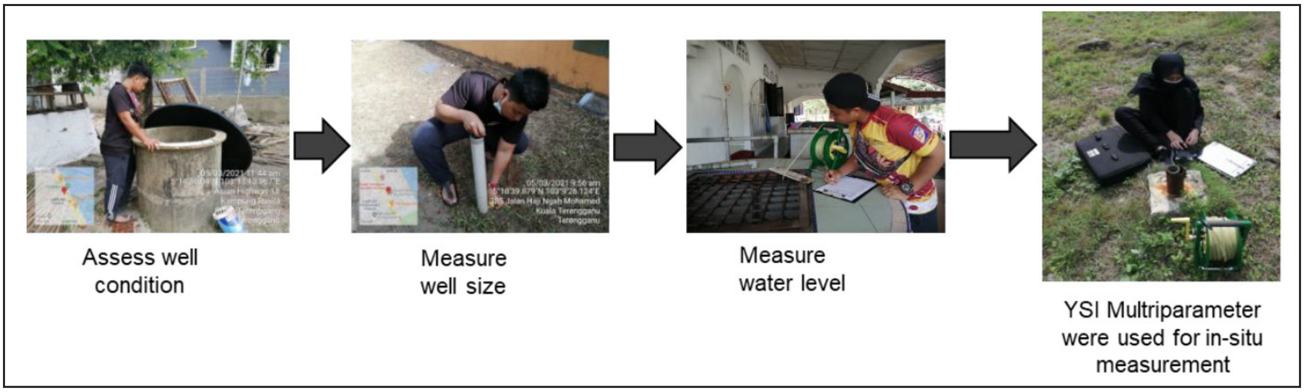

Figure 3: Sampling procedure for the well monitoring program.

W_UR_U is the product of weightage and rating for the U parameter.
W_SR_S is the product of weightage and rating for the S parameter.
W_TR_T is the product of weightage and rating for the T_2 parameter.

If the TRUST index is less than five, the well is less vulnerable, and there is a low chance of natural or induced contamination. A well with a TRUST index value between five and seven has a moderate vulnerability, implying that it is at risk of contamination once the pumping rate exceeds the safe pumping yield limit or external factors such as natural catastrophe events occur. Accordingly, preventive measures are recommended for these wells. Meanwhile, wells with a TRUST index greater than seven are at the greatest risk of contamination, as river pollution or seawater incursion can readily impair water quality. Table 1 lists the TRUST index values and grading guidelines for groundwater vulnerability.

Table 1: TRUST index value and grading guideline of groundwater vulnerability.

Parameter	Weight	TRUST Factor Variable Range	Importance Rating
Type of lithology (T)	3	Marine Sand	10
		Clay, Silt, Sand & Gravel	6.5
		Marine clay & Silt	3.5
Distance to River (R) [m]	2	<200	10
		200-350	8
		350-650	6
		650-2000	4
		>2000	2
Well Usage (U)	4	Agriculture	10
		Residential	8
		Industry/Commercial	6
		Open space	4
		Educational/Religious Facility	2
Distance to Seashore (S) [m]	5	<150	10
		150-350	8
		350-700	6
		700-1500	4
		>1500	2
Type of well (T)	1	Pumping Dug Well	10
		Pumping Tube Well	7.5
		Abandoned Well	5
		Monitoring Well	2.5

TRUST Index Value	Vulnerability	Grade
0-4.99	Low	A
5 to 7	Moderate	B
More than 7	High	C

RESULTS AND DISCUSSION

Hydraulic characteristics and behavior of monitored wells

Table 2 provides information regarding the wells analyzed in this study. The table offers comprehensive information for understanding the spatial distribution and usage patterns of the wells examined in this research. Furthermore, the data analysis demonstrates that the water levels in the monitoring wells display slight fluctuations over an extended period. For example, MW1 demonstrated a decrease in water level from January 5th (0.52 m) to September 26th (1.85 m), with intermittent fluctuations in between. Similarly, MW3 displayed fluctuations in the water level, although the overall trend remained relatively stable over the observed period. In contrast, MW4, MW6, and MW7 also demonstrated fluctuations. However, the general trend indicated a gradual increase in the water level from January to September. Wells MW10 through MW20, measured in late March and September, revealed varied water level patterns, with some experiencing minor fluctuations while others displaying more consistent water levels. Note

Table 2: The attributes of the wells in the investigation.

Well No (MW)	Coordinate		Water Level (m)	Well Head (m)	Well Use	Well Type	Well Size (mm)	Well Depth (m)
	Latitude	Longitude						
MW1	5°16’46.30”N	103° 4’15.83”E	0.52	0.350	Commercial	Pumping well	50	16
MW2	5°15’15.53”N	103° 2’0.10”E	na	0.370	Residential	Pumping well	50	10
MW3	5°23’12.61”N	103° 6’10.83”E	0.65	0.000	Industry	Pumping well	100	8
MW4	5°22’24.15”N	103° 7’9.53”E	1.90	0.600	Residential	Pumping dug well	-	5.9
MW5	5°21’36.87”N	103° 7’41.82”E	na	na	Public well	Pumping well	100	6
MW6	5°19’52.37”N	103° 7’16.59”E	0.28	0.350	Religious facility	Pumping dug well	-	2.94
MW7	5°25’31.57”N	103° 3’25.85”E	0.86	0.325	Educational facility	Pumping well	100	10
MW8	5°25’16.37”N	103° 4’20.36”E	na	na	Residential	Pumping well	50	6
MW9	5°25’17.01”N	103° 4’21.99”E	na	na	Residential	Pumping well	100	6
MW10	5°18’45.4”N	103°09’39.6”E	4.82	0.365	Public well	Monitoring well	50	28
MW11	5°18’44.6”N	103°09’38.3”E	2.92	0.265	Public well	Monitoring well	50	28
MW12	5°18’43.6”N	103°09’36.0”E	3.09	0.295	Public well	Monitoring well	50	40.12
MW13	5°18’42.4”N	103°09’33.7”E	2.86	0.240	Public well	Monitoring well	50	31.5
MW14	5°18’39.6”N	103°09’26.0”E	3.77	0.550	Educational facility	Monitoring well	50	13.5
MW15	5°14’36.2”N	103°11’14.1”E	3.92	0.860	Residential	Abandoned dug well	770	6.12
MW16	5°14’32.0”N	103°11’16.1”E	4.38	0.830	Religious facility	Pumping dug well	1530	8.16
MW17	5°11’19.6”N	103°12’52.9”E	na	0.300	Agriculture	Pumping well	50	6
MW18	5°07’23.7”N	103°15’07.3”E	na	na	Residential	Pumping well	50	3.65
MW19	5°07’23.4”N	103°15’06.3”E	na	na	Residential	Pumping well	50	3.65
MW20	5°07’21.7”N	103°15’03.0”E	3.89	1.000	Religious facility	Pumping dug well	1640	7.55

*na: The well reading is unavailable as it has been sealed with a pump

that the pumping test graph can be observed in Appendix 2. These observations suggest that the water levels in the monitoring wells are subject to temporal changes and may be influenced by factors such as precipitation, groundwater recharge, and seasonal variations.

Additionally, temporal water-level monitoring across different dates for various wells revealed intriguing patterns, as displayed in Figure 4. MW1, MW3, MW4, MW6, MW7, MW10, MW11, MW12, MW13, MW14, MW15, and MW16 experienced fluctuations in water levels, often demonstrating consistent upward trends from January to September. This signifies increasing groundwater levels. In contrast, the MW20 water levels demonstrated a consistent upward trend from March to September, potentially indicating responses to seasonal or hydrological influences. This data analysis provides valuable insights into the potential of these wells as groundwater resources and emphasizes the importance of well-specific hydraulic data for effective groundwater management strategies. However, further analysis and correlation with external factors are necessary to understand the underlying drivers of these water level fluctuations fully.

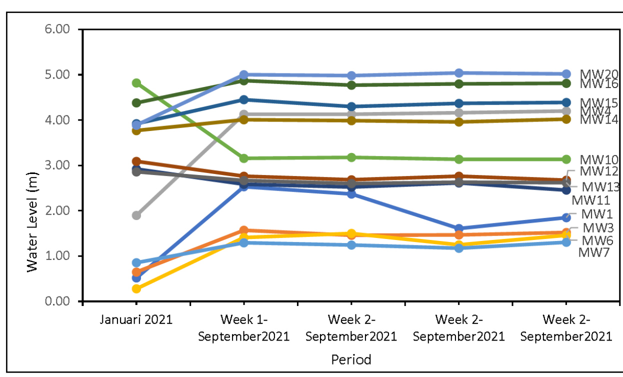

Figure 4: Groundwater level monitoring program.

A comprehensive analysis of well behavior and characteristics provides a deeper understanding of groundwater dynamics. Four wells (MW4, MW7, MW16, and MW20) underwent constant discharge rate aquifer pump tests, shedding light on their response patterns (Table 3). MW4 exhibited a discharge rate of 16.73 m^3/day on September 14th, 2021, with transmissivity and hydraulic conductivity values of 60.38 m^2/day and 11.39 m/day, respectively. MW7, tested on September 7th, 2021, exhibited remarkably high transmissivity (161.1 m^2/day) and hydraulic conductivity (16.11 m/day) despite an extremely low storativity coefficient (3.371E-21). Similarly, MW16, tested on September 15th, 2021, demonstrated moderate hydraulic characteristics, featuring a discharge rate of 19.77 m^3/day, transmissivity of 46.24 m^2/day, and hydraulic conductivity of 6.31 m/day, complemented by a storativity value of 0.08. On September 10th, 2021, MW20 exhibited a discharge rate of 23.14 m^3/day, corresponding to transmissivity and hydraulic conductivity values of 26.32 m^2/day and 4.02 m/day, and a storativity coefficient of 0.038. The in-situ measurements of this study are outlined in Appendix 3.

Groundwater quality

Table 4 provides a comprehensive overview of the various water quality parameters measured in each monitoring well. These parameters included pH, salinity, temperature, DO, conductivity, and TDS. The results offer insights into the variability and characteristics of groundwater within the study area. The pH values of the wells vary across the range of 4.49 to 11.56, indicating a wide range of acidity and alkalinity levels. Most wells fall within the expected pH range for water sources, typically 6.5 and 8.5. Notably, MW10 had an exceptionally high pH value of 11.32, which surpassed the typical range. This anomaly can be attributed to external factors or unique geological conditions affecting the water pH level. However, the standard deviations associated with pH values were relatively low, suggesting consistent measurements across the wells.

The salinity levels, expressed in parts per thousand (ppt), demonstrate a relatively narrow range, with an average of 0.02 ppt in MW1 and MW2 and 2.42 ppt in MW10. Most wells exhibited low salinity, indicating that fresh groundwater suits various applications. Nevertheless, some wells, such as MW5, MW16, and MW18, displayed higher salinity values, which could be due to variations in salt sources or geological formations. The standard deviation associated with the salinity values indicates fluctuations in the measurements, with MW10 having the highest standard deviation, suggesting variations in the salinity levels.

The results suggest that temperature values are relatively consistent across the wells, ranging from 27.96°C in MW15 to 34.4°C in MW1. DO levels exhibit variability, with mean values ranging from 1.86 mg/L in MW8 to 5.05 mg/L in MW6. Specific conductivity values indicated significant variability, with MW10 exhibiting high values, potentially due to dissolved ions. TDS, measured in g/L, suggests a wide range, from 29.67 g/L in MW20 to 271.7 g/L in MW5. According to the World Health Organization (WHO) guidelines for pH, salinity, and TDS, most monitored wells fall within safe water quality ranges. However, some wells

Table 3: The constant-rate pumping tests of the groundwater monitoring program.

Well No	Flow Rate (m^3/hr)	Initial Water Level (m)	Maximum Drawdown (m)	Well Depth (m)	Pumping Duration (mins)	Transmissivity (m^2/day)	Hydraulic Conductivity (m/day)	Storativity
MW4	0.697	4.16	0.11	4.70	120	60.38	11.39	0.154
MW7	0.82	1.30	0.52	9.68	120	161.1	16.11	3.37E-21
MW16	0.82	4.77	0.15	7.33	120	46.24	6.31	0.08
MW20	0.96	5.00	0.36	5.55	120	26.32	4.02	0.038

Table 4: Statistical summary of in-situ properties of groundwater.

Parameters		Mean	Std Deviation	Min	Max
Temp	°C	28.85	1.739	23.7	31.1
DO	mg/L	3.189	1.829	0.82	8.43
SPC	µs/cm	514.435	1396.170	42.4	6393
TDS	g/L	334.205	907.051	27.3	4153.5
Salinity	ppt	0.264	0.758	0.02	3.46
pH value		7.0075	1.409	5.16	11.39

have variations beyond the recommended ranges, such as the high pH value in MW10 and elevated salinity and TDS in several wells. This indicates the influence of local factors and the need for closer monitoring and management strategies.

This study highlights the significance of evaluating the water quality parameters of the groundwater system, as they directly affect the suitability of the water for multiple purposes. The information presented in the table is crucial for assessing water quality in the research area and making informed decisions regarding groundwater resource management and sustainable utilization.

Groundwater vulnerability index

The vulnerability assessment index values assigned to each monitoring will comprehensively understand their susceptibility to potential risks and impacts. This indicates the level of vulnerability of each well in terms of groundwater quality and availability. These values were used to classify wells into low, moderate, and high vulnerability. Wells such as MW1, MW6, MW7, and MW20 are categorized as Low vulnerability, suggesting a relatively secure groundwater quality and availability status. Meanwhile, wells MW2, MW3, MW8, MW9, MW12, MW13, and MW14 are classified as moderately vulnerable, indicating a moderate level of potential risk. Several wells, including MW4, MW5, MW10, MW11, MW15, MW16, MW17, MW18, and MW19, were classified as highly vulnerable, implying a greater susceptibility to potential threats.

Hydrological and water quality in coastal aquifers.

Pearson's correlation coefficient was used to assess the factors controlling vulnerability. The correlation matrix revealed relationships between Distance from the Seashore, Salinity, Specific Conductance, Trust Index, Distance from the River, and pH (Table 5). Each cell in the matrix contains correlation coefficients ranging from -1 to 1, indicating the strength and nature of the linear associations between pairs of variables. The analysis revealed a moderate negative correlation between Distance from the Seashore and Salinity (-0.556) and Specific Conductance (-0.563). This suggests that areas farther from the sea may experience reduced seawater influence and lower groundwater salinity and ion concentrations. Additionally, a moderate negative correlation was observed between Distance from the Seashore and Trust Index (-0.513), indicating that wells closer to the sea may have lower trust index values, potentially due to challenges in data reliability associated with coastal environments.

Note that Salinity and Specific Conductance displayed a strong positive correlation (0.999), indicating that these two variables are closely related, as expected, since specific conductance is influenced by ion concentration. Moreover, it is directly related to salinity, and the relationship between the Trust Index and Salinity (-0.287) and Specific Conductance (-0.275) suggests a weak negative correlation. This could imply that wells with higher trust index values might tend to have slightly lower salinity and specific conductance. This indicates more reliable data from less saline sources, as well as a strong positive correlation with Distance from the Seashore (0.702) and a strong negative correlation with both salinity (-0.654) and Specific Conductance (-0.642). Other than that, this could indicate that wells closer to rivers are also closer to the seashore, leading to higher salinity and specific conductance due to potential saltwater intrusion. The pH values demonstrate weak correlations with other variables, with slight positive correlations observed with Specific Conductance (0.279) and Distance from the River (0.150) and a weak negative correlation with Distance from the Seashore (-0.491). These correlations suggest that pH may be influenced by ion concentration and proximity to seashore and river sources.

Table 5: Pearson correlations for physicochemical parameters.

Parameter	Distance From Sea	Salinity	Conductivity	TRUST Index	Distance From River	pH
Distance From Seashore	1.0000					
Salinity	- 0.5556	1.0000				
Conductivity	- 0.5633	0.9987	1.0000			
Trust Index	- 0.5132	- 0.2872	- 0.2754	1.0000		
Distance From River	0.7018	- 0.6544	- 0.6419	- 0.2182	1.0000	
pH	- 0.4907	0.2539	0.2791	0.1504	- 0.3651	1.0000

CONCLUSIONS

This study examines groundwater vulnerability in a coastal region, focusing on the influence of distance from the seashore and proximity to rivers within the coastal aquifer system. This study demonstrates the efficacy of the TRUST Index in quantifying groundwater vulnerability. It reveals diverse water level fluctuations indicative of potential oceanic water recharge influences and underscores temporal water level variations among different monitoring sites. The study also provides insights into the dynamics of coastal aquifers through a correlation matrix that illuminates the interrelationships between hydrological and water quality parameters. Correspondingly, these findings are crucial for understanding the underlying mechanisms governing groundwater behavior and quality dynamics. This study revealed distinct patterns, including negative correlations between distance from the seashore and both salinity and specific conductance, indicating the impact of seawater intrusion on these parameters. Note that most wells conform to acceptable water quality ranges. Outliers such as elevated pH in MW10 and increased salinity and TDS in specific wells emphasize the relevance of local conditions. Moreover, these outcomes underscore the multifaceted nature of groundwater dynamics, quality, vulnerability, and the significance of comprehensive groundwater management strategies. In future research, it is crucial to consider the pump's capacity to ensure the accuracy of the results. Furthermore, understanding the interplay between these parameters remains pivotal for sustainable resource utilization and informed decision-making in groundwater systems. In addition, future investigations and sustained monitoring efforts will continue to enhance our understanding of the intricate hydrogeological processes within and beyond the study area.

ACKNOWLEDGEMENT

The authors wish to express their sincere gratitude to the reviewer(s) for their valuable feedback and insightful comments that significantly improved the quality of this manuscript. Also, the authors thank the Malaysian Higher Education Ministry for their financial support under the Fundamental Grant Scheme (FRGS/1/2019/WAB08/UMT/03/1) and the Universiti Malaysia Terengganu for providing the necessary facilities to conduct this research.

AUTHORS CONTRIBUTION

UQ and NBB played a key role in conceptualizing the study, designing the methodology, performing data analysis, and drafting the original version of the article. SNBS and RG were part of the research team involved in the data collection and participated in the writing process by reviewing and editing the article. MNI and EH provided guidance and oversight throughout the study and contributed to the writing process by reviewing and editing the article.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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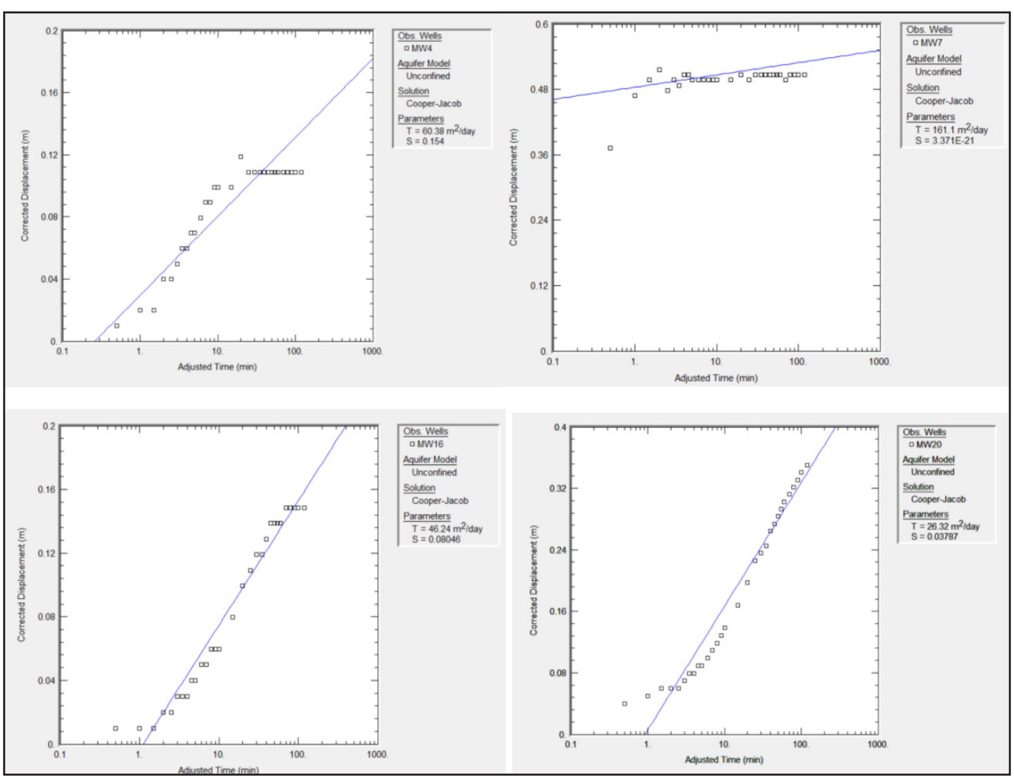
Manuscript received 10 May 2023;
Received in revised form 13 September 2023;
Accepted 13 June 2024
Available online 30 May 2025

Appendix 1. TRUST Index value and vulnerability rating.

Well No	$W_T R_T$	$W_R R_R$	$W_U R_U$	$W_S R_S$	$W_T R_T$	$\sum W \times R$	$\sum W$	TRUST INDEX	VULNERABILITY
MW1	19.5	8	24	10	7.5	69	15	4.60	Low
MW2	19.5	20	32	10	7.5	89	15	5.93	Moderate
MW3	30	4	24	20	7.5	85.5	15	5.70	Moderate
MW4	30	4	32	40	10	116	15	7.73	High
MW5	30	8	16	50	7.5	111.5	15	7.43	High
MW6	10.5	20	8	10	10	58.5	15	3.90	Low
MW7	19.5	4	8	20	7.5	59	15	3.93	Low
MW8	30	4	32	30	7.5	103.5	15	6.90	Moderate
MW9	30	4	32	30	7.5	103.5	15	6.90	Moderate
MW10	30	8	16	50	2.5	106.5	15	7.10	High
MW11	30	12	16	50	2.5	110.5	15	7.37	High
MW12	30	12	16	40	2.5	100.5	15	6.70	Moderate
MW13	30	12	16	40	2.5	100.5	15	6.70	Moderate
MW14	30	12	8	30	2.5	82.5	15	5.50	Moderate
MW15	30	16	32	50	5	133	15	8.87	High
MW16	30	16	8	50	10	114	15	7.60	High
MW17	30	8	40	20	7.5	105.5	15	7.03	High
MW18	30	20	32	40	7.5	129.5	15	8.63	High
MW19	30	16	32	40	7.5	125.5	15	8.37	High
MW20	30	16	8	30	10	94	15	6.27	Moderate

Appendix 2. The graph represents the results of a pumping test conducted using AQTESOLV software.



Appendix 3. Groundwater's physical characteristics as determined by in-situ measurements.

Parameter	Specific Conductivity (µs/cm)			Total Dissolved Solids (g/L)			Temperature (°C)			Dissolved Oxygen (mg/L)			pH			Salinity (ppt)		
Eigenvalues Station ID	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
MW1	51.88	47.80	53.80	34.40	31.20	38.10	29.04	27.10	31.10	3.58	2.57	4.44	5.73	4.88	7.50	0.02	0.02	0.02
MW2	44.72	41.80	52.30	29.00	27.30	33.80	30.48	27.10	35.20	3.71	2.84	4.29	5.31	4.64	6.83	0.02	0.02	0.02
MW3	158.22	100.90	177.50	102.86	65.70	115.10	28.54	27.70	30.70	3.84	2.33	5.25	5.89	5.48	7.25	0.07	0.05	0.08
MW4	247.36	214.90	265.60	160.82	139.80	172.90	29.50	28.30	30.50	3.29	1.70	4.73	5.58	5.11	7.24	0.11	0.10	0.12
MW5	251.98	185.40	417.80	163.82	120.30	271.70	30.24	29.20	31.50	2.14	1.47	2.65	6.47	6.00	7.22	0.12	0.09	0.20
MW6	90.06	49.60	150.30	58.64	32.50	97.50	28.54	23.70	31.30	5.05	2.51	8.43	6.98	6.37	8.22	0.04	0.02	0.07
MW7	180.08	167.60	189.40	117.30	109.20	123.50	29.16	26.70	30.80	2.54	0.88	4.79	6.21	5.77	7.36	0.08	0.08	0.09
MW8	77.36	72.00	88.00	50.20	46.80	57.20	30.14	28.90	31.60	1.86	1.14	2.23	5.80	5.33	7.36	0.03	0.03	0.04
MW9	188.64	164.70	262.40	122.74	107.30	170.30	32.28	30.40	34.30	1.93	1.30	2.27	5.31	4.49	6.46	0.09	0.08	0.12
MW10	4446.40	3040.00	6393.00	2970.50	2366.00	4153.50	31.14	30.40	31.70	2.32	0.66	7.64	11.32	11.08	11.56	2.42	1.90	3.46
MW11	423.80	310.90	833.00	274.96	202.10	539.50	31.18	30.40	31.50	2.26	0.90	6.05	6.41	6.11	7.26	0.20	0.15	0.40
MW12	243.22	228.60	269.20	157.80	148.20	174.80	31.54	31.10	31.70	3.13	1.95	4.89	6.37	5.97	7.63	0.11	0.11	0.13
MW13	288.00	277.00	293.70	187.22	180.10	191.10	31.42	28.60	32.30	2.56	1.60	3.97	7.13	6.63	8.58	0.14	0.13	0.14
MW14	298.80	255.40	437.80	194.22	165.80	284.70	30.18	29.70	30.50	3.71	0.82	5.74	6.37	6.32	6.40	0.14	0.12	0.21
MW15	250.60	96.10	310.80	162.76	62.40	202.10	27.96	27.50	28.10	4.83	4.07	6.34	5.31	4.78	6.06	0.12	0.04	0.15
MW16	154.62	147.70	159.20	100.36	96.20	103.30	29.62	28.70	29.90	3.04	1.33	4.77	5.39	5.16	5.58	0.07	0.07	0.07
MW17	121.32	109.40	128.90	78.64	70.80	83.20	28.84	27.70	30.00	2.80	1.87	3.62	5.46	5.17	5.82	0.06	0.05	0.06
MW18	95.68	89.20	98.10	62.28	57.90	63.70	30.02	28.80	31.40	4.39	4.13	4.74	5.94	5.35	6.35	0.04		0.04
MW19	86.66	81.00	91.50	56.42	52.70	59.10	29.56	28.70	30.60	4.97	4.43	5.50	5.77	5.42	6.15	0.04	0.04	0.04
MW20	101.12	72.70	175.28	65.75	47.50	114.04	28.55	28.20	29.67	3.66	2.51	4.76	5.86	5.70	6.05	0.05	0.03	0.08