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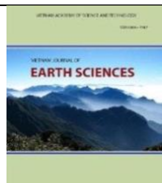

Application of GIS-Base GALDIT for vulnerability assessment to saltwater intrusion of Holocene coastal aquifer: a case of Quang Nam - Da Nang city, Vietnam

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ABSTRACT

Groundwater is an essential resource which is influenced by salt water due to the groundwater exploitation in Holocene aquifer of Quang Nam - Da Nang. Hence, the measures for preventing saltwater intrusion and better groundwater management are required. In this study, GALDIT method was utilized to identify the salt water intrusion (SWI) vulnerability zones using monitoring data in Holocene aquifer of Quang Nam - Da Nang. The results of GALDIT method indicated that Da Nang and Hoi An cities were in the high SWI vulnerability zones. The moderate SWI zones were dominant and low vulnerability zones were at the southern part of the study area. The analysis of the monitoring data showed the occurrence of SWI far inland, up to the distance of 12.5 km from the sea shore and suggested the impact of human activities on SWI. The analysis of monitoring data together with GALDIT index indicated that the important of the groundwater abstraction depth or the occurrence of fresh-salt groundwater interface should be considered to improve the result of GALDIT method for the prevention of SWI. In short, the GALDIT used in this study is an important approach for the prevention of SWI in the study area.

Keywords: saltwater intrusion; GALDIT method; Holocene aquifer; vulnerability; Quang Nam - Da Nang.

1. Introduction

Groundwater is an important resource for human life. In regions, where surface water is limited for the water supply, groundwater is a reliable source for daily water use such as drinking, irrigation, and industrial activities. Nowadays, the population blooming and rapid urbanization have put the groundwater under stress of various problems such as groundwater level declination, groundwater quality deterioration, and saltwater intrusion (SWI). In coastal areas, the supply of fresh water is mostly from groundwater, and thus, the increase of groundwater abstraction makes the aquifers in risk of SWI from the sea. The problem of SWI is similar in the Holocene aquifer of Quang Nam - Da Nang. In this area, groundwater is mostly exploited in Holocene aquifer, of which the potential exploitation reserve of fresh groundwater is up

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229,367 m^3/day (Hoang and Nguyen, 2005). However, the intensive abstraction has caused the groundwater salinization, which is commonly observed in the dry season. Especially in Da Nang city, the SWI were observed at 6 km from the seashore to the in land, with the total dissolved solid (TDS) from 1000 to 10,750 mg/L. The salinized area of Holocene aquifer in Da Nang city was more than 40 km^2 (Nguyen et al., 2018). In addition, 44% of Holocene aquifer was occupied by saline groundwater (TDS > 1000 mg/L) (Hoang and Nguyen, 2005) and, thus, the groundwater exploitation without careful management will cause the deterioration of groundwater in both quantity and quality due to SWI. Therefore, an assessment of SWI is a necessary approach supporting the management and sustainable development of groundwater in Quang Nam - Da Nang.

A map of SWI vulnerability is an effective tool for the prevention of groundwater salinization. A worldwide method used for that purpose is the GALDIT method, an index-based model (Chachadi and LoboFerreira, 2001). The assessment is based on six parameters related with SWI potential, which are **G**roundwater occurrence (**G**), **A**quifer hydraulic conductivity (**A**), Height of groundwater **L**evel above sea level (**L**), **D**istance from the shore (**D**), **I**mpact of existing status of seawater intrusion (**I**), and **T**hickness of the aquifer (**T**). The GALDIT is simple method and provide reasonable results of SWI vulnerability in coastal areas (Lobo-Ferreira et al., 2007; Trabelsi et al., 2016). Hence, the number of case studies were applied GALDIT method such as in India (Seenipandi et al., 2019; Saravanan et al., 2019), in Greece (Recinos et al., 2014; Kazakis et al., 2019), in Morocco (Kouz et al., 2018), and in Korea (Chang et al., 2019). In addition, the GALDIT parameters are also modified to improve the results of the SWI vulnerability assessment and be suitable for different study areas (Kazakis et al., 2018; Parizi et al., 2019; Chang et al., 2019; Bordbar et al., 2019).

According to the effectiveness of applications of GALDIT method in the World, the GALDIT method is firstly applied in this study for Holocene aquifer of the coastal area in Quang Nam-Da Nang. A map of SWI vulnerability resulted from the application of the GALDIT method is valuable information supporting the prevention of further salinization in Holocene aquifer of the study area. Based on the available of groundwater data, TDS was used to evaluate the current impact of SWI instead of standard GALDIT's parameters. The distance from the sea shore and the height of groundwater level above sea level are also slightly modified to clearly distinguish the vulnerable zones. The time variation of TDS observed from monitoring well is used to improve the prediction of salinization trend.

2. Materials and methods

2.1. Study area

2.1.1. Geography and climate

The study area locates at the eastern part of Quang Nam-Da Nang (Fig. 1). The topography is mostly flat with the elevation of less than 10 m in the coastal zone and becomes hilly to mountain to the northwest and southwest.

There are two main seasons including rainy season and dry season. The rainy season is from September to January next year. The dry season is from February to August. The temperature is 25.4°C on average. The average annual rainfall is high with 2770 mm. The evaporation is 2107 mm/year.

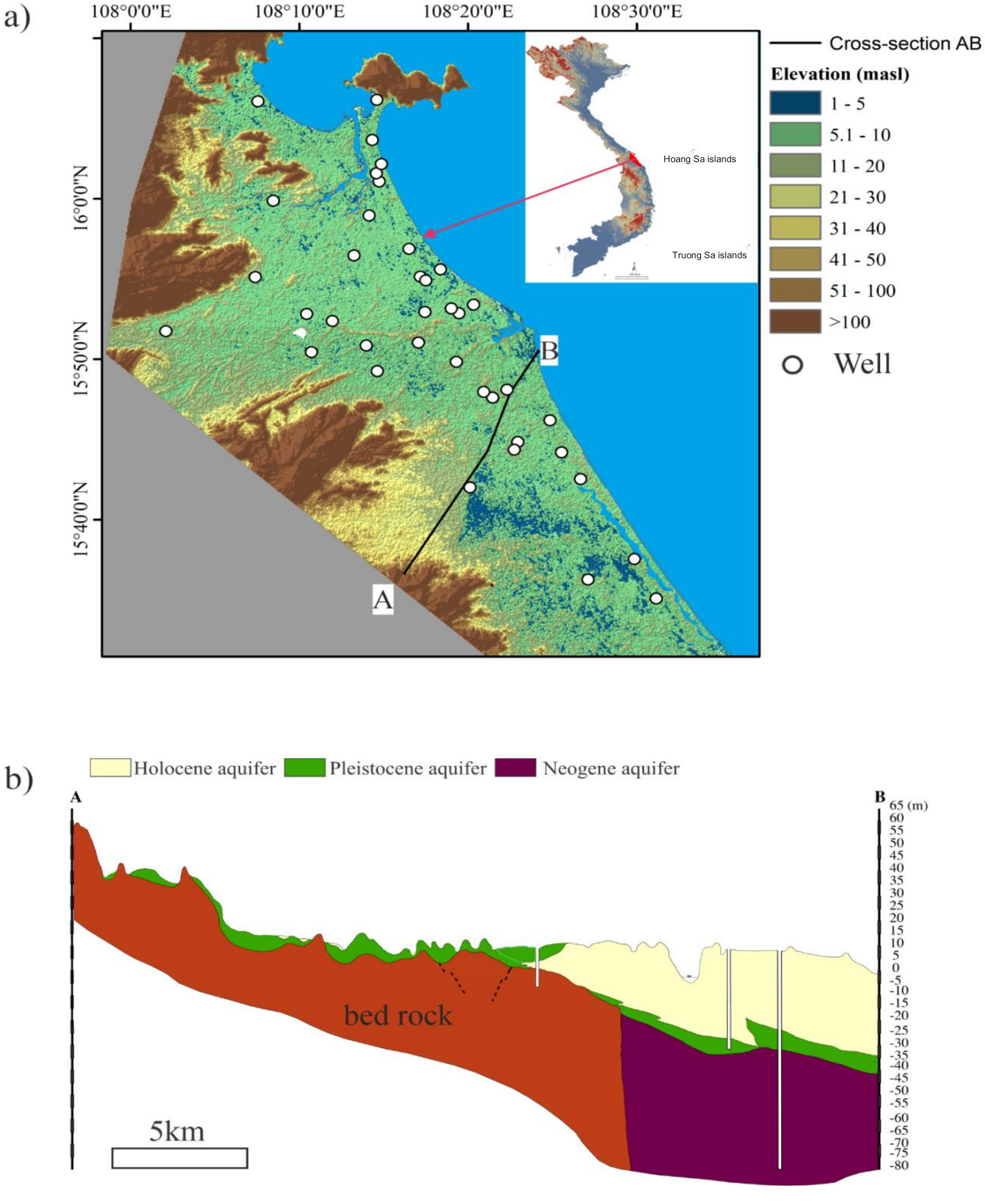

Figure 1. Topography map and location of monitoring wells in the study area (a) and cross-section AB (b)

2.1.2. Geology

The study area is mostly covered by Holocene and Pleistocene sediments with different origins such as marine, alluvial-marine, and pluvial. Those sediments compose of coarse to fine sand, silt, clay, and muddy clay with organic matter. The Neogene sediment is observed at depth from 10–160 m with thickness of 110–320 m. Jura formation is exposed at Binh Son, and its thickness is from 410–415 m (Hoang, 2016).

2.1.3. Hydrogeology and groundwater chemistry

Hydrogeologically, there are two main sedimental aquifers in the study area, which are Holocene and Pleistocene (Fig. 1b). The area of Holocene aquifer is about 840 km^2. The aquifer thickness ranges from 10 m to 40 m. The aquifer recharge mainly from the infiltration of rain water and partly from rivers. The TDS varies in a wide range of 20–28,200 mg/L. The main groundwater types are bicarbonate chloride-sodium and chloride bicarbonate-sodium. The groundwater is mainly salinized by the infiltration of seawater from river, some of saline groundwater also observed in deep depth. Pleistocene aquifer area is around 672 km^2. The thickness of this aquifer varies from 11.7 m to 34.1 m. TDS is 10–1,190 mg/L. In the salinized groundwater zone, groundwater types are chloride-sodium and chloride bicarbonate-sodium. In the fresh groundwater zone, groundwater type is mainly bicarbonate chloride-sodium. There are also fractured-porous aquifers formed from Neogene rocks, Jurassic sediments, and Paleozoic sediments. The groundwater in those aquifers are mainly observed in the weathering layers, yet they are not meaningful for groundwater supply. The bedrocks of the area are granite diorite, granite biotite, and gabbro with age from Permian to Cretaceous.

2.1.4. Hydrology and sea level

There are three main rivers in the study area, which are Cu De, Han, and Thu Bon Rivers. The rivers are strongly influenced by tide and flooding frequently occurs at the estuary areas in the rainy season. In dry season, salinity in the rivers is very high. A salinity of 7.9‰ were observed at a distance of 15.2 Km from Cua Dai estuary (Le et al., 2011). According to Le et al., 2011, when the sea level rose 12 cm, 33 cm, and 100 cm in 2020, 2050, and 2100, respectively, the areas flooded by seawater would be 979 ha, 1,064 ha, and 1,283 ha, respectively. Hence, SWI is a major issue in the study area.

2.1.5. Groundwater exploitation and SWI status in Holocene aquifer

In Quang Nam-Da Nang, Holocene has the highest potential exploitation reserves in sedimental aquifers with 363,502 m^3/day. In addition, it is the uppermost aquifer and, thus, is easy to be abstracted for domestic and agricultural use. The groundwater has been exploited 21,228 m^3/day from Holocene aquifer (National Center for Water Resources Planning and Investigation (NAWAPI), 2016). The groundwater abstraction caused the depletion of groundwater level from 0.18–0.24 m in period 2011-2015. And, SWI has developed rapidly to the inland. In recent years, the salt water boundaries (the boundaries of groundwater with TDS > 1000 mg/L) had moved about 200–500 m to the inland (MONRE, 2016). Therefore, the protection of groundwater from SWI is urgent in the study area.

2.2. Data used

The data of 46 wells in Holocene aquifer were used to assess the GALDIT parameters. The data is provided by the Division for Water Resources Planning and Investigation for Central Vietnam (CEVIW, 2019). The data of 46 wells consists of groundwater level, TDS, and aquifer thickness, which are utilized for the estimation of L, I, and T values, respectively. 29 out of 46 wells, which have additional data of hydraulic conductivity, are used for estimating the A values. G and D values are identified based on the hydrogeological conditions and geography, respectively. There also are 16 monitoring wells in the data of 46 wells. TDS was analyzed in Center of Technology and Analysis for Water Resources in Central Vietnam following standards mentioned in National technical regulation on groundwater quality (QCVN 09-MT:2015/BTNMT)

2.3. GALDIT method

The GALDIT is method that considers six hydrogeological parameters related with potential SWI. Each parameter is mapped and given a rating (Table 1). The rating variables of parameters are divided into four ranges of 2.5, 5, 7.5, and 10, indicating very low, low, medium, and very high vulnerability, respectively. The GALDIT result is a map of the weighted overlay of six maps (G, A, L, D, I, and T maps). The GALDIT index is calculated as the following equation:

$$\text{GALDIT} = \frac{\sum_{i=1}^{6} W_i \times R_i}{\sum_{i=1}^{6} W_i} \quad \text{(Eq. 1)}$$

where, R_i is the rating of i^{th} parameter; W_i is the weight of i^{th} parameter.

The weight of each indicator parameter reflects the its significance to the SWI potential (Table 1). The highest weight is 4 assigned to L and D, the weight of 3 is for A, 2 is for T, and the lowest (1) is for G and I (Chachadi and Lobo-Ferrreira, 2001). The Impact of existing status of sea water intrusion is evaluated using ratio of $Cl^-/[HCO_3^- + CO_3^{2-}]$ (Chachadi and Lobo-Ferrreira, 2001). Other researchers used alternative indicator for Cl^- / $[HCO_3^- + CO_3^{2-}]$ such as electrical conductivity (EC) and Cl^- (Chang et al., 2019; Luoma et al., 2017). In this study, TDS is an alternative indicator for $Cl^-/[HCO_3^- + CO_3^{2-}]$. The ranges of TDS for rating are less than 500 mg/L, 500–1000 mg/L, 1000–3000 mg/L, and greater than 3000 mg/L, representing the very low, low, medium, and high vulnerability to SWI, respectively. In addition, distance from the sea shore also is slightly modified to less than 500 m, 500–1500 m, 1500–2500 m, and greater than 2500 m as very low, low, medium, and high vulnerability to SWI, respectively (Table 1).

Table 1. Ranges and rating of GALDIT parameters

Parameter	Weight	GALDIT range*	Modified range	Rating
Groundwater occurrence (G)	1	Confined aquifer	Confined aquifer	10
		Unconfined aquifer	Unconfined aquifer	7.5
		Leaky confined aquifer	Leaky confined aquifer	5
		Bounded aquifer	Bounded aquifer	2.5
Aquifer hydraulic conductivity (A) (m/day)	3	>40	>40	10
		10 - 40	10 – 40	7.5
		5 - 10	5 – 10	5
		<5	<5	2.5
Height of groundwater level above sea level (L) (m)	4	<1.0	<-2.0	10
		1.0 - 1.5	-2.0 – -1.5	7.5
		1.5 - 2.0	-1.5 – -1.0	5
		>2.0	>-1.0	2.5
Distance from the sea shore (D) (m)	4	<500	<500	10
		500 - 750	500 – 1500	7.5
		750 - 1000	1500 – 2500	5
		>1000	>2500	2.5
Impact of existing status of SWI (I)	1	Ratio of Cl^- / $[HCO_3^- + CO_3^{2-}]$	TDS (mg/L)	
		>2	>3000	10
		1.5 - 2.0	1000 – 3000	7.5
		1.0 - 1.5	500 – 1000	5
		<1.0	<500	2.5
Thickness of aquifer (m)	2	>10	>10	10
		7.5 – 10	7.5 – 10	7.5
		5.0 – 7.5	5 – 7.5	5
		<5.0	<5.0	2.5

* Ferrreira and Chachadi, 2005

The GALDIT index is classified into three classes including low, moderate, and high SWI vulnerability with respect to those less than 5, 5–7.5, and greater than 7.5, respectively (Ferrreira and Chachadi, 2005).

The process for estimation of GALDIT index and SWI vulnerability map is summarized in the flow chart of Fig. 2.

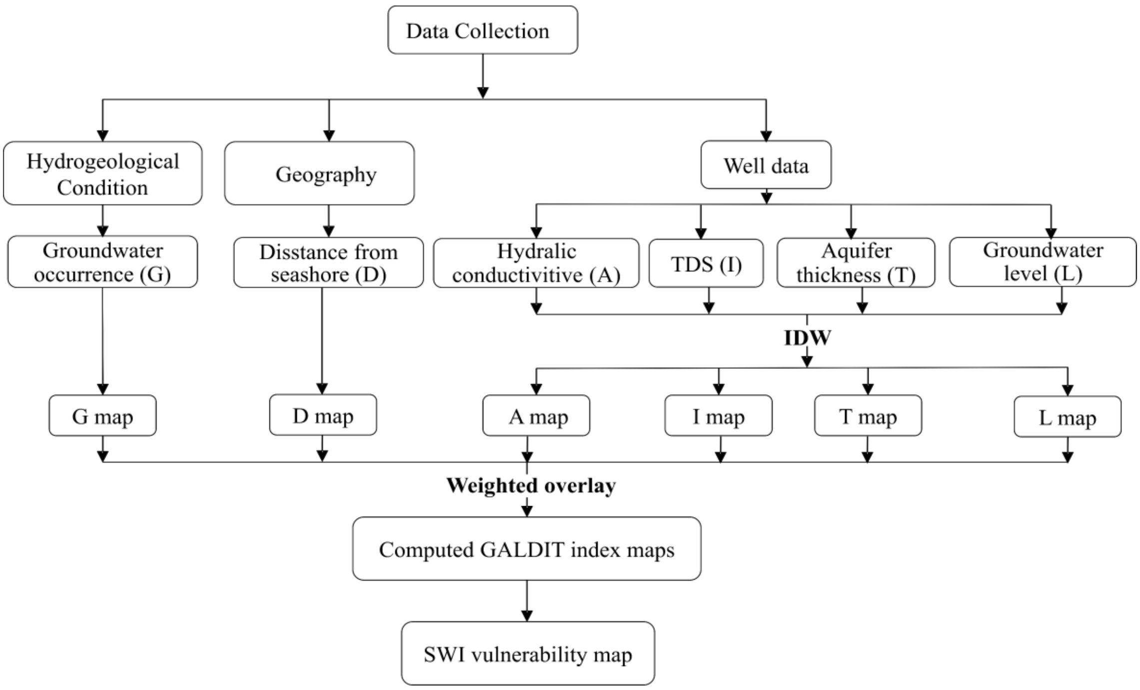

Figure 2. Flow chart of GALDIT method of seawater vulnerability assessment

2.4. Inverse Distance Weighting (IDW) method

The IDW is an interpolation method based on the concept that closer points tend to be more alike than those that are farther apart. Among spatial interpolation methods (such as Kriging, Spline, and IDW), the IDW is considered as one of the most frequently used method in the environmental sciences (Li and Heap, 2011). Since the IDW has an advantage as a simple deterministic interpolation method, it is applied for estimating the spatial distributions of A, L, I, and T in this study. The estimation using the IDW method for A, L, I, and T maps is as the following equation (Amstrong and Marciano, 1994):

$$Z_j = \frac{\sum_{i=1}^{N} W_{ij} Z_j}{\sum_{i=1}^{N} W_{ij}} \quad \text{(Eq. 2)}$$

Where,

Z_j is the estimated valued at location j;

Z_i is the known value at control point location i, and

W_{ij} is the weight that controls the effect of control points on the calculation of Z_j.

3. Results

3.1. Determination of GALDIT parameters

3.1.1. Groundwater occurrence (G)

According to the cross-section (Fig. 1b) and NAWAPI (2016), Holocene aquifer is unconfined aquifer, which mainly consists of sand. Therefore, G is assigned the rate of 7.5 for all study area.

3.1.2. Aquifer hydraulic conductivity (A)

The hydraulic conductivity observed from 29 wells shows a range from 0.49 to

30.5 m/day (Fig. 3a). The average is 10.6 m/day. The standard deviation is ±9.97 m/day. The interpolation results showed in Fig. 3a indicates that the hydraulic conductivity is mostly higher than 5 m/day in the study area. This means that the ability to transmit seawater inland is mostly low and medium with the rate of 5 and 7.5, respectively.

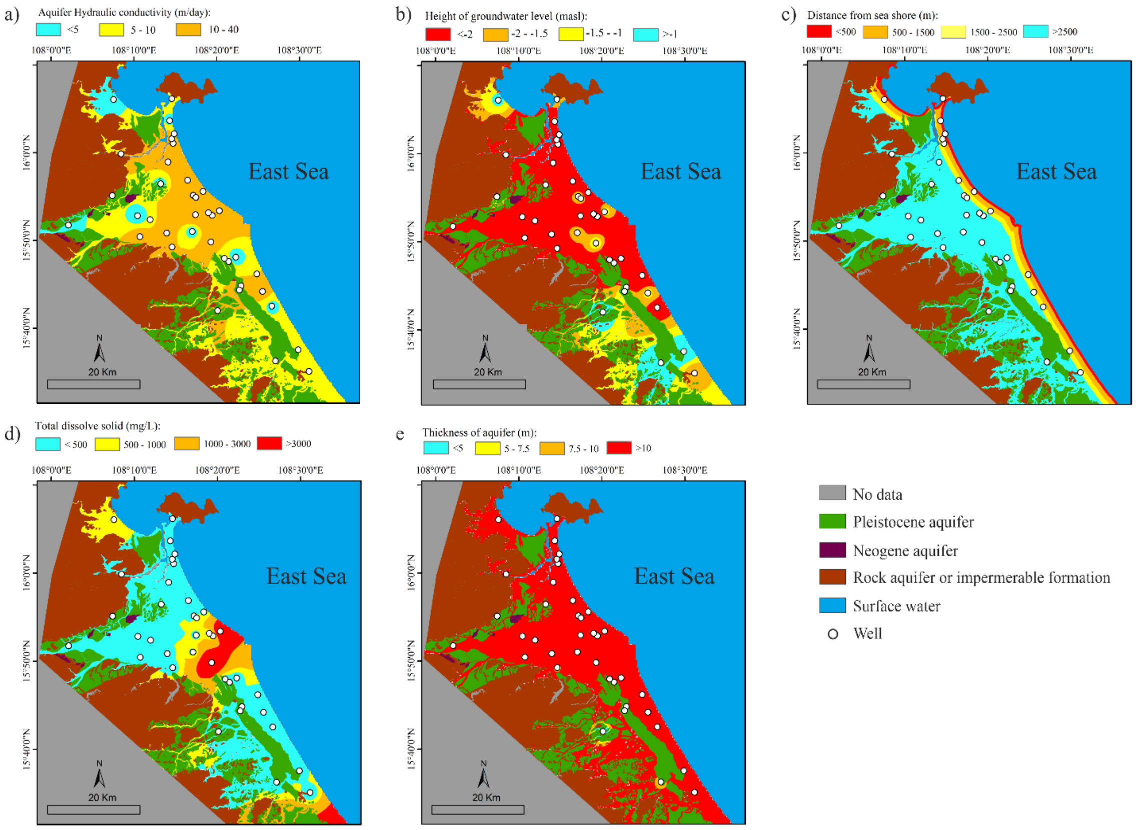

Figure 3. Distribution zones of Aquifer hydraulic conductivity (a), Height of groundwater level (b), Distance from sea shore (c), Total dissolved solid (TDS) (d), and Thickness of aquifer (e)

3.1.3. Height of groundwater level above sea level (L)

In the study area, all wells indicate the groundwater level below the mean sea water level. The groundwater level is from -7.87 m to 0 m above sea water level (masl) with an average ± standard deviation of -2.38±1.62 m. Hence, to clearly distinguish zones with different vulnerabilities, the range of L is reclassified as follows: groundwater levels of > -1.0 m, -1.5 – -1.0 m, -2.0 – -1.5 m, and < -2.0 m are rated 2.5, 5, 7.5, 10, respectively (Table 1). The distribution of groundwater level shows that the central zone is rated 10 as high risk of SWI, while the northern and southern zones are very low to medium (Fig. 3b).

3.1.4. Distance from the sea shore (D)

In this study, the distance from the sea shore greater than 2500 m is given a rating of 2.5. The rating of 5, 7.5 and 10 is given to the distance from the sea shore of 1500–2500 m, 500–1500 m, and less than 500 m, respectively (Fig. 3c).

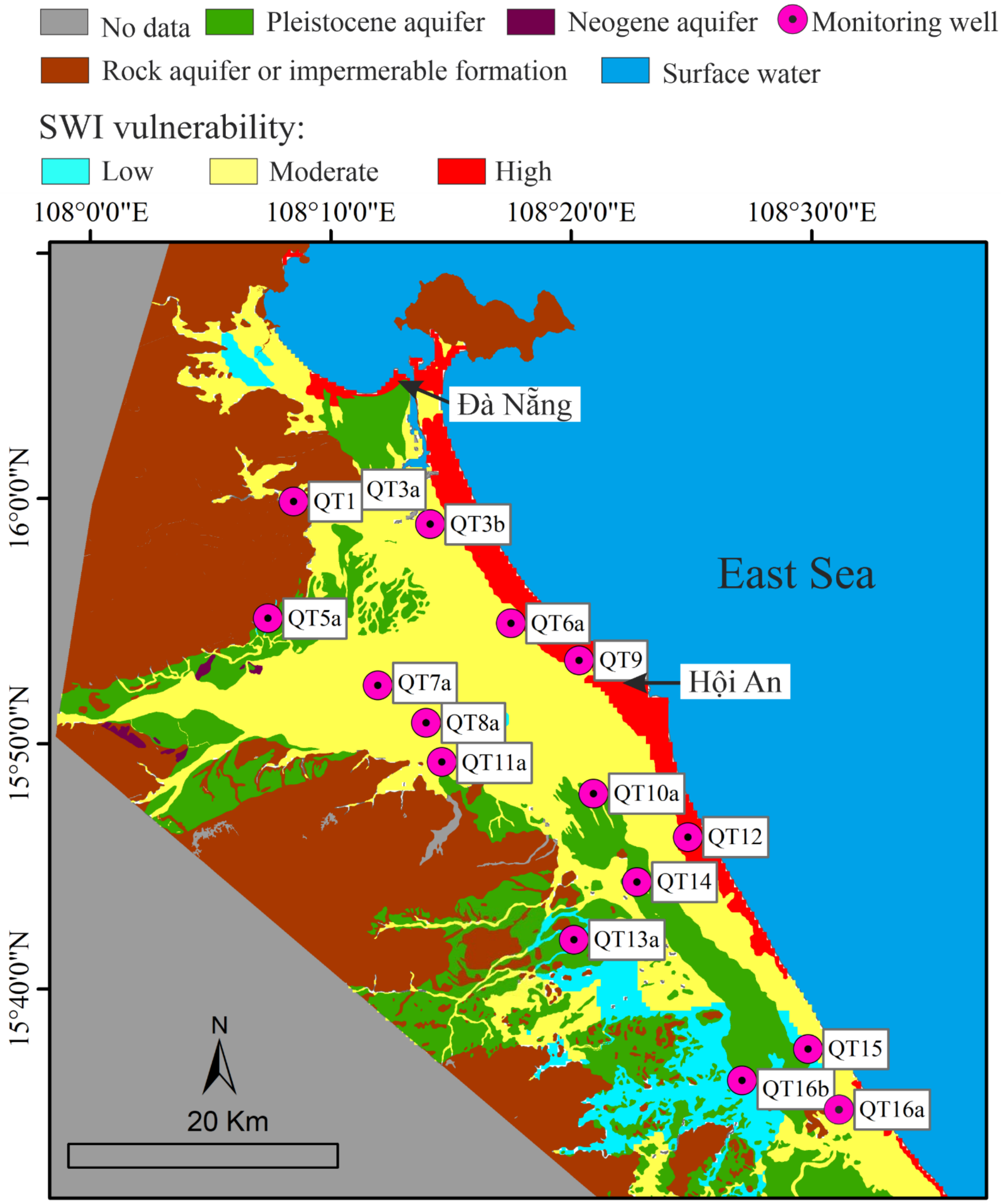

Figure 4. SWI vulnerability map by GALDIT method

3.1.5. Impact of existing status of SWI (I)

As mentioned, TDS is alternatively used for the ratio of $Cl^-/[HCO_3^- + CO_3^{2-}]$. Because salt water is considered as TDS greater than 1000 mg/L, the range of I is rated as the follows: TDS less than 500 mg/L, 500–1000 mg/L, 1000–3000 mg/L, and greater than 3000 mg/L is related to the rating of 2.5, 5, 7.5, and 10, respectively. The distribution of TDS shows that most of groundwaters are fresh. The salt water is concentrated in the populated areas such as Da Nang, Hoi An, and Tam Ky. Especially, the high TDS areas (TDS > 1000 mg/L) are at Cua Dai estuary, where is strongly affected by the SWI during dry season (Le et al., 2011) (Fig. 3d).

3.1.6. Thickness of Holocene aquifer (T)

The interpolation of the aquifer thickness in Holocene aquifer shows that the thickness is mostly greater than 10 m (Fig. 3e), and thus T is given the rating of 10. A small part near the exposure of Pleistocene aquifer has the thickness of 5–7.5 m and 7.5–10 m with respect to the rating of 5 and 7.5, respectively.

3.2. SWI vulnerability map

The SWI vulnerability index is calculated by weitghting overlaying six maps (G, A, L, D, I, and T) with weights following Eqn. 1 (Fig. 2). The result map from the weighting overlay of six maps shows the SWI vulnerability zones in the study area (Fig. 4). More than 70% of the study area indicates the moderate vulnerability to SWI. The zone of high vulnerability is along the sea shore of Hoi An, Da Nang, and Tam Ky, of which distance from the sea is less than 2500 m. The zone of low vulnerability is at the southern part of the study area.

3.3. Analysis of monitoring data

Among monitoring wells, there is one well (QT12) locating at the zone of high SWI vulnerability, three wells are at the low vulnerability zone (QT5a, QT15, and QT16b), and the remains are at the moderate vulnerability zone (Fig. 4). The variation of TDS observed in period 2011–2018 shows that even the wells locate close to the sea shore, the groundwater is still fresh with TDS less than 1000 mg/L, excepting well QT9. The TDS observed in well QT9 is greater than 8,000 mg/L (Fig. 5a). Moreover, well QT8a, which is 12,500 m far from the sea shore, also observed salt water with TDS greater than 2,000 mg/L (Fig. 5a). The high TDS of well occurred in the dry season 2011, 2013, and 2014. The plot between TDS and depth of monitoring well shows that groundwater becomes saline at the depth of 50 m (Fig. 5b).

The variation of in the period 2011–2018. GALDIT index for monitoring wells shows that there are two monitoring wells in the high SWI vulnerability (QT9 and QT12) (Fig. 5d). However, the SWI vulnerability of well QT9 changed to moderate in the rainy season of 2013–2017. The other monitoring wells indicated the moderate SWI vulnerability. There also change from moderate to low SWI vulnerability in well QT13a and QT16b, mostly in the rain season.

4. Discussions

In the coastal aquifer, groundwater is sensitive to SWI. In recent years, the population blooming has increased the water demand in the study area. And, to maintain the economic development, more groundwater is exploited from Holocene aquifer. As a result, SWI is a threat that decreases the quantity of usable groundwater and deteriorates the groundwater quality. Since the occurrence of SWI was occasionally observed in monitoring wells locating in the study area (Fig. 5c), the application of GALDIT method for identification of SWI vulnerability is a useful tool for the prevention of further SWI in the study area.

The SWI vulnerability map identified the locations of the high SWI vulnerability zones, which are coincided with populated cities (Hoi An, Da Nang, and Tam Ky) and areas closed to the river estuaries (Han River and Thu Bon River) (Fig. 4). Hence, the groundwater abstraction needs to be carefully managed to prevent further SWI in those zones. In addition, a part of groundwater in Holocene aquifer is recharged from Han River and Thu Bon River, where sea water intrusion frequently occurs. Therefore, measures are also required to mitigate the sea water intrusion along Han River and Thu Bon River and, then, prevent the SWI from rivers to Holocene aquifer.

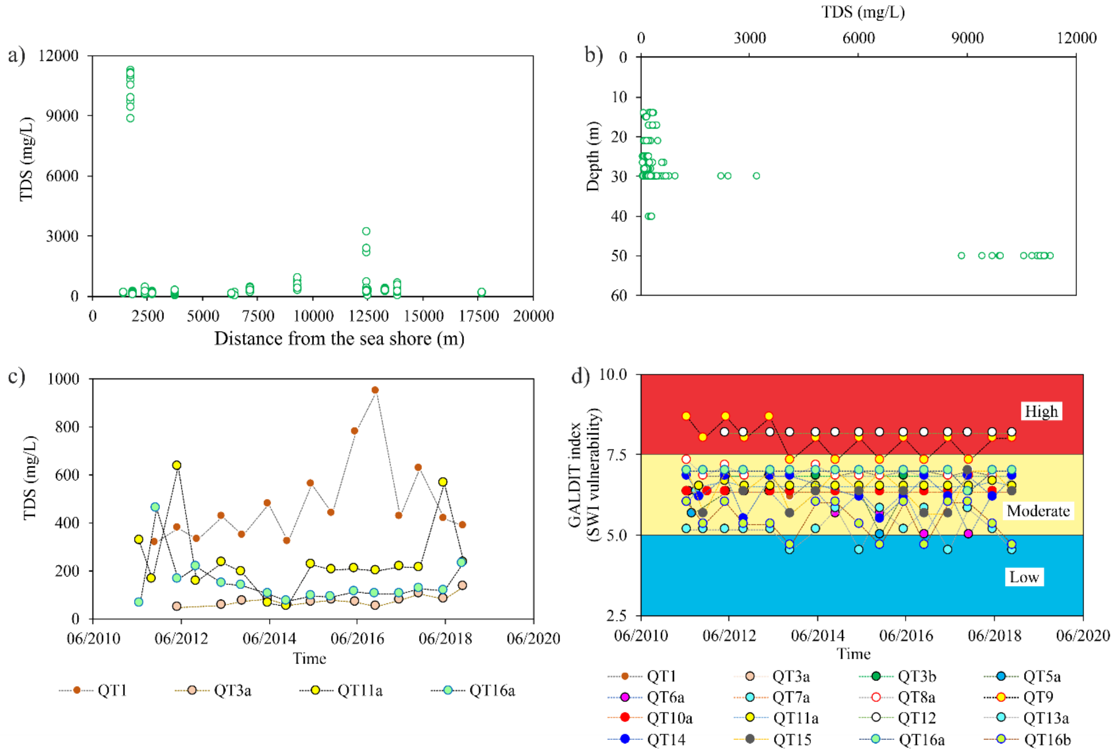

Figure 5. Plots of the relation between TDS and distance from sea shore (a) and TDS and well depth (b); monitoring data of TDS in occasional salinized monitoring wells (c), and GALDIT index of monitoring wells in Holocene aquifer (d)

According to the monitoring data, the saline groundwater observed at the depth of 50 m in well QT9 (TDS up to 11,276 mg/L) suggests that the fresh-salt groundwater interface is very close to the depth that most of abstraction wells located (around 30 m below the surface) in the study area. The intensive groundwater abstraction without controlling can cause the inland movement of the fresh-salt groundwater interface, salt water up-coning, and result in groundwater salinization. These phenomena were observed in monitoring well QT8a in the dry season of year 2011, 2013, and 2014, even though this well locates at the moderate SWI vulnerability zone. As QT8a locates at the agricultural zone of the study area, the salinization may be related to the intensive groundwater abstraction for irrigation in the dry season. Since the groundwater abstraction is not considered in GALDIT method, the SWI vulnerability can be higher than that illustrated in the GALDIT map. Therefore, the GALDIT results should be incorporated with the groundwater abstraction data in each SWI vulnerability for more efficient strategies for preventing SWI in the aquifer system.

In addition, the TDS is not so different among monitoring wells as the distance from the sea shore increases but it is getting higher with deeper depth of groundwater abstraction (Fig. 5a, b). This indicates that the groundwater is more vulnerable to the SWI in deeper depth or closer to the fresh-salt groundwater interface. Therefore, the utilization of depth of groundwater sampling and/or the occurence of fresh-salt groundwater interface with GALDIT index can also help improve the result of the identification of SWI vulnerability zones in the study area.

The time series data shows that there are changes of SWI vulnerability from high to moderate or from moderate to low (Fig. 5d). The variations mostly occurred in the rainy season, when groundwater is highly recharged. Closely analyzing the monitoring data, the changes of SWI vulnerability are related with the variations of groundwater level between rainy and dry season. The difference of groundwater level between two monitoring seasons (June and November each year) in period 2011–2018 is from 0.39 m to 2.80 m (1.10±0.57 m, on average ± standard deviation). The difference is up to four levels of the rating of parameter L for wells locate in the zones with groundwater higher than -2 m such as QT5a, QT6a, QT9, QT13a, QT15, QT16a, and QT16b. As a result, to give a better SWI prevention and groundwater management, the SWI vulnerability map is suggested to be frequently updated, according to the changes of groundwater level as well as the others parameters.

5. Conclusions

In this study, GALDIT method is applied to Holocene aquifer for the identification of SWI vulnerability zones, supporting the prevention of SWI and groundwater management in Quang Nam - Da Nang. The results showed that the high vulnerability zones were along the coastal area and coincided with populated cities and areas closed to river estuaries. The moderate vulnerability zones were dominant in the study area. The low vulnerability zones were observed at the south of the study area. The additional information from monitoring data indicated the occasional occurrence of SWI in dry seasons, and saline groundwater in the depth greater than 30 m below the surface. Based on monitoring data, groundwater abstraction and depth of groundwater sampling and/or depth of fresh-salt groundwater interface are suggested to be taken into account of the SWI assessment. A frequent update of SWI vulnerability map is suggested for a better groundwater management and SWI prevention in the study area. In addition, construction of dam for preventing salinity in river estuaries is recommended to mitigation the sea intrusion along rivers and the salinization of Holocene aquifer from the surface water.

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