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GIS based – GALDIT method for aquifer vulnerability assessment to seawater intrusion: Case of a qp_{2-3} aquifer of Mekong Delta

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ABSTRACT

Recently, seawater intrusion (SWI) in coastal aquifers is a global issue that is exacerbated by sea-level rise, climate change, and an increasing dependency on coastal fresh groundwater resources for water supply. Vietnam's Mekong Delta has a flat topography, a dense river network, and a 700 kilometer coastline covering the region's west and east. The Mekong Delta is facing increasingly serious saline intrusion. This paper describes the results of the examination using the GALDIT method as a model to evaluate the vulnerability of seawater intrusion. The method is used to determine the trend of groundwater contamination by seawater intrusion in the qp_{2-3} aquifer of the Mekong Delta, this Upper-middle Pleistocene aquifer (qp_{2-3}) is one of the main productive aquifers in the Mekong Delta. The analysis result in 2015 shows a moderate and high level of vulnerability in which the highly vulnerable area is along the Tien River and at the depression cone area in Ca Mau. The analysis is reconducted for the time of 2030 with the predicted values for the groundwater level through the forecasting tool. By comparing the model of two times of 2015 and 2030, the results indicated that the impact of the continuous decline of groundwater level is greater than the impact of sea level rise. If the rate of drawdown is kept the same, by 2030 the highly vulnerability area will have expanded to two-thirds of the Mekong Delta. The GALDIT method is a good approach for saltwater intrusion research and moreover water management, and environmental management, such as evaluating the most sensitive areas for monitoring or imposing restrictions where necessary.

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1. Introduction

Coastal aquifers serve as a significant source of freshwater supply in many countries around the world, especially in arid and semi-arid zones. Recently, seawater intrusion (SWI) in coastal aquifers has been a global issue exacerbated by sea-level rise, climate change, and an increasing dependency on coastal fresh groundwater resources for water supply (Adrian et al., 2012; Pham and Lee, 2014). The groundwater vulnerability assessment to seawater intrusion is one of the major techniques used to assist the development of groundwater protection strategies (Trabelsi et al., 2016). In general, vulnerability assessments of groundwater are a way of making complex hydrogeological information into a simple map that can easily be utilized by decision-makers and policymakers, environmental managers, as well as the general public. The resulting map would then be applied to both water management and land use planning, such as evaluating the most sensitive areas for monitoring, and/or imposing restrictions where necessary, and risk assessment among other things (Liggett and Talwar, 2009, Kura et al., 2015). One model with the ability to determine the vulnerability of an area to seawater intrusion is the GALDIT model (Sophiya and Syed, 2013; Saidi et al., 2013). This method was first created by Chachadi and Lobo-Ferreira (2001) and the idea originated from the DRASTIC model to serve as an indicator-based technique in the vulnerability assessment of an aquifer to seawater intrusion (Santha Sophiya and Syed, 2013). GALDIT is a method of expressing the vulnerability of groundwater to saltwater intrusion on a map that is based on six parameters believed to be indicators for the vulnerability of an aquifer to seawater intrusion. The major drawback of this method is the unawareness of the pumping effect on the seawater intrusion process. Despite this limit, this model still shows many advantages. It has a low cost and can be applied in extensive regions, because of the few and easy to collect, data required (Trabelsi et al., 2016).

This paper describes the results of the examination using the GALDIT method as a method to evaluate the vulnerability of saltwater intrusion in the qp_{2-3} aquifer of the Mekong Delta. This Upper-middle Pleistocene aquifer (qp_{2-3}) is one of the main productive aquifers in the Mekong Delta. By applying the analysis for two times of 2015 and 2030 (forecast), the model can show the trend of groundwater contamination by seawater intrusion in the qp_{2-3} aquifer. Firstly, the analysis is applied to the data up to 2015, and then to the forecasted groundwater level by 2030 due to continuous groundwater drawdown and sea level rise.

2. Materials and Methodology

2.1. Study area

The Mekong Delta (MKD) has an area of 40,816 km^2 including 13 provinces (Statistic Summary Book of Vietnam 2020). The Mekong Delta of Vietnam consists of flat terrain, mostly of average height of 0.7 to 1.2 m, except for some high hills in the northern delta (Report on Vietnam-Netherlands Mekong Delta Masterplan project, 2011). The delta has a dense river network and a shoreline extent of about 700 km covering both the west and east sides of the region.

The MKD, being located in the tropical monsoon region, is characterized by high temperature all year round with the average temperature around 27^{0}C. There are two distinct seasons, i.e., the rainy season from May to October, and the dry season from November to April the following year.

There are eight distinct aquifers in the delta subsurface. This Upper-middle Pleistocene aquifer (qp_{2-3}) is one of the main productive aquifers in MKD (Bui et al., 2014). Covering an area of 39,279 km^2, this aquifer is composed of Upper-Middle Pleistocene sediments of alluvial and marine origin (amQ_1^{2-3}) that consist of fine to coarse sand and gravel. The depth to the top and the thickness of the aquifer varies in space and on cross-sections. It is a weakly confined aquifer. The aquifer is overlain by an aquitard layer, consisting of silt, clay, or silty clay. Based on the model of the MKD aquifer system (Pham, 2020), this aquifer has a depth to the top of 31.6 to 81.7 m and a thickness from 3.6 to 13.5 m. The depth to the top of the aquifer varies from 30 m to 142 m, with an average of 86.88 m. The depth to the bottom of the aquifer ranges from 50 m to 207 m, with an average of 129.13 m. The thickness is from 2 m to 100.30 m, with an average of 41.4 m. The permeability varies from 0.89 to 55.07 m/day, with an average of 21.24 m/day (Pham, 2020).

MKD natural characteristics as well as human activities may affect groundwater quality due to seawater intrusion into aquifers. The distribution map of a vulnerable area to potential seawater intrusion represents the entire picture of seawater intrusion is necessary.

2.2. GALDIT method

One of the systems for evaluation of the vulnerability of aquifers to pollution and ranking includes a vulnerability index, which is computed from hydrogeological, topographical, and other aquifer characteristics is the GALDIT method (Chachadi and Lobo Ferreira, 2005; Saidi et al., 2013; Kura et al., 2015). This method was first created by Chachadi and Lobo Ferreira (2001) as a standardized indicator-based system in the vulnerability assessment of an aquifer to seawater intrusion.

The GALDIT method was applied based on six important factors controlling seawater intrusion. This method then weights each parameter and calculates the priority of each parameter in comparison with the others through a decision-making process. There are six parameters applied in the GALDIT model including:

Groundwater occurrence (G): In general, groundwater exists in geological layers, which may be unconfined, confined, leaky confined, or limited by several boundaries. The extent of saltwater intrusion depends on the original nature of aquifer media. An unconfined aquifer would be more affected by seawater intrusion compared to a confined aquifer because of the higher atmospheric pressure of a confined aquifer. Similarly, a confined aquifer may be more prone to seawater intrusion compared to a leaky confined aquifer. The aquifer layer can be seen as an unconfined aquifer if it is a shallow aquifer, underlay by thin aquitard and the water level is influenced by surface water. For deeper aquifers, the type of aquifer depends on the thickness of the aquitard overlaid, if the overlaid aquitard is thinner than 5 m, it is a leaky confined aquifer, otherwise it is a confined aquifer.

Aquifer hydraulic conductivity (A) is a representative parameter used to measure the water flow rate in the aquifer. The higher the conductivity, the higher the inland movement of the seawater fronts.

The level of groundwater (L) concerning mean sea elevation is the most important factor of the seawater intrusion evolution in an area. Because the level determines the hydraulic pressure available to push back the seawater front. In this study, the groundwater level was defined based on data of groundwater level observation during 20 years from 1995 to 2015. Distance from the shore (D): Close to the coast, we can get the maximum impact. The distances from shore of 3, 6, 10, and >10 km were chosen.

Impact of existing status of seawater intrusion in the area (I): The study area has a potential to be under stress which can already modify the natural hydraulic balance between seawater and fresh groundwater. The ratio of Cl^- / [$HCO_3^{-1} + CO_3^{2-}$] is a criterion to evaluate seawater intrusion into the coastal aquifers. While chloride is the dominant ion in seawater and it is only available in small quantities in groundwater, bicarbonate is available in large quantities in groundwater and occurs only in very small quantities in seawater. This ratio can be defined from the chemical analysis data available for the study area.

Table 1. Weight and important rate of GALDIT (Chachadi and Lobo-Ferreira , 2005).

Indicator		**G**	**A (m/d)**	**L (m)**	**D (m)**	**I**	**T (m)**
Weight		**1**	**2**	**5**	**3**	**6**	**3**
Important rating	**10.0**	Confined aquifer	> 40	< 1.0	< 500	> 2.0	> 10.0
	7.5	Unconfined aquifer	10÷40	1.0÷1.5	500÷750	1.5÷2.0	7.5÷10.0
	5.0	Leaky confined aquifer	5÷10	1.5÷2.0	750÷1000	1.0÷1.5	5.0÷7.5
	2.5	Bounded aquifer	< 5	> 2.0	> 1000	< 1.0	< 5.0

The thickness of the aquifer, which is being mapped, T: In determining the extent and magnitude of seawater intrusion in the coastal areas, aquifer thickness or saturated thickness of an unconfined aquifer plays an important role.

The weight and important ratings of each indicator suggested by Chachadi and Fereira are shown in Table 1.

For each of the above items, each parameter was classified, weighed and scored, and added by equation.

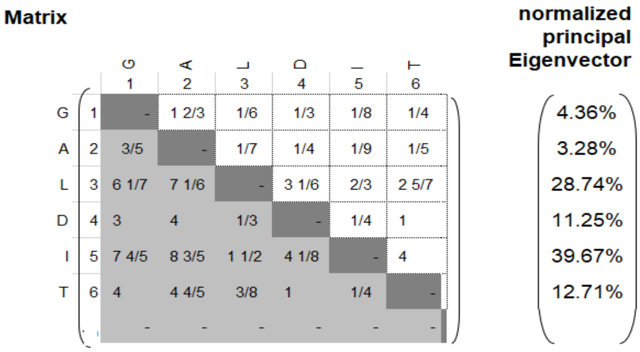
$$GWPP = \frac{\sum_1^6\{(W_i)R_i\}}{\sum_1^6 W_i} \tag{1}$$

Here, *GWPP* is the contamination potential, W_i is the weight of each item, and R_i is the score of each item. The basis of this method rests on the process of weighting, ranging, and rating of the vulnerability index. All the parameters in the GALDIT model have pre-assigned weights and rates, which afterward are used in creating individual maps of each of the six parameters as well as in the overlaying process of these parameters in a GIS environment. The resulting map would identify areas that are most likely to be affected by seawater intrusion (Saidi et al., 2013).

This method has been employed by some researchers (Sundaram et al., 2008; NAJIB et al., 2012; Saidi et al., 2013) to evaluate the groundwater vulnerability to seawater intrusion.

2.3. Apply AHP for weighting

Determining the weight of evaluation criteria is the key step that directly affects the comprehensive evaluation results. How to analyze the weights of qualitative and quantitative indicators by using evaluating methods is a vital question.



Matrix

normalized principal Eigenvector

		G 1	A 2	L 3	D 4	I 5	T 6	normalized principal Eigenvector
G	1	-	1 2/3	1/6	1/3	1/8	1/4	4.36%
A	2	3/5	-	1/7	1/4	1/9	1/5	3.28%
L	3	6 1/7	7 1/6	-	3 1/6	2/3	2 5/7	28.74%
D	4	3	4	1/3	-	1/4	1	11.25%
I	5	7 4/5	8 3/5	1 1/2	4 1/8	-	4	39.67%
T	6	4	4 4/5	3/8	1	1/4	-	12.71%
		-	-	-	-	-	-	

Figure 1. The consolidated matrix and principal Eigenvector.

One of the most broadly applied methods in the field of assisting the decision-making process is the Analytic Hierarchy Process (AHP), introduced by Saaty (1980). By capturing both subjective and objective aspects of a decision, the application of AHP helps to reduce the subjectivity in the decision-making process. In recent years, AHP has been applied in many practical aspects, including issues related to spatial data combined with GIS.

Applying AHP for the GALDIT method, with 6 criteria as the number of GALDIT indicators, the number of participants applied is 5, with consistency less than 0.1. The consolidated matrix and principal Eigenvector are analyzed and shown in Figure 1. The result provides weights and ranking of each indicator as in Table 2.

2.4. Forecasting near future groundwater level fluctuations

The level of groundwater (L) is the most important factor of the seawater intrusion evolution. The variation in the water level of coastal aquifers over time has many causes: water supply from upstream rivers, water supply from surface water, amount of groundwater extraction, and sea level rise. The time of 2030 was chosen to analyses the vulnerability of saltwater intrusion in the near future. Vulnerable assessment maps were conducted for 2030 under two conditions of variable groundwater levels due to continued groundwater exploitation and due to sea level rise, respectively. From the result, the effect of each condition can be seen. Finally, the assessment map for 2030 was analyzed due to both conditions.

Table 2. Result of GALDIT weighting using AHP.

Indicator variables	G	A	L	D	I	T
Weighting	4%	3%	29%	11%	40%	13%
Ranking	5	6	2	4	1	3

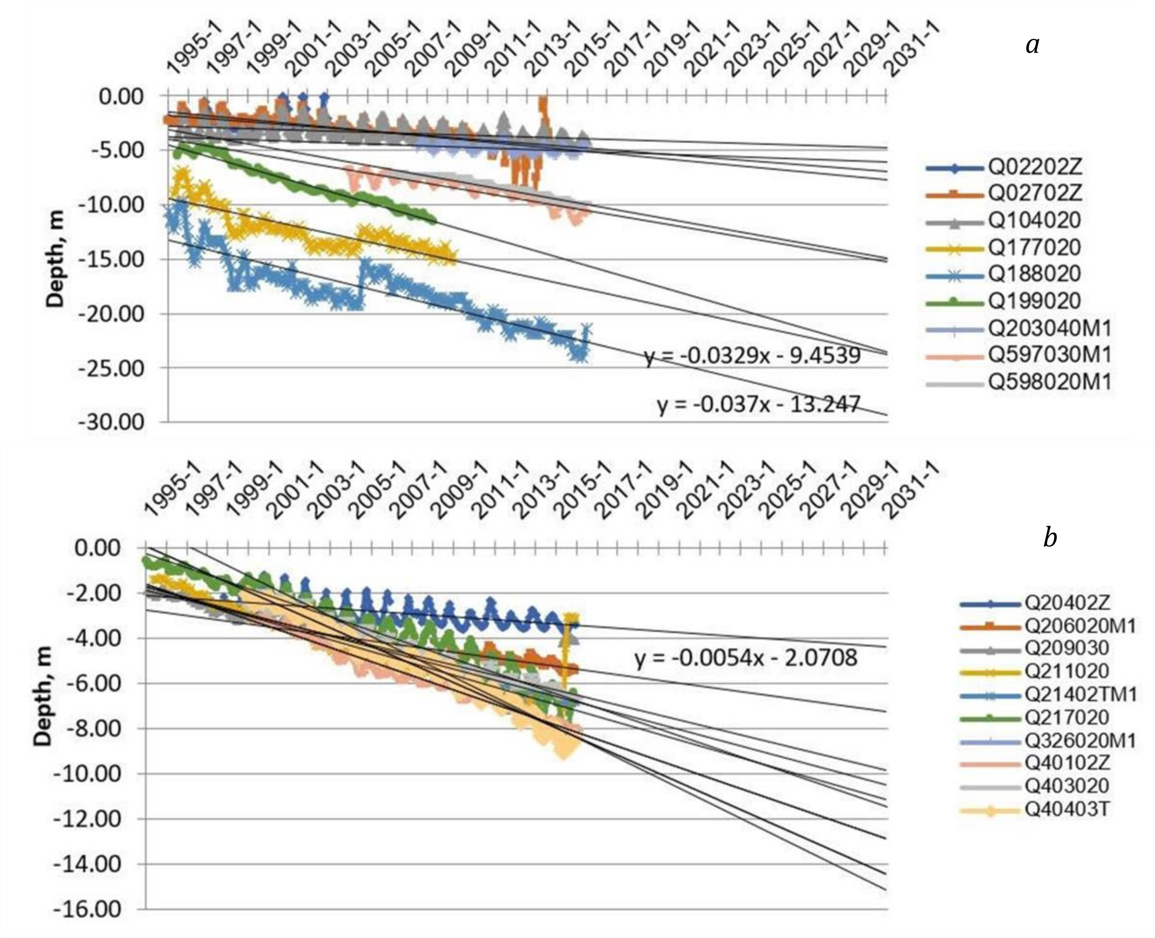


Figure 2. Predict groundwater level for 2030 for qp$_{2-3}$ aquifer.

2.4.1. Groundwater level variation

To predict the groundwater level in 2030 the trending equation was applied to observation data to predict the groundwater level (Figure 2). It shows the trend of decline at all stations. The effect of groundwater exploitation is significant. With the present trend continuing, the decline in groundwater level is becoming a reality that may largely influence the extent of saltwater intrusion in the coastal freshwater aquifers.

2.4.2. Sea level rise

According to Danet Hak et al. (2016) the observed sea level data at Vung Tau station and My Thanh station from 1985 to 2012 show an increasing trend over time, as in Figure 3. In this paper, the sea level rise is estimated based on the data of the sea level in Vung Tau station using of Geometric Brownian motion method. A geometric Brownian motion (GBM) (also known as exponential Brownian motion) is a continuous-

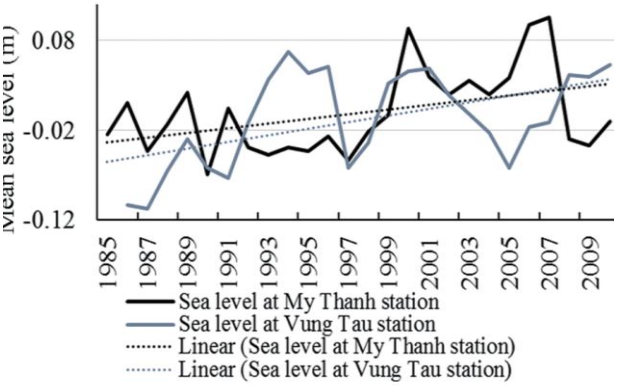
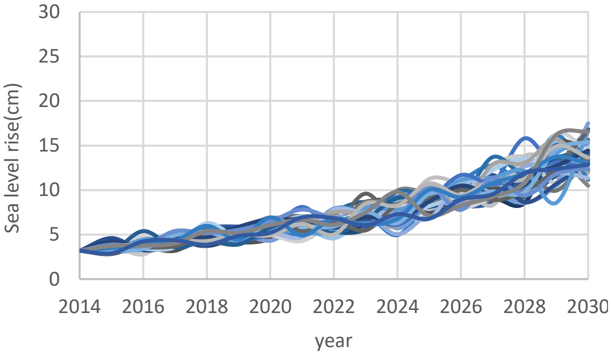


Figure 3. Inter-decadal trend of mean sea level at My Thanh and Vung Tau station, along the southern coast of the MKD (Danet Hak et al., 2016).

time stochastic process in which the logarithm of the randomly varying quantity follows a Brownian motion with drift. In this study, a geometrical Brownian motion model is used to predict sea level rise. The sea level data of Vung Tau's station from 1978 to 2014 is used to predict for a period of 2014 to 2030. Because the rise in the period 1978÷2014 is not much (+3.19 cm) the linear approximation is applied. The data from 2014÷2030 is calculated using the Geometric Brownian motion method, and the result is shown in Figure 4 below. Calculation shows that the result mainly ranges from 10÷16 cm, the average value is about 13 cm. This is in line with the forecast in the Report from the Ministry of Natural Resources and Environment of Vietnam (MNRE, 2016). The range is not too large, so it is acceptable to use the average value in the calculation.

3. Result and discussion

To apply the GALDIT method, each indicator is analyzed based on the reference to other research, the characteristics of the study area, the availability of the dataset, and the condition of each indicator, important rate was built for MKD. The indicator variables and important ratings are shown in Table 4. The weight of each indicator is calculated using the AHP method as in Table 2.



3.1. The GALDIT indicator maps

The Galdit indicator maps were established based on criteria and then reclassified according to the importance rating as shown in Table 2.

In this study, the type of aquifer can be defined based on the 3D model of the hydrogeological system. Based on the thickness of the Aquitard layer lay directly upon calculated aquifer, the aquifer layer can be sub-dived to confined and leaky confined. Aquitard thickness < 5 m – leaky confined aquifer. Aquitard thickness > 5 m – confined aquifer.

Due to the limit of data, in this study, it is assumed that the aquifer is homogeneous and has the same value of hydraulic conductivity K =2.9E-4 m/s = 25.056 m/d, between 10 - 40 so the important rate = 75.

Based on observed groundwater data from 1/1995 to 12/2015 of 19 stations, the map of groundwater level was built for 2015. The map then classifies to 4 ranking as in Figure 6.d. The lowest groundwater level was found to be in the south area of MKD, in Ca Mau where there is high pumpage and a thinner aquifer compared with the center area. In any case, the groundwater elevation in these parts was predicted to be lower than -10 m, indicating the likelihood of more pressure from the seawater to break the equilibrium interface that lies between the fresh and seawater. (Figure 6.d).

The data of hydrochemistry tests of the qp_{2-3} aquifer was divided into two groups before and

Table 3. Scenarios of sea level rise in East Sea of Viet Nam (Report from Ministry of Natural Resources and Environment of Vietnam). Unit: cm

Scenario	2030	2040	2050	2060	2070	2080	2090	2100
RCP2.6	13 (8 ~ 19)	17 (10 ~ 25)	21 (13 ~ 32)	26 (16 ~ 39)	30 (18 ~ 45)	35 (21 ~ 52)	40 (24 ~ 59)	44 (27 ~ 66)
RCP4.5	13 (8 ~ 18)	17 (10 ~ 25)	22 (14 ~ 32)	28 (17 ~ 40)	34 (20 ~ 48)	40 (24 ~ 57)	46 (28 ~ 66)	53 (32 ~ 76)
RCP6.0	13 (8 ~ 17)	17 (11 ~ 24)	22 (14 ~ 32)	27 (18 ~ 39)	34 (22 ~ 48)	41 (27 ~ 58)	48 (32 ~ 69)	56 (37 ~ 81)
RCP8.5	13 (9 ~ 18)	18 (12 ~ 26)	25 (17 ~ 35)	32 (22 ~ 46)	41 (28 ~ 58)	51 (34 ~ 72)	61 (42 ~ 87)	73 (49 ~ 103)

Table 4. Indicator variables, ranks and important rate of each GALDIT indicators (Pham, 2020).

Indicator variables						Importance rating	GALDIT Ranking	Vulnerability Classes
G	A (m/d)	L (m)	D (km)	I	T (m)			
Confined aquifer	> 40	>-15	0 - 3	> 60	> 60	100	4	Very high Vulnerability
Unconfined aquifer	10 - 40	-10 to -15	3 - 6	30 - 60	40 - 60	75	3	High Vulnerability
Leaky confined aquifer	5 - 10	-5 to -10	6 - 10	15 - 30	20 - 40	50	2	Moderate Vulnerability
Bounded aquifer	< 5	< -5	> 10	< 15	< 20.0	25	1	Low Vulnerability

after the year 2000. The piper diagram shows the increasing of Na+, and K+ content in samples after 2000, which shows the spread of saline water in underground water of the qp$_{2-3}$ aquifer. For that, the ratio of $Cl/[HCO + CO_3]$ is a criterion to identify the extent of seawater intrusion into the coastal aquifers. With the data from 125 hydro-chemical tests shown in Figure 5, the I map was built. Figure 5 shows that saltwater intrusion gets worse gradually because most of the data after 2000 are located Sea water type, compared with before 2000. The most affected area falls along the river which already has a history of seawater intrusion or fossil saltwater. The river area was rated 75÷100 as importance, another area was rated under 50 (Figure 6.e).

The thickness of the aquifer was generated from the 3D model of the aquifer system of MKD (Pham, 2020). The most affected area was the center area, with a thickness of more than 40 m. The larger the aquifer thickness, the larger the extent of seawater intrusion, and vice versa. The center area was rated 75÷100 as an important rate, another area was rated under 75 (Figure 6.f).

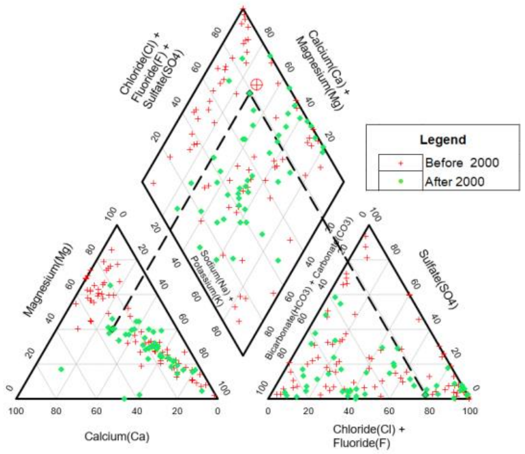


Figure 5. Hydrochemistry data.

3.2. Vulnerability analysis for 2015 of qp2-3 aquifer

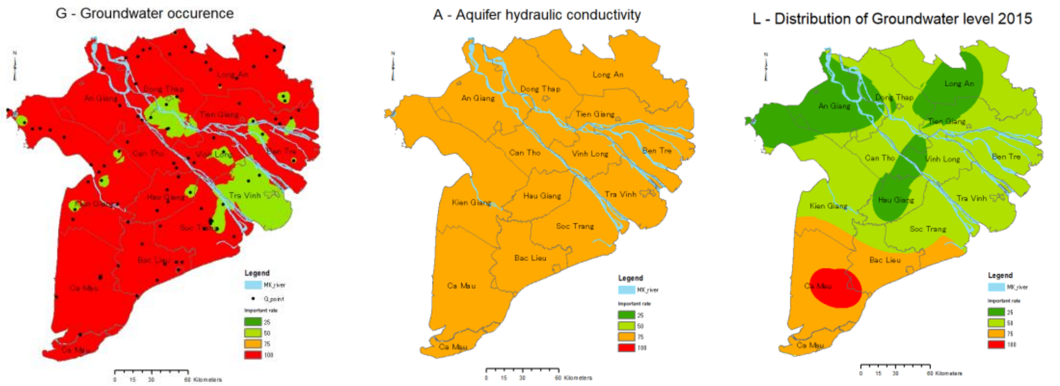
The Galdit vulnerability map is analyzed by weight overlaying of six component maps with the weight calculated by AHP as shown above. The result mostly indicates moderate to high vulnerability in all areas. This result, particularly the identification of the highly vulnerable area located along the Tien River and at the area of the depress cone in the south of MKD (Figure 7).

3.3. Vulnerability analysis for 2030 for qp2-3 due to Groundwater depression and Sea level rise

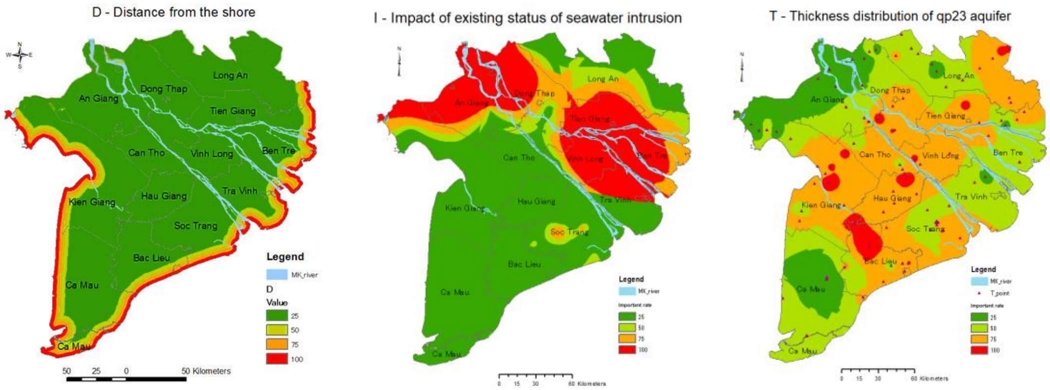
The time of 2030 was chosen to analyses the vulnerability of saltwater intrusion in the near future. Vulnerable assessment maps were conducted for 2030 under two conditions: variation of groundwater levels due to continued groundwater drawdown (as in Figure 8) and due to sea level rise (as in Figure 9), respectively. From the result, the effect of each condition can be seen. Finally, the assessment map for 2030 was analyzed due to both continued groundwater exploitation and sea level rise. The final result is shown in Figure 10.

3.4. Discussion

In the qp$_{2-3}$ aquifer, existing a large area of salt water located deep inland, along the Tien River. This may be due to the geological formation



a) The reclassified map of G. *b) The reclassified map of A.* *c) The reclassified map of L.*



d) The reclassified map of D. *e) The reclassified map of I.* *f) The reclassified map of T.*

Figure 6. Galdit indicator maps.

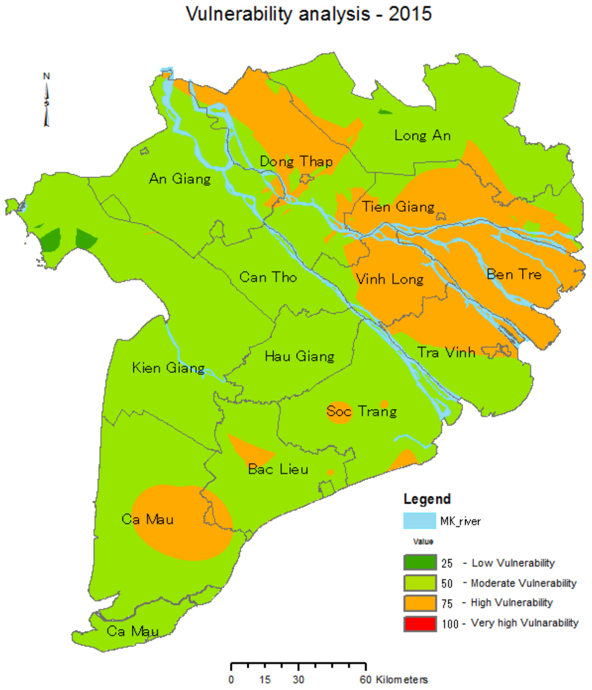


Figure 7. The vulnerability map of MKD in 2015.

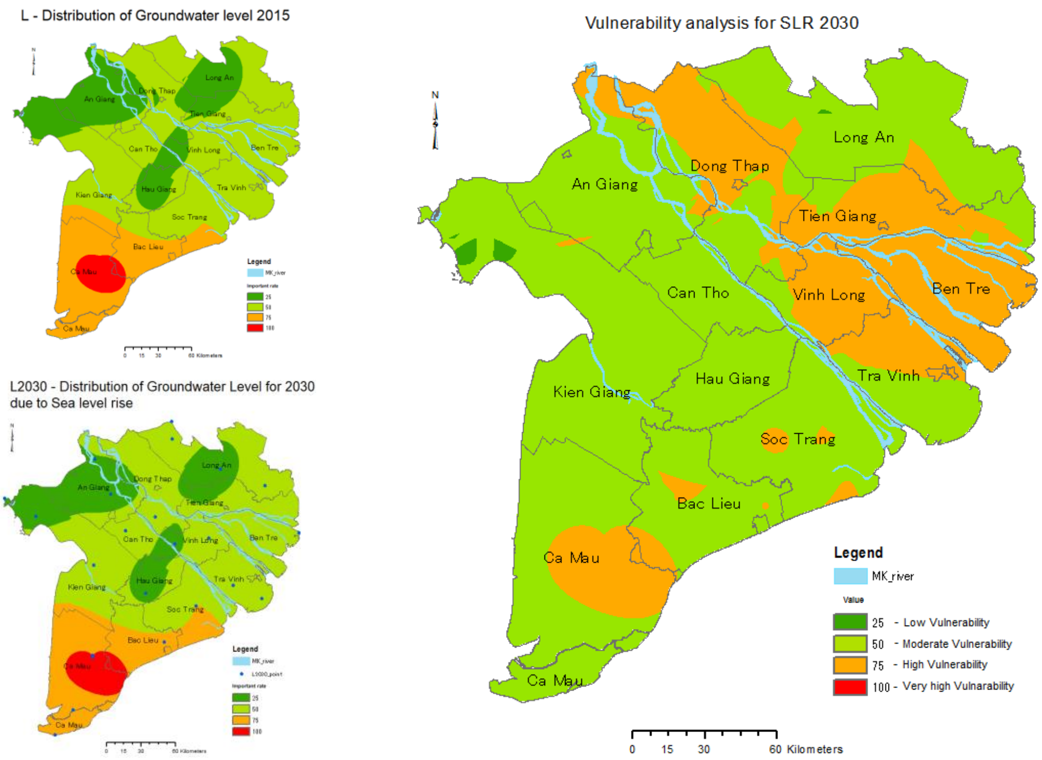


Figure 8. Vulnerability analysis for 2030 due to sea level rise.

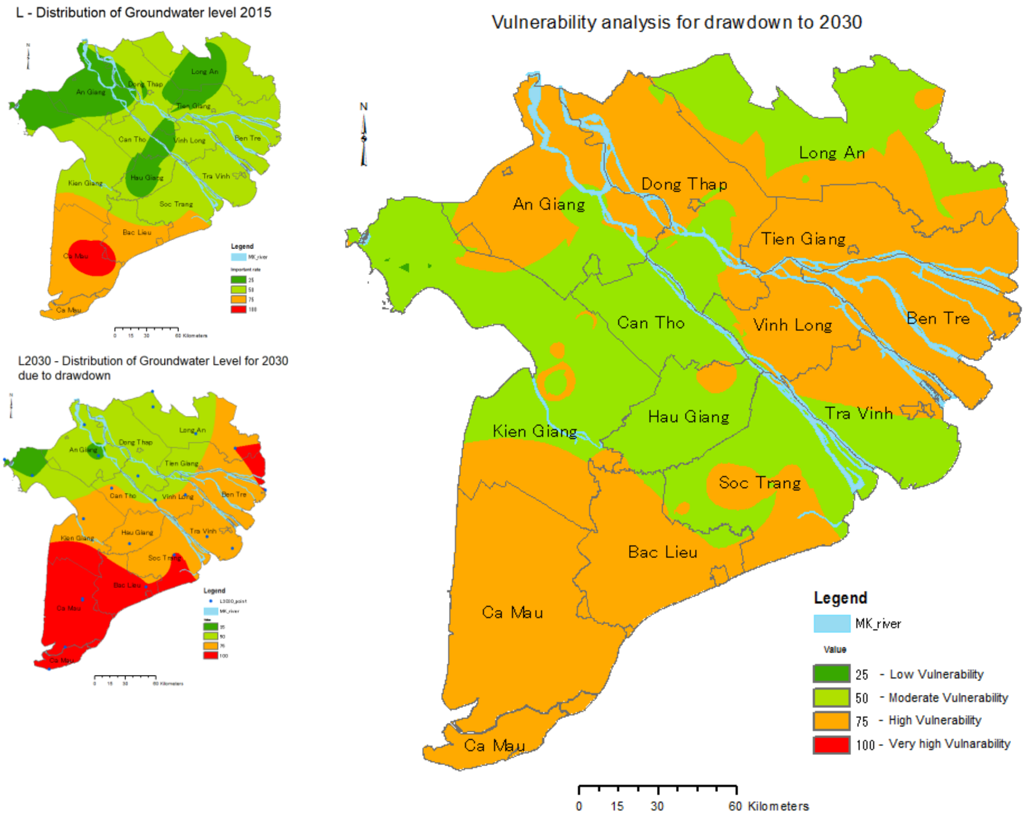


Figure 9. Vulnerability analysis for 2030 due to drawdown.

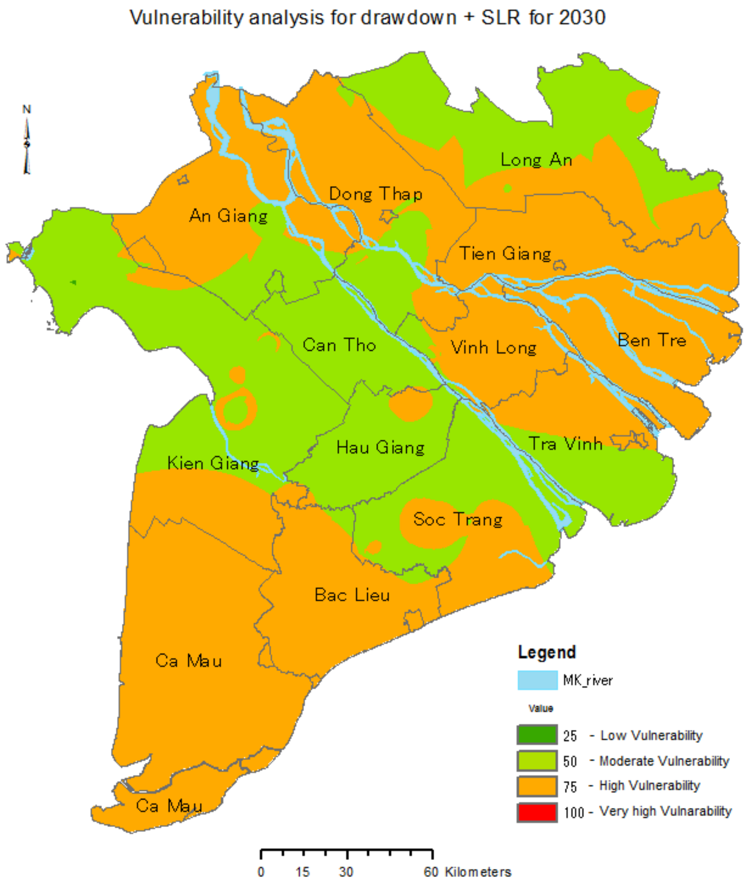


Figure 10. Vulnerability analysis for 2030 due to drawdown + SLR 2030.

history of the MKD with cycles of transgression and regression. Under the continuous exploitation of groundwater by humans, these saline areas tend to expand.

In the south of the delta, the Ca Mau area, the groundwater level drops rapidly, increasing the risk of saltwater intrusion. This is also an area with a very large and rapidly increasing amount of groundwater exploitation.

Although located quite deep, the qp_{2-3} aquifer still faces saline intrusion. If the rate of groundwater drawdown remains the same and continues, by 2030 the high vulnerability area for saline intrusion will expand to two-thirds of the MKD area

Under climate change scenarios, sea level rise exacerbates MKD's saline intrusion. However, compared to the impact from lowering the groundwater level, the impact from sea level rise is not too great.

By incorporating time forecasting tools into indicators that fluctuate over time, the Galdit method can be applied to forecast the future.

4. Conclusion

According to the results, the groundwater level of the qp_{2-3} aquifer shows a trend of gradually decreasing in all the stations. The drawdown is different from location to location, the maximum is 15 m at Q203040M1 station.

Sea level rise widens the depression cone in Ca Mau but is not too large.

According to the analysis results for 2030, it can be seen that the sea level rise will affect only the southern part of the region, which is greatly influenced by the sea due to its two sides bordering the sea. The area of very high vulnerability (red) has expanded compared with 2015, but not too much. Because the impact of sea level rise is not large, the vulnerability map is similar to the 2015 map, in which the high-risk area is along the Tien River and at the depress cone area in Ca Mau.

Unlike the impact of sea level rise, the map of groundwater level prediction in 2030 due to continued exploitation shows a big difference (Figure 9). The depression cone extends to the whole of the Ca Mau peninsula, which area of drawdown greater than 10 m accounts for two-thirds of the entire delta.

Consequently, the analysis result shows a moderate and high level of vulnerability in which the highly vulnerable area expands, occupying a very large area of more than half of the delta area. However, there are no areas with very high vulnerability as shown in Figure 9.

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Contribution of authors

Nga Viet Thi Pham contributes to the idea, collecting the data, data analysis, writing - original draft, writing - review & editing.

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