Chapter 45
Assessment of Saltwater Intrusion Vulnerability in the Coastal Aquifers in Ninh Thuan, Vietnam

Quy Nhan Pham, Thi Thoang Ta, Thanh Le Tran, Thi Thu Pham, and The Chuyen Nguyen

Abstract As surface water has declined under climate change conditions and human activities, groundwater has become the most important source of water supply for Ninh Thuan province, which is one of the most arid regions of Vietnam. The increase of groundwater extraction and sea-level rise has brought about increase in seawater intrusion, which has become the biggest concern for the groundwater resources of this coastal area; thus, it is necessary to evaluate the saltwater intrusion vulnerability in aquifers for planning and sustainable exploitation of groundwater in the province. In this study, an overview of the previous fresh–saltwater interface studies and updated geophysical investigation (Vertical Electrical Sounding – VES) was carried out to understand the situation or status of the salinity of groundwater. Besides, chemical compounds of water sources were also analysed to clarify the recharge sources and origin of saltwater in the aquifers. Based on collected and field survey data, GALDIT method was used to assess the saltwater intrusion vulnerability in the coastal aquifers of the study area with six factors incorporated: groundwater occurrence, aquifer hydraulic conductivity, depth to groundwater level, distance from shore, impact of existing seawater intrusion, and aquifer thickness. The weight of each GALDIT parameter was calculated by analytic hierarchy process (AHP) based on the results of surveys of over 50 hydrogeological experts in Vietnam to calculate the GALDIT index for the final saltwater intrusion vulnerability map of Ninh Thuan coastal aquifers.

Keywords Seawater intrusion · GALDIT method · climate change · groundwater extraction · Ninh Thuan province

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1 Introduction

The central coastal plains of Vietnam are narrow and small area plains that were filled by sediments of short and steep rivers cross the region, so central coastal aquifers of Vietnam in general and Ninh Thuan coastal aquifer in particular characterized by small and scattered in distributed areas and thickness. Saltwater intrusion in aquifers has become the biggest problem to human life in this area where limited surface water and groundwater are often the main sources of drinking water and agriculture activities. Besides the investigation to assess the status or occurrence of saltwater intrusion in the aquifer system, the assessment of saltwater vulnerability may also helpful for management of groundwater source in the area.

There are a number of methods to assess vulnerability caused by the continuous extent of seawater intrusion in coastal aquifers in which the GALDIT index model developed by Chachadi and Ferreira in 2001 was widely used over the world based on rating scores and weights of six distinct influencing hydrogeological parameters as follows: (1) the groundwater occurrence G; (2) the aquifer hydraulic conductivity A; (3) level of the groundwater level above sea level L; (4) the distance from shoreline D; (5) the impact of existing status of seawater intrusion in the area I; and (6) thickness of the mapped aquifer T. The weights of GALDIT parameters are assigned value from 1 (the least significant parameter) to 4 (the most significant parameter) from the statistics of survey results of scientists and experts (Chachadi and Ferreira, 2001).

In this study, an overview on occurrence of saltwater intrusion was carried out based on previous investigation results, geophysical surveys (VES measurements), and water sample analysis. Then, the GALDIT parameters weights were modified by analytic hierarchy process (AHP) method that is based on questionnaire survey results of over 50 hydrogeological experts in Vietnam, and the range of each factor rating is slightly changed to meet the condition of coastal unconsolidated Quaternary aquifers of Ninh Thuan province. Accordingly, GALDIT index mapping obtained with the factors values gathered from previous studies and this study, and the modified weights and parameter ratings.

2 Study Area

Ninh Thuan is located in the south central coast of Vietnam lying between latitude of 11°18'28" and 11°50'52" North, and longitudes of 108°45'19" and 109°13'54" East with total area of 3358 km^2. It is bounded by Khanh Hoa, Lam Dong, and Binh Thuan provinces to the North, West and East respectively, and faces the sea in the East. The province has three types of topography as mountains, hills, semi-mountains, and coastal plain in which the hill and mountain occupy 77.6% of the total land with the elevation ranges from 200 to 1000 meters, and the coastal plain accounts only for 22.4% of the total province area. The province has a tropical monsoon climate characterized by hot dry and windy weather with temperature ranges between 24.7 and 29.1 °C. There are two distinct seasons, that is, the rainy season lasts for 3 months from September to November which contributes to total of 40% to 80% annual rainfall, and the dry season lasts from December to August. The average annual potential evaporation is 1844.1 mm (around 153.66/month) and the highest evaporation rate is in January (about 166.2 mm) while the average annual rainfall is about 1131.4 mm (i.e. about 50% evaporation); this makes Ninh Thuan one of the most arid regions of Vietnam making groundwater resources a cause of concern in this province.

The aquifer system of Ninh Thuan coastal plain consists of Quaternary unconsolidated aquifers, fracture igneous rock and sedimentary rock aquifers formed in between Middle Jurassic and Pleistocene era. The fracture aquifers have very low productivity and are distributed at great depth; limited study has been carried out to investigate the quality and quantity of those aquifers and they are not the subject of this study as well. The Quaternary unconsolidated aquifers consists of Pleistocene, Holocene, and undivided Quaternary aquifer in which the undivided Quaternary aquifer is distributed in transition zone between the mountainous area and the plain with distributed area of around 65 km^2; the Holocene aquifer is widely distributed in Phan-Rang plain and along Cai river valley with total area of 315 km^2, and the Pleistocene aquifer is found at Tan Hai ward, the southern area of Phan Rang plain, and from Phuoc Hoa to Quang Sơn ward with a total area of 364 km^2 (Nguyen Truong Giang et al., 1998).

According to Ngo Tuan Tu and Nguyen Ton (2015), seawater was intruded to aquifer system of Ninh Thuan coastal plain due to current sea water throughout a long coastline of around 105 km and ancient seawater in depth aquifers through tectonic faults and groundwater exploitation activities. The distribution of saline groundwater depends on the aquifer system characteristics and the natural conditions: (i) the saline groundwater can be found over the whole aquifer system; (ii) saline groundwater can be found on top of aquifer system (Holocene aquifer); (iii) the saline groundwater can be found in the lower part of aquifer system (Pleistocene aquifer). Total complete saline groundwater area is around 280 km^2, and partly saline groundwater area is around 420 km^2.

In this study, the current saltwater intrusion status and the origin was investigated by 16 survey lines of vertical electrical sounding (VES) measurements in which 15 survey lines were arranged perpendicular to the coastlines in northwest-southeast direction; only survey line No.16 was arranged parallel to the coastlines in north-south direction. Forty -ive groundwater samples were collected during sampling trip for chemical analysis (both conventional and stable isotopic analysis). The ES investigation was arranged in the area of current saltwater intrusion; the results showed that the fresh–salt water interface moved toward the land at the distance up to 13 km from the shoreline and the saltwater covered almost length of all investigated lines of both Holocene and Pleistocene aquifers. The arrangement of VES survey lines, the fresh–salt (F-S) water interface and groundwater samples are presented in Fig. 45.1.

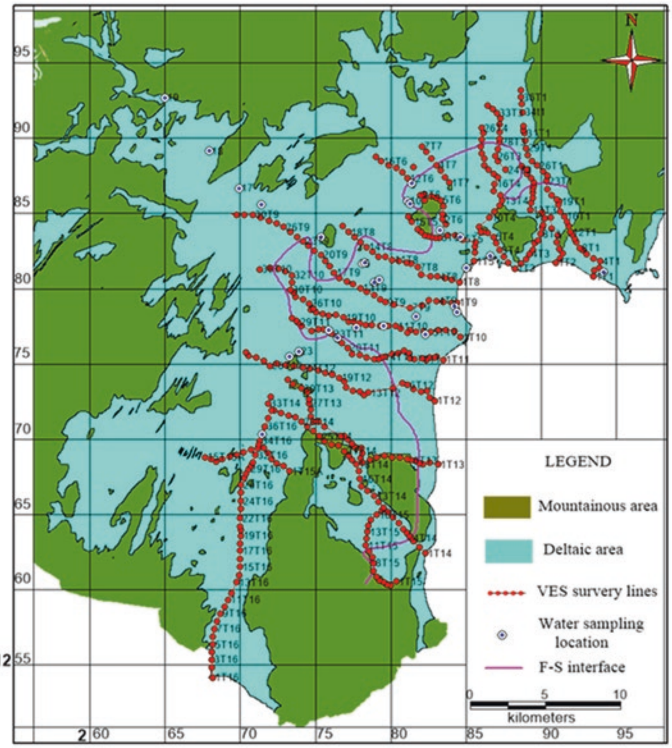

Fig. 45.1 ES surveys arrangement, F-S interface, and water sampling locations in Ninh Thuan coastal plain

One example of salt–fresh water interface analysis of the survey line No.1 can be seen in Fig. 45.2. It is clear that the saline water covered whole survey line No.1 except some part of the bedrock.

The chemical analysis showed that water samples in 40 out of 45 locations to be saltwater, and the origin of saltwater differs from place to place depending on the hydrogeological structures, groundwater flow regime; the origin can be from current saltwater intrusion found at the coastal area or from ancient seawater found in the inland area.

3 Saltwater Intrusion Vulnerability

According to Chachadi and Ferreira (2001), the final decision criteria of vulnerability to saltwater intrusion are based on GALDIT index value; the higher the vulnerability index value, the more vulnerable the aquifer is to seawater intrusion, and it

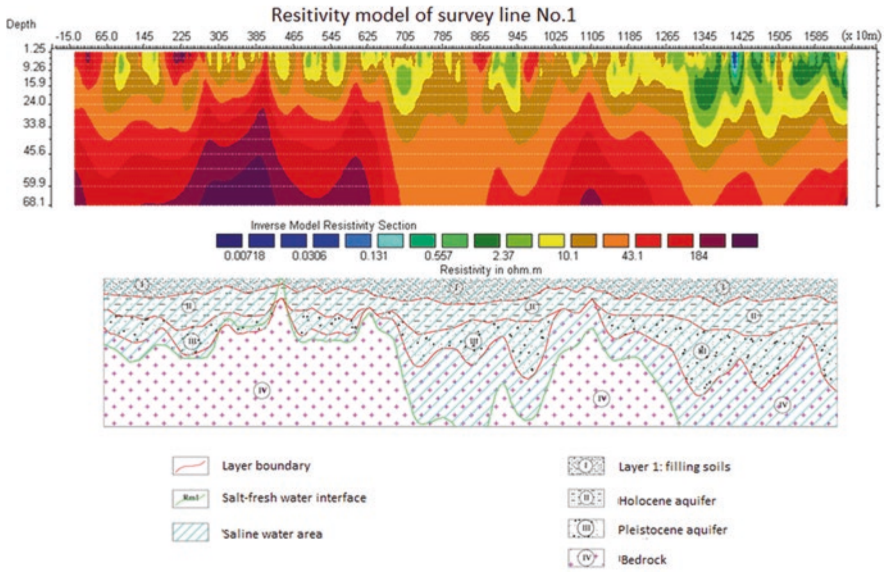

Fig. 45.2 Salt–fresh water interface analysis for VES survey line No.1

was obtained by evaluating each factor score and summing them in the following formula:

$$\text{GALDIT index} = \frac{\sum_{i=1}^{6} \text{WiRi}}{\sum_{i=1}^{6} \text{Wi}} \tag{45.1a}$$

or

$$GALDIT_{Index} = \frac{(W_1 \times G) + (W_2 \times A) + (W_3 \times L) + (W_4 \times D) + (W_5 \times I) + (W_6 \times T)}{\sum_{i=1}^{6} W_i} \tag{45.1b}$$

where:

W_i is the weight and R_i is the importance rating of the i^{th} factor.
G is the groundwater occurrence.
A is the aquifer hydraulic conductivity.
L is the level of the groundwater level above sea level.
D is the distance from shoreline.
I is the impact of existing status of seawater intrusion in the area.
T is thickness of the mapped aquifer.

3.1 Calculating the Weight of GALDIT Parameters

The weight of each GALDIT parameter was calculated using AHP method that was proposed by Thomas Saaty (1980) on the basis of pairwise relative evaluation of both the criteria and the decision-maker's experience. The process of AHP method and its application to calculate GALDIT parameter for Ninh Thuan coastal aquifers are described as follows.

The criteria weight vector is calculated based on the pairwise comparison matrix A, the m x m real matrix with a_{ij} entry of the matrix A represents the importance with respect to the goal of the i^{th} parameter relative to the j^{th} parameter. In this study, pairwise comparisons were conducted to six GALDIT parameters with effect to seawater intrusion based on survey results of 56 hydrogeological scientists and experts in Vietnam (the pairwise comparison results was presented in Table 45.1), and accordingly the A matrix for six GALDIT parameters with effect to seawater intrusion was built, as presented in Table 45.2.

A normalized pairwise comparison matrix, A*norm,* was constructed with each entry b_{jk} a result of dividing each element in every column by the sum of that column as presented in eq. (45.2), and based on A*norm* matrix, the weight of each parameter was calculated as Eq. (45.3):

$$b_{jk} = \frac{a_{ij}}{\sum_{j=1}^{m} a_{ij}} \tag{45.2}$$

Table 45.1 Pairwise comparison results for GALDIT parameters of Ninh Thuan coastal aquifer

Pairwise	Compared result	Interpretation
G and A	1/3	G is slightly less important than A
G and L	1	G and L are equally important
G and D	1/3	G is slightly less important than A
G and I	1/7	G is strongly less important than I
G and T	1	G and T are equally important
A and L	3	A is slightly more important than L
A and D	5	A is more important than D
A and I	1	A and I are equally important
A and T	5	A is more important than T
L and D	1/3	L is slightly less important than D
L and I	1/3	L is slightly less important than I
L and T	3	L is slightly more important than T
D and I	1	G and I are equally important
D and T	3	D is slightly more important than T
I and T	5	I is more important than T

Table 45.2 Pairwise comparison matrix for GALDIT parameters of Ninh Thuan coastal aquifer

Parameters	G	A	L	D	I	T
G	1.000	0.333	1.000	0.333	0.200	1.000
A	3.000	1.000	3.000	5.000	1.000	5.000
L	1.000	0.333	1.000	0.333	0.333	3.000
D	3.000	0.200	3.000	1.000	1.000	3.000
I	5.000	1.000	3.000	1.000	1.000	5.000
T	1.000	0.200	0.333	0.333	0.200	1.000
Sum	**14.000**	**3.067**	**11.333**	**8.000**	**3.733**	**18.000**

Table 45.3 The normalized pairwise comparison (A*norm*) matrix and the calculated weight of GALDIT parameters for Ninh Thuan coastal aquifer

Parameter	G	A	L	D	I	T	**Calculated weight**
G	0.071	0.109	0.088	0.042	0.054	0.056	**0.42**
A	0.214	0.326	0.265	0.625	0.268	0.278	**1.98**
L	0.071	0.109	0.088	0.042	0.089	0.167	**0.57**
D	0.214	0.065	0.265	0.125	0.268	0.167	**1.10**
I	0.357	0.326	0.265	0.125	0.268	0.278	**1.62**
T	0.071	0.065	0.029	0.042	0.054	0.056	**0.32**

$$w_i = \sum_{j=1}^{m} b_{jk} \tag{45.3}$$

where: a_{ij} is the entry of matrix A; b_{jk} is the entry of matrix A*norm.* w_i is weight of i^{th} parameter; m is number of comparison parameter

The A*norm* matrix and the weight of GALDIT parameters for Ninh Thuan coastal aquifer were calculated and presented in Table 45.3.

To check the consistency of the calculated weight, the consistent index (CI) and RI (random index) ratio was calculated; If CI/RI < 0.1, the result is reliable. The CI is calculated by eq. (45.4) and RI values for small problems ($m \leq 10$) are shown in Table 45.4.

$$CI = \frac{x - m}{m - 1} \tag{45.4}$$

Where: x equal to average value of the weighted sum value divided to the calculated weight.

m is number of compared parameter.

The weighted sum value is sum of each value in the row of a multiplied weight matrix that is constructed by taking multiple of each calculated weight to the A matrix column.

The calculation of consistency for GALDIT parameter weight of Ninh Thuan aquifer is presented in Table 45.5.

Table 45.4 Values of the random index (RI) for small problems (Thomas Saaty, 1980)

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Table 45.5 Multiplied weight matrix and consistency for the weights of GALDIT parameters

Parameter	G	A	L	D	I	T	Weighted sum value	Calculated weight		CI
G	0.419	0.659	0.566	0.368	0.324	0.317	2.652	**0.42**	6.327	
A	1.257	1.976	1.698	5.519	1.619	1.584	13.653	**1.98**	6.910	
L	0.419	0.659	0.566	0.368	0.540	0.951	3.502	**0.57**	6.187	
D	1.257	0.395	1.698	1.104	1.619	0.951	7.023	**1.10**	6.363	
I	2.096	1.976	1.698	1.104	1.619	1.584	10.076	**1.62**	6.225	
T	0.419	0.395	0.189	0.368	0.324	0.317	2.011	**0.32**	6.348	
x value									6.394	0.079

As the CI = 0.079 < 0.1, the calculation of GALDIT parameter weight is reasonably consistent so that the result can be used to process calculation of GALDIT index for this study.

3.2 Vulnerability Map of Ninh Thuan Coastal Area

The indicator variables of ratings for GALDIT parameters were slightly modified based on the questionnaire surveys and summary with calculated weights as presented in Table 45.6.

Vulnerability map was constructed based on GALDIT index that was calculated using new GALDIT factor weight, and the data gathered from previous study (type of aquifer, hydraulic conductivity, height of groundwater level above mean sea level, distance from shore, thickness of the aquifer) and this study data (status of seawater intrusion) are the basis to assign the ratings of each GALDIT factor. The final result showed that the vulnerability of Ninh Thuan unconsolidated aquifers can be classified into three levels: the high vulnerability, medium vulnerability, and low vulnerability and the distribution is around 40%, 50 and 10% to the high, medium and low vulnerability, respectively. The high vulnerability was found in the central coastline and extends landward along with Cai river where the most concentrated population and economic activities are seen as shown in Fig. 45.3.

Table 45.6 Calculated weights and ratings for GALDIT parameters

Factor	Weight	Indicator variables		Rating
Groundwater occurrence / aquifer type, (G)	0.42	Confined		10
		Unconfined		7.5
		Leaky confined		5
		Bounded		2.5
Aquifer hydraulic conductivity, (A) (m/day)	1.98	High	>40	10
		Medium	10–40	7.5
		Low	5–10	5
		Very low	<5	2.5
Height of groundwater level above mean sea level, (L) (m)	0.57	High	<1	10
		Medium	1.0–1.5	7.5
		Low	1.5–2.0	5
		Very low	>2.0	2.5
Distance to the shore, (D) (m)	1.1	Very small	<2500	10
		Small	2500-5000	7.5
		Medium	5000-10,000	5
		Far	>10,000	2.5
Impact of the existing status of seawater intrusion, (I)	1.62	High	>2.0	10
		Medium	1.5–2.0	7.5
		Low	1.0–1.5	5
		Very low	<1.0	2.5
Thickness of aquifer (saturated), (T) (m)	0.32	High	>10	10
		Medium	7.5–10	7.5
		Low	5–7.5	5
		Very low	<5	2.5

4 Conclusions

Saltwater intrusion has always been a serious concern for coastal areas. Therefore, the need of mapping groundwater vulnerability to saltwater intrusion is important in order to plan and manage this precious resource. Six factors in GALDIT method incorporated allow us to assess, numerically rank and map areas from low to high vulnerability. For more precise vulnerability map, more data is required. For specific water use such as irrigation, industry etc. important rating is required to modify to suit this purpose.

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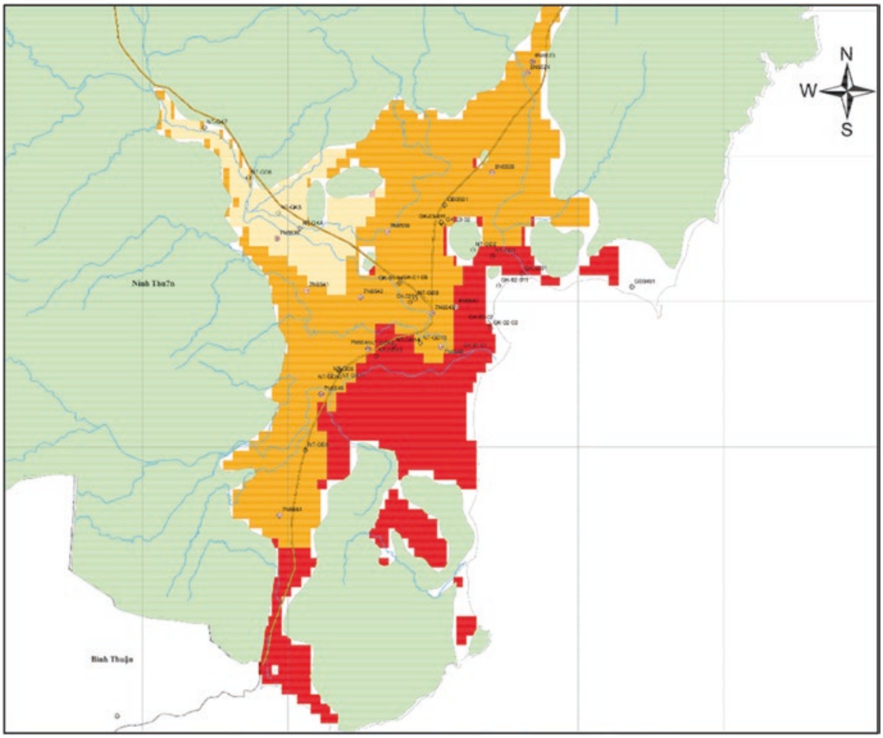

Fig. 45.3 Vulnerability map of Ninh Thuan coastal aquifers

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