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GRADUATE UNIVERSITY SCIENCE AND TECHNOLOGY



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**RESEACH ON ASSESSING VULNERABILITY DUE TO
SALTWATER INTRUSION OF COASTAL AQUIFERS IN
PROVINCES NINH THUAN, BINH THUAN**

Major: Natural Resources and Environmental Geography

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Abstract of PhD thesis in Earth Sciences

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INTRODUCTION

1. The necessity of the study

Vietnam is considered as one of the 5 countries heavily affected by climate change and sea level rise in the world. This study will contribute to complete this new approach for assessing saltwater intrusion vulnerability, and at the same time provide solutions, orientations for exploitation, management and protection of groundwater resources in coastal aquifers in Vietnam. Ninh Thuan and Binh Thuan are two coastal provinces in the South-Central Coast. This is an area with a harsh climate, the average annual rainfall is among the lowest in the country. The problems of drought and saltwater intrusion often occur every year. Groundwater in coastal aquifers in Ninh Thuan and Binh Thuan provinces is an extremely valuable resource, which is declining in quantity and quality (saltwater intrusion) due to inappropriate exploitation and climate change impact. In order to solve the problem of sustainable exploitation and use of groundwater in coastal aquifers, it is necessary to study assessment of factors affecting salt groundwater intrusion in context of climate change and sea level rise's scenarios. Therefore, the PhD thesis topic entitled: "*Research on assessing vulnerability due to saltwater intrusion of coastal aquifers in provinces Ninh Thuan, Binh Thuan*" was selected for study.

2. Objectives

Set up a scientific and practical basis for research and assessment of saltwater intrusion vulnerability in coastal aquifers on the basis of analysis of natural geographical, socio-economic, environmental factors, and climate change and sea level rise in Ninh Thuan and Binh Thuan area.

3. The key research activities

- Overviewing, selecting appropriate theoretical basis for analysis, assessment and estimation of the influence of factors on saltwater intrusion in coastal aquifers.

- Study on the characteristics of groundwater resources in Ninh Thuan and Binh Thuan area.

- Assessment of current status and characteristics of salt and fresh groundwater resources's distribution in Ninh Thuan and Binh Thuan area.

- Analysis of the factors on natural geographical, socio-economic, environmental, climate change and sea level rise affecting groundwater resources.

- Assessment of saltwater intrusion vulnerability in coastal aquifers of provinces Ninh Thuan and Binh Thuan;

- Using the groundwater flow model coupled with the variable density, solute transport model to simulate the impacts due to saltwater intrusion in coastal aquifers in Ninh Thuan and Binh Thuan provinces due to the climate change and sea level rise and socio-economic development's scenarios.

- Proposing solutions to mitigate saltwater intrusion in coastal aquifers in context of climate change and sea level rise.

CHAPTER 1. RESEARCH ON SALT GROUNDWATER INTRUSION VULNERABILITY AN OVERVIEW

1.1. Overview on studies of saltwater intrusion vulnerability in the world

1.1.1. Research groundwater vulnerability assessment methods

Nowadays, there are many different groundwater vulnerability assessment methods, such as DRASTIC, SINTACS, CVI, AVI,

GALDIT, EPIK, GOD, COP, PL..

1.1.2. Studies of salt groundwater intrusion

Seawater intrusion into coastal aquifer has been extensively studied for more than a century. The scientific research has two main groups: evaluation by analytical methods and by numerical modeling methods.

In general, researches around the world have used many methods and techniques to determine the distribution, origin and assessment of groundwater salinity, and they very specifically studied the origin as well as the change of groundwater salt-fresh interface under the influence of natural conditions and socio-economic development so that there can be management measures to improve the efficiency of usage and sustainably exploiting this rare and precious groundwater resources.

1.1.3. Studies on salt groundwater intrusion vulnerability in the context of climate change and sea level rise

There are a lot of international research publications which have shown the severe impact of climate change and sea level rise on groundwater as follows:

Climate change causes a change of rainfall. The change of rainfall will change groundwater recharge and consequently change of groundwater resource availability.

When the temperature changes, it will cause drought, leading to an increase in water demand, increasing the rate of groundwater exploitation. As a result, the groundwater quantity, quality and level will decline.

Sea level rise will cause saltwater from the sea to intrude deep inland, reducing fresh water, causing scarcity of water resources in coastal areas. The sea level rise will flood the coastal aquifers around the coastal

areas and estuaries, causing salinization in whole or part of the aquifers.

Thus, assessing the salt groundwater intrusion vulnerability in the context of climate change and sea level rise has been studied and applied widely in developed countries. The results of these studies contribute to the orientation of sustainable exploitation and provide appropriate solutions to mitigate saltwater intrusion in coastal aquifers.

1.2. Overview on studies of saltwater intrusion vulnerability in Vietnam

The problem of saltwater intrusion of coastal aquifers, especially in the context of climate change and sea level rise is a challenge for scientific community in recent years. In Vietnam, there have been many research projects on saltwater intrusion, groundwater availability and reserves' assessment, and especially assessing the saltwater intrusion vulnerability to coastal areas and solutions to mitigate their impacts.

The saltwater intrusion and assessment of salt groundwater intrusion vulnerability has also been mentioned since the late 80's of the last century. Some authors concerned these issues are: Do Trong Su and Nguyen Kim Ngoc; Dang Huu On; Dang Dinh Phuc; Doan Van Canh; Pham Quy Nhan; Nguyen Van Hoang; Dang Tien Dung; Nguyen Van Lam, Hoan Van Hoan, etc. For the study of typical SW injuries with some authors such as: Nguyen Kim Cuong, Pham Quy Nhan, Vu Ngoc Tran, Vu Thi Minh Nguyet, Bui Tran Vuong, Nguyen Ngoc Truc ...

However, appropriate approach and the weight of factors affecting saltwater intrusion have not been considered as well when assessing the salt groundwater intrusion vulnerability in Vietnam. Besides, the impacts of climate change and sea level rise and socio-economic development occurring in the past as well as in the future in the study area have been

causing fluctuations in the potential and reserves of groundwater due to variable of salt and fresh water distribution in aquifers. Solutions to mitigate the impact of salt groundwater intrusion on the basis of the results of saltwater intrusion vulnerability assessment in coastal aquifers and hydrogeological characteristic in the study area have not been considered so far.

Based on the advantages and disadvantages of methods for salt groundwater intrusion vulnerability's assessment, the most suitable one to apply in Ninh Thuan, Binh Thuan area is the GALDIT method in which the most related weights factor to seawater intrusion into coastal aquifers have been clarified.

CHAPTER 2. METHODS AND MATERIALS

2.1. Methods and techniques used

2.1.1. Synthesis and analysis of collection data

2.1.2. Statistical method

2.1.3. Investigation and field survey

The author has directly participated in investigation, field survey with members of the national research project code CC.16/16-20 with the following activities: The current status of groundwater exploitation and pollution risk sources; Geophysical measurement; Double ring infiltration test; Seepage meter experiment; Sampling and analysis water samples.

2.1.4. Method for groundwater resources availability.

The groundwater resources availability is defined by the following equation:

$$Q_{TN} = \frac{V_t}{t} + Q_{bc} \quad (2.1)$$

Where:

Q_{tn} - groundwater resources availability (m^3/day);

V_t - static volume of water stored in aquifers (m^3);

Q_{bc} - the total groundwater recharge from different sources (rainwater, surface water and etc.) (m^3/day);

t - proposal exploitation time (day).

2.1.5 The method for groundwater exploitable reserves

Based on the experiences of current groundwater exploitation, from many case studies which internationally published, and reference from previous study which have assessed groundwater resources in Ninh Thuan, Binh Thuan and the South-Central coast in the project "Complilling - Mapping groundwater resources with scale of 1:200,000 in Ninh Thuan and Binh Thuan provinces", we assume that exploitable reserves is equal to 30% of the total groundwater storage and recharge, or other words is 30% of the total groundwater resources availability in the study area..

2.1.6. Modeling method

The purpose of building a groundwater numerical modeling for the study area is to validate the reliability of above-mentioned saltwater intrusion vulnerability assessment and to propose solutions in order to mitigate the impact of saltwater intrusion into the groundwater in the study area.

2.1.7. Assessment methods to the salt groundwater intrusion vulnerability in coastal Quaternary aquifers

Within the scope of this thesis, the GALDIT method developed by Chachadi, A. G., and Joao Paulo Lobo Ferreira (2005) for assessing saltwater intrusion vulnerability in coastal aquifers has been selected.

GALDIT is composed of the first letters of the group of factors affecting salt groundwater intrusion with the following components:

G is groundwater occurrence, A is the aquifer hydraulic

conductivity, L is the height of groundwater level above the mean sea level, D is the distance from the shore, (in case of the clearly clarified salt-fresh interface of the aquifers D is the distance from that salt-fresh interface to the study site) I is the impact of the existing status of seawater intrusion, and T is the thickness of the saturated aquifer.

Equation to calculate GALDIT index is below:

$$GALDIT_{index} = \frac{(W_1 \times G) + (W_2 \times A) + (W_3 \times L) + (W_4 \times D) + (W_5 \times I) + (W_6 \times T)}{\sum_{i=1}^6 W_i} \quad (2.16)$$

Where:

W1, W2, ..., W6 are parameter (or factor) weights

G, A, L, D, I, T are parameter rates.

2.1.8. Expertise method and hierarchical analysis method (AHP)

In this study, AHP is used to calculate the weights of GALDIT factors according to the following steps:

Step 1: Build a matrix to comparing factors

Step 2: Calculate the standard matrix

Step 3: Checking the consistency

2.2. Logical framework for research activities

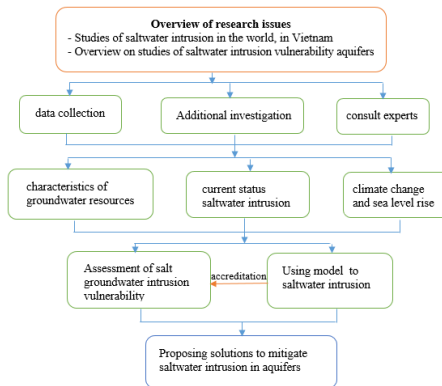


Figure 2.1. Logical framework for research activities

2.3. Research data

Results of data collected from previous projects, additional investigations and experiments in the study area with the following activities: Additional measurement of 16 vertical electrical sounding lines; investigation of the current status of groundwater exploitation and usage and pollution sources in the study area; collecting and analyzing 22 stable isotope samples; conducting 75 points of double ring infiltration test and 38 locations of seepage meter experience; questionnaire sheets from 23 experts.

CHAPTER 3. NATURAL, SOCIAL - ECONOMIC CHARACTERISTICS AND GROUNDWATER RESOURCES IN THE COASTAL ZONE OF NINH THUAN, BINH THUAN

3.1. Hydrogeological characteristic

In Ninh Thuan and Binh Thuan provinces, there are 03 sedimentary aquifers (q, qh, qp), 04 fractured and fissured aquifers (n_2 , βn -q1, k2, j2) and aquitards. However, within the scope of the thesis, unconsolidated Quaternary aquifers (qh, qp) with high potential along the coastline of Ninh Thuan and Binh Thuan provinces have been focused on.

3.1.1. Computation of groundwater resources

a). Storativity

Based on the salt - fresh groundwater distribution we measured and computed the total storage volume in qh and qp aquifers as: $9,161 \times 10^6 \text{m}^3$ (fresh water is $6,091 \times 10^6 \text{m}^3$, salt water is $3,070 \times 10^6 \text{m}^3$).

b). Groundwater recharge

Total groundwater recharge of qh and qp aquifer is: 608,457 m^3/day (fresh water is 275.941 m^3/day , saltwater is 332,516 m^3/day).

c). Groundwater resource availability

The total groundwater resource availability of qh and qp aquifers is: 1,524,594 m³/day (fresh water is 885,030 m³/day, salt water is 639,564 m³/day).

3.3.2. Computation of groundwater reserves.

The groundwater exploitable reserves in Ninh Thuan province calculated with 30% of the total groundwater resource availability. Therefore, the total exploitable fresh groundwater reserve for the whole region is 265,509 m³/day.

CHAPTER 4. ASSESSMENT OF VULNERABILITY DUE TO SALT GROUNDWATER INTRUSION AND PROPOSED SOLUTIONS TO MITIGATE SALTWATER INTRUSION OF THE COASTAL QUATERNARY AQUIFERS IN NINH THUAN - BINH THUAN AREA

4.1. Determination of the weight of GALDIT factors for the coastal areas of Ninh Thuan - Binh Thuan area

Author has built a comparison matrix for GALDIT factors based on the results of expertise consultation on the pairwise comparison of factors, then calculated the standard matrix and validated the consistency of the factors as the importance of the factors. After modifying the range of values and scores of some GALDIT factors to suit the geological and hydrogeological characteristics of the study area. The weights and rates for the GALDIT index applied to the study area are detailed in Table 4.6.

Table 4.6. Rating scale according to GALDIT method for Ninh Thuan - Binh Thuan area.

Factor	Weight	Rate of factors			
		2.5	5	7.5	10
Occurrence of aquifer	0,42		Leaky aquifer	Unconfined aquifer	Confined aquifer

Factor	Weight	Rate of factors			
		2.5	5	7.5	10
Hydraulic conductivity of aquifers (m/day)	1,98	<5	5 - 10	10 - 40	> 40
Elevation of groundwater level (m)	0,57	> 2	1,5 - 2	1 - 1,5	< 1
Distance from the coastline to the aquifers distribution location (m)	1,10	> 1000	750 - 1000	500 - 750	< 500
Ratio of Cl/HCO ³⁻	1,62	< 1	1 - 1,5	1,5 - 2	> 2
Aquifer thickness (m)	0,32	< 5	5 - 7,5	7,5 - 10	> 10

4.2. Assessment of salt groundwater intrusion vulnerability of coastal aquifers in Ninh Thuan - Binh Thuan area

4.2.1. Assessment of salt groundwater intrusion vulnerability of coastal Holocene aquifers (qh) in Ninh Thuan - Binh Thuan area

The results of assessment of the salt groundwater intrusion vulnerability in the coastal Holocene aquifer qh in Ninh Thuan and Binh Thuan area are as follows: Low-risk saltwater intrusion vulnerability area occupies a very small area with 0.4687km² (accounting for 0.4%) is distributed in Ninh Hai district and Phan Rang - Thap Cham city, Ninh Thuan province; Medium risk with an area of 160.6km² (accounting for 12.75%) is distributed in coastal communes; High-risk areas occupying most of the area with 1,083km² (accounting for 86%) is distributed throughout the study area; very high-risk areas occupying an area of 15.25km² (accounting for 1.21%) distributed in Ninh Hai and Ninh Phuoc districts of Ninh Thuan province and Tuy Phong and Bac Binh districts of Binh Thuan province (see Figure 4.7).

4.2.2. Assessment of salt groundwater intrusion vulnerability of coastal Pleistocene aquifers (qp) in Ninh Thuan - Binh Thuan area.

The results of assessment of the salt groundwater intrusion vulnerability in the coastal Holocene aquifer qh in Ninh Thuan and Binh Thuan area are as follows: Low-risk saltwater intrusion vulnerability area occupies an area of 25.15 km² (accounting for 1.2%) is distributed in Ham Thuan Nam district, Binh Thuan province; Medium risk with an area of 788.1 km² (accounting for 37.61%) is distributed in coastal communes; High-risk areas occupying most of the area with 1,265 km² (accounting for 60.36%) is distributed throughout the study area; Very high-risk areas occupying a smallest area of 17.39km² (accounting for 0.83%) distributed in Ninh Hai, Ninh Phuoc, Ninh Son districts, Ninh Thuan province and Tuy Phong district, Binh Thuan province (see Figure 4.14).

4.3 Validation of salt groundwater intrusion vulnerability's assessment of coastal aquifers in Ninh Thuan - Binh Thuan area

**** Predicted groundwater levels and salt and fresh groundwater interface's movement in Ninh Thuan - Binh Thuan area in context of climate change scenarios:***

A model to predict the movement of groundwater salt-fresh interface up to 2100 is built based on calibrated flow model. The RCP4.5 and RCP8.5 scenarios were used, which are the updated version of climate change and sea level rise scenarios in 2020 launched by the Ministry of Natural Resources and Environment, Vietnam. The modeling boundary conditions related to sea level and precipitation/evaporation are adjusted and assigned according to the RCP4.5 and RCP8.5 scenarios. The current status of exploitation is kept as of year 2020. Predicted results is calculated till the year 2100.

a) Predicted groundwater levels in Ninh Thuan and Binh Thuan provinces in context of the climate change scenarios

The predicted groundwater levels showed that the difference of water level between aquifers qh and qp in both Ninh Thuan and Binh Thuan is not large. Seasonal different groundwater levels are unclear with calculated time periods. However, the groundwater level difference between the two scenarios is obvious and noticeable. The overall groundwater level of RCP8.5 scenario is higher than the RCP4.5 scenario. The main groundwater flow direction is towards the sea (see Table 4.20, Figure 4.38 and 4.45).

b) Predicted results of groundwater salt-fresh groundwater interface's movement in Ninh Thuan and Binh Thuan provinces in context of climate change scenarios

According to the results of running and adjusting the predictive model for saltwater intrusion in Ninh Thuan and Binh Thuan area in context of climate change scenarios, the salinity area in Ninh Thuan - Binh Thuan area is relatively similar to the areas of vulnerability assessment. High risk and very high risk's area of saltwater vulnerability assessed by the GALDIT method in the two aquifers are distributed in the urban areas such as districts Phan Rang, Ninh Son, Ninh Phuoc, Ninh Hai of Ninh Thuan province and districts Tuy Phong, Bac Binh, Ham Thuan Bac, Phan Thiet city, Ham Tan, Ham Thuan Nam of Binh Thuan province (see Table, Figure 4.46 and 4.53).

The predicted results from saltwater intrusion model in context of climate change scenarios show that aquifers in the area over time tend to decrease in salinity area as follows:

- In Ninh Thuan province, saltwater area of qh aquifer decreases by 3.5km² and qp aquifer decreases by 4.7km² in scenario RCP4.5 and

qh	163, 7	162, 2	-1,5	161, 8	-1,9	161, 1	-2,6	160, 6	-3,1	160, 2	-3,5	159, 1	-4,6
qp	629, 9	628, 3	-1,6	627, 9	-2,0	626, 1	-3,8	625, 7	-4,2	625, 2	-4,7	624, 8	-5,1
Bin h Thu an													
qh	526, 2	523, 4	-2,8	522, 8	-3,4	519, 8	-6,4	519, 0	-7,2	517, 3	-8,9	516, 9	-9,3
qp	291, 9	287, 3	-4,6	286, 8	-5,1	283, 5	-8,4	282, 9	-9,0	280, 3	-11,6	279, 4	- 12,5

Notes:

- The (+) sign represents an increase in the saltwater area of aquifer in the scenarios compared to 2020.

- The sign (-) sign represents a decrease in the saline area of aquifer in the scenarios compared to 2020

4.4. Proposing solutions to mitigate saltwater intrusion in coastal Quaternary aquifers in Ninh Thuan and Binh Thuan provinces.

4.4.1. General principles for solutions to exploit effectively groundwater resources to mitigate saltwater intrusion.

On the basis of analysis and assessment of reasons and mechanisms of saltwater intrusion into aquifers, the solutions which are proposed to mitigate saltwater intrusion are based on following principles:

- Decreasing the gradient of groundwater level at salt-fresh interface areas.

- Abstracting groundwater for water supply far from salt-fresh interface.

- Applying advanced technologies to treat saltwater for water supply.

Overall solutions include:

1. Pumping saltwater from aquifers to reduce saltwater intrusion into exploitation wells and to increase the fresh groundwater resources because of decrease of fresh water flow toward the sea.

2. Increasing the natural groundwater recharge in order to increase freshwater reserves in aquifers.

3. Re-arranging water exploitation wells to mitigate saltwater intrusion and less loss of fresh water flow towards the sea

4. Using more surface water sources from rivers and lakes to reduce pumping rate of exploitation wells.

5. Application of advanced technologies in treatment of saltwater for water supply plants.

4.4.2. Design and selection of solutions to mitigate saltwater intrusion of coastal aquifers in Ninh Thuan province

a) Design of infiltration basin for groundwater artificial recharge

The area selected to build an infiltration basin is at An Hai, Phan Rang - Thap Cham city, Ninh Thuan province. The size of the basin is 180x120m corresponding to 21,600m². The depth of the tank is about 5.3m.

To evaluate the performance of the infiltration basin, the author arranged 03 exploitation wells with the pumping rate is 200 m³/day. The results from the model show that the groundwater level in the study area has increased after the infiltration basin's operation. Likewise, the groundwater level during pumping when infiltration basin's operation was greatly reduced compared to before its operation. If there is no groundwater artificial recharge, the wells will stop pumping in the dry season due to the groundwater level depletion.

b) Design an underground dam

The location selected is at Ho Binh area, Ninh Hai district, Ninh

Thuan province. Dimensions of the underground dam are: length $L=300\text{m}$, depth $H_{\text{tb}} = 6.5\text{m}$, and width $d = 80\text{cm}$.

This specific numerical model of this area is detailed and extracted from the MODFLOW model for the entire Ninh Thuan province. Finite difference grid size $30 \times 30\text{m}$. The model has a length of 3000m and a width of 2600m .

Comparing simulation results of two modeling before and after underground dam operation in the dry season and the rainy season. The graph showed that the groundwater level has increased significantly from $0.2 - 2.0\text{m}$ in upstream location close to the dam in both rainy and dry seasons. The groundwater level downstream close to the dam only decreases slightly in the rainy season.

For the study area, two solutions of infiltration basin and underground dam selected for suitable areas have been evaluated on groundwater flow model. The modeling results showed that the elevation of groundwater level in the study area has increased after the operation of the infiltration basin and the underground dam. Thus, these solutions are very promising and can meet the requirements of clean water supply for socio-economic development.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. On the basis of an overview of methods for assessing aquifers saltwater intrusion vulnerability; analysis of the advantages and disadvantages of each method, and comparison with hydrogeological characteristics and available data in the study area, GALDIT method was selected. This method is the most suitable with clarified weights related to factors of saltwater intrusion vulnerability in coastal Quaternary aquifers in provinces Ninh Thuan and Binh Thuan.

2. The fresh and salt groundwater resource availability in coastal unconsolidated Quaternary aquifers (Holocene and Pleistocene aquifers) in Ninh Thuan - Binh Thuan area is about 885,030m³/day and 639,564 m³/day, respectively. The reserve of fresh groundwater exploitable is about 265,509 m³/day. Thus, it can be seen that groundwater resources and reserves of the coastal aquifers in Ninh Thuan and Binh Thuan provinces have limited.

3. Through the assessment of salt groundwater intrusion vulnerability, it can be seen that in the aquifers qh, qp, the area of high and very high risk of vulnerability, account for over 87% and over 60% of the total distribution area of aquifer. Thus, it can be seen that Quaternary sedimentary aquifers along the coast of Ninh Thuan and Binh Thuan provinces are very vulnerable to saltwater intrusion.

The predicted results of the movement of salt - fresh interface by modeling method and the results of assessing saltwater intrusion vulnerability are completely consistent, which shows that the GALDIT method is completely appropriate to assess saltwater intrusion vulnerability in the coastal areas of Vietnam.

5. The predicted results from the calibrated saltwater transport model in Ninh Thuan and Binh Thuan areas under the climate change and sea level rise scenarios updated version in 2020 published by the Ministry of Natural Resources and Environment show that the salt and fresh distribution is suitable with the results of assessing saltwater intrusion vulnerability by the GALDI method, It means that the GALDIT method can be applied to assess the saltwater intrusion vulnerability in coastal estuaries of Vietnam.

6. For the study area, two solutions of underground dam and infiltration basin are selected for suitable areas. The modeling results

showed that the solution is effective and can meet the requirements of clean water supply for socio-economic development.

RECOMMENDATIONS

1. The additional investigation methods in association with GALDIT method with the clarified weights of factors affecting the saltwater intrusion vulnerability of coastal aquifers which determined from this study can be applied to the coastal regions in Vietnam.

2. When using GALDIT method to assess saltwater intrusion vulnerability, further research is needed to clarify the weight of the distance from the coastline to the study site (D). The distance from the study site to the salt-fresh interface of the aquifers should be more reliable for the rest coastal areas in Vietnam.

3. When building a groundwater flow model for predicting groundwater level and salt-fresh interface's movement using SEAWAT code under climate change and sea level rise scenarios until 2100, the author used the groundwater exploitation's figure was unchanged (as the guideline for groundwater exploitation limitation by local government). However, in the future, when the amount of groundwater extraction increases, more studies are needed to deal with this reality.

4. The research results also confirmed the limit of groundwater resource potential and saltwater intrusion vulnerable of coastal Quaternary sedimentary aquifers of Ninh Thuan - Binh Thuan area. Therefore, the following recommendations should be considered:

- To monitor continuously the saltwater intrusion of Holocene and Pleistocene aquifers, and the its change for updating and post-auditing the model in context unforeseen climate change, sea level rise and socio-economic development.

- To set up a monitoring system to for groundwater level and water quality in the Holocene and Pleistocene aquifers.

- To enhance restricted areas for exploitation and protection corridors of groundwater resources in the study area.

5. To strengthen the management and planning of groundwater exploitation to ensure the security and safety of water sources in the study area.

NEW CONTRIBUTIONS OF THE THESIS

1) Using combination of methods, an appropriate method to be applied to assess the saltwater intrusion vulnerability of aquifers in the driest region in Vietnam.

2) Based on analysis, evaluation and computation of available data, the groundwater availability of fresh and saltwater in the coastal strip of Ninh Thuan - Binh Thuan are 885,030m³/day, 639,564 m³/day, respectively. The exploitable fresh groundwater is 265,509 m³/day.

3) The study results have clarified the current status of groundwater saltwater intrusion vulnerability of coastal aquifers in provinces Ninh Thuan and Binh Thuan.

4) A groundwater model using Visual MODFLOW has been set up for groundwater flow system simulation. Next step, variable density flow SEAWAT code was applied to predict the saltwater intrusion impact in the coastal Quaternary aquifers due to climate change, sea level rise in scenarios developed and published by the Ministry of Natural Resources and Environment in version 2020 and socio-economic development.

5) Based on the study results of assessing groundwater saltwater intrusion vulnerability, proposed solutions are to build an infiltration

basin and an underground dam for the study area. The proposal solutions showed that they are very effective and can meet the requirements of potable water supply for local socio-economic development.

FIGURES AND GRAPHS

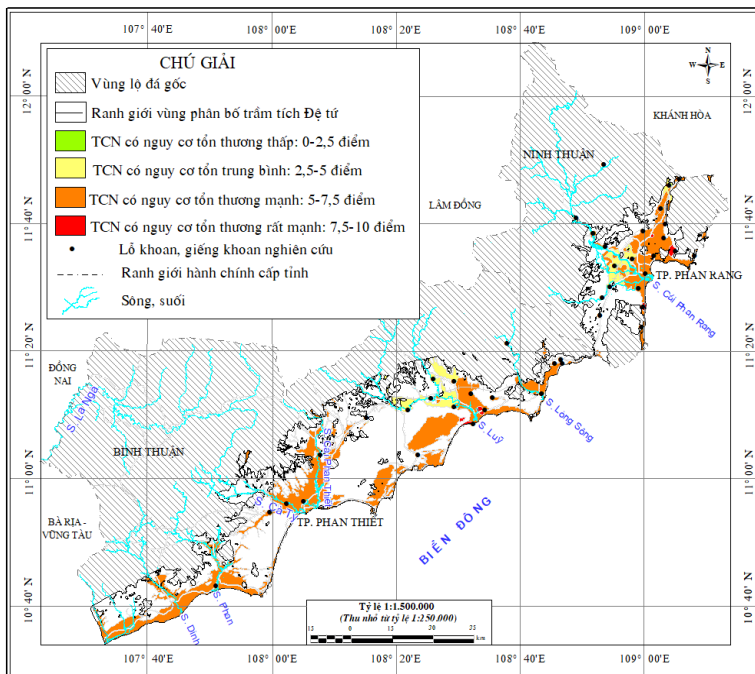


Figure 4.7. Map of the distribution of saltwater intrusion vulnerability - qh aquifer

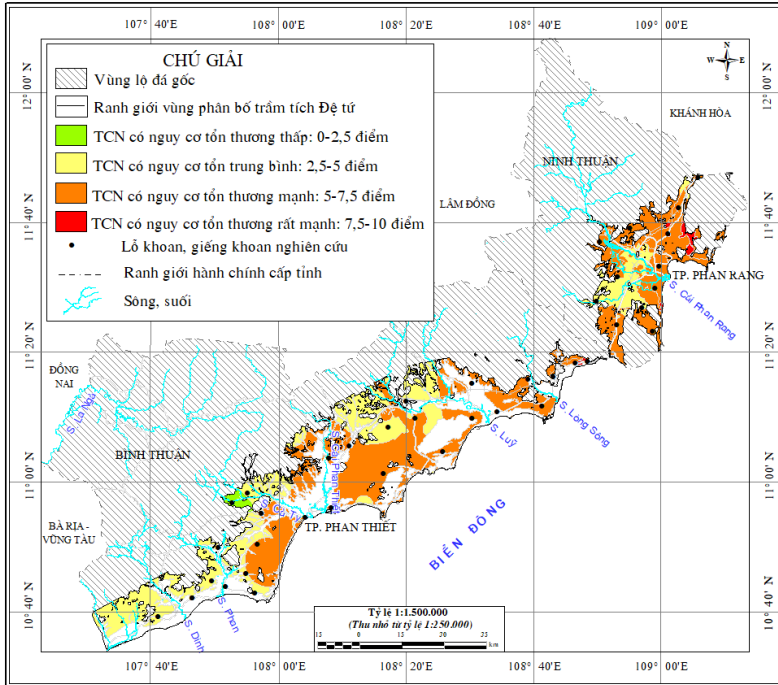


Figure 4.14. Map of the distribution of saltwater intrusion vulnerability - qp aquifer

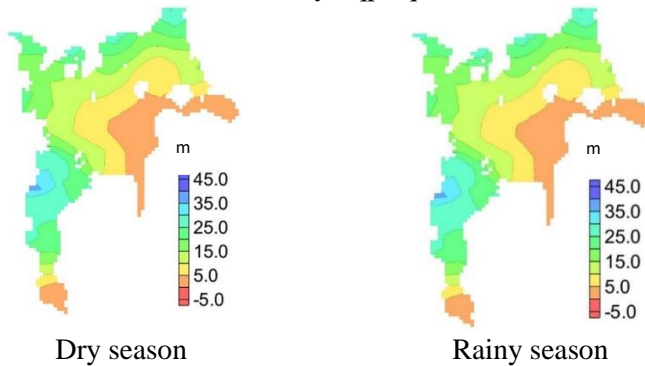


Figure 4.38. Elevation of groundwater level in Ninh Thuan province in 2100, corresponding to scenario RCP4.5

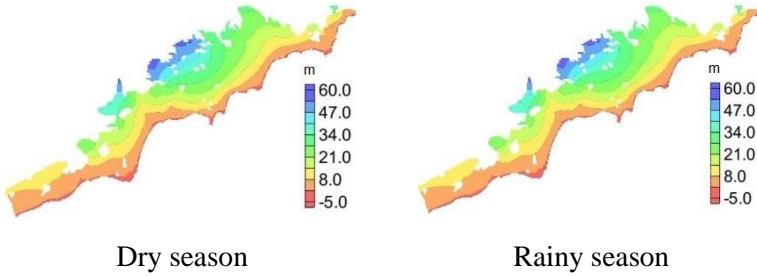


Figure 4.45. Elevation of groundwater level in Binh Thuan province in year 2100 corresponding to scenario RCP8.5

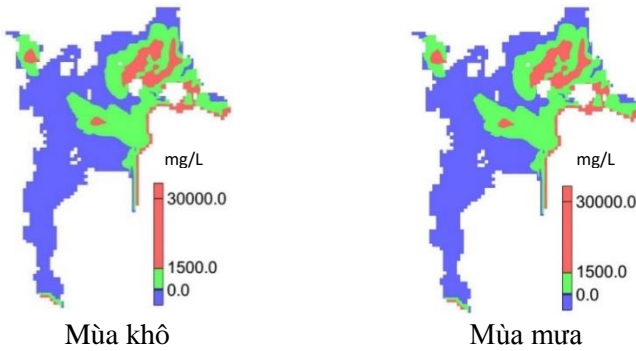


Figure 4.46. Salt, fresh water distribution of Holocene aquifer qh in Ninh Thuan province in the year 2100, corresponding to scenario RCP4.5

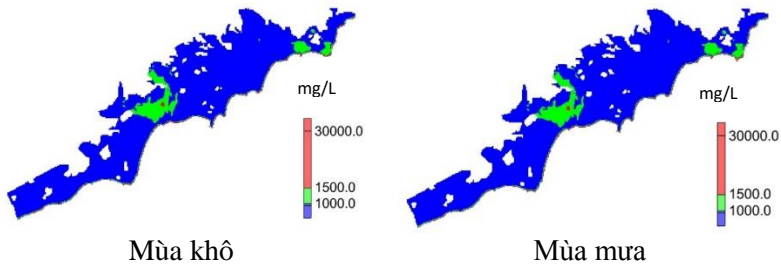


Figure 4.53. Salt, fresh water distribution of Pleistocene aquifer qp in Binh Thuan province in the year 2100, corresponding to scenario RCP8.5

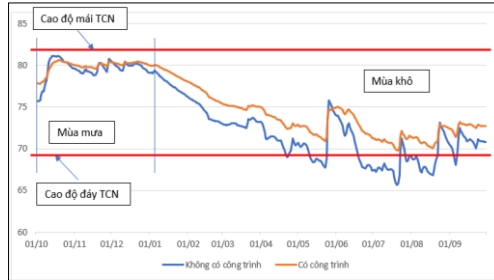


Figure 4.57. Groundwater levels before (blue line) and after (orange line) infiltration basin's operation at the production well G1 which located close to the basin

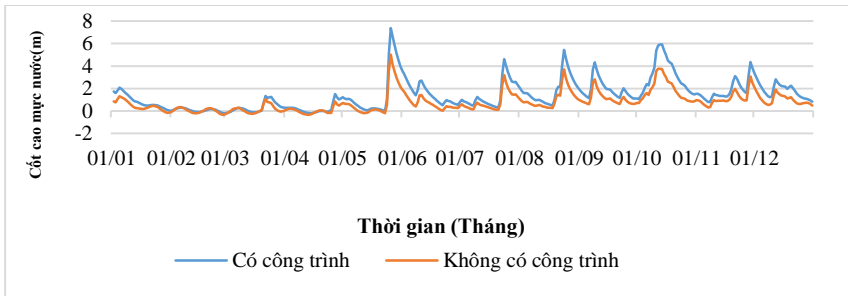


Figure 4.60. Groundwater levels at an upstream location close to underground dam before (orange line) and after (blue line) the dam operation

LIST OF PUBLICATIONS

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5. Pham Quy Nhan, **Nguyen The Chuyen** (2021). *Assessing Impacts of Climate Change and Sea-Level Rise on Seawater Intrusion in Coastal Aquifers in Ninh Thuan - Binh Thuan Plains*. The international workshop 16-17, September 2021 (Southeast Asia Research-based Network on Climate Change Adaptation Science) "Beyond Interlocal Lessons Learnt on Climate Change: Mapping, Fertilizing and Social Permeating" at Ibaraki University, Japan.

6. Nguyễn Thế Chuyên, Phạm Quý Nhân, Phan Thị Thanh Hằng, *Đánh giá nguy cơ tổn thương do xâm nhập mặn nước dưới đất tầng chứa nước Pleistocen ven biển tỉnh Ninh Thuận, Bình Thuận bằng phương pháp GALDIT và đề xuất giải pháp bảo vệ nước dưới đất*, Tạp chí Tài nguyên nước, số 1 năm 2022.