



Assessment the Impact of Climate Change and Sea Level Rise on the Unconfined Aquifer at the Red-River Delta of Vietnam: A Case Study at Thai Binh Province

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Abstract. Thai Binh is a coastal province in the Red River Delta in Vietnam, which is bounded by river systems and coastline, causing complicated hydrogeological characteristics of aquifers including the Holocene aquifer. Groundwater plays a crucial role to water supply system in Thai Binh province. The Holocene aquifer is a heterogeneous aquifer interspersed between saltwater and freshwater zones. The total dissolved solids (TDS) of its groundwater ranges from 0.2 to 4.8 g/l. Compare to the research in 1996, the distribution area of the freshwater zone is increased 180 km² especially in the area that the upper soil layer has good permeability. However, groundwater resources in this province are highly vulnerable to human activities, climate variation and sea-level rise. Insights into impacts of climate variation and sea-level rise is an essential task to sustainable groundwater management in this area. The present study aims to investigate potential impacts of climate change and sea-level rise on the groundwater by using a three-dimensional transient density-driven groundwater flow model (the SEAWAT package) based on the impacts of the groundwater exploitation activity, rainfall, river and sea-level rise. The results obtained revealed that the groundwater table in Holocene aquifer in 2100 was decreased from 0.5 to 0.8 m depending on different locations in the study area. The most affected area ranges within 3.0 km from the shoreline. The areas of the Holocene aquifer with saline water, especially coastal areas such as Tien Hai and Thai Thuy, will increase as seawater intrusion intensifies. The increase in seawater intrusion will vary according to each climate change and sea-level rise scenario. The predicted increase is 79.9 km² for Scenario B1, 94.1 km² for Scenario B2, and 109.7 km² for Scenario A2, whereas the remaining freshwater reserves in the Holocene aquifer for each scenario are 513.243, 505.282, and 492.443 million m³, respectively. This paper concludes with proposed solutions for sustainable groundwater usage in this region. It is our hope that these results will contribute to Vietnam's sustainable development by providing necessary information for resource managers to control groundwater usage, reduce pollution, limit saline intrusion, and save natural resources.

Keywords: Aquifer · Climate change · Sea-level rise · Intrusion · Vietnam

1 Introduction

In recent years, climate change and sea-level rise are widely recognized as the most severe issues causing many negative impacts on the environment, economy and society. Along the shoreline impacts include beach erosion and marine inundation resulting from the increased frequency and magnitude of waves. For inland areas, include reduced infiltration, drainage, and saltwater intrusion [1]. The field of water resources was concerned as one of the important research issues. Especially in areas with severe conditions, such as coastal areas where freshwater sources play an essential role in life and society. While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and poorly understood. The greater variability in rainfall could mean more frequent and prolonged periods of high or low groundwater levels, and saline intrusion in coastal aquifers due to sea-level rise and resource reduction. Groundwater resources are related to climate change through the direct interaction with surface water resources, such as lakes, rivers, and sea and indirectly through the recharge process. The literature reviews showed that some studies evaluated the effect of climate change and sea level rise to groundwater at coastal area [2–11]. Climate change researchers have assessed the restoration of groundwater levels and the intrusion of seawater in groundwater sources, including the unconfined Holocene Aquifer. The studies show that the changing quality and quantity of groundwater depends on geological, topographic, hydrogeological, and climate conditions, the geological evolution and socio-economic history of each region, and sea-level rise [12–14]. Because groundwater in aquifers is recharged mainly by precipitation or interactions with surface water bodies, the direct influence of climate change on precipitation and surface water will ultimately affect groundwater systems [15]. The changing of salt of groundwater was influenced by seawater and rainwater [2, 16, 17].

Assessing the impact of climate change and sea level rise on groundwater requires a combination of advanced knowledge and innovative methods. Methods applied to studies of sea-level rise and seawater intrusion include numerical simulation and analytical approaches [5, 18]. Monitoring wells along the coast are used to analyze the radius of sea-level rise to determine its impact on saltwater intrusion [2, 4–6, 12]. Evaluating the impact of climate change and sea-level rise on groundwater resources is generally based on simulations of groundwater recharge, groundwater levels, surface-groundwater interactions, and seawater intrusion [5, 6]. Besides, changes in the quality and volume of groundwater were also simulated using a 3D numerical model based on climate change scenarios, using key factors such as rainfall, sea level, groundwater level and exploitation data. Most of the researches use mathematical models and the salinity - light shift mechanism. Groundwater flow is adapted to take into account density differences between fresh, brackish and saline groundwater. Previous studies have also used this code to simulate and quantify future salinization processes in the subsurface, calculate

the effects of future climactic and anthropogenic scenarios, and devise measures to combat salinization [7–9, 16–24].

Base on the Intergovernmental Panel on Climate Change's assessment, Vietnam is one of the countries that will be affected seriously by climate change and sea-level rise. Climate change impacts on Vietnam are serious and threaten sustainable development goals, such as poverty reduction and the realization of millennium goals. Sea level rise in the coastal areas of Vietnam will be higher than the average global sea level rise [25]. In Vietnam, some research was carried out to assess the impact of climate change and sea-level rise on the groundwater in coastal regions. Vu Thanh Tam et. al (2016) studied and assessed the impact of climate change on a quaternary groundwater system on the narrow sloping coastal plain of Central Vietnam [15]. Nguyen Thi Ha (2016) assessed the saltwater intrusion into the river and groundwater by climate change in Hau Loc, Thanh Hoa province, and Tan Thanh, Ba Ria – Vung Tau province [26]. It is obvious that climate change and sea-level rise have highly potential impacts on groundwater resources in coastal areas. However, the impacts of these phenomena are still high uncertainty depending not only on regional climate system but also specific geographical and geological conditions as well human activities of a certain area. In the Red River Delta plain, Thai Binh is one province that will be heavily influenced by sea-level rise. Challenges, in particular, include water shortage, scarcity of freshwater, and saltwater intrusion. Therefore, studying their impact on the Holocene aquifer is necessary to anticipate, prevent, minimize, or mitigate adverse effects.. This research emphasized the need to development management models that simulate seawater intrusion in the Holocene aquifer, assess future compound groundwater challenges, and provide solutions, protective measures, and sustainable exploitation methods.

2 Study Area and Data

2.1 Description of the Study Area

Thai Binh is a coastal provinces in the Red River Delta plain with an area of 1,542.24 km². Thai Binh experiences two seasons with a mean annual rainfall ranging from 1,600 to 1,800 mm. The rainy season lasts from April to September, and the dry season lasts from October to March. Annual evaporation is about 600 mm. According to statistics, the average temperature has increased slightly from 22.8 to 23.6 °C since 1996. This has additionally contributed to an increase in the number of storms. The mean annual maximum temperature is 40.2 °C, while the minimum is 7 °C. Thai Binh has 52 km of coastlines, which is directly affected by seawater and tides, leading to the possibility of saltwater intrusion inland. The unconfined aquifer, known as the Holocene Aquifer, is distributed throughout the study area and is the main water source for production and other domestic uses. It also plays a vital role in maintaining the ecological value of the area (Fig. 1).

2.2 Data Used

Topography of Thai Binh is low plain, flat. The average elevation is 1–2.5 m above the sea level and lower in the East. The studying area has two main aquifers that are Holocene

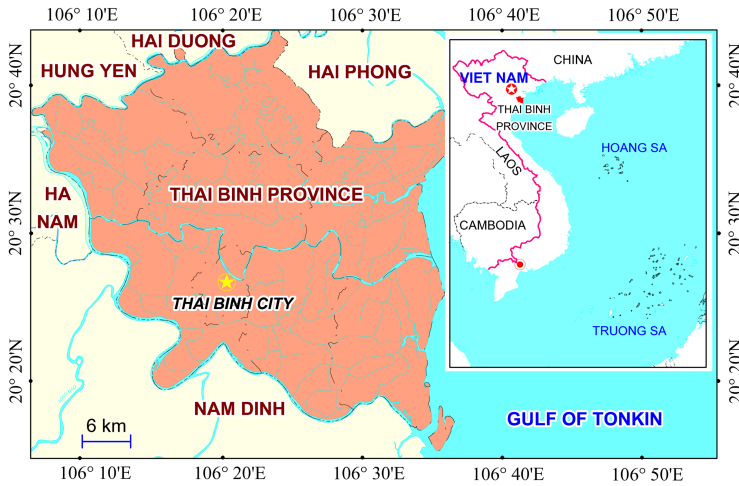


Fig. 1. Map of Thai Binh province

(qh) and Pleistocene (qp) aquifers. These aquifers were separated by the clay layer of Hai Hung and Vinh Phuc formation. The Holocene aquifer is distributed and exposed to most areas of the province. The distribution of aquifers and aquitards is shown in Fig. 2. Upper Holocene unconfined aquifer (qh₂) is the groundwater in Quaternary sediments, has the sources from the sea, sea - wind, and river sea origin. This aquifer distributes throughout the province is about 1,200 km².

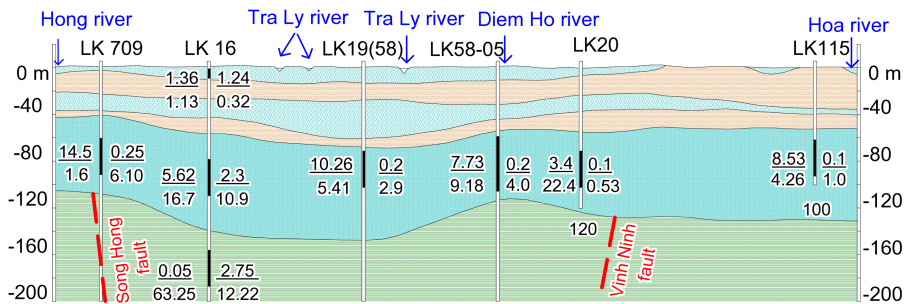


Fig. 2. Hydrogeological cross section in Thai Binh province [27]

It has mainly composed of sand with little silt, capable of absorbing and circulating water good. The thickness increases from the North – North West to the South – South East, with a maximum is 25 m. The groundwater level is from 1 to 2 m depending on the seasons. According to the pumping and hydrogeological test shown that well capacity is from 0.1 to 0.7 l/s, average transmissibility coefficient is 1.8 m²/day, hydraulic conductivity is 1.49 m/day, and storage coefficient is 0.18. To assess the recharge capacity of rainwater and surface water to Holocene aquifer, the parameters of surface coating and hydrogeological characteristics were investigated and summarized in Table 1.

Table 1. The parameters of surface coating

Location	Area, km ²	K, m day ⁻¹	P, mm year ⁻¹	Tv, mm year ⁻¹	Cv	I, mm year ⁻¹
Tan Hoa, Hung Ha	80	0.005	1,680	845	0.62	134.4
Minh Tan, Dong Hung	30	0.004	1,695	840	0.63	135.6
Bach Thuan, Vu Thu	40	0.003	1,740	830	0.65	139.2
Song An, Vu Thu	30	0.070	1,740	830	0.25	104.4
Quang Trung, Kien Xuong	25	0.150	1,750	830	0.26	140.0
Tay Phong, Kien Xuong	30	0.300	1,750	845	0.25	140.0
Nam Hung, Tien Hai	32	0.220	1,770	855	0.22	141.6
Thuy Luong, Thai Thuy	35	0.007	1,780	860	0.24	142.4
An Thai, Quynh Phu	84	0.009	1,700	840	0.45	136.0
Thuy Truong, Thai Thuy	46	0.015	1,780	860	0.43	142.4
Bach Thuan, Vu Thu	150	0.025	1,740	830	0.3	139.2
Tay An, Kien Xuong	330	0.030	1,750	850	0.3	140.0
Dong Huy, Dong Hung	130	0.020	1,695	840	0.28	135.6
Nam Hung, Tien Hai	120	0.028	1,770	855	0.22	141.6
Hung Dung, Hung Ha	280	0.020	1,680	845	0.47	134.4
Dong Tien, Quynh Phu	100	0.050	1,700	840	0.48	136.0

The quality of Holocene aquifer in this region is not uniform: it is interspersed between fresh and saline groundwater zones. The thickness have affected the complementary roles of rain, rivers, and sea, changing the salt - freshwater boundary of groundwater. To assess the relationship of the qh aquifer with climate and hydrological factors, we have analyzed concentrations of Na⁺, Cl⁻ and TDS. Total dissolved

solids is considered as another indicator of the amount of contaminant present in the groundwater which is directly proportional to EC [28]. According to the standard QCVN 01:2009/BYT, TDS between 0 g/l to 1 g/l is freshwater. If TDS more than 1,000 mg/l is poor for drinking use and unacceptable if it is greater than 2,000 mg/l. In whole province, TDS changed from 0.3 g/l to 18.3 g/l. The concentration of Cl^- changed from 72.0 mg/l to 1,569 mg/l. The concentration of Na^+ in the water varied widely, and many places had a concentration higher than the standard.

The area has medium permeability coefficient, high flow rate of groundwater and the component is mainly composed of fine to medium coarse sand, gravel that is salinely cleaned by rainwater and surface water. The freshwater area has TDS that is 0.3 to 0.8 g/l and mainly distributed in Hung Ha district, Vu Thu district, a part of Thai Binh city, and the riverside of Tien Hai district, Thai Thuy district. The chemical composition of qh₂ aquifer in fresh areas has Mg - Na - Ka - Cl type and is shown in the following formula [27]:

$$M_{0.5} \frac{Cl_{60}HCO_{37}}{Mg_{39}(Na + K)_{35}Ca_{26}} pH_{8.5} \quad (1)$$

In the area which has low permeability coefficient, a low flow rate of groundwater and the component of soil is mainly composed of silt and clay, the groundwater flow rate is less related to river water so that the groundwater is not salinely cleaned. We can divide this aquifer into two representative areas saline based on the TDS value that is Quynh Phu - Dong Hung area and Hong river - Tra Ly river with one part of Vu Thu district. The chemical composition of qh₂ aquifer in saline areas has Na - Ka - Cl type and is shown in the following formula [27]:

$$M_{11.15} \frac{Cl_{92}}{(Na + K)_{88}Mg_{10}} pH_{8.1} \quad (2)$$

Surveying results of the TDS content of groundwater in Holocene aquifers are shown in Fig. 3, showing the current status of the distribution of salty and freshwater zones of this aquifer. In particular, the freshwater area is about 521.1 km² and mainly distributed in the central and the southeast of the study area. These freshwater zones were located in Hung Ha, Dong Hung Quynh Phu, and Kien Xuong districts. Compared with the previous research results in 1996 by Lai Duc Hung et al., the distribution area of these freshwater bodies has changed quite a lot. The area of the saltwater bodies is narrowed 180 km², mainly in the coastal area of Tien Hai and Thai Thuy districts.

The over exploitation through excessive abstraction of groundwater resource exceeding its replenishment capacity is the cause of lower water levels and saline intrusion. So the study has surveyed and assessed the status of using groundwater of local people. The exploitation quantity of groundwater in this area is nearly 300,000 m³/day. According to the statistic data of Thai Binh Department of Natural resources and Environment and field survey result, the whole province had 216, 926 wells funded by UNICEF with capacity about 200,000 m³/day, 100 industrial exploitation wells with exploitation capacity about 20,852 m³/day, and 6 groundwater treatment plants. Aside from, there are many well that is self - exploitation and treatment by households in this area (Table 2) [29].

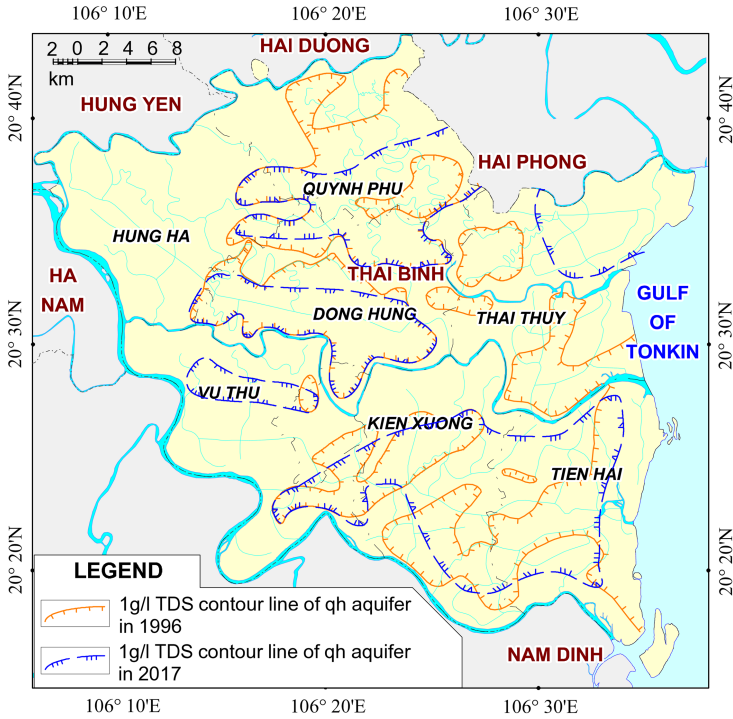


Fig. 3. Distribution salt-freshwater boundary of Holocene aquifer in 1996 and 2017

Table 2. The currently status of exploitation groundwater and the population using clean groundwater in Thai Binh province

No	District	Population	Private well	Dug well	Water supply system, $m^3 \cdot day^{-1}$	The population using clean groundwater	%
1	Thai Binh	66,937	13,250	10,145	30,000	53,395	80
2	Kien Xuong	237,410	38,460	37,895	8,001	84,356	35
3	Thai Thuy	259,629	53,975	47,675	9,996	111,646	43
4	Dong Hung	252,220	76,000	34,015	6,003	116,018	46
5	Hung Ha	247,349	72,150	40,315	4,007	116,472	47
6	Quynh Phu	240,013	74,200	48,655	6,240	129,095	54
7	Tien Hai	206,874	27,040	34,930	5,172	67,142	32
8	Vu Thu	228,726	36,850	43,960	4,003	84,813	35

The exploitation process is caused making the changes of groundwater, which has been making groundwater level of this aquifer go down, and changing the distribution of salty and freshwater zones of this aquifer. Hence, this study will be the basis for forecasting the changes in the quantity and quality of Holocene aquifer under the impact of climate change and sea-level rise on the future.

To evaluate the impact of climate change, sea-level rise on quality changes and groundwater reserves in the study area and forecast the impact of climate change and sea-level rise on groundwater in the future need to assess the relationship between groundwater and seawater, rainwater. Most of the groundwater resources are mainly renewed (recharged) directly from rainwater i.e., precipitation through infiltration into the saturated zone, thereby maintaining the recharge potential of an aquifer seems essential for the sustainability of that aquifer. Therewith, the climate change and sea-level rise scenarios for Thai Binh province is essential to assess the seawater intrusion on groundwater [25]. The simulation input data is based on the result of predicted and built scenarios with climate change and sea-level rise by the Ministry of Natural Resources and Environment, Vietnam. Climate change and sea-level rise scenarios are assumed belong to the increase of greenhouse gas emissions that leading to an increase in temperature, humidity, precipitation and sea level in the future. Climate change and sea-level rise scenarios for Vietnam are formulated based on different assumptions of greenhouse gas emissions: low emission (B1), medium emission (B2), and high emission (A2) [25]. In particular, the annual average temperature in Thai Binh province under the A2 emission scenario will increase about 1.3 °C in 2050 and 3.1 °C in 2100 compared to the year (1980–1999) [30].

Table 3. Scenarios of increasing rainfall and sea-level rise compared to the year (1980–1999) in Thai Binh province [30]

No	Year	Rainfall, %			Sea level rise, cm		
		B1	B2	A2	B1	B2	A2
1	2030	2.0	2.1	2.3	10 ÷ 12	11 ÷ 12	11 ÷ 13
2	2040	2.8	3.0	3.3	14 ÷ 17	15 ÷ 17	16 ÷ 18
3	2050	3.6	3.9	4.1	19 ÷ 22	20 ÷ 24	22 ÷ 26
4	2060	4.2	4.7	4.9	23 ÷ 29	25 ÷ 31	29 ÷ 35
5	2070	4.5	5.5	5.8	28 ÷ 36	31 ÷ 38	38 ÷ 46
6	2080	4.8	6.2	6.9	33 ÷ 43	36 ÷ 47	47 ÷ 58
7	2090	4.9	6.8	8.1	38 ÷ 50	42 ÷ 55	56 ÷ 71
8	2100	4.9	7.4	9.4	42 ÷ 57	49 ÷ 64	66 ÷ 85

In addition, three sea-level rise scenarios will be set up, including the sea-level will rise up to 50 cm, 70 cm and 85 cm. Then forecasting the areas that is risk by climate change and sea-level rise. The report of the Ministry of Natural Resources and Environment, Vietnam is shown the risk of flood in coastal areas in Thai Binh province [30]. So that,

this research estimated the flood area under three types of sea-level rise scenarios: a sea-level rise of 0.5 m per century, 0.7 m per century and 0.85 m per century. The impact of sea-level rise has changed the land use area by the increase of flood. Wetland areas in different regions under the climate change scenarios are shown in Table 4.

Table 4. Scenarios of Flood area in Thai Binh province [30]

District	Area (km ²)	Scenario of Flood area (km ²)			Percent Flood area (%)		
		50 cm	70 cm	85 cm	50 cm	70 cm	85 cm
Tien Hai	195.97	58.79	117.58	156.78	30	60	80
Thai Thuy	258.77	38.82	90.57	168.20	15	35	65
Kien Xuong	215.51	32.33	43.10	86.20	15	20	40
Quynh Phu	208.40	10.42	20.84	52.10	5	10	25
Đông Hưng	205.83	6.18	14.41	20.580	3	7	10
Hung Ha	212.93	4.26	10.65	17.04	2	5	8
Vu Thu + Thai Binh city	244.84	19.59	29.38	36.73	8	12	15
Province	1,542.24	170.37	326.53	537.62	11.05	21.17	34.86

In the scenario of a sea-level rise of 0.85 m by 2100, the area of the flooded land will account for 34.86% of the total area of the province, and the coastal areas are the places that will be most affected. This will push saltwater going far into the land and penetrate the aquifer.

3 Background of the Methods Used

3.1 Monitoring the Water Level

Monitoring the groundwater level, seawater level, and TDS of groundwater at coastal areas where seawater intrusion was report or a seawater intrusion risk was high. The groundwater monitoring well was located at 1.5 km to 3.5 km from the coastal line and close to the tide gauge station that to investigate seawater intrusion for this study. The observed data were used for this study to assess the relationship of groundwater and river water, seawater. After that, the recharge of river water and seawater to dissolution and diffusion of the saltwater into the aquifer is forecasted.

3.2 Physically Based Model

A based model of a groundwater system under possible climate change based on available data is very important to prevent the deterioration of regional water-resource problems in the future. Although uncertainties are inevitable, new response strategies in water resource management based on the model may be useful. Based on the physical and chemical characteristics are researched and the features of the models, using Visual Modflow model and Seawat code to predict the effect of climate change and sea-level rise to the qh aquifer. The modeling approach was validated by solving Henry's steady-state solution. Model describes the groundwater flow system with the river and coastal boundaries, topographic condition, hydrogeology parameters (hydraulic conductivity, specific yield, groundwater level), exploited condition, land use and precipitation, evaporation, sea-level rise.

The model is established based on hydrogeological characteristics of the study area and the hydrogeological structure of the whole Northern Delta. Structure model consists of 04 layers: (1) Surface layer having low permeability; (2) Holocene aquifer (qh1, qh2), (3) Weak permeability layer separate the Holocene aquifer and the Pleistocene aquifer, and (4) Pleistocene aquifer (qp). The area of the simulation model of the study area is 1,554 km² consisted of a rectangular grid of 98 rows and 108 columns with grid cells size 500 m x 500 m. Topographic data were obtained from the digital elevation model (DEM). Hydrogeological parameters (hydraulic conductivity, specific yield, groundwater level) were based on the results of previous researches and survey results. Amount of water recharged for the aquifer was determined by rainfall which was given in Table 5 and Fig. 6. The three types of boundary conditions used in the model are river boundary, general head boundary (GHB), and sea boundary ($H = \text{const}$). After the simulation model is adjusted according to the actual current situation, it will be used to predict the changes in groundwater dynamics of the Holocene aquifer under 3 climate change scenarios A2, B1 and B2 were shown in Tables 3 and 4. Coastal and river boundary conditions will be changed by the effect of climate change and sea-level rise both value and position on nodes. In which, with sea boundary the position and water level on the boundary position were determined based on the flood map and the change of sea level over the years in each climate change scenario. For river boundary, there is only change in water level at the nodes. The amount of water recharged for groundwater was determined based on the rainfall for each scenario.

Thence, the model was calibrated to observations of groundwater altitude and contrasted in salinity detected in boreholes by using data collected as part of our ongoing investigation. A three-dimensional transient density-driven groundwater flow model, considering open boundary conditions for coasts and a sharp interface between freshwater and saltwater, was applied to the aquifer under steady-state conditions for freshwater surplus and deficits at the coastline. When recharges of saltwater occur at the coastline, essentially of freshwater deficits, a hypothesis of mixing for the freshwater-salt water transition zone allows the model to calculate the resulting seawater intrusion in the aquifer. Hence, adequate treatment and interpretation of the hydrogeological data, which are available for the coastal aquifer, were of main concern in satisfactorily applying the proposed numerical model. The results of the steady-state simulations showed

reasonable calculations of the water table levels and the freshwater and salt-water thicknesses, as well as the extent of the interface and seawater intrusion into the aquifer for the total discharges or recharges in the delta and along the coastline. From the modeling application on Thai Binh province, it appears that, on an annual basis, most tested scenarios predict a decrease in groundwater levels and reserves in relation to variations in climatic conditions. So that, the map of the groundwater level of the aquifer and the map of the distribution of salt and freshwater zones in Holocene aquifer are established in the model. The model results are proper groundwork that helps to calculate the quantity of this aquifer and show the impact of climate change and sea-level rise to the Holocene aquifer in this study area.

4 Proposed Methodology for the Assessment the Impact of Climate Change and Sea Level Rise on the Unconfined Aquifer in This Research

Step 1: Data collection and processing

To research and forecast the saltwater intrusion of Holocene aquifer under the climate change and sea level rise, the combinatorial hydrogeology methods including outdoor and indoor were used. Firstly, collecting the data from the previous research by Lai Duc Hung in 1996 about the distribution salt - fresh water boundary of Holocene aquifer, the hydrogeology and geology characteristics of the aquifers, distribution of aquifers and division of hydrological geological structure [27]. Thence, the study designed a survey roadmap perpendicular to the saline boundary that is surveyed in 1996 to re-correct the current saline boundary (Fig. 3). Besides that, a field survey was conducted to collect data about the currently status of exploitation, using groundwater for people in the districts and direction of using groundwater in the future.

Especially, to evaluate the impact of climate change, sea-level rise on quality changes and groundwater reserves in the study area and forecast the impact of climate change and sea-level rise on groundwater in the future need to assess the relationship between groundwater and seawater, rainwater. Most of the groundwater resources are mainly renewed (recharged) directly from rainwater i.e., precipitation through infiltration into the saturated zone, thereby maintaining the recharge potential of an aquifer seems essential for the sustainability of that aquifer. Thence, the data of precipitation, river water level and seawater level were collected from the Vietnam Center of Hydro - Meteorological Data and the groundwater level data of monitoring wells (Q155, Q156, Q158, Q159) was collected from NAWAPI. Our observed results were combined with other observation results of NAWAPI to assess the relationship of the tide, river water level and groundwater level. Similar, the data about the status of land use and direction of using land in the future was collected to assess the recharge of rainwater and surface water to the aquifers. Final, collecting the climate change and sea-level rise scenarios by the Ministry of Natural Resources and Environment, Vietnam is necessary to assess the impact climate change and sea-level rise on groundwater in this province.

Step 2: Field survey and hydrogeological test

First of all, field survey to study the geological structure to clarify the formation of sediments, lithological composition, and hydrogeology characteristics of Holocene

aquifer in this study area. The permeability coefficient of the topsoil layer was determined by double ring infiltrometer test in the excavation hole and combined with petrographic analysis of the core sample in the laboratory. The location of the field test points and the drilling positions for lithological sampling were arranged evenly and alternatively together. However, the double ring infiltrometer test is arranged more often in riverside areas to evaluate the replenishment capacity of surface water for aquifers or vice versa. The total number of in situ testing and lithological sampling was 55 points.

Step 3: Sampling and in situ measurement

To assess the impact of climate change and sea level rise in qh aquifer, the changing of saltwater quality over time had to study. In this research, the authors carrying out survey, observation, rapid measurement method and sampling to evaluate the water quality at the 98 boreholes in the rainy and dry seasons over the studying area. These survey points located in the area that is around the salt-light boundary defined in 1996 by Lai Duc Hung and in the riverside and coastal areas to correct the salt-light boundary at the time of the study. This data is used as the basis for forecasting the shift boundaries under the impact of climate change and sea-level rise in the future. Locations of observation points are shown in Fig. 4.

Step 4: Monitoring the groundwater level, river water and sea level over time in the study area to assessment the relationship each other. Collecting the data of monitoring the groundwater level from the NAWAPI to study the fluctuation of water level in some boreholes in whole province to assess the complementary of rainwater and surface water to Holocene aquifer over time. Besides that, carry out monitoring of water level fluctuations in the 15 boreholes at the coastal areas (Thai Thuy, Tien Hai) to assess the relationship and effect of tide on the Holocene aquifer (Fig. 4).

Step 5: Groundwater sample analysis in laboratory

After that, using the analysis sample method in laboratory to assess the quality of groundwater. The number of samples was analyzed is about 30 samples. The quality of groundwater results and the distribution of TDS are used to build the salt - fresh water boundary in the study area (Fig. 3). It is the basis for forecasting the movement of this boundary under the impact of climate change and sea level rise.

Step 6: Summary and calculation

Calculation and prediction of the recharge of rainwater, surface water for qh aquifer based on the results of field surveys, observation, sampling and analysis data in this study. The groundwater recharge is calculated as [17]:

$$R = P - Sv - Tv - I \quad (3)$$

where P is the precipitation [L], I is the interception [L], Sv is the surface runoff [L], Tv is the actual transpiration [L] and R is the groundwater recharge [L]

$$Sv = Cv (P - I) \quad (4)$$

where Cv is the surface flow coefficients depend on soil composition, vegetation cover and topographic slope.

Then, using a three-dimensional transient density-driven groundwater flow model by the SEAWAT package to simulate saltwater intrusion in a coastal aquifer for three types of sea-level rise scenarios: a sea-level rise of 0.5 m per century, 0.7 m per century, and 0.85 m per century to assess the impact of sea-level rise on groundwater. Finally, the quantity of fresh groundwater will be estimated under the scenarios in the future.



Fig. 4. Map showing the sampling locations for groundwater of Holocene aquifer, in situ measurements and monitoring the groundwater level in coastal area

5 Results and Discussion

5.1 Groundwater Flow Dynamics

The results of monitoring the water level in the Holocene aquifer, seawater level, and rainfall in Fig. 5 shows that the trend of the groundwater level is rise up and similar to the change of the rainfall in the study area. This shows that rainwater has a close relationship with groundwater and has an influence on the formation of water storage of this aquifer. The groundwater level in Holocene aquifer is increased over time.

From the above results, we can clearly see that the rainwater directly affects the quantity of groundwater and implement this aquifer. In this study, the effects of climate

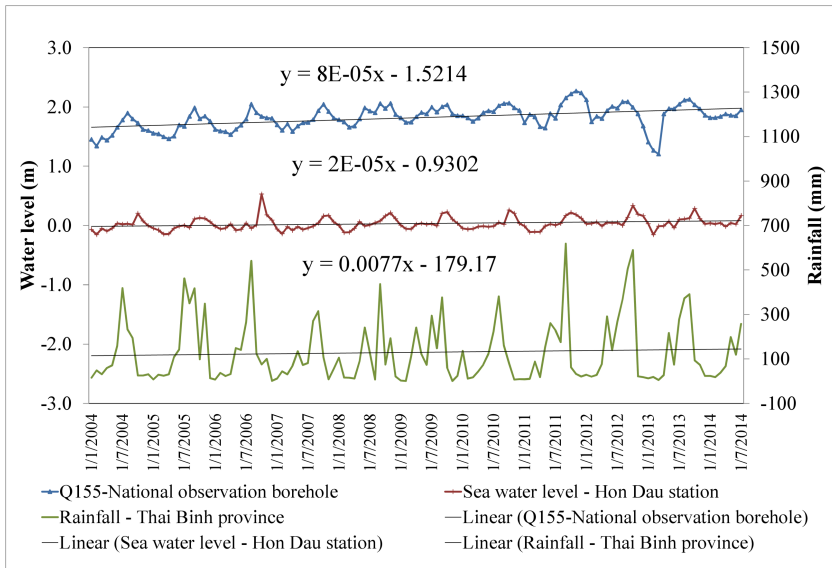


Fig. 5. The changing of rainfall, groundwater level and sea level over time in the study area

change on the groundwater system of the catchment are assessed based on changes in the recharge and baseflow. Studies on the effects of rainfall intensity on groundwater recharge are the basis for calculating flow simulations and assessing changes in groundwater quality [31]. Therewith, the quality of water in the Holocene aquifer is changing. Rainwater and surface runoff have accelerated the process of saline washing for this aquifer, especially in a coastal area where the upper layer has good permeability. This result is similar to the previous research (Mzila et al., 2003) that studies the unconfined aquifers in coastal areas of Singapore. Saline intrusion intensity is inversely proportional to the rainfall [19]. The rising of the groundwater table will reduce the saline intrusion process of the saltwater mass. Based on Eqs. (3) and (4), the amount of rainwater for groundwater has been calculated as shown in Table 5 [32]. According to the calculation results, the amount of recharge for aquifers varies depending on the characteristics of each area. The amount of water recharge to the Holocene aquifer is an average total about of 26% of the total precipitation [33]. The total amount of water replenished is about 345,460 m³/day.

According to the results of calculating the amount of rainwater recharges to groundwater, the map of the distribution recharge area of rainwater to groundwater was built. This is an essential condition to put into the Seawat model to predict the recharge of rainfall to groundwater in the future under the climate change and sea-level rise scenarios.

The study of the impact of sea-level rise on groundwater is important to study the saline intrusion at the coastal areas [10, 34]. Based on the results of the field surveys, groundwater level monitoring at the coastal area of Tien Hai, Thai Thuy, the study has built a hydraulic relationship between seawater level and groundwater level of Holocene aquifer at different distances of 1.5 km, 3.0 km and 3.5 km which is shown in Fig. 7.

Table 5. The amount rainwater recharges to Holocene aquifer

Location	Area, km ²	Sv, mm year ⁻¹	R, mm year ⁻¹	Ratio of concreted areas	Percent supplemented by rainwater, %
Tan Hoa, Hung Ha	80	517.7	182.9	0.5	5.5
Minh Tan, Dong Hung	30	538.65	180.75	0.52	5.1
Bach Thuan, Vu Thu	40	591.5	179.3	0.45	5.7
Song An, Vu Thu	30	227.5	578.1	0.45	24.6
Quang Trung, Kien Xuong	25	239.2	540.8	0.4	24.7
Tay Phong, Kien Xuong	30	226.25	538.75	0.4	24.3
Nam Hung, Tien Hai	32	201.3	572.1	0.3	25.5
Thuy Luong, Thai Thuy	35	220.8	556.8	0.3	25.0
An Thai, Quynh Phu	84	382.5	332.3	0.4	14.8
Thuy Truong, Thai Thuy	46	352.6	333	0.2	15.9
Bach Thuan, Vu Thu	150	273.0	497.8	0.45	20.0
Tay An, Kien Xuong	330	270.0	490	0.4	20.2
Dong Huy, Dong Hung	130	239.4	480	0.5	19.8
Nam Hung, Tien Hai	120	201.3	572.1	0.38	20.0
Hung Dung, Hung Ha	280	392.45	308.15	0.45	10.6
Dong Tien, Quynh Phu	100	412.8	311.2	0.45	10.1

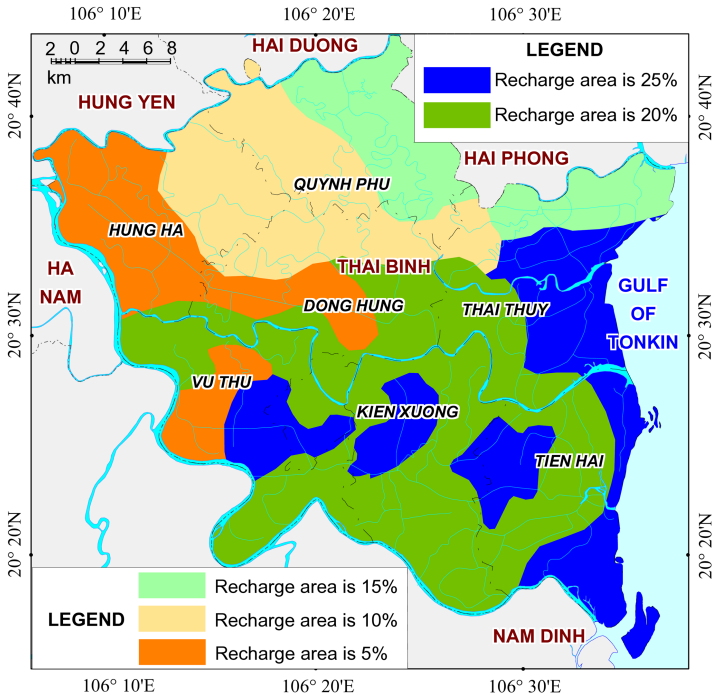


Fig. 6. The distribution recharge area of rainwater to groundwater

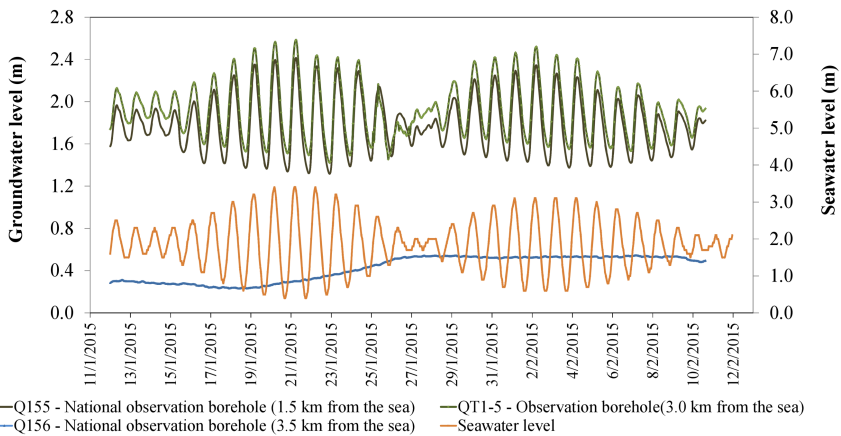


Fig. 7. The changing of the groundwater level at the 1.5 to 3.5 km distance far from the sea

As assessed about the effect of seawater to Holocene aquifer at different distances, the graph of the groundwater table by different distances from the coast and the sea level shows the fluctuation of the underground water level in sync with the sea level by the tide. At the distance of 1.5 km from the sea, the groundwater level in the observation borehole

155 is rising up and fluctuating the same with the seawater level. And in borehole QT 1–5 at 3.0 km is the similar to Q155. This result is the same as the research of Hoover, D.J et al., 2017 which assess the effect of the tide on the groundwater in coastal at Malibu, California. The research built a relationship between the groundwater levels and observed tide at Santa Monica. Note that well and tide data are plotted with different scales to facilitate visualization of tidal response in wells are 60 m, 65 m and 115 m from the ocean, respectively [11]. More recent data show that the significant damping of the tidal happened with the respective distance from shore. The further inland, the less impact of the tide to groundwater.

Moreover, this also shows that the groundwater of Holocene aquifer has a hydraulic relationship with the sea. The change of the water table under the fluctuation of the tide decreases when going far inland. The area where the Holocene aquifer is most affected by tides is within 3.0 km of the coastline. The relationship between sea level by tide and groundwater is the linear relationship shown in Fig. 8 and is shown by Eq. 3.

$$y = 0,3254 x + 0,00946 \tag{5}$$

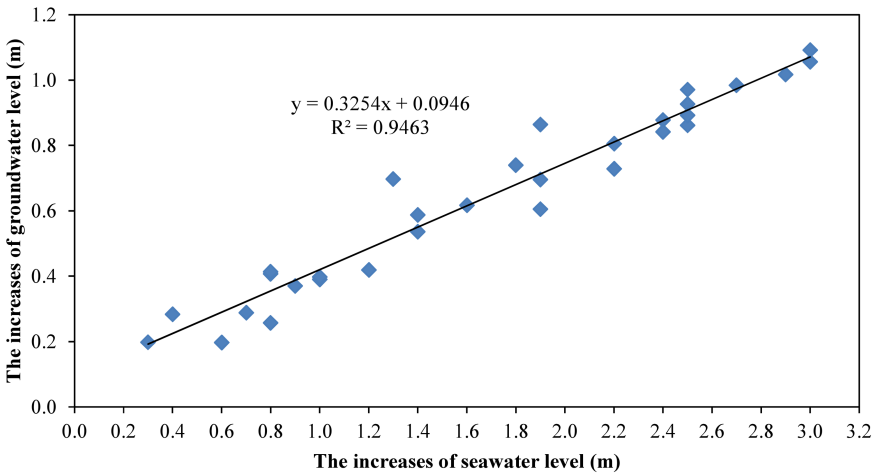


Fig. 8. The relationship between seawater level and groundwater level of Holocene aquifer

5.2 Simulation of Changes in Holocene Aquifer According to Climate Change Scenario

The principal focus of climate change research with regard to groundwater has been on quantifying the direct impacts of changing precipitation, temperature and sea level rise. It is generally known that climate change may have impacts on sea-level rise and precipitation, which may be associated with freshwater recharge rates and that seawater intrusion is influenced by not only sea level but also freshwater recharge rates. While a higher freshwater recharge rate could lower salinity in groundwater, a higher sea level

may increase seawater intrusion [23]. Such studies have used a range of modeling techniques such as soil water balance models, empirical models, conceptual models and more complex distributed models. Changes to the groundwater system in response to sea-level rise at this site may be of concern to those of continued coastal evolution and shoreline change considering the periodic climate change overwash that currently affects groundwater flow in this area using Visual Modflow model to describe the groundwater flow system in Thai Binh province with the river and coastal boundaries, topographic condition, hydrogeology parameters. The new steady state condition for the salt wedge simulated by the model after raising the sea level. After that, the map of the groundwater level of the qh aquifer and the map of the distribution of the supplement area are established in the model. According to climate change and sea-level rise scenarios for Thai Binh province, this model can be simulated the groundwater flow and forecast the change of groundwater level over time (Fig. 9).

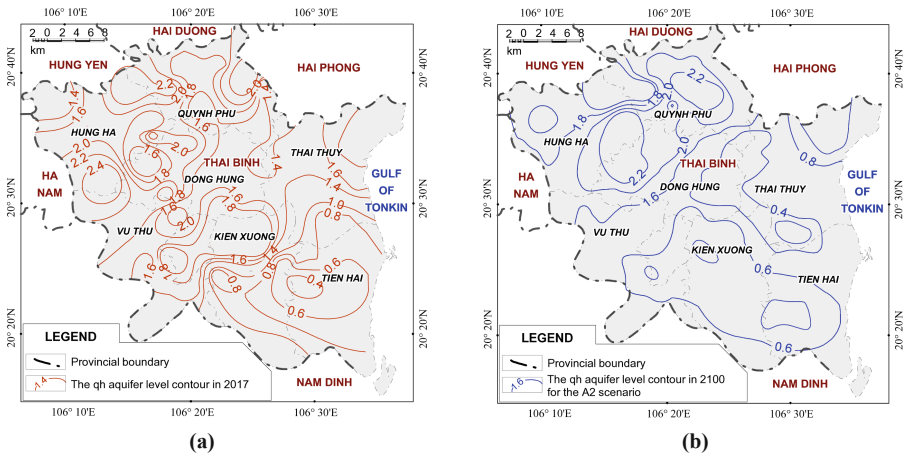


Fig. 9. The groundwater level of Holocene aquifer over time, (a) - The groundwater level in 2017, (b) - The groundwater level in 2100 with A2 scenario

According to the simulation results in Fig. 9, the water level of the Holocene aquifer until 2100 has changed compared to 2017. Results obtained revealed that the groundwater table in Holocene aquifer in 2100 was decreased from 0.5 to 0.8 m depending on different locations in the study area. The water level at the seaside boundary will abruptly increased from 1 to 2 m to simulate an instantaneous sea-level rise in the future. After that, the map of saline intrusion into river system, and the map of the distribution of the supplement area are established in the SEAWAT model. (Fig. 10).

Later, the simulations transient effects of the sea-level rise on saltwater wedge in Holocen aquifer with vertical sea-land interface by this model. This method has been used by many studies in the world. Besides the raising of sea level based on the scenario, another condition of the model is that the rainfall in the studying area will be increased over time. As the results of the TDS content of Holocene aquifer, the area of freshwater zones along the Tra Ly River in Dong Hung, Kien Xuong, and Tien Hai districts and in

the center of studying area are expanded. In the study about the relationship of seawater with the qh aquifer, it shows that the influence area of seawater is within 3.0 km from the coast. Due to the climate change and sea level rise, the qh aquifer is affected by the saline intrusion from the sea to inland.

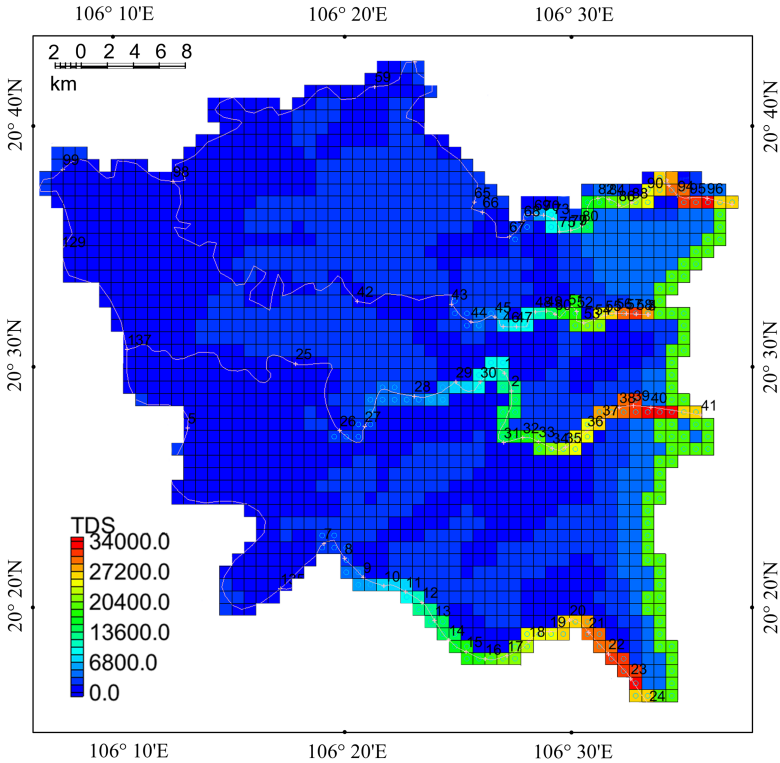


Fig. 10. Simulation of saline intrusion into river system in Thai Binh province by SEAWAT model with A2 scenario

Modeling result showed that qh aquifer is affected by seawater intrusion, especially in coastal areas such as Tien Hai and Thai Thuy districts. The area of saltwater in this area will be expanded by 20% compared to 2017. Furthermore, it also gives out the boundaries between saline and fresh water in the future will be changed so much. The salt-and-fresh area of qh aquifer tends to be narrowed down but not significantly. Forecast to 2100, the area of saltwater in Holocene aquifer will be increased respectively with scenarios B1, B2, A2 is 79.9; 94.1 and 109.7 square kilometres. The mixing zone between fresh and saline water in Holocene aquifer will be moved into inland 1,700 m respectively with sea-level rise is 0.85 m per century. Figure 11 is shown the distribution of saltwater boundary of Holocene aquifer with A2 scenario. The research result is similar to some studies in the world. In which, the research of Oude Essink et al., 2010 assessed the effect of climate change to Holocene aquifer at the coast of Netherlands. The results of this study showed that the sea level rise about 0.5 m per century will increase the salinity in

the Holocene aquifer within 10 km from the shoreline [6]. According to the research of Sherif et al., 1999, the sea level in the Mediterranean Sea increases by 50 cm, the saline boundary in the aquifer Holocen in the Nil Delta (Egypt) moves further inland than 9 km. As for the sea level in the Bay of Bengal (India) will be increased by 50 cm, the saline boundary of the aquifer only moved deep into the continent 0.4 km [20]. Moreover, by the research of Carretero et al., 2013, with a 1m rise in sea level, an increase in saltwater intrusion length by more than 200 m into the coastal aquifer, Partido de La Costa, Argentina will severely degrade the aquifer. Punta Médanos would be the most affected by the sea-level rise; this is something to be considered because the are presents the main reservoir for Partido de La Costa [35].

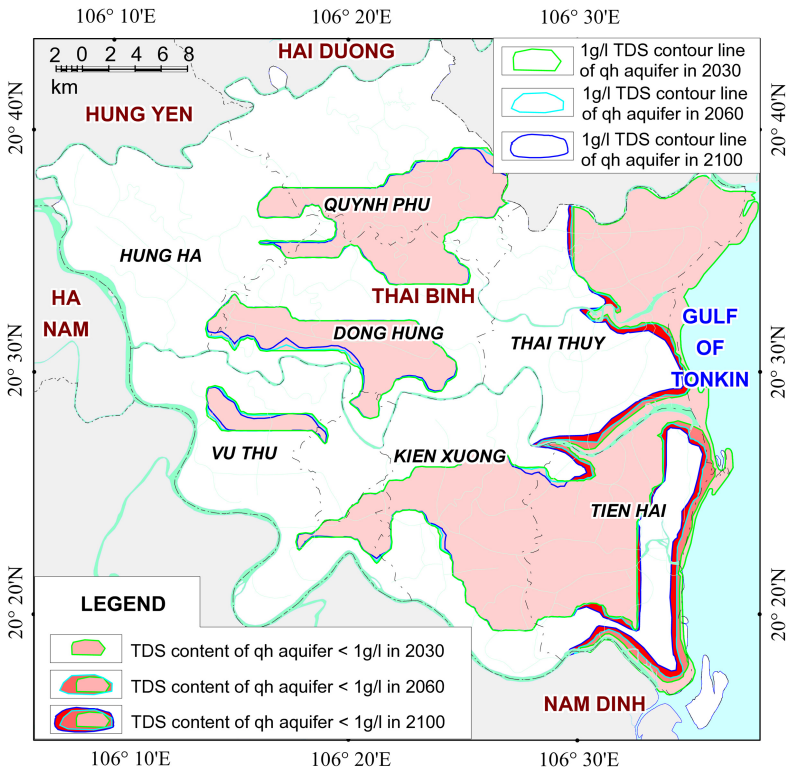


Fig. 11. Distribution of saline and fresh groundwater boundary of Holocene aquifer with A2 scenario

From the forecast result about the area of saltwater of Holocene aquifer, the research will be estimated the quantity of fresh groundwater under the scenarios in the future. The calculation results of the potential of the groundwater storage are given in Table 6. The distribution of this freshwater mass is uneven throughout the area. Freshwater zones with large storage were distributed mainly in Thai Thuy, Hung Ha, Vu Thu districts and Thai Binh city. In 2100, the groundwater storage will be reduced by 263.663 Mio. m³ compared to 2017 with the A2 scenario.

Table 6. The quantity of fresh groundwater in Holocene aquifer with the three scenarios

District	The quantity of fresh groundwater (million m ³)						
	2017	B1 scenario		B2 scenario		A2 scenario	
		2060	2100	2060	2100	2060	2100
Dong Hung	50.750	45.006	39.377	44.838	39.207	44.450	39.037
Hung Ha	121.298	110.347	98.343	110.299	98.295	110.200	98.185
Kien Xuong	64.115	58.012	49.901	57.492	49.439	56.842	48.955
Quynh Phu	84.945	77.677	70.198	77.623	69.382	77.569	69.382
Thai Thuy	206.371	156.146	116.553	150.161	113.696	141.078	107.254
Tien Hai	101.447	62.579	35.531	58.480	31.667	52.717	26.436
Vu Thu and Thai Binh city	127.180	114.795	103.341	114.763	103.595	114.717	103.194
Total	756.106	624.562	513.243	613.655	505.282	597.573	492.443

6 Conclusion

While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and poorly understood. In Thai Binh province, there have been many studies relating to the effect of climate changes on surface water. However, this study is the first research about the potential effects of climate change and sea-level rise on groundwater in this area. The research was carried out based on the results of field surveys, in situ tests, analysis in laboratory and simulation results, from which to predict saline intrusion and changes in water quality of Holocene aquifers under the impact of climate change and sea level rise in the future.

The study show that the Holocene aquifer has a close relationship with runoff, and groundwater is recharged by surface water and rainy water. The groundwater recharge and discharge conditions are a reflection of the precipitation regime, climatic variables, landscape characteristics, and human impacts such as agricultural drainage. In it, the fresh, brackish water and saltwater areas are intertwined. In 2017, the area of saltwater zones is smaller than that of 1996 by 180 km². The amount of rainfall supplying for Holocene aquifer is 345,460 m³/day. The Holocene aquifer is most affected by tides is within 3.0 km of the coastline. By using the Visual Modflow model and Seawat code, groundwater flow, and the movement of salt and freshwater boundaries in Holocene aquifer under the impact of climate change and sea-level rise with scenarios were simulated. And the area of the saltwater zone of the Holocene aquifer will be expanded maximum with A2 scenario, more 109.7 km² by 2100. By assessing the status of the

distribution of saline and freshwater zones in the Holocene aquifer in Thai Binh province and the movement of this boundary in the future, estimate the quantity of fresh groundwater under the scenarios in the future. This is the main aquifer to be used for domestic water supply in this area. The research results will be the basis that helps the managers give out protective solutions and sustainable using methods for this natural resource. Hence, we need to relocate reasonably the exploiting wells far away from the saline boundary to limit the movement of this boundary by the exploitation process. Reducing the number of private wells and replacing them with water plants to protect the aquifer from pollution sources and to control exploitation activities. Enhance the role of management, reasonable using and exploitation for sustainable development.

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