Doi: 10.31276/VJSTE.60(4).82-88

Projection of saline intrusion into groundwater in the context of climate change in the coastal zone of Ha Tinh province

Van Dai Nguyen*, **Tien Anh Do, Kim Tuyen Nguyen**

Vietnam Institute of Meteorology, Hydrology and Climate Change

Received 30 June 2018; accepted 19 September 2018

Abstract:

In addition to surface water, groundwater is an essential source of water for agriculture, industry, and living in Ha Tinh province (central Vietnam). However, overexploitation and unreasonable use of groundwater has put this resource at risk of endangerment and pollution. In the coastal areas especially, the impact of climate change and the rise in sea-level has increased the risk of salt-water intrusion into groundwater. In this study, the groundwater system model (GSM) is applied to simulate the intrusion of saline water in different climate change scenarios in the coastal area of Ha Tinh province. The result reveals that saline intrusion into groundwater is becoming more complex and is a rising trend in climate change scenarios RCP4.5 and RCP8.5.

Keywords: **climate change, coastal, groundwater, Ha Tinh, saline intrusion.**

Classification number: **5.2**

Introduction

Salt-water intrusion into surface water and groundwater is a frequent problem in the coastal areas of Ha Tinh province, as well as in other provinces and cities. With the current socio-economic growth rate, water demand from various sectors is increasing dramatically; on the other hand, with the impact of climate change, surface water as a resource is diminishing and pollution levels are rising. This, in turn, depletes the available store of surface water that sectors depend on. In this context, groundwater would be an effective solution to provide for the needs of socio-economic development, especially where exploitation of surface water is no longer possible. However, as with surface water, groundwater also faces the risk of seawater intrusion; hence, if there are no solutions to reducing saltwater infiltration, or rationally using and supplementing fresh water for groundwater, coastal resources will diminish and fail to supply the needs of socio-economic development. In this study, the GSM is applied to simulate groundwater level and assess saline intrusion in climate change scenarios over extended periods of time in the coastal areas of Ha Tinh (including seven coastal districts, two towns, and one city: Nghi Xuan, Duc Tho, Can Loc, Loc Ha, Thach Ha, Cam Xuyen, and Ky Anh districts; the city of Ha Tinh; and the towns of Ky Anh, Hong Linh). The primary objective of this study is to assess the impact of climate change on coastal groundwater resources.

Method and data

Method

The GSM model was applied to simulate the groundwater resource for the coastal area of Ha Tinh province:

The GSM is a model that integrates the MODFLOW [1] groundwater flow model and the MT3DMS [2] water-quality model to simulate groundwater flow and quality.

In the MODFLOW model, the three-dimensional

*Corresponding author: Email: nguyendai.tv@gmail.com.

movement of a groundwater level of a constant density through porous earth material may be described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where:

- K_{xx}, K_{yy}, K_{zz}: are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T).

- h: is the potentiometric head (L).

- W: is a volumetric flux per unit volume representing sources and/or sinks of water, with W < 0.0 for flow out of the groundwater system, and W > 0.0 for flow into the system (T^{-1}).

- S: is the specific storage capacity of the porous material (L^{-1}).

- t: is time (T).

This equation describes water-level dynamics in heterogeneous and anisotropic environments.

With the MT3DMS water quality model, transporting solutions in a porous environment is a complex chemical and physical process. Two basic components of the process are (i) the transporting of hydrodynamics and (ii) diffusion of ions and particles are dissolved in water from the high concentration to the low concentration. When contaminated water flows through the porous environment, it mixes with uninfected water by means of mechanical dispersion that dilutes it and reduces its concentration. Molecular diffusion and mechanical dispersion cannot be separated in an underground stream and both processes are referred to as hydrodynamic dispersion.

The partial differential equation describing the fate and transporting of contaminants of species k in 3D, transient groundwater flow systems can be written as follows:

$$\frac{\partial(\theta C^k)}{\partial t}=\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial(\theta C^k)}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(\theta v_i C^k)+q_s C_s^k+\sum R_n \quad (2)$$

where:

θ: the porosity of the sub-surface medium, considered to be dimensionless.

C^k: dissolved concentration of species k, ML^{-3}.

t: time, T.

$x_{i,j}$: distance along the relevant Cartesian coordinate axis, L.

D_{ij}: hydrodynamic dispersion coefficient tensor, L^2T^{-1}.

v_i: seepage or linear pore water velocity, LT^{-1}; this is related to the specific discharge or Darcy flux by means of the relationship $v_i = q_i/\theta$.

q_s: volumetric flow rate per unit of the volume of the aquifer, representing fluid sources (positive) and sinks (negative), T^{-1}.

C_s^k: concentration of the source or sink flux for species k, ML^{-3}.

$\sum R_n$: chemical reaction term, $ML^{-3}T^{-1}$.

The left-hand side of Equation 2 can be expanded into two terms:

$$\frac{\partial(\theta C^k)}{\partial t}=\theta\frac{\partial C^k}{\partial t}+C^k\frac{\partial\theta}{\partial t}=\theta\frac{\partial C^k}{\partial t}+q'_s C^k \quad (3)$$

where: $q'_s=\frac{\partial\theta}{\partial t}$ is the rate of change in transient groundwater storage (unit, T^{-1}).

The chemical reaction term in equation 2 can be used to include the effect of general biochemical and geochemical reactions on the fate and transport of contaminants. Considering only two basic types of chemical reactions, that is, aqueous-solid surface reactions (sorption) and first-order rate reactions, the chemical reaction term can be expressed as follows:

$$\sum R_n=-\rho_b\frac{\partial\overline{C}^k}{\partial t}-\lambda_1\theta C^k-\lambda_2\rho_b\overline{C}^k \quad (4)$$

where:

ρ_b: bulk density of the sub-surface medium, ML^{-1}.

$\overline{C}^k$: concentration of species k sorbed on the subsurface solids, MM^{-1}.

λ_1: first-order reaction rate for the dissolved phase, T^{-1}.

λ_2: first-order reaction rate for the sorbed (solid) phase, T^{-1}.

Substituting equations 3 and 4 into equation 2 and omitting the species index in order to simplify the presentation, Equation 2 can be rearranged and rewritten as:

$$\theta\frac{\partial C}{\partial t}+\rho_b\frac{\partial\overline{C}}{\partial t}=\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(\theta v_i C)+q_s C_s-q'_s C-\lambda_1\theta C-\lambda_2\rho_b\overline{C} \quad (5)$$

Equation 5 is a mass balance statement, that is, the change in the mass storage (both dissolved and sorbed phases) at any given time is equal to the difference between the mass inflow and outflow due to dispersion, advection, sink/source, and chemical reactions.

Local equilibrium is often assumed for the various sorption processes (i.e., sorption is sufficiently fast relative to the transport time scale). When the local equilibrium assumption is invoked, it is customary to express equation 5 in the following form:

$$R\theta\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(\theta v_i C)+q_s C_s-q'_s C-\lambda_1\theta C-\lambda_2\rho_b\overline{C} \quad (6)$$

where: R is referred to as the retardation factor, which is a dimensionless factor defined as:

$$R=1+\frac{\rho_b}{\theta}\frac{\partial\overline{C}}{\partial C} \quad (7)$$

when the local equilibrium assumption is not appropriate, sorption processes are typically represented through a first-order kinetic mass transfer equation, as discussed in the section on chemical reactions.

Data

Input data for the GSM include:

- Hydrometeorological data: meteorological and hydrographic data up to 2014 from the project "Technical consultancy on the hydrological/hydraulic model of the Rao Cai river basin and the drainage model in the city of Ha Tinh, Ha Tinh province" were also part of the project "Integrated water resource management and urban development in Ha Tinh province", conducted by the Vietnam Academy for Water Resources [3]. Additional data up to 2016 were collected from the Hydrometeorological Data Centre of the National Center of Meteorology and Hydrology (now the Meteorological and Hydrological Administration).

- Land-use data: land-use status data for Ha Tinh from 2015 were collected from Center for Land Assessment under Center for Land Survey and Planning under General Department of Land Administration.

- Stratigraphic data: the 2014 1:200,000-scale hydro-geological map of Ha Tinh province was sourced from the National Center for Water Resource Planning and Investigation.

- The stratigraphic data on hydro-geological boreholes were inherited from the project "Planning, exploitation, utilization, and protection of water resources in Ha Tinh province up to 2020", conducted by the 2F Division for Water Resources Planning and Investigation of the Ministry of Natural Resources and Environment in 2011 [4].

- Survey data: survey data were collected by means of interviews with local people using pre-designed table templates, and by means of direct water sampling. The scope and subjects of the survey were the current status of water use in 330 households and 20 organisations in 10 coastal districts/cities/towns of Ha Tinh province.

- Climate-change scenarios: climate-change in Ha Tinh province was examined in terms of two scenarios, RCP4.5 and RCP8.5, for temperature (Table 1), precipitation (Table 2) and sea level rise (Table 3) extraction from climate change and sea-level rise scenarios for Vietnam, which were updated by Ministry of Natural Resources and Environment in 2016 [5].

Table 1. Changes in temperature (^{o}C) compared to the period 1986-2005 in terms of different climate change scenarios in Ha Tinh province.

Temperature	RCP4.5			RCP8.5		
	2016-2035	*2046-2065*	*2080-2099*	*2016-2035*	*2046-2065*	*2080-2099*
Annual	0.6 (0.3÷1.0)	1.5 (1.0÷2.1)	2.0 (1.4÷2.9)	0.9 (0.6÷1.3)	1.9 (1.3÷2.8)	3.5 (2.8÷4.8)
Winter	0.6 (0.3÷1.0)	1.3 (0.7÷1.8)	1.6 (1.0÷2.1)	0.9 (0.6÷1.2)	1.7 (1.2÷2.4)	2.8 (2.0÷3.7)
Spring	0.6 (0.1÷1.2)	1.3 (0.7÷1.9)	2.0 (1.2÷2.9)	0.9 (0.5÷1.3)	1.8 (0.9÷2.8)	3.2 (2.0÷4.5)
Summer	0.8 (0.4÷1.3)	1.9 (1.2÷3.0)	2.6 (1.8÷3.6)	1.0 (0.5÷1.5)	2.3 (1.4÷3.6)	4.1 (3.2÷5.7)
Autumn	0.6 (0.3÷1.1)	1.5 (1.0÷2.2)	2.0 (1.2÷2.9)	0.8 (0.4÷1.4)	2.0 (1.3÷3.0)	3.6 (2.7÷5.0)

Source: Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN).

Table 2. Changes in rainfall (%) relative to the period 1986-2005 in terms of climate change scenarios in Ha Tinh province.

Rainfall	RCP4.5			RCP8.5		
	2016-2035	*2046-2065*	*2080-2099*	*2016-2035*	*2046-2065*	*2080-2099*
Annual	11.3 (6.0÷16.6)	16.3 (8.5÷24.4)	13.0 (3.4÷22.6)	12.9 (6.8÷18.9)	14.1 (8.9÷19.0)	17.4 (10.6÷24.4)
Winter	12.0 (4.1÷19.5)	21.0 (11.4÷30.4)	12.8 (5.4÷20.0)	3.5 (-2.1÷9.2)	13.0 (1.6÷24.4)	19.8 (6.5÷33.2)
Spring	2.8 (-3.7÷9.2)	14.5 (4.3÷23.9)	9.4 (-1.8÷20.5)	-4.2 (-14.4÷5.8)	5.0 (-3.5÷13.0)	16.1 (2.1÷30.5)
Summer	21.1 (-3.7÷44.7)	9.1 (-2.1÷20.3)	4.8 (-5.7÷16.1)	40.6 (5.0÷70.7)	18.6 (-6.5÷43.4)	22.2 (3.0÷41.8)
Autumn	9.9 (3.8÷16.1)	19.0 (5.2÷31.6)	17.6 (3.8÷30.3)	8.2 (-0.1÷15.8)	15.1 (6.6÷23.4)	17.6 (8.2÷27.0)

Source: IMHEN.

Table 3. Sea-level rise scenarios for the coastal areas of Ha Tinh province (cm).

Scenarios	Timeline of the 21st century							
	2030	*2040*	*2050*	*2060*	*2070*	*2080*	*2090*	*2100*
RCP4.5	13 (8÷18)	17 (10÷24)	22 (13÷31)	27 (16÷39)	33 (20÷47)	39 (24÷56)	46 (28÷65)	53 (32÷75)
RCP8.5	13 (9÷18)	18 (12÷26)	25 (17÷35)	32 (22÷45)	40 (28÷57)	50 (34÷71)	60 (41÷85)	72 (49÷102)

Source: IMHEN.

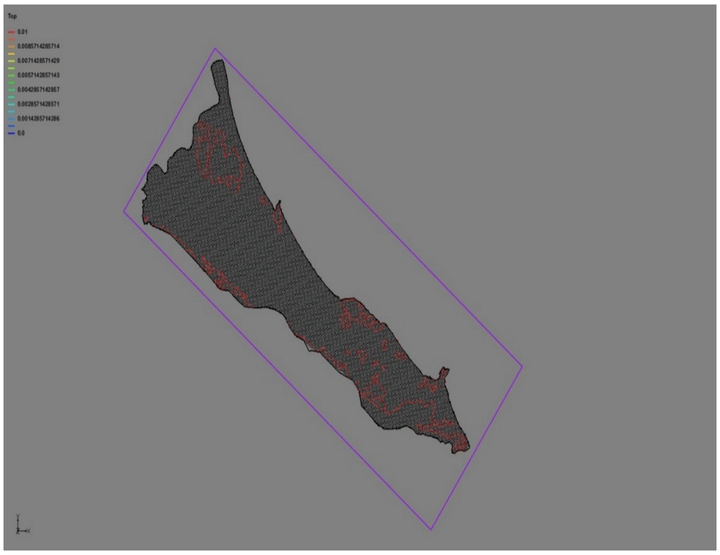

Fig. 1. Computational domain and computational grid of the research area.

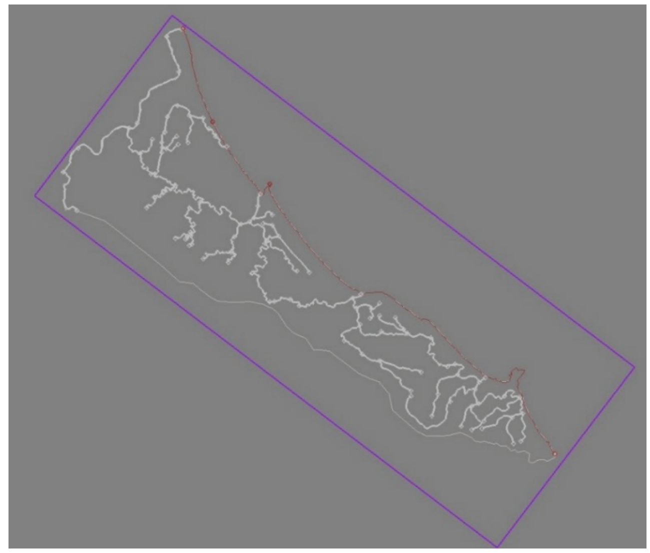

Fig. 2. Sea and river boundaries in the research area.

Results and discussion

The GSM model constructed for the coastal area of Ha Tinh province

- The computational domain includes the coastal districts of Nghi Xuan, Duc Tho, Can Loc, Loc Ha, Thach Ha, Cam Xuyen, and Ky Anh; the city of Ha Tinh; and the towns of Ky Anh, Hong Linh (Fig. 1).

- The computational grid includes 563,060 grid points, including 294,865 computational points. Grid cell size is 200 m x 200 m.

- Boundary conditions:

+ The sea boundary is approximately 143 km, from the Lam river mouth to the end of Ky Anh town, next to Quang Binh province.

+ The river boundary comprises four major rivers, the Lam, Ha, Lui, Quyen, and their major branches (Fig. 2).

+ The groundwater restoration boundary was calculated by subtracting the evaporation boundary from the precipitation boundary in the corresponding exposure area of geological layers in the research area (Fig. 3 and Table 4).

Table 4. Classification of the groundwater restoration area in the coastal area of Ha Tinh province.

No.	Restoration area	Restoration rate from rainfall (%)
1	*Holocene*	35
2	*Pleistocene*	35
3	*Neogen, Triat, Ordovic-Silur*	15

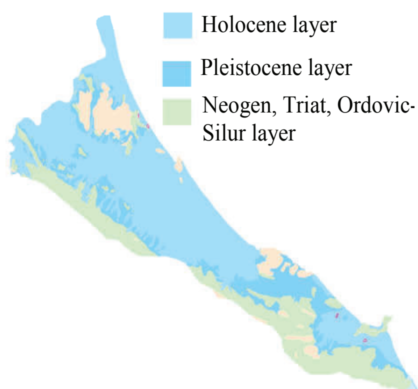

Fig. 3. Exposure area of geological layers in the research area.

- A 3-year period was used to warm up the model to reduce the effect of initial conditions.

- Computational time step: daily.

Calibration and validation

For model calibration, this research employs monitoring data from January 2014 to December 2016 from four groundwater level stations within research area (Table 5).

Table 5. Differences between the simulated water level and the water level measured at groundwater level monitoring wells in the research area.

No.	Station	Mean absolute difference	Root mean square deviation	Maximum difference (m)
1	QT2a-HT_0	0.05	0.004	0.15
2	QT5a-HT_0	0.13	0.023	0.32
3	QT6-HT_0	0.18	0.057	0.91
4	QT6b-HT_0	0.13	0.039	0.81

The results of the model calibration and validation show that the model parameters are reliable and can be applied to research on groundwater in the coastal area of Ha Tinh.

Salt-water reserve in terms of the climate change scenarios

The results of calculating the salt-water storage in the Holocene and Pleistocene layers in 2020 and 2030 in terms of scenarios RCP4.5 and RCP8.5 compared to the current situation (the average of the period 1986-2005) in the coastal area of Ha Tinh province are shown in Figs. 4A , 4B.

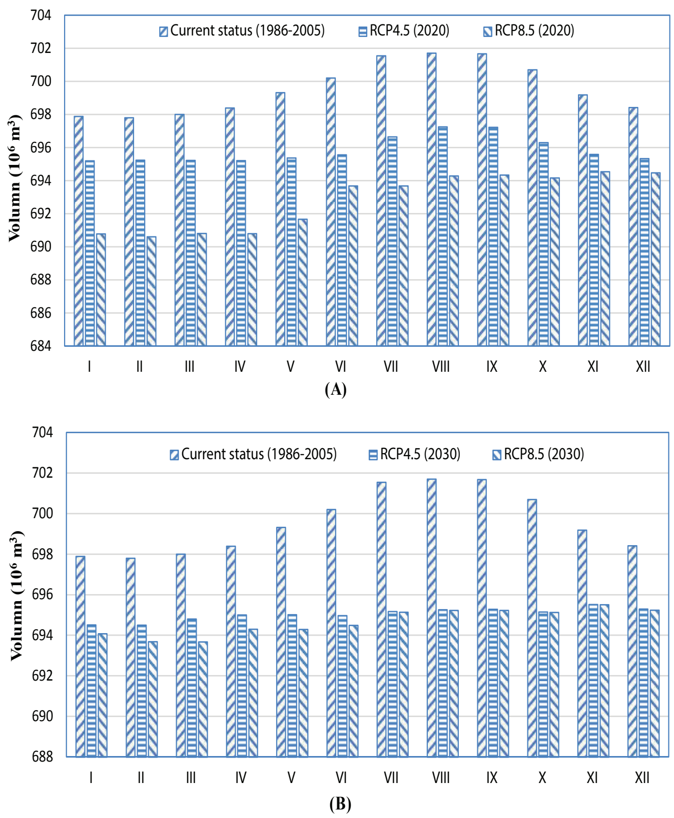

Fig. 4. Salt-water storage diagrams in the Holocene and Pleistocene layers in 2020 (A) and 2030 (B) in the research area according to scenarios RCP4.5 and RCP8.5.

The results in Fig. 4 show that groundwater salinity in the research area in 2020 in terms of scenarios RCP4.5 and RCP8.5 tends to decrease compared with the current situation. By 2020, the level of salinity intrusion tends to decrease in all months of the year in both the RCP4.5 and RCP8.5 scenarios. For both scenarios, the largest decrease occurs in July, and the smallest in January for RCP4.5, and in December for RCP8.5. This phenomenon occurs due to the hypothesis of the problem claims that the amount of groundwater extraction remains unchanged relative to the current situation; this change may primarily be due to the change of rainfall and a sea level rise of 0.09 m. By 2030, in terms of scenarios RCP4.5 and RCP8.5, the storage tends to decrease relative to the current situation. In that year, the level of salinity intrusion tends to decrease in all the months of the year in terms of both RCP4.5 and RCP8.5 scenarios, with the largest decrease occurring in August. This change is primarily due to a change in rainfall by 2030, which is quite similar for both RCP4.5 and RCP8.5 scenarios and the scenario of a 0.13 m rise in sea level.

The magnitude of saline intrusion in 2020 and 2030 is less than that of the (current) baseline period due to a significant increase in rainfall in these years.

The results of calculating salt-water storage in the Holocene and Pleistocene layers for the periods 2016-2035, 2046-2065, and 2080-2099 in terms of the RCP4.5 and RCP8.5 scenarios compared to the current situation in the coastal area of Ha Tinh province are shown in Figs. 5A, 5B.

Figure 5 shows the trends of salinity intrusion into groundwater in the research area, which are very complex. With scenario RCP4.5, in the early years of the 21st century (2016-2035) the level of salinity intrusion tends to decrease;

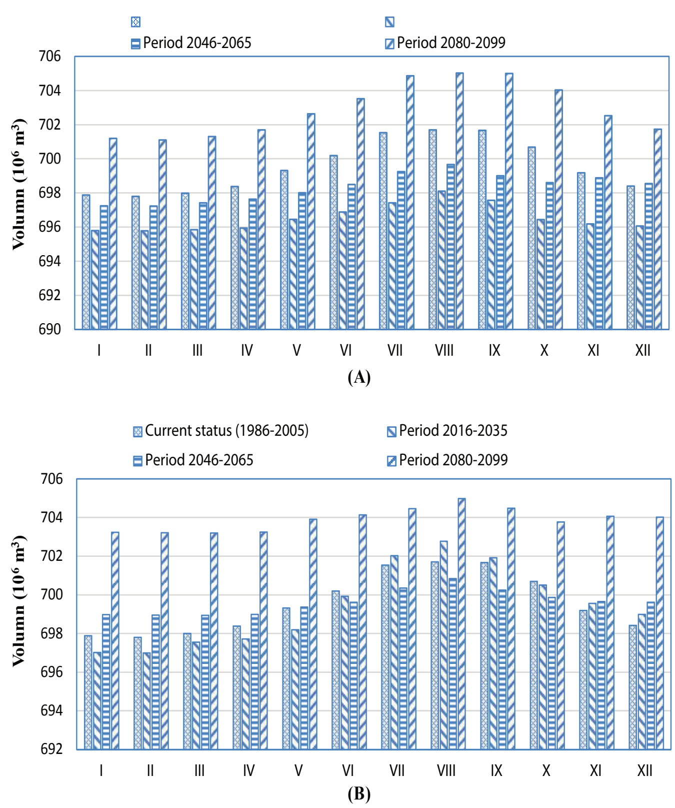

Fig. 5. Saltwater storage charts in the Holocene and Pleistocene layers of the research area for the periods 2016-2035, 2046-2065, and 2080-2099 in terms of scenarios RCP4.5 (A) and RCP8.5 (B).

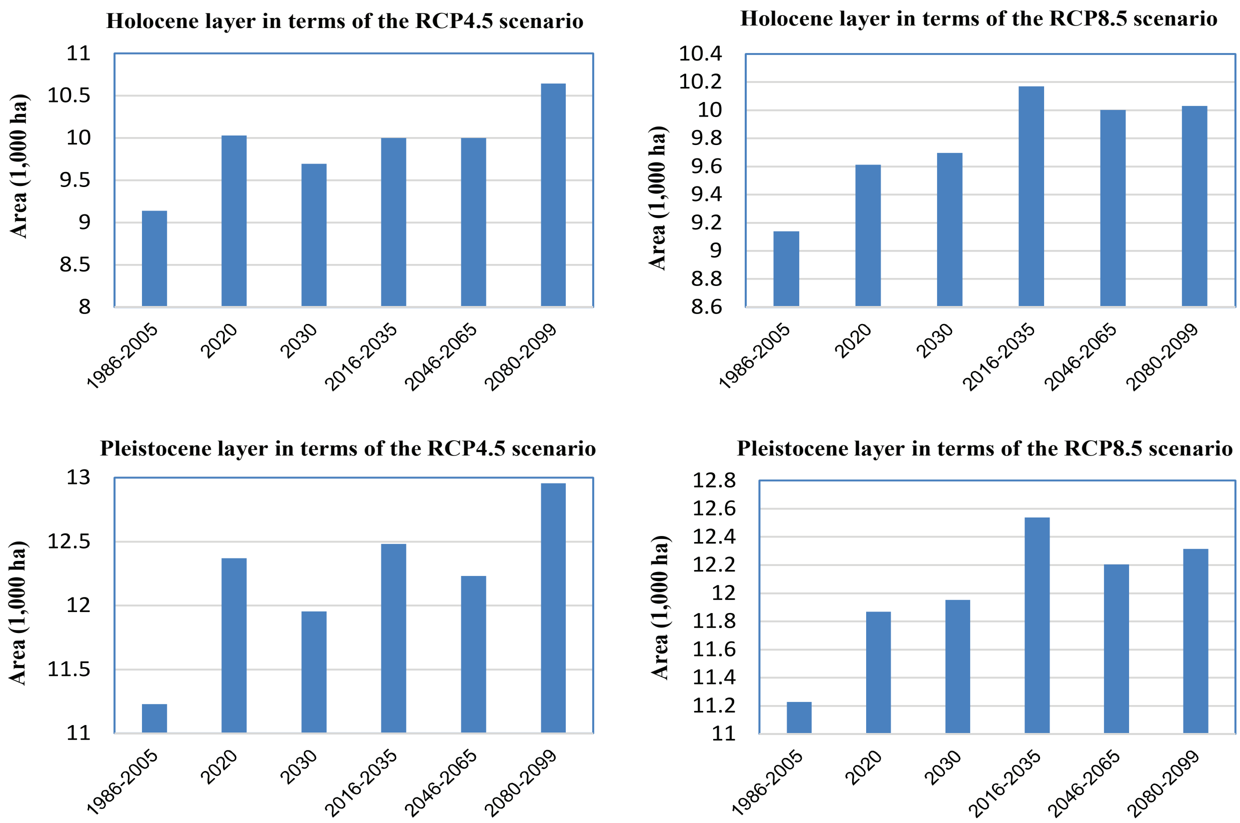

Fig. 6. Surface area of groundwater salinisation in terms of the climate change scenarios in the coastal area of Ha Tinh province.

then it increases gradually at the end of the century (2080-2099). With scenario RCP8.5, in the early years of the 21st century (2016-2035) groundwater salinity intrusion increases in July, August, September, November, and December compared to the current situation, and decreases in the remaining months. However, in the last years of the 21st century (2080-2099), saline intrusion into groundwater tends to increase sharply in comparison with that of all months of the year.

Area of salinity intrusion in terms of the climate change scenarios

As shown in Fig. 6, by 2020 and 2030, salinity will intrude into both the Holocene and Pleistocene layers in terms of both climate change scenarios, RCP4.5 and RCP8.5; however, in the 1986-2005 baseline period, intrusion only occurred near the river banks and rivermouth area.

The results in Fig. 6 show that, in terms of all climate change scenarios considered, the area of saline groundwater in both the Pleistocene and Holocene layers slightly varies from month to month during the year. The changing trends in the area of saline groundwater intrusion in the Holocene and Pleistocene layers are similar in each climate change scenario. In terms of the RCP4.5 scenario, the area of saline groundwater is lower than the current one in the early and mid-21st century and is higher at the end of the century. In terms of the RCP8.5 scenario, the area of saline groundwater does not change substantially relative to the status in the early and mid-21st century, and increases at the end of the century.

As shown in Fig. 7, the area of salt-water intrusion in the Holocene layer is primarily in Ky Anh town and Nghi Xuan, Thach Ha, and Cam Xuyen districts, with area itself ranging from 1,500 ha to over 2,000 ha; while in the coastal districts, the area of saline intrusion into the groundwater ranges from 300 ha to over 600 ha. In the Pleistocene layer, the largest areas of saltwater intrusion are in Ky Anh district and Ky Anh town with over 2,000 ha. Nghi Xuan and Cam Xuyen districts experience 1,900 ha of intrusion and Thach Ha district approximately 1,500 ha. In the remaining districts, the area of saltwater intrusion is approximately equal to that which occurs in the Holocene layer. This trend of changes in the area of saline intrusion into groundwater is similar to that in the other areas in coastal Ha Tinh.

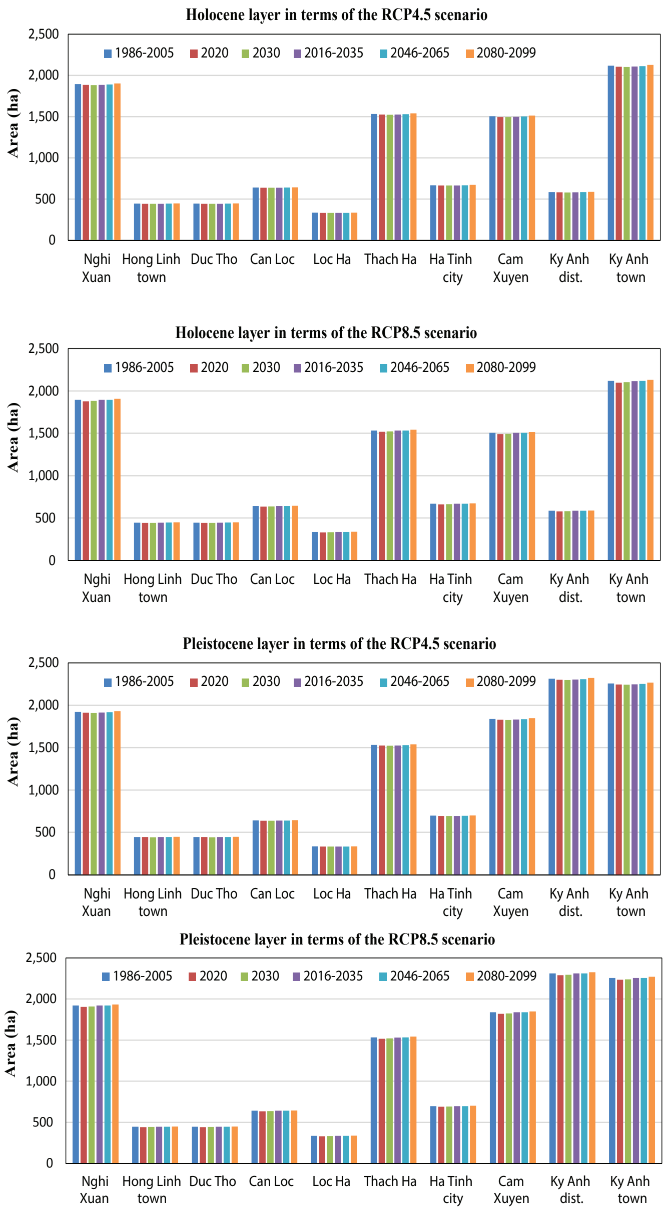

Fig. 7. Surface area of groundwater salinisation in terms of the climate change scenarios in the coastal districts of Ha Tinh province.

Conclusions

Saline water intrusion tends to decrease in terms of the two climate change scenarios considered - RCP4.5 and RCP8.5 - by 2020 and 2030: salt-water storage will decrease by 0.53 to 0.96% and by 0.65 to 0.70% by 2020 and 2030, respectively.

In terms of both RCP4.5 and RCP8.5 scenarios, the average for the future periods 2016-2035, 2046-2065, and 2080-2099 shows that the development of groundwater salinity in the research area is quite complex. In the early and mid-century, the level of saline intrusion tends to decrease slightly, and thereafter it increases gradually at the end of the century.

According to the climate change scenarios, at the beginning of the century, rainfall in Ha Tinh increased and so did the reserve of underground water in the province; at the end of the century, the sea level in Ha Tinh will rise (by 68 cm), saline intrusion into groundwater will increase, and groundwater saline storage will tend to decrease slightly relative to the beginning of the century.

These results are calculated based on the averages for periods of heavy and light rainfall, so the trend of an increase in levels of salinity in groundwater is not clear. In fact, salt-water intrusion frequently occurs during the years of light rainfall, especially in the months of the dry season. It is therefore necessary to undertake a more detailed examination for each year, especially those of lighter rainfall in order to obtain a more specific assessment of the impact of climate change on groundwater. The results of this study provide the premise and basis for further research.

ACKNOWLEDGEMENTS

The research was supported by the project "Consultant to study the impact of climate change on underground water resources in Ha Tinh province and propose a sustainable management solution".

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] 2F Division for Water Resources Planning and Investigation (2011), *Project "Planning, Exploiting, Utilizing and Protecting Water Resources in Ha Tinh Province up to 2020"*.

[2] Arlen W. Harbaugh (2005), *MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model - the Ground-WaterFlow Process*, Chapter 16 of Book 6, Modeling techniques, Section A, Ground Water, U.S. Department of the Interior and U.S. Geological Survey, Reston, Virginia.

[3] Chunmiao Zheng, P. Patrick Wang (1999), *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems, Documentation and User's Guide*, Department of Geological Sciences, University of Alabama, Tuscaloosa.

[4] Ministry of Natural Resources and Environment (2016), *Scenarios for climate change and sea level rise for Vietnam.*

[5] Vietnam Academy for Water Resources (2016), *Project "Technical consultancy on hydrological/hydraulic model of Rao Cai river basin and drainage model in the Ha Tinh city, Ha Tinh Province".*