

Effect of Climate Change on the Salinity Intrusion: Case Study Ca River Basin, Vietnam

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Abstract: Climate change and global warming are expected to have significant effects on water resources planning and management, especially in estuary areas. One-dimensional model was established and applied to the Ca River Basin. The model was calibrated and validated with available hydrographical measured data in 1996, 1997, 1999 and 2000. The results of calibration and validation water level showed a high conformity about phase and water amplitude between calculated and observed data. The effect of global warming on salinity intrusion in estuarine areas was simulated in this study. The results of current state scenario (2010) and climate change scenario in 2030, 2050 and 2100 showed an overall effect of salinity intrusion process on precipitation and sea level rise. The distance of salinity intrusion in the river is increasing and this could be detrimental to the economic development, especially for the agriculture sector. The rise in sea level due to global warming will not significantly affect the situation of salinity intrusion for Ca River in 2030. However, comparing the results of scenario (2100) and the current state scenario (2010), the impact on salinity intrusion process in the Lam-Ca River system is found to be significant.

Keywords: Hydrodynamic; Advection-dispersion; Salinity intrusion; Climate change; Ca River.

Introduction

Climate change is a serious threat to countries with high population density and economic activity in estuary regions. Studying the effects of global warming and climate change requires multi-disciplinary research, especially when considering hydrology and global water resources (Eckhardt and Ulbrich, 2003; Gerten et al., 2004; Hitz and Smith, 2004; Labat et al., 2004; Dasgupta and Meisner, 2009; Doan et al., 2015). The potential impacts of climate change on estuary and coastal areas include progressive inundation from sea level rise, heightened storm damage, loss of wetlands, and increased salinity from saltwater intrusion. Most of the research has focussed on the long-run effects of

inundation as the sea level rises, along with associated losses from heightened storm surge (Ali, 2003; Agarwala et al., 2003; Nicholls, 2003, 2006; Kabir et al., 2006; Dasgupta et al., 2009; Dasgupta et al., 2010; Hanson et al., 2011). Saltwater intrusion into freshwater coastal rivers and aquifers has been, and continues to be, one of the most important global challenges for coastal water-resources managers, industries, and agriculture (Bear et al., 1999; Doan et al., 2014). The implication of climate change for saltwater intrusion and its impact on livelihoods and adaptation alternatives have not been investigated in great detail (World Bank, 2009). The problem of saltwater intrusion is expected to become more severe in low-lying coastal areas throughout the world, with increased sea level caused by climate

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change (Bates et al., 2008; Akhter, 2012). Hence, the understanding of socio-economic impacts of salinity ingress and adaptation alternatives is key requirement for long-term development and they are objectives of our on-going research.

Assessment of water resources is an important task in water resources planning and management. Most of the times, hydrologic models with effective tools can do the task. The characteristics of flow and salinity intrusion such as the discharge distribution among the river branches and the isohalines for certain water salinities are then derived from the simulated results and observed data. The variation in upstream inflow affects the downstream flow and the salinity intrusion. Due to these reasons, the hydrodynamic and advection-dispersion models are required and applied in the studies on flow and salinity intrusion in the Ca River Basin (Vu, 2009).

In order to assess the water resources in the Ca River Basin by mathematical modelling, the hydrodynamic and advection-dispersion modules should be applied whenever there are any changes in boundary conditions. The model functions consist of tidal elevations along the downstream boundaries and freshwater discharges from the upstream boundaries of the Ca River with observed

data in 1996, 1997, 1999 and 2000. Hydrodynamic (HD) and advection-dispersion (AD) modules were used for this study. The objective is to simulate the hydrodynamic regime in the river flow and salinity intrusion at specific locations in the network system for water management purpose under hydrologic conditions of upstream inflow and tides in river estuaries.

Material and Methods

Description of Study Site

The Ca River system is one of the nine biggest river systems with coordinates latitude ($18^{\circ} 33' 10'' \text{ N} - 20^{\circ} 01' 43'' \text{ N}$) and longitude ($103^{\circ} 52' 53'' \text{ E} - 105^{\circ} 48' 50'' \text{ E}$) that connects the north to the south in Vietnam (Figure 1). The main river is originated from Lao, flowing through Nghe An province territory, called Ca River. The river flows to Nam Dan and joins with the Lam River (originated from Ha Tinh) at Cho Trang and flows to the sea. The section from Cho Trang to the sea is called the Lam River. The Ca River system basin is located in both countries of Lao and Vietnam, in which, upstream area is in Phong Sa Van and Sam Nua Lao provinces. In Vietnam, the basin is located in three provinces of Thanh Hoa, Nghe An and Ha Tinh (Figure 1).

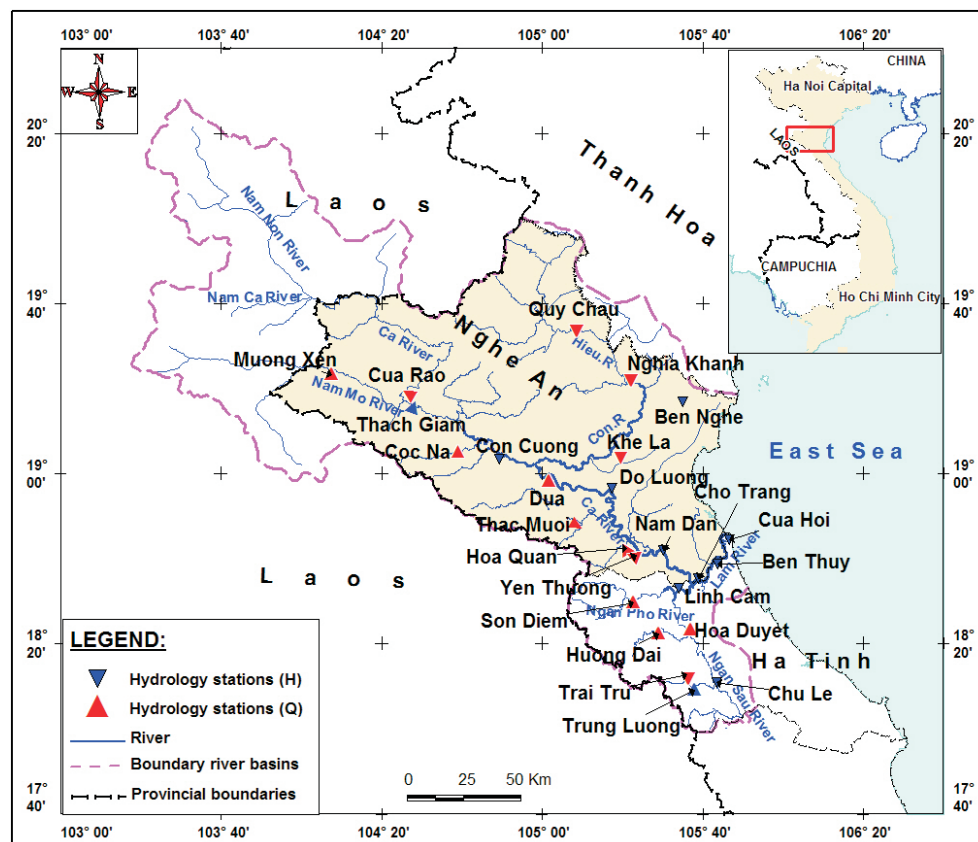


Figure 1: Location of study area.

Model

Model Description

Many models have been developed to study saltwater intrusion. In respect of water quality modelling, one-dimensional MIKE 11 model provides an advection-dispersion module which is based on the one-dimensional equation of conservation of mass of dissolved or suspended material (Doan et al., 2013). One-dimensional equations governing the river flow are known as Saint-Venant equations (Shooshtari, 2008). These are expressed as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \quad (2)$$

where Q is discharge, A is the cross-sectional area, q is lateral inflow, C is Chezy roughness coefficient, R is hydraulic radius and α is momentum correction coefficient.

Based on differential equations and finite difference method, the flow depth (h -points) and the flow discharge (Q -points) at nodes are calculated (Figure 2).

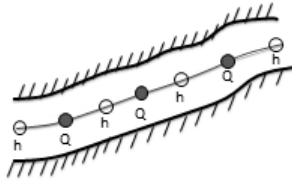


Figure 2: Schematic nodding of h -points and Q -points for a river section MIKE 11 model.

The advection–dispersion equation in one-dimensional model is as follows. This equation considers two transport mechanisms of advective and dispersive transports.

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} + \frac{\partial}{\partial x} \left(AD \frac{\partial C}{\partial x} \right) = -AKC + C_2q \quad (3)$$

where C is the concentration, D is the dispersion coefficient, A is the cross-sectional area, K is the linear decay coefficient, C_2 is the source/sink concentration, q is the lateral inflow discharge, x is the space coordinate and t is the time coordinate.

The solution of the equations of continuity and momentum is based on an implicit finite difference scheme developed by Abbott and Ionescu (1967). The

finite difference scheme used in one-dimensional model (6-point Abbott scheme) allows Courant numbers up to 10-20 if the flow is clearly sub-critical (Froude number less than 1). A graphical view of this method is shown in Figure 3). As we can see at $n+1/2$ step, the model brings data from steps n and $n+1$, so unknowns will obtain simultaneously for each time step. The model used implicit difference method to solve the problem and there is no limitation about computational ability (Price, 2009).

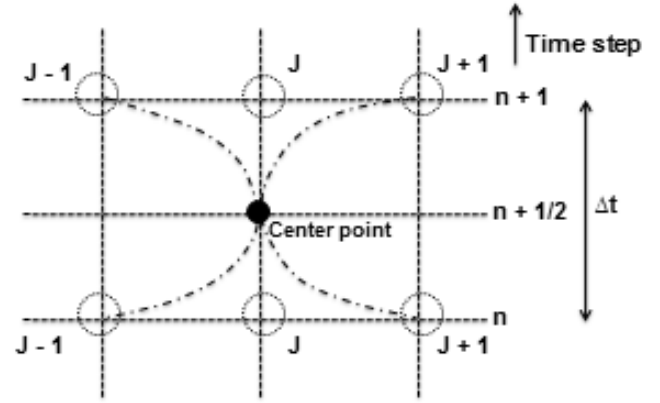


Figure 3: Centered six-point Abbott scheme.

The evaluation of simulated results was based on the Nash Sutcliffe Index (NSI) criterion, or so-called coefficient of model efficiency, which is expressed in Equation (4) below.

$$NSI = 1 - \frac{\sum (Q_{obs} - Q_{cal})^2}{\sum (Q_{obs} - \bar{Q}_{obs})^2} \quad (4)$$

where Q_{obs} is observed stream flows/stage; $\bar{Q}_{obs}$ is observed mean stream flow/stage and Q_{cal} is calculated stream flow/stage.

Materials Model

In this study, a one-dimensional hydrodynamic model has been established for Ca River system and simulated saltwater intrusion process. Simulation salinity intrusion process was presented according to four steps (Figure 4).

The river network system is schematized in Figure 5. The topographical data were observed and processed in 2007 under a project on water resources development in Ca River Basin. Cross-section survey data with (x, z) coordinate is entered into table cross-section in the model to locate corresponding cross-section on the river. There are totally 135 cross-sections on the river system as follows: Ca River, Giang River, Ngan Pho River, Ngan Sau River and Lam River.

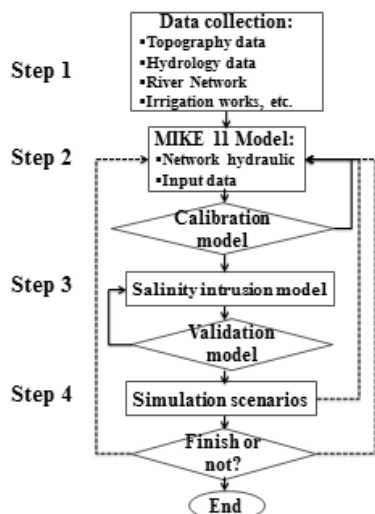


Figure 4: Calculation procedures of the simulation.

Upper boundary is the river discharge in the dry season at Dua, Thac Muoi, Son Diem and Hoa Duyet hydrology station. Lower boundary is the water level process in the dry season at Cua Hoi hydrological station. Observed data at Do Luong, Yen Thuong, Nam Dan and Linh Cam were used to calibrate and validate the model. The data in the dry season from December, 1996 to April, 1997 were used to calibrate the hydrodynamic model. The data in the dry season from December, 1999 to May, 2000 were used to validate the hydrodynamic model.

Observed salinity data at Ben Thuy and Trung Luong in the dry season from December, 1999 to May, 2000 were used to calculate and simulate salinity intrusion process in the Ca River estuary.

Results and Discussions

Calibration of the Hydrodynamic Model

The calibration model used observed water level processed at four hydrology stations on the system to compare with the computed results in the driest period of December 21, 1996 to April 20, 1997 (Figure 6). The calculated results showed a high conformity with the Nash-Sutcliffe Index (Nash and Sutcliffe, 1970) criterion from 0.75 to 0.87 for the phase and water amplitude between the calculated and observed water level data. A suitable hydrodynamic model was obtained. These characteristics of the model enable it to be employed as a validation model for the salinity intrusion process.

Validation of the Hydrodynamic Model

The validation model used water level data from four hydrology stations such as Nam Dan, Linh Cam, Do

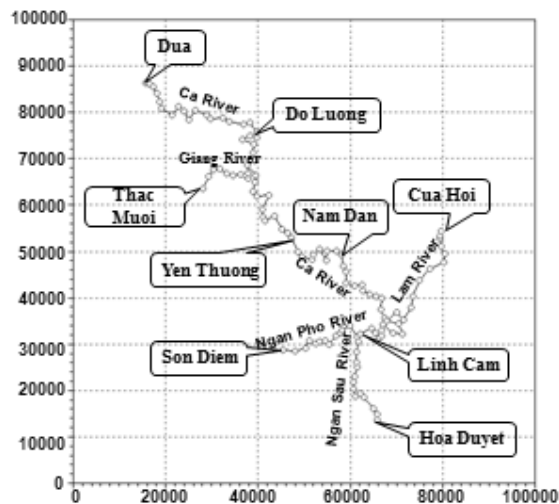


Figure 5: Hydraulic scheme formulated in MIKE 11.

Luong and Yen Thuong in the driest period of December 16, 1999 to May 14, 2000. The results revealed that the calculated and observed water levels have a high conformity with the Nash-Sutcliffe Index (NSI) criterion from 0.76 to 0.89 for the phase and water amplitude (Figure 7). The results of the validation and calibration model showed that the hydrodynamic process in this study site was adequately simulated. The model can be used to simulate the salinity intrusion process.

Salinity Intrusion Model

The results of salinity intrusion used the observed salinity concentration data from the period of December 16, 1999 to May 14, 2000. The simulated results of salinity concentration are presented at two stations Ben Thuy and Trung Luong (Figure 8). The results showed that there is a good agreement between simulated and observed salinity concentration. The residual between observed and simulated results arrange with NSI criterion from 0.92 to 0.94. It means that MIKE 11 can be used to calculate and predict the salinity intrusion process in the future. The results of salinity intrusion process in current state scenario used the data in 2010 to simulate the scenarios. The processes of salinity intrusion in each river are presented in Figure 9.

Limnologists and chemists often define salinity in terms of mass of salt per unit volume, expressed in units of mg per litre (Wetzel, 2003). Direct density measurements are also used to estimate salinities, particularly in high saline rivers or lakes (Anati, 1999). Sometimes density at a specific temperature is used as a proxy for salinity. At other times, an empirical salinity/density relationship developed for a particular body of water is used to estimate the salinity of samples from

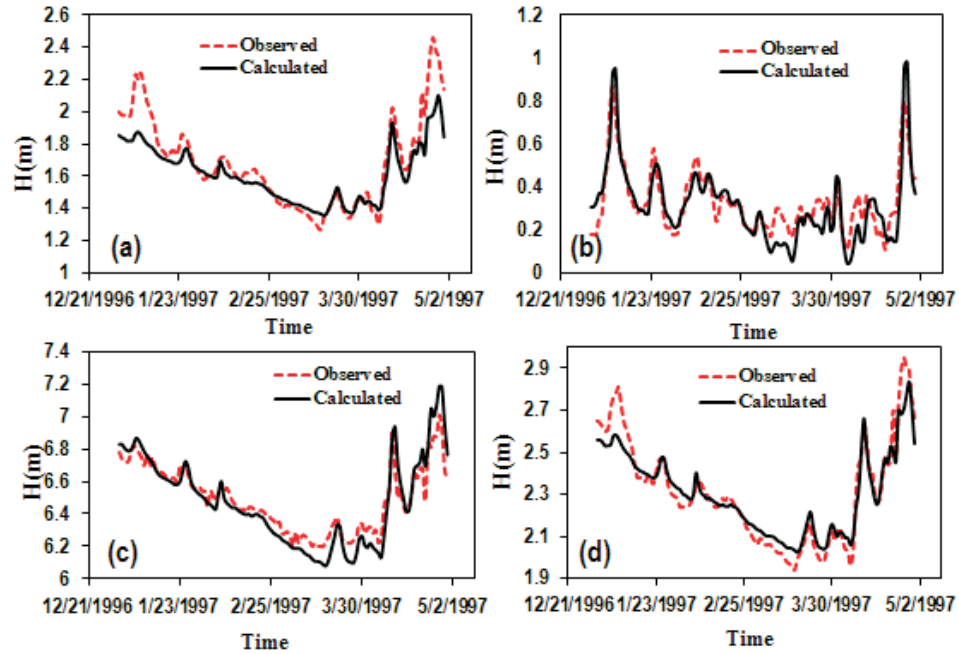


Figure 6: Calculated and observed water level for the calibrated period of December 21, 1996 to April 20, 1997 at Nam Dan with $NSI = 0.84$ (a), Linh Cam with $NSI = 0.86$ (b), Do Luong with $NSI = 0.75$ (c) and Yen Thuong with $NSI = 0.87$ (d).

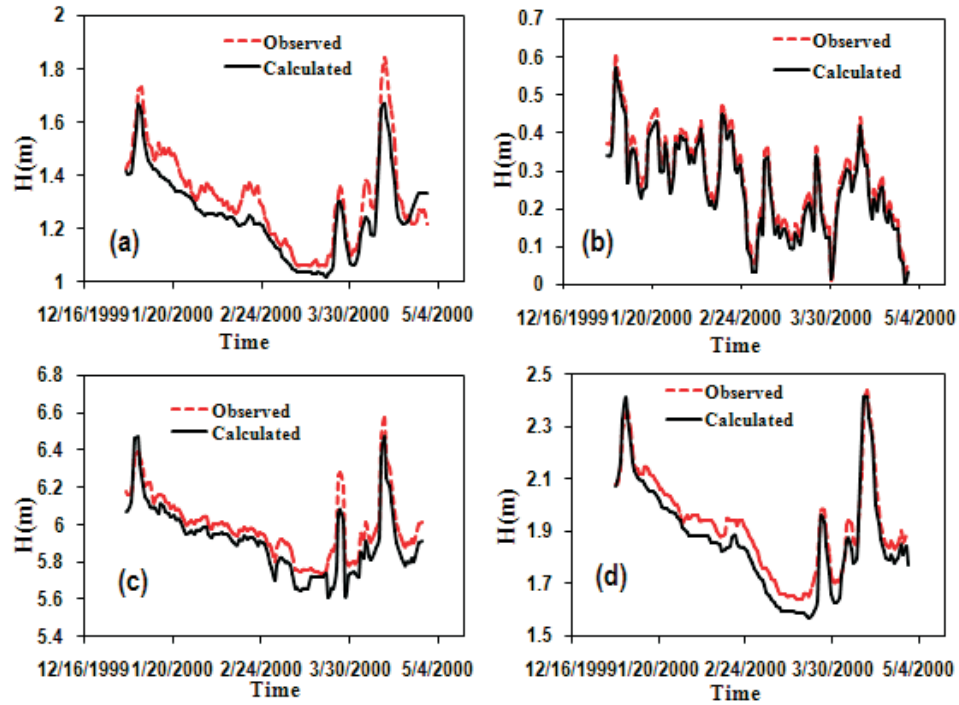


Figure 7: Calculated and observed water level for the validated period of December 16, 1999 to May 14, 2000 at Nam Dan with $NSI = 0.82$ (a), Linh Cam with $NSI = 0.89$ (b), Do Luong with $NSI = 0.76$ (c) and Yen Thuong with $NSI = 0.85$ (d).

a measured density. The classification of water salinity is presented in Table 1.

Table 2 is modified from Por (1972); it follows the Venice system (1959). In contrast to homoiohaline

environments are certain poikilohaline environments, in which the salinity variation is biologically significant (Dahl, 1956). Poikilohaline water salinities may range anywhere from 0.5 to greater than 300.

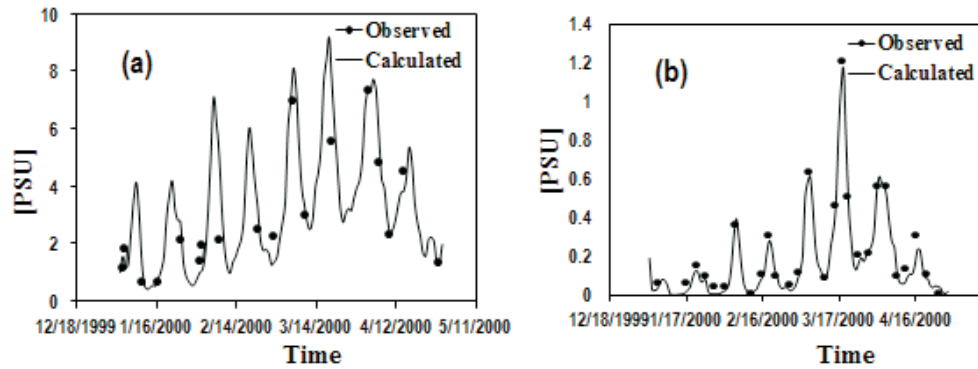


Figure 8: Calculated and observed salinity concentration from December 16, 1999 to May 14, 2000: (a) Ben Thuy with NSI = 0.92; and (b) Trung Luong with NSI = 0.94.

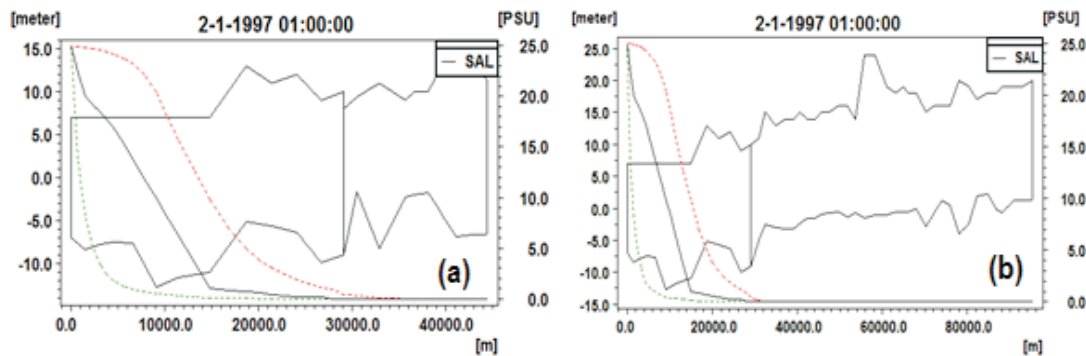


Figure 9: Boundary salinity intrusion: (a) Cua Hoi to the Lam River; and (b) Cua Hoi to the Ca River.

Table 1: Classification of water salinity

Classification	Salinity [PSU]
Fresh water	< 0.5
Brackish water	0.5 - 30
Saline water	30 - 50
Brine	>50

Table 2: The water salinity variation

Classification	Salinity [PSU]
Oligohaline	0.5
Mesohaline	5
Polyhaline	18
Mixoeuhaline	30
Metahaline	40
Hyperhaline	60-80
Thalassic series	>300

Based on the classification of water salinity (Tables 1 and 2) and the results of current state scenario, salinity intrusion process is shown as follows:

On the Lam River, the salinity wedge spreads around 7.5 km from the intersection at Cho Trang hydrology station along upstream. However, the biggest salinity value observed at the intersection is about 0.45 PSU. According to the classification of water salinity in the river, the water in Lam River is fresh water. It means that the calculated results for the present condition scenario in the La River are not affected by salinity intrusion process (Figure 9a).

On the Ca River, the salinity wedge spreads around 34 km from Cua Hoi along the river to upstream of Lam-Ca River. However, the water salinity value is smaller than 0.5 PSU intrusions up to 30.5 km from Cua Hoi. According to the classification of water salinity, the fresh water zone is 30.5 km from the mouth of Cua Hoi. Brackish water starts from 11.5 km to 30.5 km from Cua Hoi to upstream (Figure 9b).

It can be seen that the simulation of present condition does not consider the elements of climate change; saltwater intrusion process affects are quite deep on the Lam-Ca River.

Simulation Salinity Intrusion Process on Account of Climate Change

The climate change scenarios are selected from the “Climate change scenarios and sea level rise for Vietnam” (the Ministry of Natural Resources Environment, 2012). This study selected B2 scenario to simulate salinity intrusion process on account of climate change. The sea water rising scenarios for Vietnam is calculated according to an average emission scenario (B2). The calculated results of an average emission scenario in the 21st century showed that the water level could increase at Hon Dau-Deo Ngang region in 2030 from 11 to 13 cm, in 2050 from 20 to 24 cm, and in 2100 from 49 to 65 cm (Table 3).

According to an average emission scenario in the mid 21st century, spring precipitation decreased in most of the territory of country, precipitation in the Northern area is less than 2%, from Thanh Hoa to Ha Tinh precipitation decreased from 2% to 6%. The increased precipitation only occurred in a few places in the North with an increase approximately 2%. At the end of the 21st century, spring precipitation in the Northern region decreased about 4%. The precipitation decreased in majority from Thanh Hoa to Southern regional about 4% to 10%. The Highland area and a small part of Central area have decreased precipitation, specifically spring precipitation change in Nghe An province (Table 4).

With climate change scenarios selected an average emission scenario (B2); salinity intrusion process is simulated in three scenarios in 2030, 2050 and 2100. In order to simulate salinity intrusion process, we have to create upper boundaries and lower boundaries for three scenarios.

Scenario 1: Simulation of salinity intrusion process with sea water level rise and precipitation change following an average emission scenario B2 in 2030.

Scenario 2: Simulation of salinity intrusion process with sea water level rise and precipitation change following an average emission scenario B2 in 2050.

Scenario 3: Simulation of salinity intrusion process with sea water level rise and precipitation change following an average emission scenario B2 in 2100.

Boundaries Condition

Lower boundary of model uses the water level of Cua Hoi hydrology station according to the climate change scenario B2 in which the sea water level will be increased by 13 cm in 2030, 24 cm in 2050 and 65 cm in 2100.

The natural water source supply for the water using region is very important input for the calculation of water balance. This water source is affected by changes in buffer surface in the basin and the variability of climate conditions. To identify this water source, beside the measured data, the calculation of rainfall data is necessary. This study has used SWAT model with many suitable features to calculate flow simulation from rain. However, the application of SWAT model to simulate rainfall-runoff process needs a lot of data and time to calibrate and validate model. Thus, this paper has inherited the calculation results of the project “Impact assessment of climate change on water resources of Nghe An province” to simulate flowing at the hydrology station in the study area corresponding to the climate change scenario in 2030, 2050 and 2100 (Table 4).

Results Assessment of Salinity Intrusion in Different Scenarios

Scenario 1

Figure 10 showed that the salinization boundaries 1‰ were in the Cho Trang intersection about 3km; Hung Lam, Hung Chau, Duc Tung and Duc La communes start influenced salinity intrusion. The salinity concentration

Table 3: The sea level rising following the period of future scenario (B2). Unit: cm

Regional	The timeline of the 21 st century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Hon Dau-Deo Ngang	7-8	11-13	15-18	20-24	25-32	31-39	37-48	47-56	49-65

Table 4: Spring precipitation change in Nghe An province. Unit: %

Regional	The timeline of the 21 st century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Nghe An	-1.2	-1.8	-2.5	-3.2	-3.9	-4.6	-5.2	-5.7	-6.2

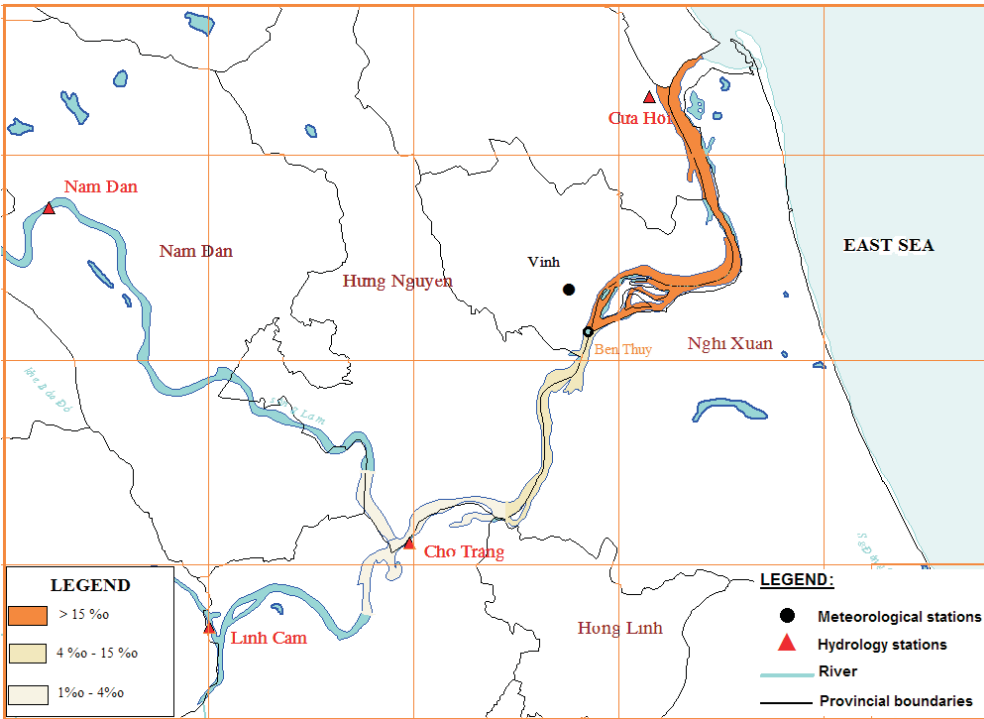


Figure 10: The boundaries salinity intrusion in 2030.

is not affected to agricultural production but is the thresholds affective to fresh water quality. Therefore, the people in these communes should have solution treatments before being put into use. Salinization boundaries 4‰ affected Hung Nhan and Trung Luong communes. This is the maximum salinity threshold that the rice can tolerate. From the simulated results, Hung Nhan commune authorities have to have solution to respond with salinity intrusion process, in order to reduce the impact of salinity to agricultural production.

This paper focused analytical results salinity intrusion with the value of 1‰ and 4‰, respectively. There are two thresholds affecting the economy and life of the people in the study area.

Scenario 2

The simulation results of salinity intrusion corresponding to the climate change scenarios and the sea water level rising in 2050 give an overview salinity intrusion within 35 years under the influence of climate change.

Table 5: Change percentage (%) the flow value between the future period time in the hydrological stations on Ca River

Station	Period	Change percentage (%)												Average year	Flood season	Dry season
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII			
Yen Thuong	2020 - 2039	0.4	0.4	0.1	-3.4	-4.1	-2.2	0.5	0.8	0.9	0.4	2.1	3.0	0.4	0.6	-0.1
	2040 - 2059	3.1	2.3	1.4	-4.4	-9.5	-7.1	2.2	4.1	1.5	1.7	1.7	2.2	1.0	1.4	-0.4
	2060 - 2079	6.7	3.2	1.8	-5.6	-17.0	-12.0	8.5	8.6	1.9	5.4	1.2	0.9	2.4	3.5	-1.4
	2080 - 2099	8.9	4.2	2.2	-7.2	-23.0	-16.7	12.8	12.6	3.2	8.1	2.1	2.0	3.8	5.4	-1.7
Hoa Duyet	2020 - 2039	-0,4	-2,0	-1,3	-4,4	-6,6	-6,3	-4,8	-0,3	0,68	1,30	1,25	1,07	-0,42	0,95	-3,79
	2040 - 2059	-0,8	-3,1	-2,6	-9,7	-12,8	-10,4	-6,4	0,3	1,42	2,02	1,76	1,81	-0,77	1,63	-6,67
	2060 - 2079	-1,1	-4,2	-3,8	-14,2	-18,5	-14,2	-8,0	0,9	2,18	2,77	2,25	2,54	-1,03	2,32	-9,29
	2080 - 2099	-1,1	-4,7	-4,4	-17,2	-22,7	-17,0	-9,1	1,7	2,91	3,48	2,80	3,35	-1,06	3,01	-11,1
Son Diem	2020 - 2039	-0,6	-2,0	-1,8	-2,5	-5,6	-5,1	-5,5	-1,9	0,17	1,06	0,92	1,11	-0,84	0,44	-3,48
	2040 - 2059	-1,0	-3,0	-2,5	-5,0	-10,6	-8,2	-7,4	-2,0	0,48	1,37	1,00	1,39	-1,42	0,65	-5,70
	2060 - 2079	-1,4	-3,8	-3,2	-7,0	-15,0	-11,0	-9,2	-2,2	0,85	1,72	1,11	1,73	-1,89	0,90	-7,67
	2080 - 2099	-1,4	-4,1	-3,6	-8,1	-18,3	-13,1	-10,5	-2,1	1,26	2,21	1,35	2,23	-2,07	1,28	-8,98

Figure 11 showed that the salinization boundaries 1‰ have entered more than 3 km compared with 2030. Salinization 1‰ affected He Hung Xuan, Nam Cuong and Bui Xa, where salinization 4‰ has entered into >4 km compared with 2030. These simulation results

will help the Nghe An provincial authorities initiative in responding to the current state of salinity intrusion.

Scenario 3

Figure 12 presents the simulation results of salinization in 2100. The results markedly have a difference about

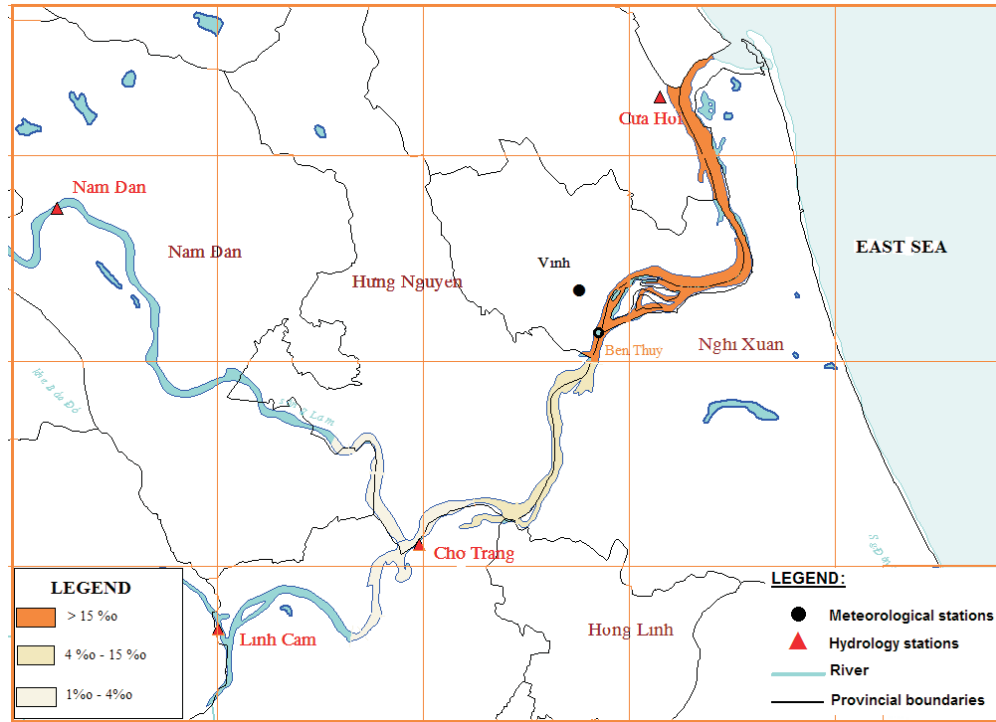


Figure 11: The boundaries salinity intrusion in 2050.

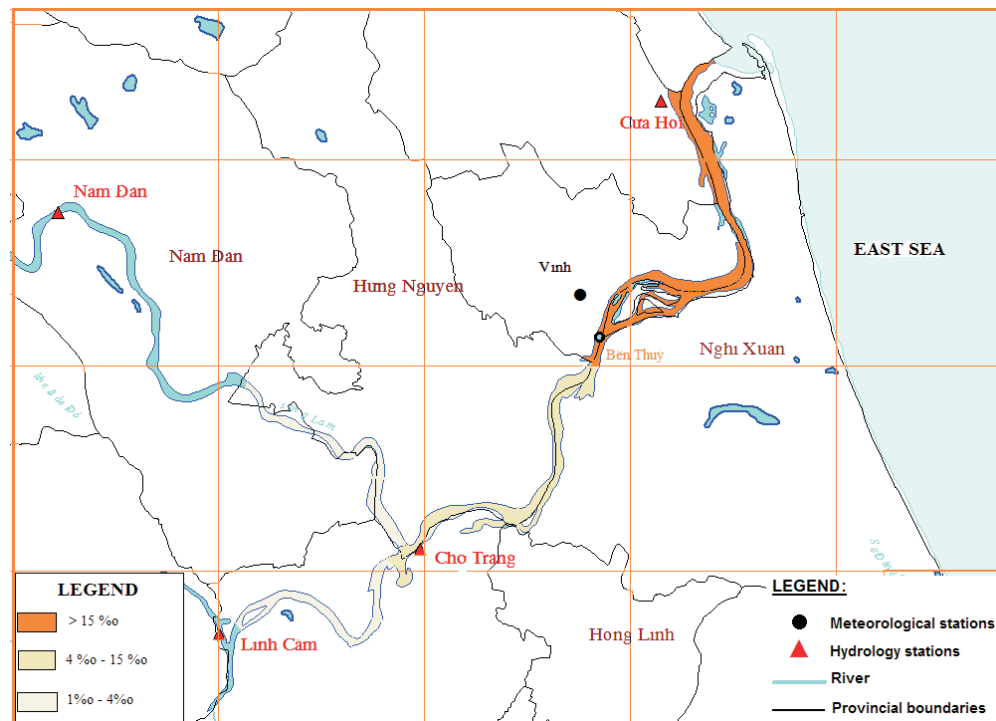


Figure 12: The boundaries salinity intrusion in 2100.

salinity intrusion boundaries in the river. Salinization threshold 1‰ was going into 55 km compared to inlet and affected Hung Linh, Khanh Son and Duc Tho communes. Salinization boundary 4‰ has encroached on over Cho Trang intersection. It can be seen that due to the impact of climate change and sea water level rising within 80 years, salinization boundary will move deep into the mainland, which significantly affected the living of people on both sides of the river.

The comparison between the calculated results of the distance of salinity intrusion of climate change scenarios are presented in Table 6. Table 6 shows an overview of salinity intrusion process over the climate change scenarios about precipitation and sea water level rise. It can be seen that the distance of salinity intrusion on the river is increasing and this could be detrimental to the economic development, especially the development of agriculture. In the most unfavourable case in 2100, the sea level rise due to global warming has significantly affected the situation of salinity intrusion in the Ca River.

Conclusions

The model was developed using a MIKE 11 one-dimensional hydraulic model and advection-dispersion model to simulate hydraulic regime in the river and salinity intrusion in the estuary areas. The model has been successfully applied to the river network in the Ca River Basin in Vietnam. The calculation results from the hydrodynamic calibration and validation processes showed a high conformity between the calculated and measured water level data at Nam Dan, Linh Cam, Do Luong and Yen Thuong for the phase and water amplitude. The good agreements between simulated results and observed data demonstrate the capability of the model to simulate the tidal dynamics, wetting and drying processes, and salt intrusion in the estuary. The overview of salinity intrusion boundaries in the climate change scenarios is shown in Table 6. Salinity intrusion process corresponding to climate change scenarios in

2030 did not change significantly compared with the scenario in 2050.

Table 6 shows that the salinity intrusion process has minor differences between scenario 1 and scenario 2. The sea water rise between two scenarios is not large enough to significantly affect salinity intrusion process in Ca River estuaries. However, comparing the results of scenario 3 with the current state scenario, the impact of salinity intrusion process on the Lam-Ca River system is found to be significant. As per model calculations, the maximum salinity concentration averaged over the cross-section depends on the amount of water flowing down. Maximum salinity intrusion distance in Ca River is 60 km in scenario 3 (2100). It means that, indeed, one has to be careful to take much water from the river system for socio-economic activities especially for irrigation purpose during dry season when inflow is less.

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Table 6: The distance of salinity intrusion

Salinity concentration	The distance of salinity intrusion (km)		
	Scenario 1	Scenario 2	Scenario 3
	2030	2050	2100
1‰	42	48	60
4‰	30	36	41

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