Lowland Technology International 2015; 17 (2): 93-104
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

Applying numerical method to understand the effect of climate change on the salinity intrusion in Ca River Basin, Vietnam

Q.T. Doan [1], N. C. Don [2], Y.C. Chen [1] and P.K. Mishra [3]

ARTICLE INFORMATION

Article history:

Received: 26 March, 2015
Received in revised form: 01 July, 2015
Accepted: 21 July, 2015
Publish on: September, 2015

Keywords:

Hydrodynamic
Advection-dispersion
Salinity intrusion
Climate change
Ca River

ABSTRACT

Climate change and global warming are expected to have significant effects on water resources planning and management, especially in estuary areas. One-dimensional MIKE 11 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 2020, 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 2020. 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.

1. 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 (Arnell, 1999, 2004; Hulme, 1999; Eckhardta and Ulbrichb, 2003; Gertena et al., 2004; Hitz and Smith, 2004; Labat et al., 2004; Dasgupta and Meisner, 2009). The potential impacts of climate change on estuary and coastal areas includes progressive inundation from sea level rise, heightened storm damage, loss of wetlands, and increased salinity from saltwater intrusion. Most of the research has focused on the long-run effects of inundation as the sea level rises, along with associated losses from heightened storm surge (Ali, 1996, 2003; Ali and Chowdhury, 1997; 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

[1] Phd, Department of Environmental Engineering, Dayeh University, TAIWAN, doanquangtrikttv@gmail.com
[2] IALT member, Department of Water Resourses Engineering, Thuyloi University, Hanoi, VIETNAM, ncaodonwru@gmail.com
[3] Department of Wood Science, Mendel University In Brno, CZECH Republic
Note: Discussion on this paper is open until December 2015

alternatives have not been investigated in great detail the 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 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. However, for the water systems strongly affected by tides and salinity intrusion, these tools are limited. 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 modeling, 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.

2. Material and methods

2.1. Description of Study Site

The Ca River system is one of the nine biggest river systems with coordinates latitude (18^0 33' 10" N – 20^0 01' 43" N) and longitude (103^0 52' 53" E – 105^0 48' 50" E) that connects the north to the south in Vietnam (Fig.1). The main river is originated from Lao, flowing through almost of 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 (Fig. 1).

About 80% of the catchment is mountainous area and the remainder 20% is a narrow strip along the river and coastal plain. This area is potential for socio-economic growth which requires high quantity and quality of water resource. The total catchment area is of 27,200 km^2 in which Lao democratic republic accounting for 9,470 km^2. 80% population lives in 7,800 km^2 of hilly and plain areas, and the rest 19,400 km^2 is mountainous topography. The total length of main Ca River is 531 km and it originates from the western side of Truong Son mountain range in which 170 km runs through Lao and 361 km runs through Vietnam. When flowing down, Ca joins with Lam River which originates from Ha Tinh - Cho Trang that is about 30 km from river estuary.

2.2. Model

2.2.1. Model description

Many models have been developed to study saltwater intrusion. In respect to water quality modeling, 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. The detailed description of the advection-dispersion module can be found in the "Reference Manual" the Danish Hydraulic Institute (2004).

One-dimensional equations governing the river flow are known as Saint-Venant equations (Shooshtari, 2008). These are expressed as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad [1]$$

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

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

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

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} + \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) = -AKC + C_2 q \qquad [3]$$

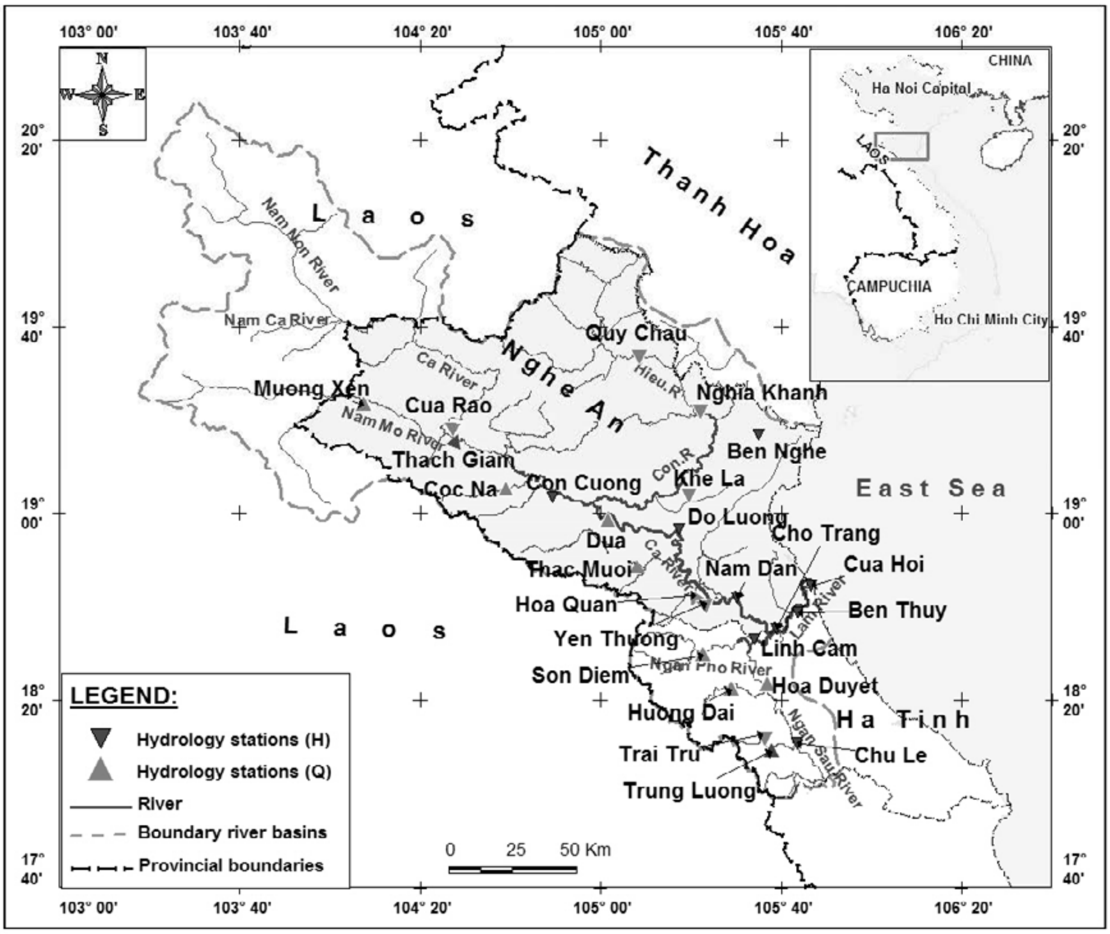

Fig. 1. Location of the study area.

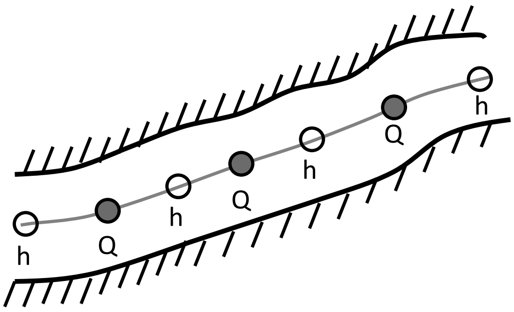

Fig. 2. Schematic nodding of h-points and Q-points for a river section MIKE 11 mode (Eaton and Franson, 2005).

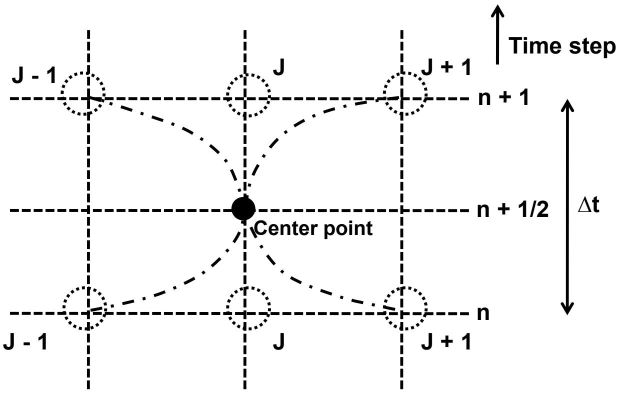

Fig. 3. Centered 6-point Abbott scheme.

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 showed as below (Fig. 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).

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 Eq. 4 below.

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

2.2.2. 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 as follows (Fig. 4):

Step 1: Preparing, analyzing and assessing data are basically initial steps with the topography data (topographic maps, elevation maps, river network, cross-section Rivers and streams), hydrology (water level, flow), irrigation structure, etc. This is the basic data in model building as well as in analysis, evaluation and simulation salinization process.

Step 2: Developing model: Main content is to build river network for model, calibration, validation model with the measured data in comparison with building continue salinity intrusion model.

Step 3: Simulating salinity intrusion process is one of the specific requirements to response the study objectives.

Step 4: Developing scenarios is to comprehensively assess the impact of salinity intrusion process with different conditions.

The river network system is schematized in Fig. 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.

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 hydrology 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.

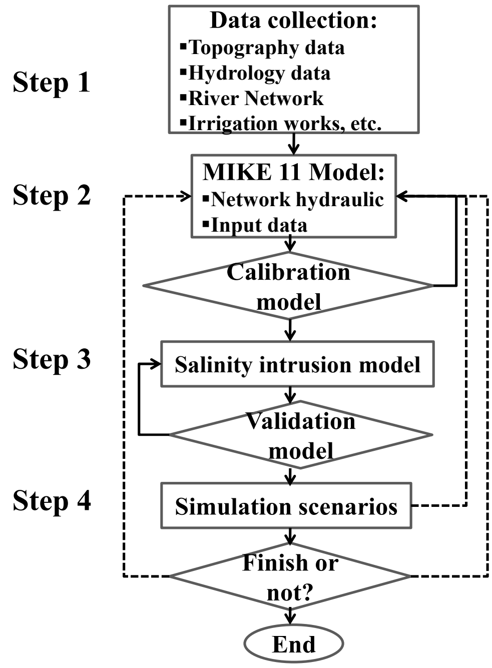

Fig. 4. Calculation procedures of the simulation.

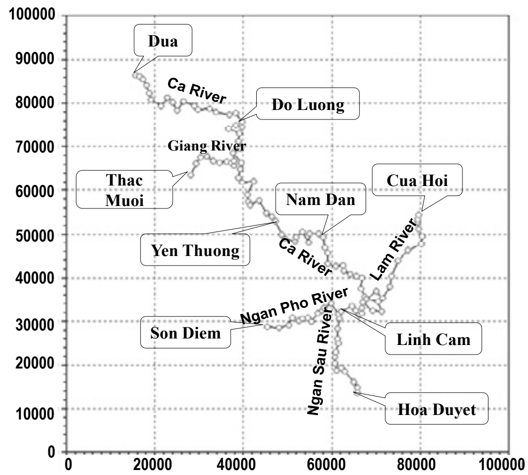

Fig. 5. Hydraulic scheme formulated in MIKE 11.

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.

3. Results and discussions

3.1. 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 (Fig. 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.

3.2. Validation of the hydrodynamic model

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

3.3. 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 (Fig. 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 Fig. 9.

Limnologist and chemists often define salinity in terms of mass of salt per unit volume, expressed in units of mg per liter (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 a measured density. The classification of water salinity is presented in Table 1.

Marine waters are those of the ocean, another term for which is euhaline seas. The salinity of euhaline seas is 30 to 35. Brackish seas or waters have salinity in the range of 0.5 to 29 and metahaline seas from 36 to 40. These waters are all regarded as thalassic because their salinity is derived from the ocean and defined as homoiohaline if salinity does not vary much over time (essentially constant). The 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.

Based on the classification of water salinity (Table 1 and Table 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 (Fig. 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 (Fig. 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.

3.4. Simulation salinity intrusion process in 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 (2009). The report selected B2 scenario to simulate salinity intrusion process in account of climate change (Table 3).

The sea water rising scenarios for Vietnam is calculated according to the lowest emission scenario (B1), an average emission scenario (B2) and the highest emission scenario (A2). The calculated results of low emission scenario, and average and high emission scenario in the middle of the 21st century showed that the water level could increase from 28 to 33 cm; and at the end of the 21st century, the sea water level could increase from 65 to 100 cm (Table 4).

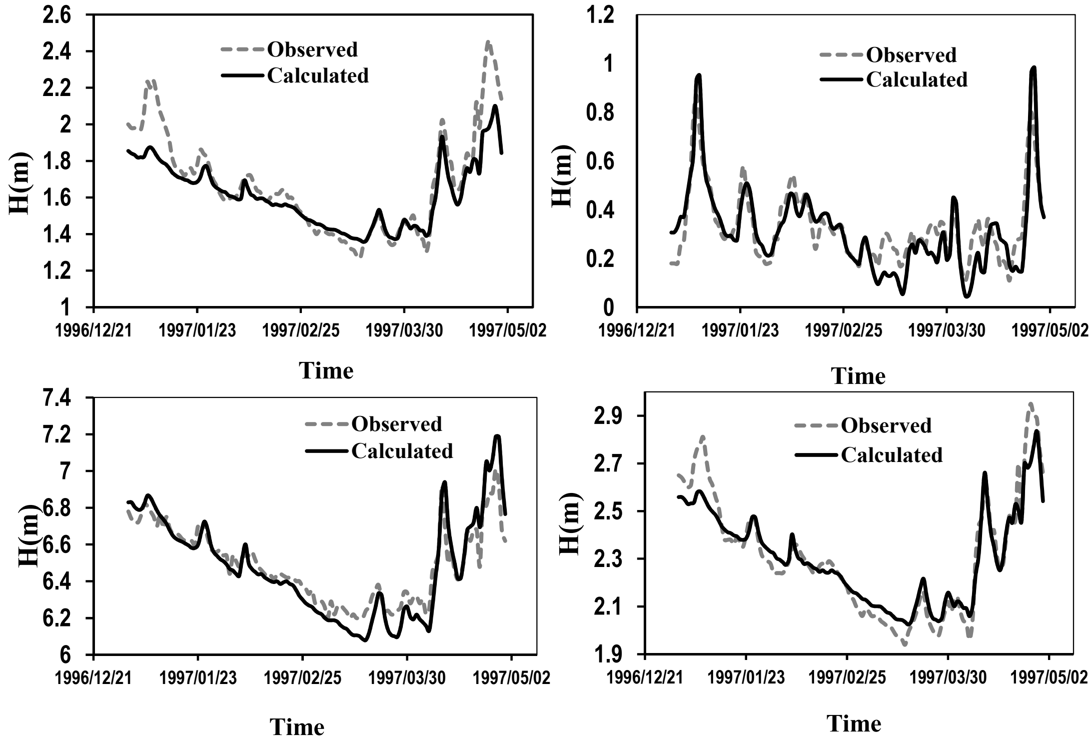

Fig. 6. Calculated and observed water level for the calibrated period of December 21, 1996 to April 20, 1997: (a) Nam Dan with NSI = 0.84; (b)Linh Cam with NSI = 0.86; (c) Do Luong with NSI = 0.75; (d) Yen Thuong with NSI = 0.87.

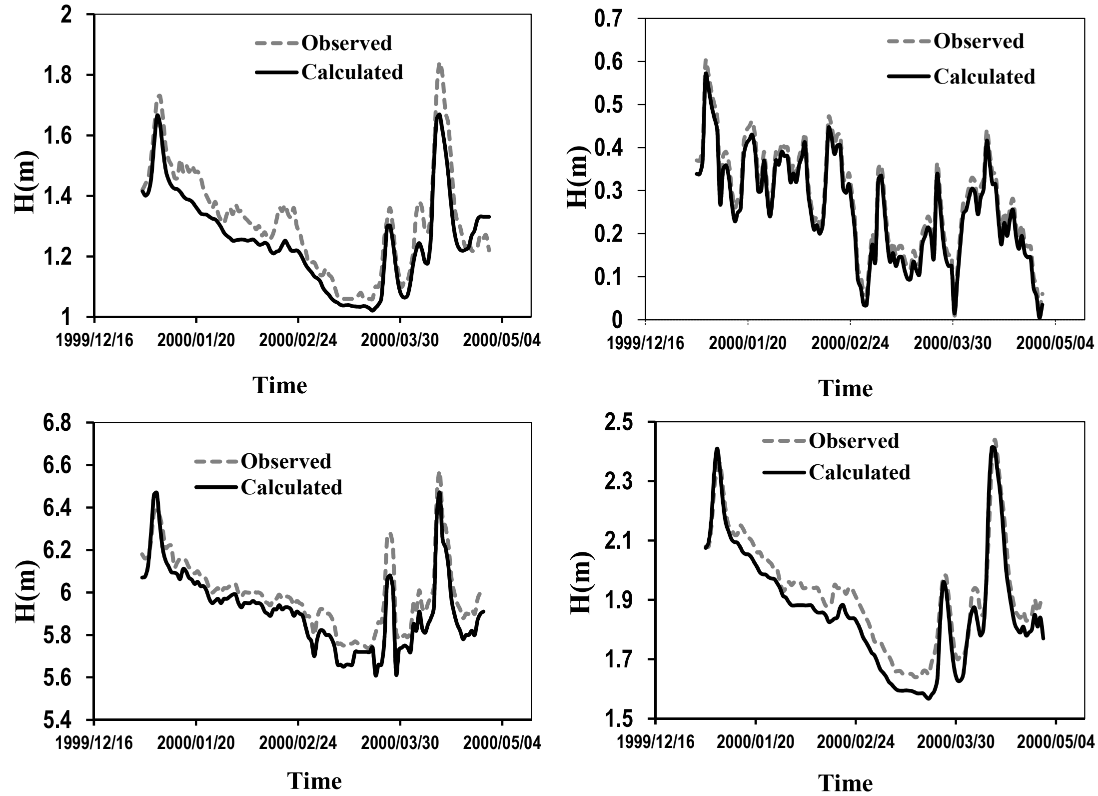

Fig. 7. Calculated and observed water level for the validated period of December 16, 1999 to May 14, 2000: (a) Nam Dan with NSI = 0.82; (b) Linh Cam with NSI = 0.89; (c) Do Luong with NSI = 0.76; (d) Yen Thuong with NSI = 0.85.

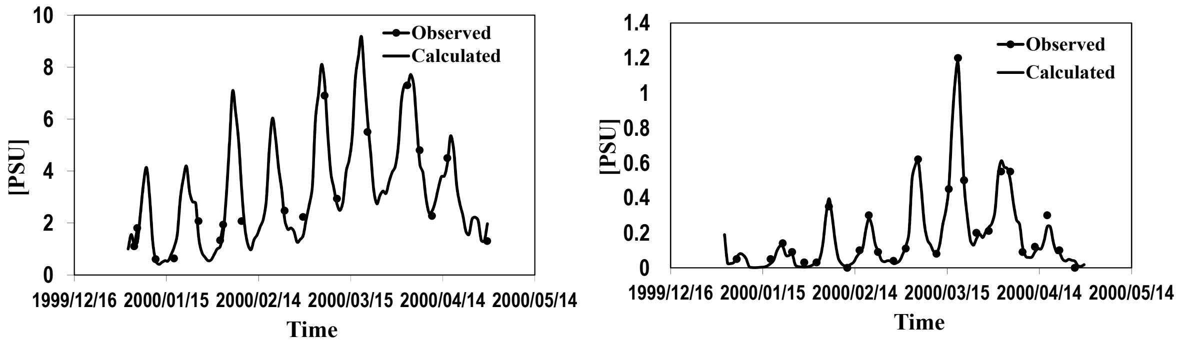

Fig. 8. Calculated and observed salinity concentration from December 16, 1999 to May 14, 2000: (a) Ben Thuy with NSI = 0.92; (b) Trung Luong with NSI = 0.94.

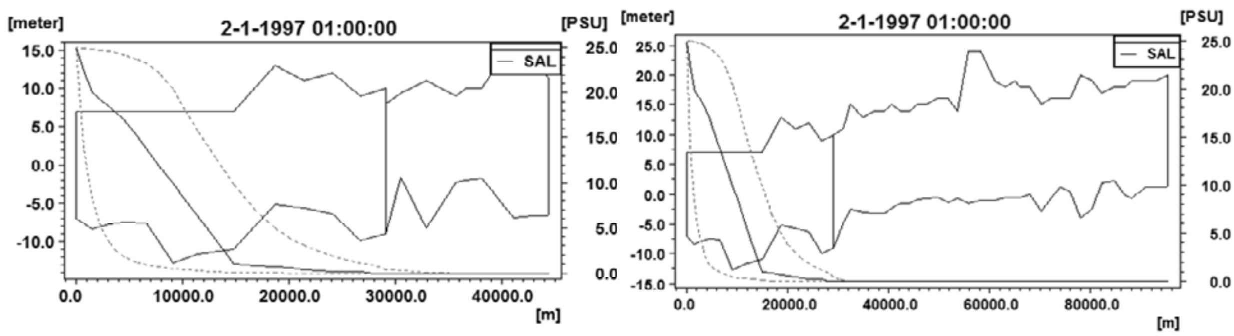

Fig. 9. Boundary salinity intrusion: (a) Cua Hoi to the Lam River; (b) Cua Hoi to the Ca River.

With climate change scenarios selected an average emission scenario (B2); salinity intrusion process is simulated in three scenarios in 2020, 2050 and 2100. In order to simulate salinity intrusion process, we have to create upper boundaries and lower boundaries for three scenarios.

Scenario1: Simulation of salinity intrusion process with sea water level rise and rainfall change following an average emission scenario B2 in 2020.

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

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

3.4.1. 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 12 cm in 2020, 30 cm in 2050, and 75 cm in 2100.

Upper boundaries are set of climate change scenarios about the rainfall, after the relationship between flow month in dry season and rainfall month in dry season was calculated in the study period. Using the contour map of the rainfall on March in Ca Basin River combined with the flow mean on March for many years at the stations in the study area, we calculated value pairs (X_k, Y_k) for each station and built rainfall-runoff correlation in study area.

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

In order to build the rainfall-runoff relationship, we have to select the geographic areas with similarity about both scope and rainfall. According to the rain partition table on the territory of Vietnam, the study site lies in two rain zones as follows:

Zone 1: the southern part of Ma River in Thanh Hoa province, Chu River Basin, Con River, Ca River, the

Table 3. Increasing an average temperature (^0C) the following emission scenario (B2).

Scenario	Period	The timeline of the 21st century								
		2020	2030	2040	2050	2060	2070	2080	2090	2100
B2	XII - II	0.6	0.9	1.2	1.6	1.9	2.2	2.5	2.8	3.0
	III-V	-1.9	-2.9	-4.0	-5.2	-6.3	-7.3	-8.3	-9.1	-9.9
	VI -VIII	2.9	4.2	5.9	7.6	9.3	10.8	12.2	13.4	14.6
	IX - XI	1.7	2.5	3.5	4.5	5.4	6.3	7.1	7.8	8.5
	Annual	1.5	2.2	3.1	4.0	4.9	5.7	6.4	7.1	7.7

Table 4. The level of rainfall fluctuations (%) the following an average emission scenario (B2).

Scenario	The timeline of the 21st century								
	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low (B1)	11	17	23	28	35	42	50	57	65
Average (B2)	12	17	23	30	37	46	54	64	75
High (A2)	12	17	24	33	44	57	71	86	100

Table 5. Characteristic rainfall-runoff of the driest month at the observed station in Ca River Basin

No.	Hydrology station	Rainfall of the driest month	Layer flow of the driest month	Flow module of the driest month	Flow of the driest month
		(mm)	(mm)	(l/s.km^2)	(m^3/s)
1	Khe La	34,8	138	5,3	0,146
2	Ben Nghe	31.5	85	2,7	0,356
3	Cua Rao	45	155	5,1	64,7
4	Dua	47,5	183	5,8	121
5	Yen Thuong	47,5	205	6,5	150
6	Muong Xen	50	220	7,4	19,4
7	Coc Na	50	465	14,8	6,16
8	Huong Dai	59	1027	32,6	13,3
9	Son Diem	57	853	27,1	21,4
10	Hoa Duyet	58	822	26	48,9
11	Trai Tru	62	1208	38,4	3,69

southern boundary of the watershed between the Ca River and Ngan Pho River.

Zone 2: consist of Dien-Yen-Quynh, Nghi Hung, Nghia Dan, Do Luong, Thanh Chuong and Nghi Xuan.

From the data in Table 5, we proceed to build the relationship $Y_0 = f(x_0)$ for two zones as follows:

The relationship of Zone 1 consisting of representative stations such as Khe La, Ben Nghe, Cua Rao, Dua and Yen Thuong are presented in Fig. 10. The relationship of Zone 2 including representative stations such as Coc Na, Son Diem, Hoa Duyet, Huong Dai and Trai Tru are presented in Fig. 11.

After building the relationship between flow layer and the driest month rain for study areas from the observed flow data at four boundary stations, the rainfall (mm) is calculated according to two equations as follows:

$$Y_{K1} = 5.716X_{K1} - 82.64 \quad [5]$$

$$Y_{K2} = 60.73X_{K2} - 2599 \quad [6]$$

From scenario B2 of precipitation change in 2020, 2050 and 2100, we calculated the rainfall process at four upper boundary stations, after using Eq. 5 to calculate the flow process. By using the calculated results of upper and lower boundaries corresponding to three scenarios, salinity intrusion process is simulated for each scenario.

3.5. Results assessment of salinity intrusion in different scenarios

Scenario 1:

On the Lam River: the salinity wedge spreads around 12km along the Lam River from intersection at Cho Trang hydrology station along upstream. However, the classification of the salinity water in Table 4 shows that the freshwater starts at 6.8 km from Lam River downstream back upstream. Thus, if we compare with the current state, the salinity intrusion process in the scenario of climate change in 2020 spreads into the Lam River about 5km.

On the Ca River: the salinity wedge spreads around 40 km from Hoi station along the upstream of Lam-Ca River. However, the classification of salinity water in Table 4 shows that the freshwater starts at 35 km along upstream. Comparison between the results of climate change scenario and the current state scenario shows that salinity intrusion process spreads into the Ca River around 6 km.

Scenario 2:

On the Lam River: the salinity wedge spreads around 14 km along Lam River from intersection at Cho Trang hydrology station along upstream. However, the classification of salinity water in Table 4 shows that the freshwater starts at 8 km from Lam River downstream back upstream. Thus, comparison between the results of climate change scenario and the current state scenario shows that salinity intrusion process spreads into the Lam River around 6.5 km.

On the Ca River: the salinity wedge spreads around 44 km from Hoi station along the upstream of Lam River – Ca River. According to the classification of salinity water in Table 4, the freshwater starts at 37 km back upstream. Comparison between the results of climate change scenario and the current state scenario shows that the salinity intrusion process spreads into Ca River around 10 km.

Scenario 3:

On the Lam River: the salinity wedge spreads around 15 km along Lam River and continue to penetrate upstream of Ngan Pho River and Ngan Sau River. However, the classification of salinity water in Table 4 shows that the freshwater starts at 11 km from Lam River downstream back upstream. Thus, a comparison between the results of climate change scenario and the current state scenario shows that salinity intrusion process spreads into the Lam River around 8 km.

On the Ca River: the salinity wedge spreads around 53 km from Hoi station along the upstream of Lam-Ca River. According to the classification of salinity water in Table 4, the freshwater starts at 43.5 km back upstream. The comparison between the results of climate change scenario and the current state scenario shows that the salinity intrusion process spreads into Ca River around 19 km.

The comparison between the calculated results of current state salinity intrusion and 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 unfavorable case in 2020, the

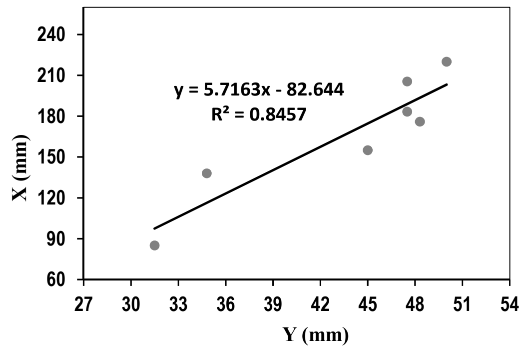

Fig. 10. The relationship chart of rainfall-runoff at Zone 1.

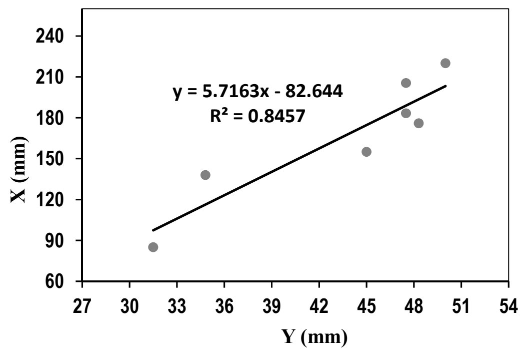

Fig. 11. The relationship chart of rainfall-runoff at Zone 2.

Table 6. The distance of salinity intrusion.

River	The distance of salinity intrusion (km)			
	Current State	Scenario 1	Scenario 2	Scenario 3
	2010	2020	2050	2100
Ca	34	34	44	53
Lam	7,5	12	14	>15

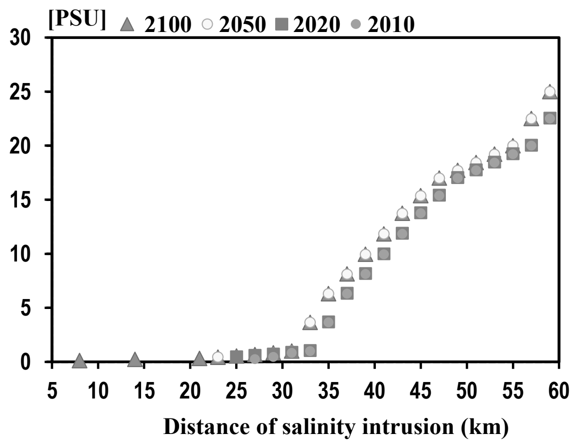

Fig. 12. Boundaries of salinity intrusion through the three scenarios.

sea level rise due to global warming has not significantly affected the situation of salinity intrusion in the Ca River.

4. Conclusions

1. 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.

2. 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.

3. The overview of salinity intrusion boundaries the current state and climate change scenarios is shown in Fig. 12. Salinity intrusion process corresponding to climate change scenarios in 2020 did not change significantly compared with the current state scenario in 2010. Figure 12 showed that the salinity intrusion process has minor differences between scenario 2 and scenario 3. The sea water rise between two scenarios is not large enough to significantly affect to 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.

4. As per model calculations, the maximum salinity concentration averaged over the cross-section depends on the amount of water flowing down. Maximum salinity intruded distance in Ca River is 53 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.

Acknowledgements

We are grateful and thank Quach Thanh Tuyet and Ha Trong Ngoc for their assistance with the collection of topography, meteorological, and observed data for this paper. We are thankful to HMEC for this research opportunity and for the facilities used to perform the study.

References

Abbott, M.B. and Ionescu, F., 1967. On the numerical computation of nearly-horizontal flows. J. Hydraulic Research, **5** (2): 97-117.

Ali, A., 1996. Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges. Water, Air and Soil Pollution, Springer, **92** (1-2): 171–179.

Ali, A. and Chowdhury, J.U., 1997. Tropical cyclone risk assessment with special reference to Bangladesh. J. Meteorology, Hydrology and Geophysics, **48**: 305–322.

Arnell, N.W., 1999. Climate change and global water resources. Global Environmental Change, Elsevier, 9: S31-S49.

Anati, D.A., 1999. The salinity of hypersaline brines: concepts and misconceptions. Intl. J. Lakes & Reservoirs, **8** (1): 55-70.

Ali, A., 2003. Storm surge flood in Bangladesh. Paper presented at the Launch Workshop of the Research Project on Impact of Climate and Sea Level Change in the Indian Sub-Continent (CLASIC), January 30, 2003, Bangladesh University of Engineering and Technology (BUET), Dhaka: 47-56.

Agarwala, S., Ota, T., Ahmed, A.U., Smith, J. and Aalst. M., 2003. Development and climate change in Bangladesh: Focus on coastal flooding and the sunderbans. Organisation for Economic Co-operation and Development, Paris: 86-120.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change, Elsevier, **14** (1): 31–52.

Akhter, S., Hasan, M. and Khan, Z.H., 2012. Impact of climate change on saltwater intrusion in the coastal area of Bangladesh. Proc. 8th International Conference on Coastal and Port Engineering in Developing Countries (ICCPEDC, 2012), February 20-24, 2012, IIT Madras Chennai: 123-130.

Bear, J., Cheng, A.H.D., Sorek, S., Ouazar, D. and Herrera, I., 1999. Seawater intrusion in coastal aquifers - concepts, methods and practices. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P., 2008. Climate change and water. Technical Paper, VI of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva: 42-96.

Dahl, E., 1956. Ecological salinity boundaries in poikilohaline waters. Oikos (Oikos) **7** (1): 1–21.

Danish Hydraulic Institute (2004). A modelling system for Rivers and Channels-MIKE11 Reference and User Manual. http://www.scribd.com/doc/94010463/Mike-11-Reference-Manual.

Dasgupta, S. and Meisner, C., 2009. Climate change and sea-level rise: A review of the scientific evidence. Environment Department, World Bank, Washington, DC: **118**: 229-247.

Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D. and Yan, J., 2009. The impact of sea-level rise on developing countries: A comparative analysis. Climatic Change, **93** (3): 379-388.

Dasgupta, S., Mainul, H., Zahirul, H.K., Manjur, M., Zahid, A., Nandan, M. and Khan, K.P., 2010. Vulnerability of Bangladesh to cyclones in a changing climate: potential damages and adaptation cost. Policy Research Working Paper 5280. World Bank, Washington, DC: 334-389.

Doan, Q.T., Nguyen, C.D., Chen, Y.C. and Mishra, P.K., 2014. Modeling the influence of river flow and salinity intrusion in the Mekong river estuary, Vietnam. Lowland Technology International, **16** (1), 14-25.

Eckhardta, K. and Ulbrichb, U., 2003. Potential impacts of climate change on groundwater recharge and stream flow in a central European low mountain range. J. Hydrology, **284**: 244–252.

Gertena, D., Schaphoffa, S., Haberlandtb, U., Luchta, W. and Sitcha, S., 2004. Terrestrial vegetation and water balance-hydrological evaluation of a dynamic global vegetation model. J. Hydrology, **286** (1-4): 249-270.

Hulme, M., Mitchell, J., Ingram, W., Lowe, J., Johns, T., New, M. and Viner, D., 1999. Climate change scenarios for global impacts studies. Global Environmental Change, Elsevier, **9**: S3-S19.

Hitz, S. and Smith, J., 2004. Estimating global impacts from climate change. Global Environmental Change, Elsevier, **14** (3): 201–218.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C. and Chateau, J., 2011. A global ranking of port cities with high exposure to climate extremes. Climatic Change, **104** (1): 89-111.

Kabir, M.M., Saha, B.C. and Hye, J.M.A., 2006. Cyclonic storm surge modelling for design of coastal polder. Institute of Water Modeling. http://www.iwmbd.org/htm/PUBS/publications/P024.PDF, 2014.

Labat, D., Godd, Y., Probst, J.L. and Guyot, J.L., 2004. Evidence for global runoff increase related to climate warming. Advances in Water Resources, Elsevier, **27** (6): 631–642.

Ministry of Natural Resources and Environment, Vietnam (2009). Climate change scenarios and sea level rise for Vietnam. http://www.preventionweb.net/english/professional/publications/v.php?id=11348.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: part I - A discussion of principles. J. Hydrology, **10** (3): 282-290.

Nicholls, R.J., 2003. An expert assessment of storm surge “Hotspots.” Final Report (Draft Version) to Center for Hazards and Risk Research, Lamont-Dohert Observatory, Columbia University: 62-78.

Nicholls, R.J., 2006. Storm surges in coastal areas. Natural disaster hot spots case studies. Edited by Margaret Arnold et al. Washington, DC: World Bank. Chapter 3: 79-103.

Por, F.D., 1972. Hydrobiological notes on the high-salinity waters of the Sinai Peninsula. Marine Biology, **14** (2): 111-120.

Price, Roland, K., 2009. Volume-conservative nonlinear flood routing. J. Hydraulic Engineering, **135** (10): 838-845.

Shooshtari, M.M., 2008. Principles of flow in open channels. Shahid Chamran University Press, **15** (2): 643-745.

Venice system, 1959. The final resolution of the symposium on the classification of brackish waters. Archo Oceanography Limnology, **11**: 243-248.

Vu, M.C., 2009. Simulation of saline water intrusion into lower part of Ca River and solutions to mitigate economic losses in dry season. http://www.worldscientific.com/doi/pdf/10.1142/9789814287951_0076.

Wetzel, R.G., 2003. Limnology: Lake and river ecosystems, Third Eds., The Quarterly Review of Biology, **78** (3): 368-369.

World Bank, 2009. Implications of climate change on fresh groundwater resources in coastal aquifers in Bangladesh. Agriculture and Rural Development Unit, Sustainable Development Department, South Asia, World Bank, Washington, DC. http://www.eldis.org/go/home&id=60997&type=Document.

Symbols and abbreviations

A	Cross-sectional area
C	Chezy roughness coefficient (Eq. 2)
C	Concentration (Eq. 3)
C_2	Source/sink concentration
D	Dispersion coefficient
h	Flow depth
K	Linear decay coefficient
Q_{obs}	Observed stream flow/stage
$\overline{Q}_{obs}$	Observed mean stream flow/stage
Q_{cal}	Calculated stream flow/stage
Q	Discharge
q	Lateral inflow
R	Hydraulic radius
t	Time coordinate
x	Space coordinate
X_K	Average dry season rainfall in many years
Y_K	Average runoff courses layer in many years
α	Momentum correction coefficient