Simulating impacts of sea level rise on salinity intrusion in the Mekong Delta, Vietnam in the period 2015-2100 using MIKE 11

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***Abstract* – The Mekong Delta was studied to quantify the impact of sea level rise on the salinity intrusion in the period 2015-2100. Sea level rise (RCP 4.5 and RCP 8.5) scenarios suggested that the sea level increases by 0.07 to 0.48 m in the future (2030s, 2050s, and 2080s). The MIKE 11 model (Hydrodynamic module and Advection-Dispersion module) was used to investigate the impact of saltwater intrusion under sea level rise scenarios. The model was calibrated and validated using observed data. The calibration and validation results indicated that the MIKE 11 model was able to simulate the streamflow and salinity concentration, with NSE values exceeding 0.53 for both calibration and validation periods. Their differences in simulating the salinity concentration under sea level rise scenarios were also analyzed. The results indicate salinity concentration increases by 1.2% to 10% in the future. This means that the saltwater will move deeply inland in the future and have significant impacts on agricultural activities and livelihoods of farmers in the Mekong Delta.**

Keywords – Mekong delta, MIKE 11, Sea level rise, Salinity intrusion.

1. INTRODUCTION

Climate change is one of the biggest challenges to humanity in the 21st century. The Intergovernmental Panel on Climate Change - Fifth Assessment Report (IPCC-AR5) indicated that the coastal countries in Southeast Asia, including Vietnam, are highly vulnerable to climate change and sea level rise [1]. The Mekong Delta is considered the largest granary of Vietnam, contributing 40% of national food production and more than 85% of annual rice exports [2]. However, rising sea levels are likely to increase salinity gradients in large parts of the Mekong Delta, especially in the dry season. Approximately 1.8 million ha of delta land is subject to increased dry-season saline [3]. This has reduced agricultural productivity and caused declining rice production in the Mekong Delta. The objective of this study was to evaluate the impact of sea level rise on salinity intrusion in the Mekong Delta. Many studies have addressed the change in salinity intrusion with impacts of sea level rise scenarios [2, 4, 5], but no studies have investigated the impact of sea level rise scenarios from IPCC-AR5 on salinity intrusion in the study area. The results obtained in this study are expected to provide more insight into the changes in salinity intrusion in the future and to provide local managers useful information in managing water resources and planning agriculture.

2. STUDY AREA

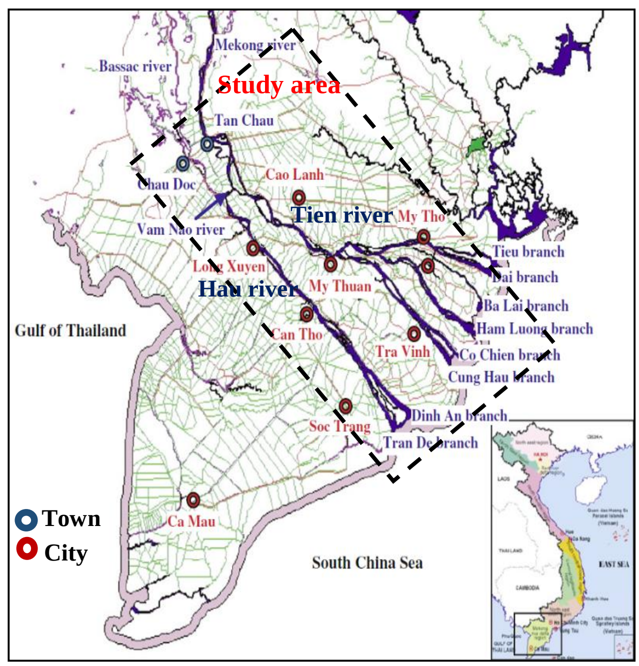

Figure 1 Location of Mekong Delta and study area [6]

The Mekong Delta is the region in the far south of Vietnam, roughly forming a triangle of 3.9 million ha stretching from My Tho in the east to Chau Doc and Ha Tien in the northwest, down to Ca Mau at the southernmost tip of Vietnam [6]. The Mekong Delta begins at Phnom Penh, Cambodia where the river divides into two branches, the Bassac (known as the Hau river in Vietnam) and the Mekong (known as the Tien river in Vietnam). These two branches form the Mekong Delta (figure 1). As a typical delta, The Mekong Delta is affected by both river floods and tides with a mixed diurnal and semi-diurnal character. The river flood is high during the rainy season, which has had average flows of 18,640 m^3/s at the Tan Chau station and 5,890 m^3/s at the Chau Doc station. However, the flow in the dry season is very low, with an average flow of around 2,600 m^3/s. In addition, the Mekong Delta is very flat and low, with an average elevation of about 1m above mean sea level. Thus, the seasonal flood and salinity intrusion are considered as unavoidable phenomena in the delta. Approximately 1.7 million hectares are affected annually by salinity intrusion, while about 1.6 to 2.0 million hectares are covered by annual flooding [4]. In 2012, the total population in the delta was about 17 million inhabitants. The Mekong Delta is the most important rice production region contributing to Vietnamese national food security.

3. METHODOLOGY

3.1 MIKE 11 Model

MIKE 11 model is a dynamic, one-dimensional modeling tool for simulating flow, water quality, and sediment transport in river and channel network [7]. The governing equations used in MIKE11 in solving hydraulic problems in rivers and channels are known as Saint-Venant equations. These are written as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

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

Where Q is flow discharge, h is flow depth, A is the cross-sectional area, q is lateral inflow, C is Chezy resistance coefficient, R is hydraulic radius, α is momentum distribution coefficient, x is the space coordinate, and t is the time. The solution of these equations is based on an implicit finite difference scheme.

The advection-dispersion equation in MIKE 11 model is based on the mass conservation equation. This is written as follows:

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

where C is the concentration, D is the dispersion coefficient, K is the linear decay coefficient, and C_2 is the source/sink concentration. Further details can be found in the MIKE11 Reference Manual [7].

3.2 MIKE 11 Model Set-Up

Two modules of the MIKE11 model applied to simulate the salinity intrusion in the Mekong Delta were the hydrodynamic (HD) module for flow simulation and the advection-dispersion (AD) module for simulation of salinity intrusion. In the HD module, the computational scheme consisted of two discharge boundaries at the upstream boundary of the delta and eight water-level boundaries at the downstream boundary of the delta. The discharge and water level data in 2012 and 2013 were collected from the Hydro-Meteorological Data Center of Vietnam (HDMC). The topography of the rivers was collected from the Southern Institute of Water Resources Research (SIWRR). In the AD module, the salinity concentration of the upstream boundaries was zero and the salinity concentration of the downstream boundaries was given by measured data. The salinity data in 2012 and 2013 also were collected from HDMC. The HD and AD modules were calibrated by using observed data in March 2013 and validated by the data in March 2012. The location of observed stations used was shown in figure 2.

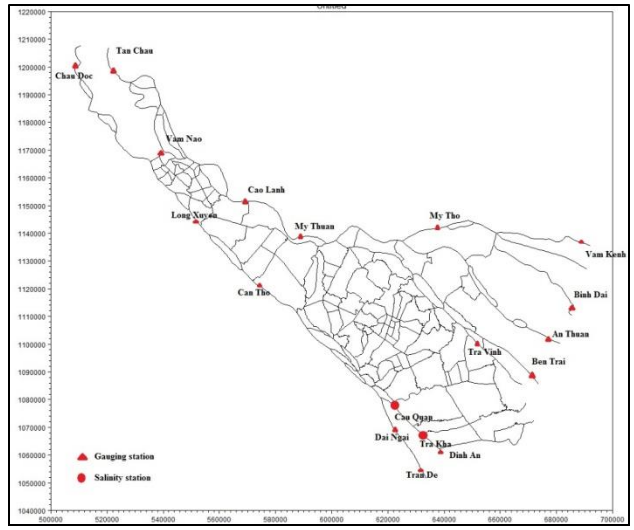

Figure 2 River network in MIKE 11 with observed stations

The model performance was evaluated using two statistical indices; coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE). According to Moriasi et al. (2007), model simulation can be considered as satisfactory if NSE and R^2 are above 0.5 [8].

3.3 Sea Level Rise Scenarios

In this study, scenarios of sea level rise for the Mekong Delta were suggested based on the study conducted by Katzfey et al. (2014). We focused on RCP 4.5 (low emission) and RCP 8.5 (high emission) scenarios. Table 1 summarize the changes in sea level for the 2030s (2015-2040), 2050s (2045-2070), and 2080s (2075-2100) under the RCP 4.5 and 8.5 scenarios. The analysis of changes in sea level suggested that the sea level will increase from 0.07 to 0.36 m for the RCP 4.5 scenario and from 0.07 to 0048 m for the RCP 8.5 scenario.

Table 1 Sea level rise scenarios for Mekong Delta

Period	RCP 4.5	RCP 8.5
2030s	0.07m	0.07m
2050s	0.22m	0.26m
2080s	0.36m	0.48m

4. RESULTS AND DISCUSSION

4.1. Calibration and Validation of MIKE 11

Calibration and validation were performed to improve model performance at the main gauging stations. Hydrodynamic calibration was conducted first, followed by salinity calibration.

(a)
(b)

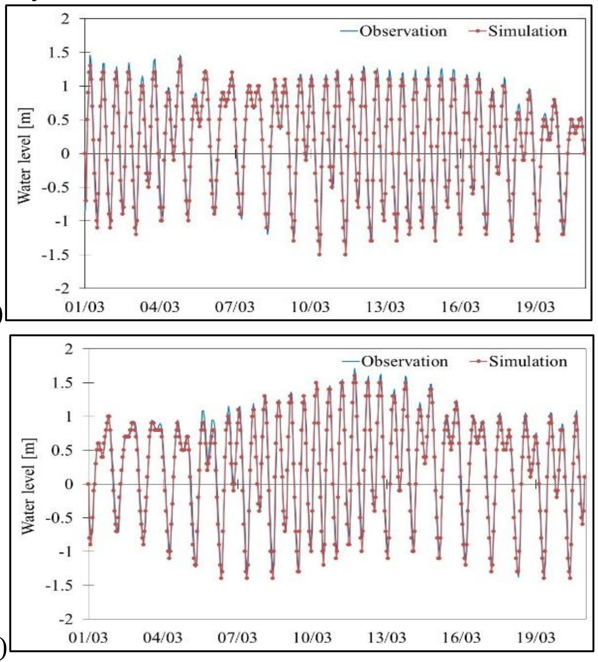

Figure 3 The comparison plot of observed and simulated water level at the Tra Vinh station, (a) calibration (in March 2013) and (b) validation (in March 2012)

(a)
(b)

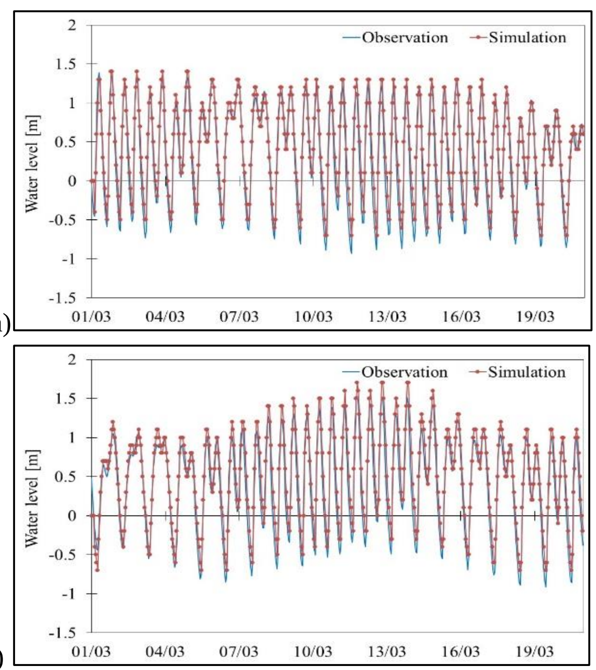

Figure 4 The comparison plot of observed and simulated water level at the Can Tho station, (a) calibration (in March 2013) and (b) validation (in March 2012)

Figures 3 and 4 compare simulated and observed hourly water levels for calibration and validation periods at the Tra Vinh and Can Tho stations. Good agreement can be seen between the simulated and observed water level during these periods. The NSE and R^2 values for hourly calibration and validation are listed in table 2. For both calibration and validation periods, all NSE and R^2 values exceed 0.76. These values indicated good MIKE 11 performance in simulation of streamflow according to the performance criteria in [8]. This is important for simulation of salinity intrusion.

(a)
(b)

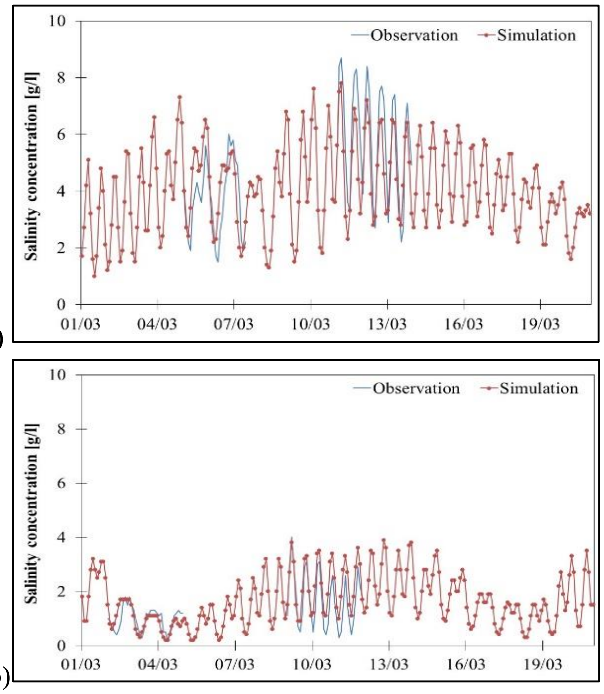

Figure 5 The comparison plot of observed and simulated salinity concentration at the Tra Vinh station, (a) calibration (in March 2013) and (b) validation (in March 2012)

Table 2 The performance of MIKE 11 for the simulation of flow

Station	Calibration (Mar.2013)		Validation (Mar. 2012)	
	R^2	NSE	R^2	NSE
Cao Lanh	0.95	0.94	0.93	0.90
Can Tho	0.96	0.94	0.94	0.91
Dai Ngai	0.99	0.96	0.77	0.76
Long Xuyen	0.96	0.90	0.92	0.87
My Tho	0.96	0.96	0.96	0.95
My Thuan	0.97	0.92	0.96	0.90
Tra Vinh	0.97	0.97	0.98	0.97
Vam Nao	0.86	0.81	0.88	0.76

Because of a lack of salinity data, the salinity calibration was performed for only a few days. The comparison plot of simulated and observed salinity concentration for the calibration and validation periods at the Tra Vinh station was presented in figure 5. The results of statistical

evaluations (table 3) suggest a fit between measured and simulated salinity concentration. This is confirmed by the NSE and R^2 values above 0.53.
streamflow and salinity concentration satisfactorily for the Mekong Delta and the well-calibrated model was used to investigate the salinity intrusion under the sea level rise scenarios

Table 3 The performance of MIKE 11 for the simulation of salinity intrusion

Station	Calibration (Mar. 2013)		Validation (Mar. 2012)	
	R^2	NSE	R^2	NSE
Cau Quan	0.58	0.58	0.67	0.53
Tra Kha	0.71	0.54	-	-
Tra Vinh	0.75	0.58	0.83	0.67

4.2. Impact of SLR on Salinity Intrusion

Table 4 shows the average changes in salinity concentration under the impact of sea level rise. The predicted changes of salinity concentration are expected to increase in the future with changes of approximately 1.2%, 4.2-4.3%, and 7.8-7.8% for the RCP 4.5 scenario; and 1.4%, 5.0-5.1%, and 9.8-10.0% for the RCP 8.5 scenario. These changes mean that the saltwater will move further inland of the Mekong Delta in the future and have significant impacts on agricultural activities as well as the livelihoods of farmers.

Table 4 Percentage changes in salinity concentration under sea level rise scenarios

Period	Cau Quan		Tra Vinh	
	RCP4.5	RCP8.5	RCP 4.5	RCP8.5
2030s	1.2%	1.4%	1.2%	1.4%
2050s	4.2%	5.0%	4.3%	5.1%
2080s	7.7%	9.8%	7.8%	10.0%

5. CONCLUSION

This study investigated the effects of sea level rise on salinity intrusion by using the MIKE 11 model. The model calibration and validation were carried out to evaluate mode performance in simulation of streamflow and salinity concentration. The results indicated that the MIKE 11 is a useful tool for assessing impacts of climate change and sea level rise in the Mekong Delta. Under the possible sea level rise, the saltwater will move inland, especially in the dry season. The results obtained in this study could be useful for managing water resources in this region through enhancing the understanding of the impact of various sea level rise scenarios on salinity concentration. Further

Considering the goodness-of-fit statistics and the statistical evaluations discussed above, it is generally concluded that the MIKE 11 model can simulate the
workis in progress to improve the model performance in simulation of salinity intrusion by collecting additional data on salinity data. In addition, to have a general view of salinity intrusion in the Mekong Delta under the impact of climate change, we will take changes in discharge in the upstream into account in the simulation scenarios in the future study.

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