Assessing the impact of sea level rise due to climate change on seawater intrusion in Mekong Delta, Vietnam

D. T. Vu, T. Yamada and H. Ishidaira

ABSTRACT

In the context of climate change, salinity intrusion into rivers has been, and will be, one of the most important issues for coastal water resources management. A combination of changes, including increased temperature, change in regional rainfall, especially sea level rise (SLR) related to climate change, will have significant impacts on this phenomenon. This paper presents the outcomes of a study conducted in the Mekong Delta of Vietnam (MKD) for evaluating the effect of sea water intrusion under a new SLR scenario. Salinity intrusion was simulated by one-dimensional (1D) modeling. The relative sea level projection was constructed corresponding to the RCP 6.0 emission scenario for MKD based on the statistical downscaling method. The sea level in 2050 is projected to increase from 25 cm to 30 cm compared to the baseline period (in 2000). Furthermore, the simulated results suggested that salinity greater than 4 g/l, which affects rice yield, will intrude up to 50–60 km into the river. Approximately 30,000 ha of agricultural area will be affected if the sea level rise is 30 cm.

Key words | numerical model, salinity concentration, sea level rise, statistical downscaling method

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INTRODUCTION

Vietnam has a rice-based agricultural economy. Rice planting plays a significant role in agricultural activities. 82% of agricultural land is used for paddy rice. It creates 20% of total annual production, and provides 40% of the intake protein of the Vietnamese (Ricepedia 2008). The most productive agricultural zone of Vietnam is the Mekong Delta (MKD) (or Cuu Long Delta in Vietnamese). About 52 percent of the country's rice and nearly all rice exports are produced in the MKD. However, this region is vulnerable to natural disasters such as hurricanes, storm surges, and especially salinity intrusion due to its low elevation of less than 5 m above mean sea level. 1.7 million ha out of 3.9 million ha of land in MKD have been affected by salinity intrusion (Massouda 1974; Wassmann *et al.* 2004; Vu 2006; Vo 2012), leading to extensive economic losses. In the dry season of 2005, considered as a drought year with significant salinity intrusion in the MKD, the economic losses estimated by the Vietnamese Ministry of Agriculture and Rural Development were 45 million USD. These losses could intensify under sea level rise (SLR) in the future.

The effect of SLR on seawater intrusion has recently received considerable attention by researchers (Sherif & Singh 1999; Rice *et al.* 2012; Bhuiyan & Dutta 2012; Yuan *et al.* 2013; Hussain & Javadi 2016), whereas few studies have been carried out to evaluate seawater intrusion under SLR in MKD (Nguyen. 2008; IMHEN 2010; Trieu & Phong 2014) by employing several existing SLR scenarios for Vietnam from previous researches (Hoang 2005; IPCC 2007; MONRE 2009; MONRE 2012). Using an SLR scenario constructed for a large scale (i.e. Vietnam) to apply to the small scale (i.e. MKD) will not be able to reflect the degree of change in SLR. Our study highlighted construction of a relative sea level projection corresponding to the RCP 6.0 emission scenario for MKD based on the statistical downscaling method; and then use a 1D numerical model including hydrodynamic and advection-dispersion modules to evaluate changes to salinity intrusion. By constructing a new scenario from an empirical statistical method which is computationally inexpensive, and allowing for substantial flexibility, it is expected that the impact of salinity intrusion in the future

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can be investigated under the new approach. This study is among very few studies that have assessed seawater intrusion due to the sea level rise scenario from IPCC AR5 in MKD.

STUDY AREA AND DATA

The study area was MKD (Figure 1), which originates from China and flows through six countries before splitting into two branches called the Bassac River and the Mekong River in Vietnam. The delta area is approximately 39,000 km^2, of which 29,000 km^2 is used for agriculture. However, our study took into account the basin around the main river with an area of 22,000 km^2 (Figure 1). The area has characteristics of tropical monsoon weather, with two seasons; the rainy season starts from May to October and the dry season starts from November to April. From January to June, the average rainfall is very low in this area, at about 20–30% of total annual rainfall.

To assess salinity intrusion by 1D modeling, data at two in-situ hourly discharge stations, eight hourly water level gauging stations in estuaries from January to June of 2000 and 2001 were acquired for setting up boundary conditions. In addition, seven in-situ hourly discharge, water level and salinity data were gathered to calibrate and validate the model. The topographical data of the Mekong Delta were surveyed by the Southern Institute of Water Resources Research in 2004. To project SLR 21-year observed water level data (1993–2013), 35-year water level data (1978–2013) extracted from satellite image at Vung Tau station (VT) collected from Viet Nam Institute of Meteorology, Hydrology and Climate change (Figure 1), and the sea level data for the RCP6.0 averaged from 14 GCMs were used.

METHODOLOGY

Numerical model

Hydrodynamic model MIKE 11, developed by DHI water and environment for simulating flows, water quality and sediment transport in the rivers, estuaries, irrigation and other water bodies (DHI 2005), was selected to simulate salinity intrusion in this study. Of all modules in MIKE 11, the hydrodynamic module (HD) and advection-dispersion module (AD) will be used to compute salinity to rivers.

Hydrodynamic module

HD solves the two following basic equations, the equation of continuity and equation of momentum, to calculate

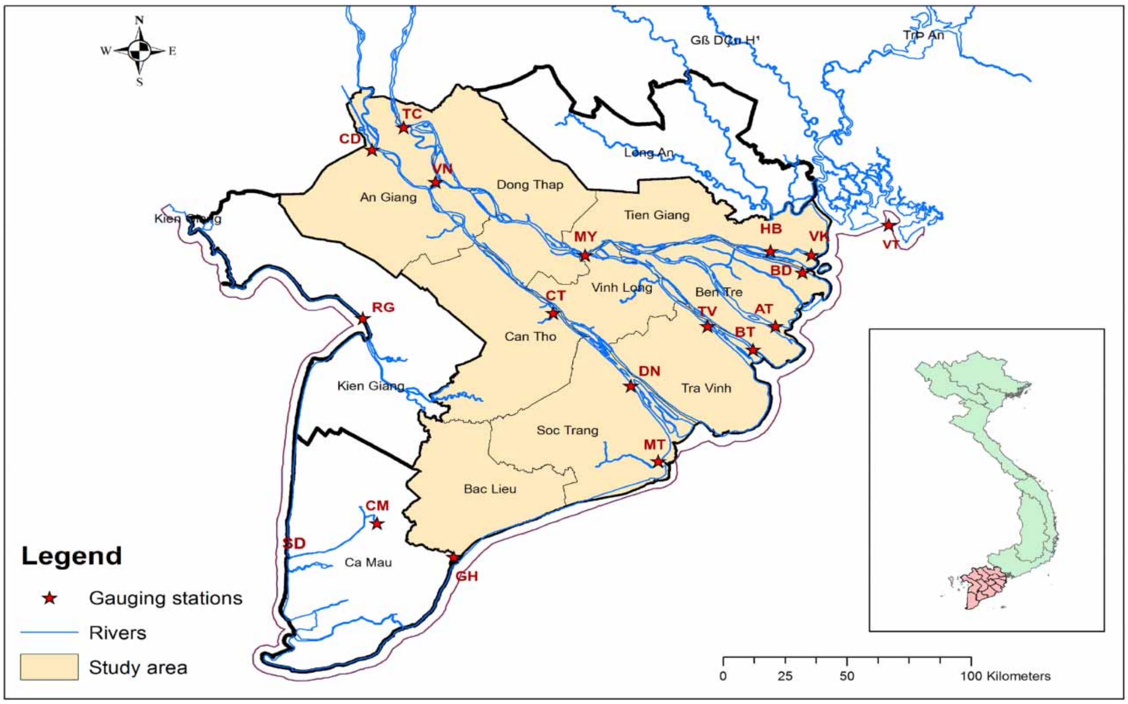

Figure 1 | Study area map and location of gauging station in Mekong Delta, Vietnam.

discharge and water level:

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

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

where Q is the discharge, A is the cross-section area, x is the space independent variable, t is the time independent variable, g is the acceleration gravity, h is the water stage, q is the lateral flow per unit length, R is hydraulic radius, C is the Chezy coefficient and α is kinematic energy correction factor.

Advection-dispersion module

AD depends on 1D equation of conservation of mass to estimate salt concentration:

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

C is the concentration, C_2 is the source/sink concentration, K is linear decay coefficient and D is the dispersion coefficient given by:

$$D = aV^b \tag{4}$$

where a is the dispersion factor and b is the dispersion exponent. Typical value ranges for D: 1–5 m^2/s (for small streams), and 5–20 m^2/s (for rivers).

Boundary conditions

The observed hourly discharge at two upstream stations, CD and TC (Figure 1), was defined as the upstream boundary for the HD module, whereas hourly water level at 5 downstream stations VK, BD, AT, BT, and MT was assigned Due to non-availability of observed salinity, the salinity at upper and lower boundary was set to a constant value of 0, and 33 g/L (salinity of sea water), respectively.

Using implicit finite difference scheme developed by Abbott & Ionescu (1967), allows Courant numbers up to 10–20 if the flow is clearly sub-critical (Froude number less than 1) Equations (1) and (2) were solved. And salinity intrusion was solved in Equation (3) by a fully time and space centered implicit finite difference scheme. NSE-Sutcliffe model efficiency coefficient and coefficient of determination R^2 were used to evaluate the performance of the model.

Statistical downscaling method

To develop a sea level rise scenario, there are various types of methods such as using direct General Circulation Model (GCM) outputs, applying a statistic downscaling model, applying dynamic downscaling model, using regional climate model (RCM), using interpolation method and extrapolation method. However, in this study, we construct relative sea level projection corresponding to RCP 6.0 emission scenario for MKD based on statistical downscaling method so called Model Output Statistic-MOS.

At first, input data series is divided in 2 groups, group 1 including 21-year observed sea level data (1993–2013) and simulated sea level data, and group 2 including 35-year sea level data extracted satellite images (1978–2013) and simulated sea level data to verify the uniformity based on evaluation of the correlation relationship. The simulated sea level data are the results from a combination of multiple GCMs under the RCP6.0 scenario. Representative Concentration Pathway, namely RCP6.0, was chosen because it is consistent with certain of Vietnam's socio-economic development. Fisher's test (F-test) and Student's test (t-test) were chosen to test the correlation coefficient in each group. Next, the transfer function will be determined depending on the best relationship between two groups of data. Finally, the local sea level rise until 2100 was downscaled using transfer function and the projected global sea level.

RESULTS

HD and AD module calibration and validation

The HD was calibrated with data from January to June, 2001, and then validated with data from January to June in 2000. The calibration process consists of adjusting Manning's roughness and initial water level of all rivers. The calculated outputs at typical stations such as Vam Nao (VN), My Thuan (MY) and Can Tho (CT) (Figure 1) agreed with observed discharge and water level data (Figure 2) with NSE and R^2 range from 0.79 to 0.9 (Table 1). Although there is an overestimation of observed discharge at the VN and underestimation of observed at the MY in some days, the model can successfully predict the overall trend of discharge.

The performance of the AD module was checked with comparison of observed and simulated salinity at three

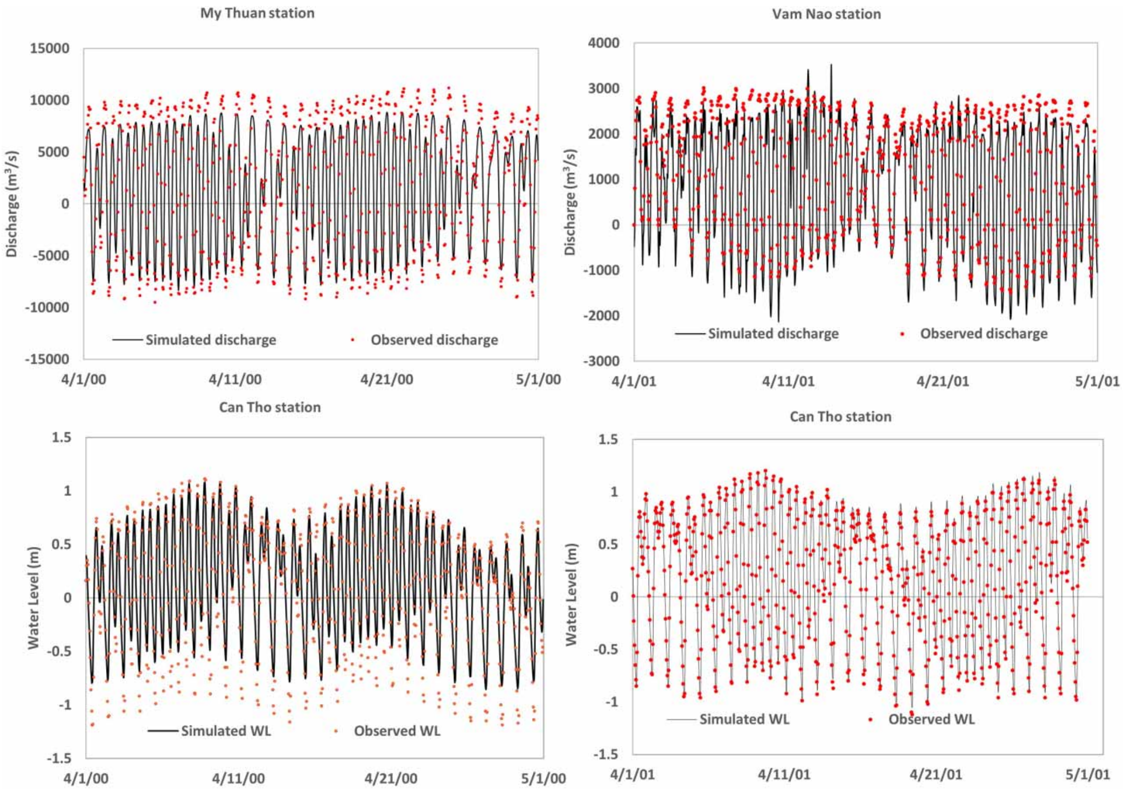

Figure 2 | Comparison between simulated results and observed data in My Thuan (MY), Vam Nao (VN) in the dry season 2001, and in Can Tho (CT) in the dry season 2000 and 2001.

Table 1 | HD module performance in calibration (2001) and in validation (2000)

	Observed discharge (m^3/s)		Simulated discharge (m^3/s)				
Station	**Max**	**Min**	**Max**	**Min**	**NSE**	**R^2**	**RMSE (m^3/s)**
VN (Vam Nao) (2001)	6,140	−1,700	6,151	−2,677	0.87	0.96	299.5
MY (My Thuan) (2001)	14,241	−9,250	15,625	−6,732	0.77	0.79	2766.9
	Observed water level (m)		**Simulated water level (m)**				
Station	**Max**	**Min**	**Max**	**Min**	**NSE**	**R^2**	**RMSE (m)**
CT (Can Tho) (2001)	1.46	−1.29	1.55	−1.26	0.79	0.80	0.12
CT (Can Tho) (2000)	1.29	−1.19	1.33	−0.86	0.74	0.78	0.13

stations such as Vam Kenh (VK), Binh Dai (BD), and Hoa Binh (HB) for the period of January to May in two years, 2001 and 2000 (Figure 3). The model performance is described in Table 2. These results demonstrate that the model results are acceptable, and the simulated salinity follows the similar trend to the observed salinity. Therefore, the model can be used to predict salinity in the rivers.

Salinity intrusion in 2000

Figure 4 shows the spatial distribution of salinity in the river and in the basin around the river in the year 2000. The salinity concentration indicated here is maximum average monthly salinity. The magnitude and distance of salinity intrusion are different in each river and province. In general,

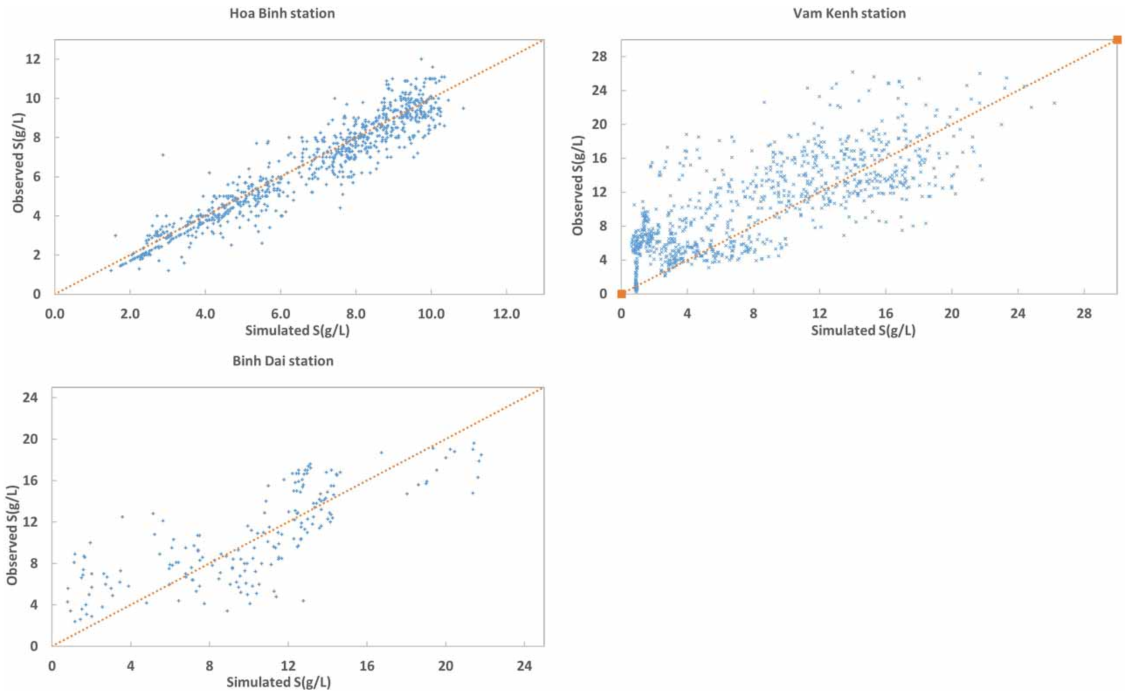

Figure 3 | Comparison between simulated results and observed data in salinity in Vam Kenh (VK), Binh Dai (BD) in the dry season 2001, and in Hoa Binh (HB) in the dry season 2000.

Table 2 | AD module performance in calibration (2001) and in validation (2000)

Station	Observed salinity (g/l) Max	Observed salinity (g/l) Min	Simulated salinity (g/l) Max	Simulated salinity (g/l) Min	NSE	R^2	RMSE (g/l)
HB (Hoa Binh) (2000)	12.0	1.2	10.9	1.5	0.69	0.72	0.8
VK (Vam Kenh) (2001)	26.2	0.00	26.2	0.2	0.71	0.8	3.8
BD (Binh Dai) (2001)	21.9	0.00	20.8	0.3	0.78	0.82	4.4

the salinity with a concentration greater than 4 g/l, which affects rice yield, has intruded up to 30–40 km into the rivers and the area around the river, especially the provinces very near the sea such as Soc Trang, Tra Vinh, and Ben Tre. Areas that are close to the sea reached very high salinity up to 30–35 g/l. The salinity concentration reduces when it goes up to the upstream river. In Ben Tre province, because of having salinity control structures, the salt concentration only intrudes up to 10 km into the river. Meanwhile, Tien Giang province recorded the maximum length of salinity intrusion, up to 50 km, with the maximum salinity of 20 g/l.

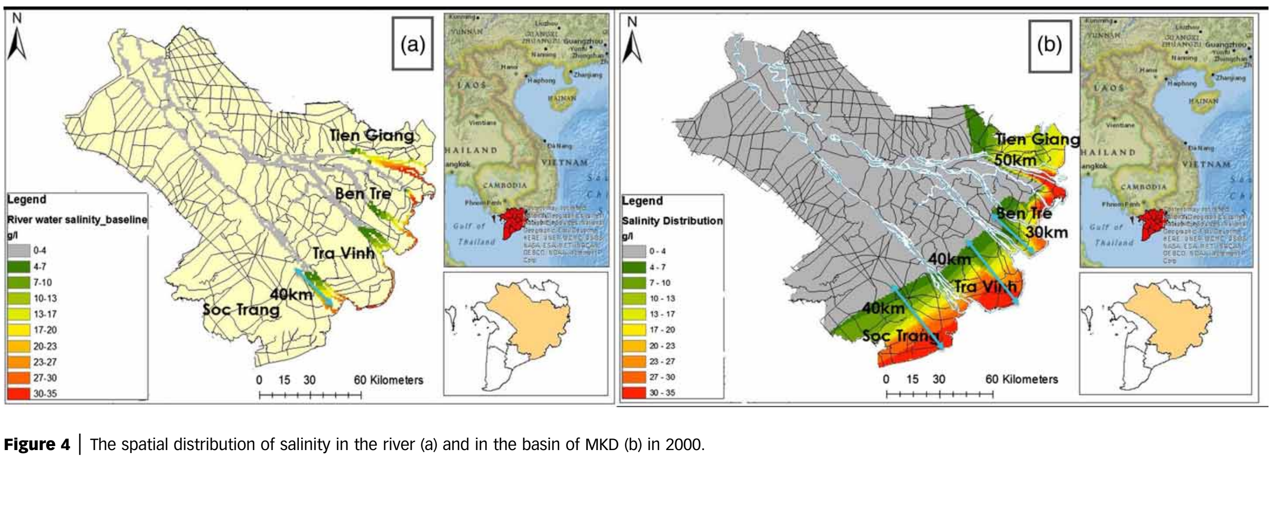

Figure 4 | The spatial distribution of salinity in the river (a) and in the basin of MKD (b) in 2000.

Sea level rise scenario

The results from assessment uniformity criteria using t-test and F-test at 5% significance level for two groups show that there exists a relationship between two series data in each group. The correlation relationship of group 1 (R = 0.82, Standard error = 1.98) is better than group 2 (R = 0.49, Standard error = 5.14). Therefore, the 21-year observed sea level data were used for local sea level rise projection (Figure 5).

The sea level rise is expected to continue beyond the end of this century at high speed (average 5–7 cm per 10 years); the period from 2005 to 2100 especially will have a rate of sea level rise much faster than the period from 1978 to 2005. The sea level in 2050 is projected to increase from 25 cm to 30 cm compared to the sea level in 2001, while it is projected to increase from 60 cm to 78 cm in 2100. The result is compatible with predicted sea level rise estimated by MONRE (2016). MONRE indicated that the sea level will rise by 14 to 31 cm in 2050, and 37 to 81 cm in 2100 in MKD using the IPCC method calculated as the sum of eight components, including thermal expansion, ice melting, surface mass balance in Greenland and the South pole, ice sheet dynamic in Greenland and the South pole, glacial isostatic adjustment, and land water storage.

Salinity intrusion in 2050

In this scenario, only sea level rise induced by climate change was considered. The result indicates that the seawater intrusion length tends to increase by 10 km in estuary areas, especially in the Tien Giang province, and affects the river basin (Figure 6). A salt concentration larger than 4 g/l, which can affect crops, will shift upstream 50 km to 60 km, and there will be a supposed increment of 0.5 g/l to 2.5 g/l in places about 15 km from the sea in 2050. A salinity increase of 1–1.5 g/l will intrude up to 30 km. Also, no change in salinity is recorded in the area of the estuaries because these regions have reached the maximum salinity concentration.

DISCUSSION AND CONCLUSIONS

According to the results, four out of eight farming provinces including Tien Giang, Ben Tre, Tra Vinh and Soc Trang (see Figure 1 for location) in the research area are affected seriously by salinity intrusion in the context of sea level rise. The agriculture area affected by medium salinity (greater than 4 g/l) will expand by 30,000 ha (Figure 7). According to the rice production data from the Ministry of Agricultural and Rural Development, the average rice production in

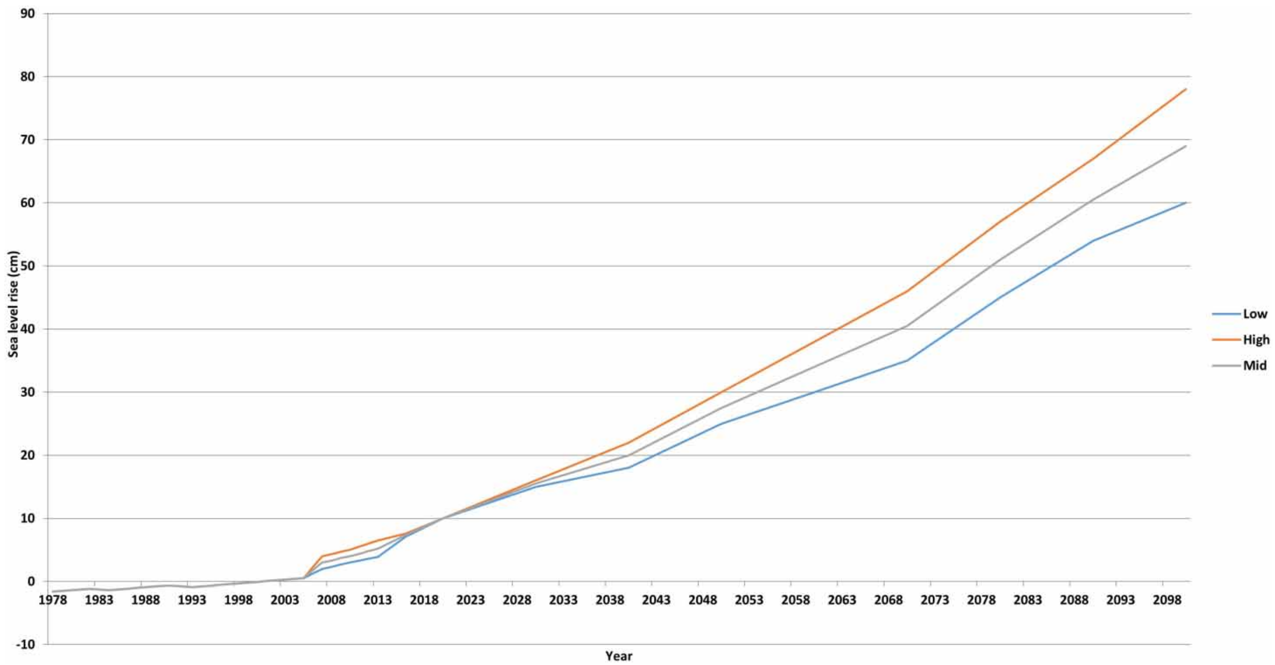

Figure 5 | Projection of sea level rise for Mekong Delta, Vietnam under RCP 6.0 scenario for the period 2020–2100.

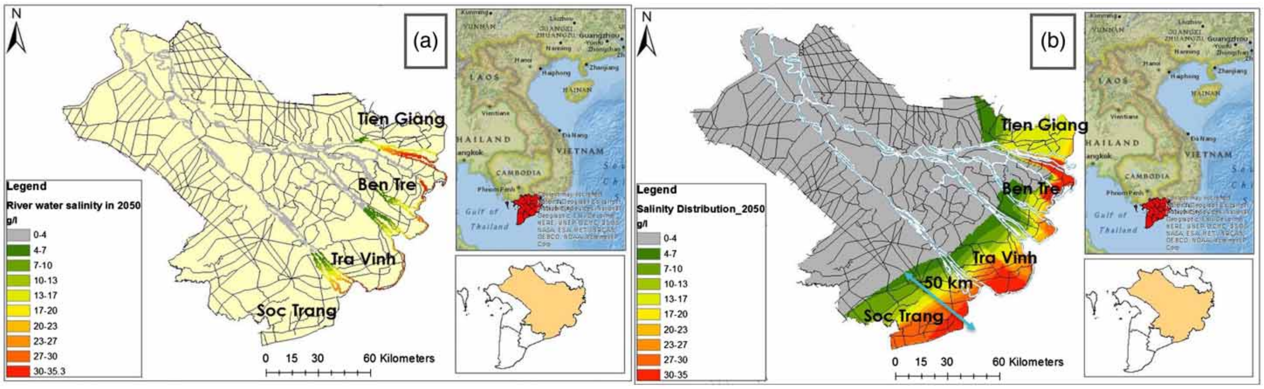

Figure 6 | The spatial distribution of salinity in the river (a) and in the basin of MKD (b) in the dry season 2000.

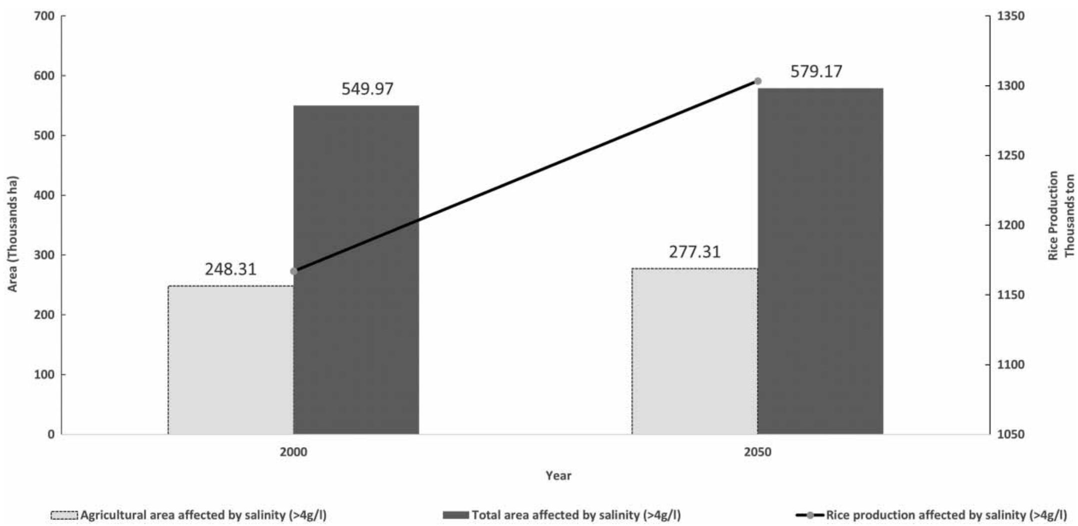

Figure 7 | Area affected by salinity of irrigation water in 2000 and 2050.

MKD in 2015 is approximately 8 tons/ha. So, that is roughly equivalent to a loss of 240,000 tons of rice.

There always exist errors and uncertainty in modeling due to its simplification of reality, but it is also relatively useful. Therefore, it is very important to be aware of errors when using models. We employed two modules in 1D modeling: the HD module and the AD module, to calculate and predict the salinity in the present, and in the future. There are possible source errors in these two modules, including errors from topography, cross-sections, and lack of long term salinity, and discharge data. The statistical downscaling method depends mainly on the basis of using climate change scenarios for Vietnam in 2011, combined with the results from scenarios 6.0 RCP (Representative Concentration Pathways). Thus, in further study, comparing with other methods is the best way to improve the accuracy of the results.

This research was conducted to evaluate the salinity intrusion situation in the MKD, Vietnam currently, and for different amounts of sea level rise under future climate conditions for the Mekong River Delta. A set of parameters has been calibrated, including roughness coefficient n and dispersion coefficient D in the main rivers of the Mekong River system with high reliability, and a new sea level rise scenario for MKD was constructed. The sea level is projected to increase with higher speed in the future under effects of climate change. The research hopes to contribute significantly to irrigation water management, land use planning, and salinity control strategies, and a 'Smart agriculture' development adapted to climate change in future (FAO 2013) for MKD.

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