

## SALINITY DYNAMICS UNDER SEA LEVEL RISE SCENARIOS IN THE RED – THAI BINH RIVER DELTA, VIETNAM

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### ABSTRACT

Salinity dynamics in the Red – Thai Binh River delta in Vietnam is now becoming a highly concerning issue, for its freshwater is an essential supply for sanitation, agriculture and industry in the North of Vietnam. This study investigates current and future river hydrodynamics and seawater intrusion under sea level rise scenarios, by using 1D model MIKE 11. Simulations indicate an increase trend in maximum salinity concentrations in each river branch from the current condition to 2100 for two sea level rise scenarios (RCP4.5 and RCP8.5). A noticeable intrusion of salinity is expected to occur in the main stream of Red River, while Thai Binh River systems should be affected by a less intense, but still considerable, impact. Two salinity thresholds 1 ‰ and 4 ‰ are also considered for agriculture purposes; their assessment shows a significant salinity increase from baseline year to 2100 RCP8.5.

*Keywords:* salinity, sea level rise, water level, discharge

### 1. INTRODUCTION

Seawater intrusion into river deltas has recently emerged as an increasingly serious threat to coastal areas, due to the higher rate of freshwater exploitation, the decrease in riverflow and the sea level rise (SLR). The extensive intrusion of seawater limits the amount of available freshwater, as river waters and groundwaters feature high levels of salt, which are very harmful to humans, flora and fauna eco-systems Oude (2001). According to standards of different countries, at a certain level of salinity, the water could cause damage to plants, animals and even human health, being withdrawn for irrigation or drinking water purposes.

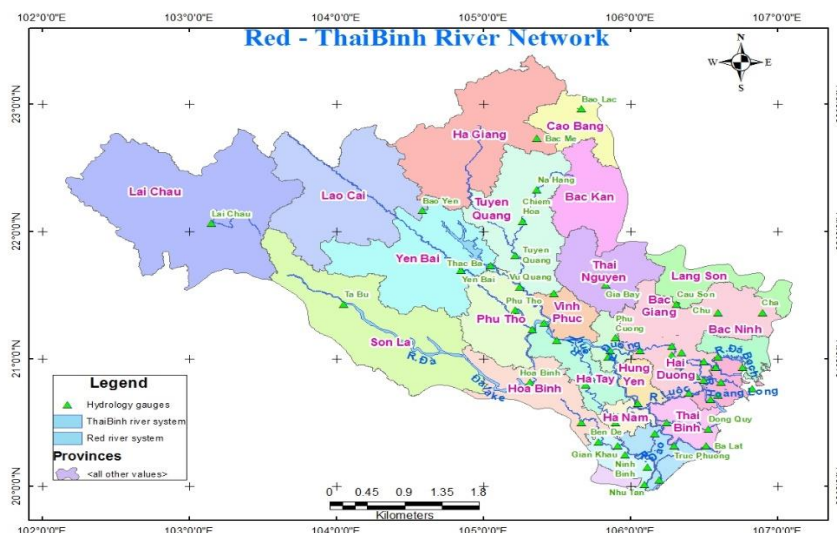


Figure 1. Red - Thai Binh River network

An emblematic example is provided by the delta of Red – Thai Binh River (Figure 1), which is the second largest river in Vietnam and covers many coastal provinces along its nine flat estuaries. The combination of tidal effects and low discharges presently leads to frequent and severe seawater intrusions, which are compromising the ecological services of this humid habitat and are affecting the socio-economic development (Nguyen, N.T, Trinh, H.T., 2013; Hien et al., 2018). In addition, the development of hydraulic structure such as dikes, embankments along the river is decreasing the sediment transport. This coupled with high subsidence rates in the area is leading to a great vulnerability to saltwater intrusion. Nevertheless, there are still a few researches on the whole river system (Thi et al, 2016). Actually, hydrodynamic analyses require a large amount of data and involve an intense computational effort to model this large river network.

The research, hence, evaluates current and future river hydrodynamics and salinity dynamics, by using a model developed in MIKE 11, calibrated through field data and conditioned by different SLR scenarios. Observations of salt concentrations and hydrologic variables have been collected since 1960, while SLR scenarios were updated according to MONRE (Vietnamese Ministry of Natural Resources and Environment) report 2016 for RCP4.5 and RCP8.5 in 2050 and 2100.

## 2. INPUT DATA AND MODEL EVALUATION

The data are collected on the Red – Thai Binh River for the numerical model MIKE 11 simulation includes water level, discharge, salt concentration in 2010 and 2011 and river morphology through cross sections of all simulated streams from the survey in 2000 to 2006.

MIKE 11 developed by DHI Water and Environment is a professional engineering software package for the simulation of flow, water quality and sediment transport at the estuary, river, irrigation system, canals and other water body. This is a user-friendly, fully dynamic and one-dimensional tool for detailed analysis, design, management and operation of both simple and complex river and channel systems. With its flexibility, speed and user-friendly environment, MIKE 11 provides a complete and effective design environment for engineering and water resources, water quality management and planning application.

The modeling river network includes the Da river starting from downstream of Hoa Binh River, the Thao River from Yen Bai hydrology station, the Chay River from downstream of Thac Ba reservoir, Lo River from Ham Yen hydrology station, Gam River from downstream of Tuyen Quang reservoir, Pho Day River from Quang Cu station, the Cau River from downstream of Thac Huong dam, the Thuong River from Cau Son hydrology station and the Luc Nam River from Chu station. In general, the model boundary conditions are described in Figure 2.

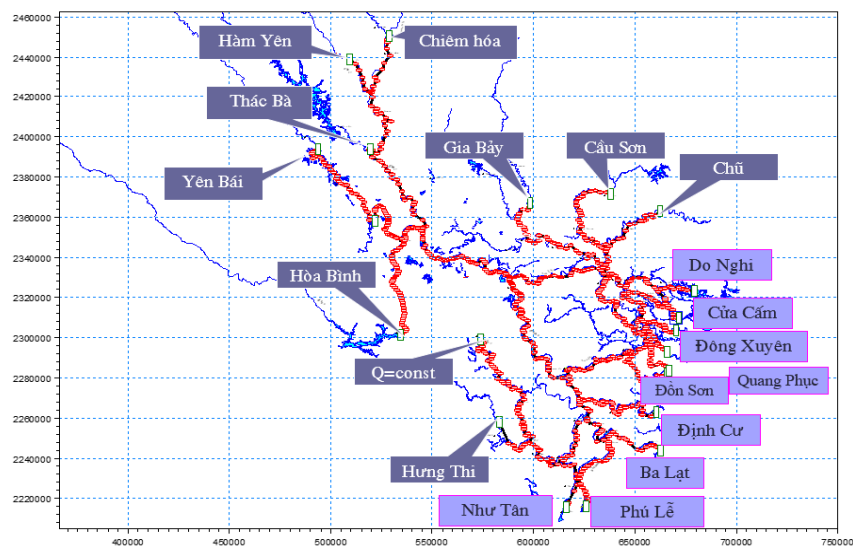


Figure 2. River network in MIKE 11

*Upstream conditions:* discharge including Hoa Binh (Da river), Yen Bai (Thao river), Thac Ba (Chay river), Ham Yen (Lo river), Chiem Hoa (Gam river), Phu Cuong (Ca Lo river), Thac Huong (Cau river), Cau Son (Thuong river), Chu (Luc Nam river), Ba Tha (Day). *Downstream conditions:* water level and salinity at Do Nghi (Da Bach river), Cua Cam (Cam river), Kien An (Lach Tray river), Quang Phuc (Van Uc river), Dong Xuyen (Thai Binh river), Dinh Cu (Tra Ly river), Ba Lat (Red river), Phu Le (Ninh Co river), Nhu Tan (Day river). The complex river network is imported into the model by considering 36 branches of about 800 cross sections.

Testing stations used to evaluate the model performance for water levels, discharges and salt concentrations are selected along the river network as described in Figure 3, where H is the water level, Q is the riverflow discharge and S is the salt concentration.

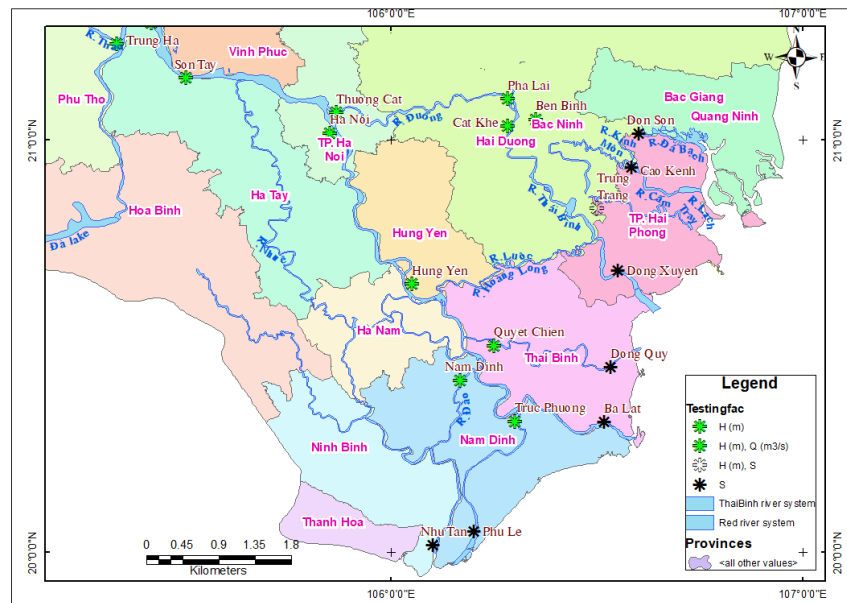


Figure 3. Testing stations for MIKE 11 model

## Model Evaluation

In this research the dry year 2010 was used for model calibration and 2011 was used for model validation according to the available hydrological data which shows a very low water level and less rainfall during dry season. The simulation periods span from 20/01/2010 to 28/02/2010 and from 20/01/2011 to 28/02/2011. Table 1 and 2 show the calibration results of hydrodynamic module (HD) and Advection – Dispersion (AD) module in all station using different criteria while Figure 4 illustrates the observed and calculated water levels and discharges, as well as, salt concentrations.

Table 1. Hydrodynamic calibration results at testing stations

Station	River	Max: H(Q); (m)/(m <sup>3</sup> /s)		$\Delta H(\Delta Q)$ (m)/(m <sup>3</sup> /s)	NSE (%)
		Calculated	Observed		
Trung Ha (H)	Da	9.67	9.64	0.03	95.2
Viet Tri (H)	Lo	6.89	7.34	-0.45	93.4
Son Tay (H)	Hong	5.52	5.5	0.02	98.5
Son Tay (Q)	Hong	2266	2590	-324	92.8
Thuong Cat (H)	Duong	2.23	2.21	0.02	95.1
Thuong Cat (Q)	Duong	1050	1000	50	86.3
Ha Noi (H)	Hong	2.4	2.38	0.02	93.2
Ha Noi (Q)	Hong	1420	1530	-110	90.3
Hung Yen (H)	Hong	1.72	1.62	0.1	86.3
Quyet Chien (H)	Tra Ly	1.54	1.53	0.01	90
Pha Lai (H)	Thai Binh	1.78	1.57	0.21	83.6
Ben Binh (H)	Kinh Thay	1.72	1.66	0.06	90.5
Cat Khe (H)	Ninh Co	1.77	1.68	0.09	91.3
Trung Trang (H)	Van Uc	1.68	1.57	0.11	84.5

Table 2. Advection – Dispersion calibration results

No	Station	Maximum salinity (%)		Time to peak difference (hrs)	Relative Error %
		Observed	Calculated		
1	Phu Le	25.6	25.5	0	0.5
2	Nhu Tan	18.9	18.8	2	0.08
3	Dong Quy	25.5	25.1	1	1.6

No	Station	Maximum salinity (‰)		Time to peak difference (hrs)	Relative Error %
		Observed	Calculated		
4	Trung Trang	6.6	6.8	2	4.1
5	Dong Xuyen	12.3	12.8	2	4.1
6	Cao Kenh	1.6	1.5	1	0.3
7	Ba Lat	23.5	24.3	2	3.7
8	Don Son	4.9	5.2	3	5.7

Such results show a satisfactory agreement between the computed values and observations for both HD and AD modules. The observation and the computed time patterns describe reasonable trends, especially for the water level at upper station e.g Trung Ha, Son Tay, Thuong Cat and Ha Noi, which feature Nash-Sutcliffe Efficiencies NSE greater than 90%. However, some of the stations have satisfactory NSE values. Yet, they evidence a discrepancy between the simulated and observed water level patterns. This could be explained by the strong tidal effects affecting these downstream stations. In general, the peak estimates and NSE of water level, discharge and salinity lie in acceptable ranges confirming the suitability of the model parameterization to be applied in the validation phase.

Table 3 and 4 report hydrodynamic and advection – dispersion module validation results, while the Figure 5 presents computed and observed values in the river network.

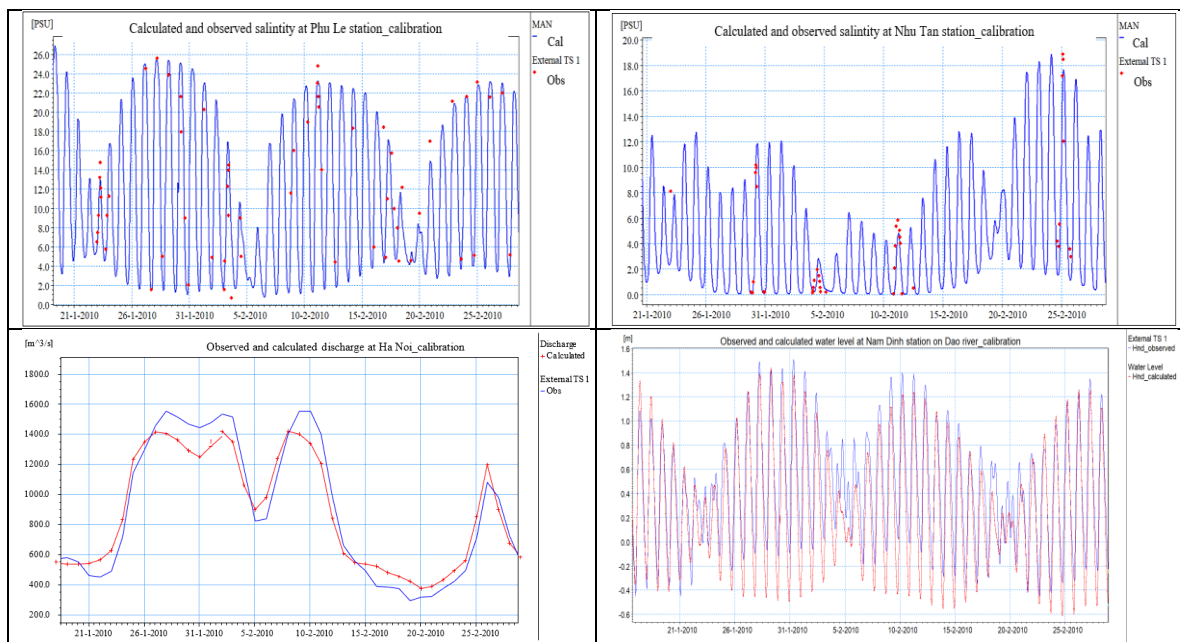


Figure 4. Computed and observed values at different stations for both HD and AD modules in calibration step

Table 3. Hydrodynamic validation results at testing stations

No	Station	River	Hmax(Qmax) m(m <sup>3</sup> /s)		$\Delta H(\Delta Q)$ m(m <sup>3</sup> /s)	NSE (%)
			Calculated	Observed		
1	Son Tay (H)	Red	5.4	5.42	-0.02	99.4
2	Son Tay (Q)	Red	2488	2570	-82	99.9
3	Thuong Cat (H)	Duong	2.24	2.2	0.04	96.3
4	Thuong Cat (Q)	Duong	1121	1200	-79	86.7
5	Ha Noi (H)	Hong	2.43	2.48	-0.05	86.3
6	Ha Noi (Q)	Hong	1479	1770	-291	91.1
7	Pha Lai (H)	Thai Binh	1.5	1.51	-0.01	85.8
8	Ben Binh (H)	Kinh Thay	1.44	1.58	-0.14	90.8
9	Cat Khe (H)	Thai Binh	1.47	1.6	-0.13	86.3
10	Dong Xuyen (H)	Thai Binh	1.51	1.69	-0.18	80
11	Trung Trang (H)	Van Uc	1.35	1.54	-0.19	80
12	Kien An (H)	Lach Tray	1.55	1.6	-0.05	93.5

Table 4. Advection – Dispersion module validation results

No	Station	Maximum salinity (‰)		Time to peak difference (hrs)	Relative Error %
		Observed	Calculated		
1	Phu Le	23.9	25	1	4.4
2	Nhu Tan	25	28	3	10.7
3	Dong Quy	26	24	2	7.7
4	Trung Trang	1.1	1.03	1	6.4
5	Dong Xuyen	11	12.1	3	9.1
6	Cao Kenh	1.3	1.29	2	0.15
7	Ba Lat	27.5	29.5	2	7.3
8	Don Son	2.2	2.3	4	4.3

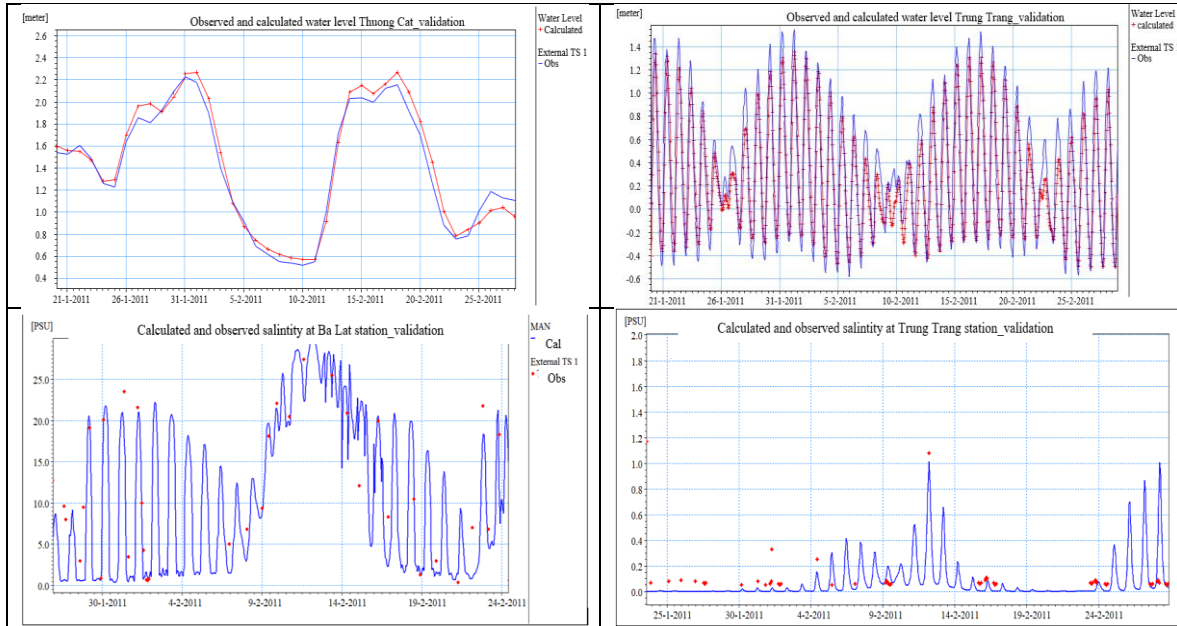


Figure 5. Simulation results and observations in the validation phase at different stations

The validation results provide a demonstration of model performance goodness both for hydrodynamics and salinity dynamics in the whole river system. As can be seen in Figure 5, discharge and water level follow very similar patterns, being the NSEs greater than 80%. Similarly, the salinity dynamics demonstrates comparable patterns between observations and computations, featuring very close times to peak.

In consideration of the observation and calculated values for both hydrodynamics module and advection-dispersion module on Red- Thai Binh River network, the model is assumed to be capable of simulating the future regime under different sea level rise scenarios. The good performance of MIKE 11 specifically on the river network was also verified in different researches in Vietnam (e.g Viet, 2011, Duc et al., 2014). Therefore, the study was developed towards the simulation of the river hydrodynamics and seawater intrusion in the future under different sea level rise scenarios.

### 3. SALINITY UNDER SEA LEVEL RISE EFFECT

Two sea level rise scenarios corresponding to RCP 4.5 and RCP 8.5 are considered for the period of 2050 and 2100. Seawater intrusion profile are then, presented along the selected rivers accordingly.

#### 3.1 Salinity profile in the Hong River (main branch in Red River delta)

The maximum salt concentration on the Hong River varies significantly from 0‰ to 30‰ with respect to the year and scenario as shown in figure 6. In general, the gradual increase trend in salinity is clearly seen throughout the years, especially near the river mouth e.g from base timeline to 2100 RCP 8.5, maximum salt concentration is predicted to grow up to 9.12‰ at the distance of 20 km from the sea.



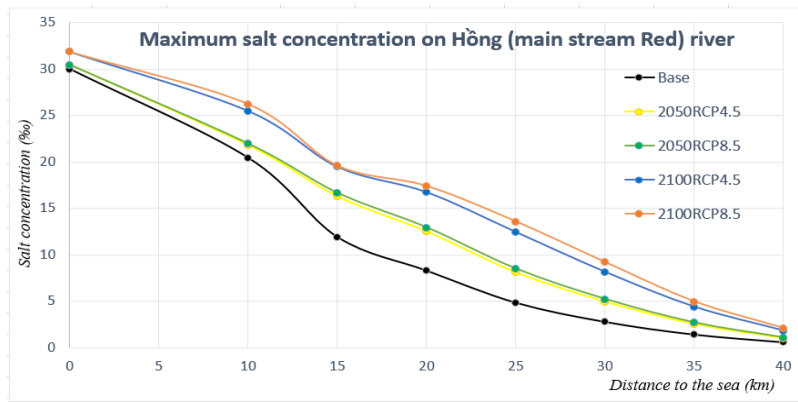


Figure 6. Maximum salt concentration on mainstream Red River at different scenarios

First of all, the seawater interface is expanding until approximately 40 km from the sea for both SLR scenarios in 2050 and 2100. The higher the sea level rises, the higher the salt concentration is. In particular, the noticeable reduction in maximum salt concentration is found in 2100 at the rate of around 8.7-9.5 ‰/km in the first 10 km from the sea. The second section, between KM15 to KM20, the rate decreases down to about 6‰/km. Moreover, similar trends are predicted in the year 2050 for both SLR scenarios, featuring a lower value of salinity reduction rate around 1‰/km all along the river. It is also understandable that salt concentration slightly decreases from the river mouth toward upstream.

In addition, at the section of more than 40 km, the maximum salt concentration is quite stable at around 1‰ in 2050 (both RCP 4.5 and 8.5). Nevertheless, in 2100 RCP 8.5, this value could reach up 2.1‰, closely followed by 1.8‰ for the RCP 4.5. A dramatic variation of salinity over the years is predicted at the distance of 20 to 25 km from the sea. The two thresholds 1 ‰ and 4 ‰ in 2100 RCP 8.5 are forecasted to move upstream of about 38 km and 32 km, respectively; such values are estimated in 35 km for 1 ‰ and 27 km for 4 ‰ in 2050.

### 3.2 Salinity profile in the Day River

The maximum salt concentration drops significantly from KM10 for all the considered SLR scenarios; such a river section represents a sharp salinity interface. At the distance of 35-40 km from the sea, maximum salinity slightly changes from around 0.92‰ to 0.47‰ between 2100 and 2050. The noticeable changes in salinity from current to 2100 RCP8.5, on the other hand, are found at KM32 at the pace of 4.47‰. Salt concentration is also predicted to increase about 3‰ and 4‰ at KM15 and KM20, respectively.

Seawater intrusion as could be seen from the profile in the Figure 7 could invade rapidly to upstream of the Day river in all the scenarios. Particularly, the threshold of maximum 4‰ in 2050 RCP 4.5 is forecasted to be found at the distance of around 25.69 km, then expands for approximately 3 km in 2100. By comparison, its quick extension is predicted also for the threshold 1‰ from 32.6 km in 2050 to almost 35 km in 2100 RCP8.5.

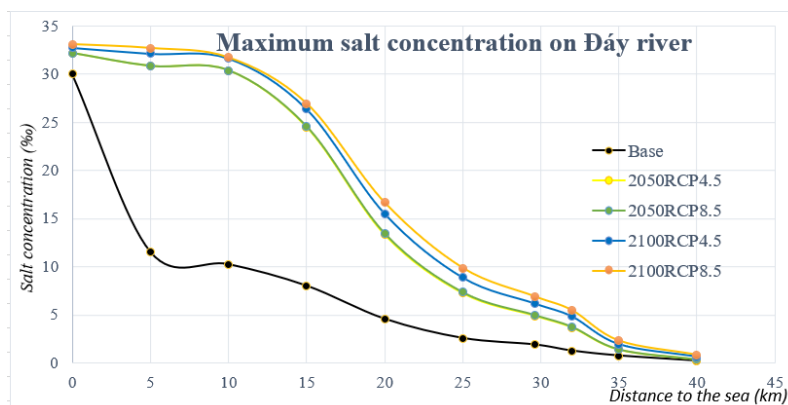


Figure 7. Maximum salt concentration on the Day River at different scenarios

### 3.3 Salinity profile in the Tra Ly River

The variation of maximum salt concentration on the Tra Ly follows similar trend in both RCP4.5 and RCP8.5 over the two periods of time, with only a dramatic rise in 2100 RCP8.5 as demonstrated in Figure 8. In general, maximum salinity doesn't change much in the first 5km from the sea which also evidences a negligible effect of sea level rise. The section between 15 to 25km shows the highest decrease in maximum salt concentration throughout the years. Particularly, the section of 5km between 20 and 25km from the sea, salinity decrease about 13‰/km in 2100, following by the last 10km from the sea with about 6.7‰/km.

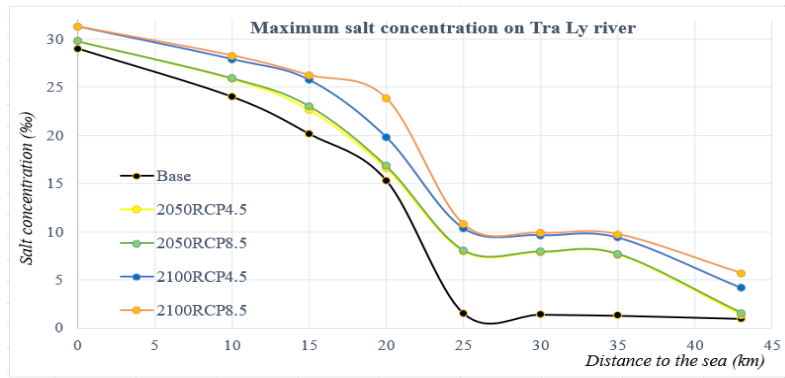


Figure 8. Maximum salt concentration on the Tra Ly River

The second part from 25 to 35 km, maximum salinity almost remains stable at about 8‰ to 10‰ from 2050 to 2100. Seawater intrusion in Tra Ly River is predicted at 43 km even up to 5.7‰ in 2100 RCP 8.5 and less than 1.5‰ in 2050, whereas this value is about 0.86‰ in the baseline. Salinity goes up significantly to about 8.5‰ from base timeline to 2100 RCP8.5 at KM20, followed by KM15 with 4.46‰.

Considering the salinity thresholds, it seems that there will be a gradual moving back in 4 ‰ up to almost 15 km over 50 years. In details, 4 ‰ could locate at the distance of around 25 km in 2050 for both scenarios, and about 35 km and 39.4 km in 2100 RCP 4.5 and RCP 8.5, respectively. Similarly, the Tra Ly River also should experience a notable growth of 1 ‰ from 34.67 km in baseline to 40.94 km in 2100. These changes in the river are considered to be the most severe effects of seawater intrusion in the river system in response to sea level rise scenarios in the future.

### 3.4 Salinity profile in the Thai Binh River

Salinity dynamics on the Thai Binh River, on the other hands, shows very less variation throughout the years and scenarios of SLR, especially at the distance of less than 10 km from the sea and KM20 toward upstream as illustrated in Figure 9.

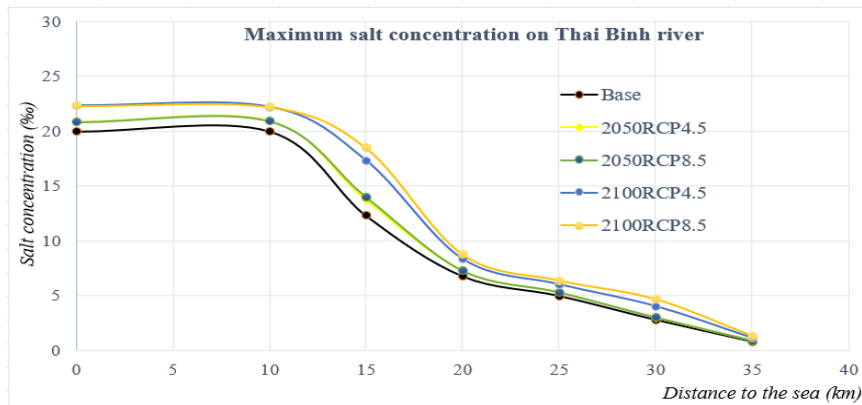


Figure 9. Maximum salt concentration on the Thai Binh River at different scenarios

Seawater intrusion could stretch up to approximately 39 km from the sea over the years with the furthest distance in 2100 RCP8.5 of about 41 km. The largest variation of maximum salt concentration is predicted between the sections from 10 km to 20 km. Therein, the highest salinity growth is forecasted at KM 15 and amounts to about 6 ‰ from baseline to 2100 RCP8.5. It is expected that there is less variation in salinity in the area of the first 10 km from the sea on Thai Binh River, because of the flat estuary and the Van Uc River confluence. Similarly, a trivial change in 1 ‰ and 4 ‰ over the years on the Thai Binh River is expected. In 2050, 1 ‰ and 4 ‰ could occur at the distance of 29 km and 24 km, respectively, thus, extend a bit further of around 1 km to 2 km in 2100.

### 3.5 Salinity profile in the Van Uc River

As a tributary of the Thai Binh River system, the Van Uc River seems to be affected by the least significant changes in maximum salt concentrations with respect to both 2 SLR scenarios. In particularly, the first 10 km from the sea and the section between 25 km to around 40 km, salinity dynamics is predicted to be quite stable over the years. Figure 10 shows the salinity dynamics on the Van Uc River from baseline to 2100 RCP8.5. However, at the distance of 10 to 20 km, there is a very steep slope of saltwater intrusion in the river. In particular, the section between 15 km to 20 km from the sea, maximum salinity decreases with the rate of about 9‰/km in 2050 and 15‰/km in 2100 RCP8.5.

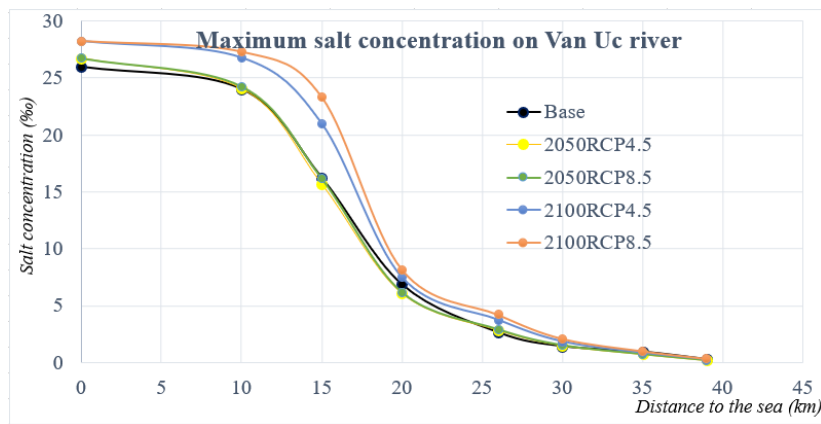


Figure 10. Maximum salt concentration on the Van Uc River at different scenarios

The lower rate of reduction in salt concentration is predicted in 3.9 ‰/km from KM10 to KM15 in 2050 and 9 ‰/km in 2100. Furthermore, maximum salt concentration is forecasted to increase gradually over the years from 1.48 ‰/km to 9.44 ‰/km within the distance of 26 km and 15 km, respectively. The maximum threshold of 4 ‰ on Van Uc River varies between the distance of 24 km to 27.5 km throughout the years and scenarios. Moreover, the threshold of 1 ‰ shows to change slightly over the time only about 2.09 km in 2100 from around 34.1 km in baseline.

#### 4. CONCLUSIONS

The research shows scenarios of a severe intrusion of salinity in the delta of Red – Thai Binh River network from the current situation till the end of the century. In general, salinity dynamics in the whole river delta is suitably represented by MIKE 11 1D hydrodynamics and advection-dispersion modelling. The future dynamics simulations predict an increase trend in salt concentrations over the years and SLR scenarios in all of the rivers, especially in main branch of the Red River. Conversely, the least effect is predicted in Thai Binh minor branches and the Van Uc River. The effect of sea level rise is dominant mostly at the distance of less than 25 km from the sea in most of the rivers while upstream, minor impacts of the sea level rise are foreseen. These outcomes quite agree with those of other researches in the Red River Delta (Nguyen, 2008; On et al., 2014; Hien et al., 2018). The study has only taken surface waters into account to examine saltwater intrusion in the delta using 1D modelling. However, the groundwater uptake is now greatly increasing in the area for the growing population's demand rise. This intensifies pressure on ground waterbodies in the coastal zone. Therefore, future researches will have to focus on groundwater salinity dynamics, to evaluate and determine salt concentration profiles in both vertical and horizontal ways.

#### ACKNOWLEDGMENTS

The authors are thankful to the Vietnam Institute of Meteorology, Hydrology and Climate Change for the data providing, the University of Brescia for financial support to conduct the study and the Italian Development Cooperation Agency.

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