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Salinity dynamics under different water management plans coupled with sea level rise scenarios in the Red River Delta, Vietnam

Nguyen Thi Hien [a], Nguyen Hai Yen [a], Matteo Balistrocchi [b], Marco Peli [a], Vu Minh Cat [c], Roberto Ranzi [a,*]

[a] *Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, via Branze 43, 25123 Brescia, Italy*
[b] *Department of Engineering Enzo Ferrari, University of Modena and Reggio Emilia, via Pietro Vivarelli 10, 41125 Modena, Italy*
[c] *Faculty of Marine and Coastal Management, Thuyloi University of Vietnam, 175 Tay Son, Dong Da, 10000 Hanoi, Viet Nam*

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ABSTRACT

In recent years, saltwater intrusion in river estuaries has become more severe and frequent worldwide. The common reasons lie in increasing freshwater withdrawal, river flow regulation and sea level rise due to global warming. In particular, the Red River Delta in northern Vietnam is facing a strong population growth worsening the pressure on freshwater resources for drinking water and irrigation needs. During the dry season, increasing conflicts and constraints in freshwater availability have already been experienced. Adverse combinations of river flow regulations and high sea levels lead to severe upstream propagations of salinity. This study takes advantage of a statistical characterization of discharges released from Hoa Binh reservoir and observed at Son Tay station, the main river flow control upstream of the river delta, along with downscaled and updated sea level rise scenarios to estimate the future extents of saltwater intrusion under different options of water release from reservoirs in the dry season. To do so, a 1D hydraulic model of the river delta network was implemented using MIKE11 software. The hydraulic and the quality modules were calibrated and validated with respect to the present scenario by using water stages and salinity concentrations observed in estuary branches. Sea level rise projections for 2050 and 2100 referred to RCP4.5 and RCP8.5 AR5 emission scenarios were then considered. Results show that river flow regulation can provide an effective mitigation measure. A 20–30% increase in the discharge released from the Son Tay station would be beneficial to push downstream the saltwater intrusion in the main Red River branch during the dry season. For instance, in 2050 the 1‰ salt concentration front is expected to be pushed back at least 6 km when the exceeding probability of the discharge released by Son Tay station decreases from 95% to 25%.

1. Introduction

Saltwater intrusion is the upstream flux of saline water into the freshwater zone, affecting both river-flows and groundwaters. This phenomenon can be observed in coastal aquifer and estuaries as a result of the higher density of saltwater than freshwater. Unfortunately, high salinity levels in drinking water could lead to hypertension, especially for pregnant women, with significant risks of high blood pressure, pre-eclampsia and infant mortality (Vineis et al., 2011, Rasheed et al., 2016, Islam and Majumder, 2012). Saltwater intrusion is worsening due to human activities, such as freshwater withdrawal and river-flow regulation in coastal areas, and to sea level rise (SLR) triggered by climate change (Oude Essink et al., 2010; Deng et al., 2017; Werner and Simmons, 2009; Abd-Elhamid and Javadi, 2008). Moreover, human pressure on coastal and estuarine freshwater resources is expected to increase, due to global population growth, migration from rural areas to urban areas (Creel, 2003) and the increase of life quality standards.

The two most important thresholds of salinity derived from general standards for agriculture and aquaculture in Vietnam, i.e. 1‰ and 4‰ concentration, expressed in terms of mass of salt per mass of water, are evaluated in this research (QCVN 08-MT:2015/BTNMT standards). If the salt concentration is less than 1‰, the water quality is acceptable for households and irrigation while if it is more than 4‰, water is considered as saltwater and cannot be used for any purposes or any type of

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* Corresponding author.
E-mail addresses: h.nguyenthi@unibs.it (N.T. Hien), h.nguyen001@unibs.it (N.H. Yen), matteo.balistrocchi@unimore.it (M. Balistrocchi), marco.peli@unibs.it (M. Peli), roberto.ranzi@unibs.it (R. Ranzi).

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crops. In the 1‰ to 4‰ range water can be used for agriculture, with some limitations and depending on the crop type.

The Intergovernmental Panel on Climate Change (IPCC) has outlined different climate change and SLR scenarios over the years in every Assessment Report since 1990 (AR1-6). The global mean SLR projections in Assessment Report 5 (AR5) of all Representative Concentration Pathways (RCPs) show that the rate of sea level rising in the 21st century is very probably higher than the observed rate in the period of 1971 to 2010 (IPCC, 2013), a projection confirmed with slightly worse scenarios in the AR6 (IPCC, 2021). The Vietnamese Ministry of Natural Resources and Environment (MONRE) published reports on climate change including SLR scenarios regarding the whole Vietnam coast (nine coastal regions) based on IPCC AR5 (MONRE, 2016). A substantial increase in sea levels in Vietnam is thus expected, which will likely enlarge the coastal areas vulnerable to saltwater, causing many drawbacks to aquaculture, agriculture and ecosystems and losses of local habitats and humid environments (Dasgupta et al., 2007). It is agreed that understanding the river flow and salinity responses to the sea level rise is fundamental for coastal habitats and ecosystems as well as for water resources management.

There are many studies dealing with saltwater intrusion assessment and mitigation under the effects of climate change, sea level rise or land use change and their combined impacts. Yang et al. (2015) investigated the influence of climate and land cover changes by examining the sea level rise and upstream discharge on salinity and water depth in the Snohomish River estuary. The research applied a Distributed Hydrology-Soil-Vegetation Model (Wigmosta et al., 1994) to estimate river flow discharges under different scenarios up to 2050. The watershed hydrology model was then coupled with an unstructured-grid Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2003) for the Snohomish River estuary and floodplain to take into account the eight major tidal harmonic constituents. The study indicated that salinity intrusion in the Snohomish River estuary distributaries is not linear with respect to the river flow condition while it is linear with respect to the sea level rise in the inundated areas. FVCOM was also applied by (Xue et al., 2009) to study the saltwater intrusion mechanism in the Changjiang River by considering different forcings (e.g., tidal currents, wind, and river discharge). The results indicated that the tidal rectification becomes dominant in the dry season if the surface elevation gradient forcing reduces. Similarly, to study the multiple forcing functions on salinity variation, Huang and Foo (2002) simulated the water level, freshwater input and wind change (speed and direction) on seawater intrusion problem in the Apalachicola River, Florida.

In addition, research by Zhang et al. (2013) simulated the seawater intrusion condition in the Pearl River network through a long period of time (1960s to 2005). Therein, 1-D transient flow and salinity model was calibrated and validated with respect to the water level, discharge and salt concentration at 40 gauges. By considering the historical data and the simulation results, the study pointed out that the crucial reason for salinity outbreak in the Pearl River system is human activities, specifically large – scale sand excavation.

To investigate the salinity dynamics in the southwest coastal areas of Bangladesh, Dasgupta et al. (2007) adopted a 1D MIKE 11 model and a 2D MIKE 21 model to simulate river hydrodynamics and tidal dynamics respectively. The set of models were applied to forecast the salinity intrusion areas for the year 2050 over 27 alternative scenarios of climate change. MIKE 11 was selected for the study after a thorough literature review in seawater intrusion modeling over 9 different models, for its 20 years of application history in Bangladesh (Akhter et al., 2012; Adhikary et al., 2011; Saha, 2007).

Also in the Mediterranean rivers the saline water intrusion is a reason of severe concern for drinking water supply, e.g. in the Po river delta Bellafiore et al. (2021) simulated saline intrusion with the Shallow water hydrodynamic Finite Element Model vs. extensive observation campaigns: the extent of seawater intrusion (SWI) in the major river branch is projected to increase up to 80% and the persistence of SWI at the same site is expected to increase 100% longer.

A research by Hens et al. (2018) summarized the coastal zone conditions under the effect of sea level rise in terms of salinization, inundation and flood dynamics in Vietnam and in the Pacific coast of Asia. The study focuses on the threat of sea level rise speed in the region, especially in Vietnam where the rate was estimated to be about 3.3 mm/year (1993–2014), higher than the global average (3 mm/year). The severe salinity intrusion problems already experienced in Vietnam can therefore be set in this highly challenging context and make it evident the need for understanding and dealing with the problem.

Solutions for salinization have been proposed through different studies worldwide e.g. controlling the pumping stations in the coastal zones, building sea dike systems or salinity control dams. However, it is utmost important to be able to well assess and analyze the seawater intrusion movement and its development in each stream of the river network. According to such studies, the problem can be handled by using different approaches and methods to mitigate the seawater intrusion.

Some studies were conducted to evaluate the salinity dynamics in different river basins in Vietnam, e.g., the Mekong River Delta (Loáiciga et al., 2012 by using the approach by Brown and Barnwell (1985), the Ma–Yen River basin (Hoang and Tran, 2014; Tran et al., 2017) and the Red River Delta. For instance, Nguyen et al. (2014) attempted to assess the saltwater intrusion under SLR forcing by applying three different SLR scenarios according to the IPCC AR4 (IPCC, 2007) and to national downscaling by (MONRE, 2009).

The research investigated Savenije's (2006) theory for saltwater intrusion modeling in alluvial branched estuaries to assess salinity dynamics of the Red River Delta. The general results indicated a severe salinity problem in most parts of the Red River Delta due to sea level rise especially when coupled with the higher tide. The research was focused on the estuary geometry and sea level rise, instead of considering other climate change effects or groundwater aquifer interaction.

Similarly, one of the earliest studies on salinity dynamics in the Red River related to tidal ranges was conducted by Ca et al. (1994), to evaluate salinity concentrations in the main streams of the Red River Delta. The study revealed that during the spring tide, a salinity concentration value of 1‰ can be observed almost in all the length of the Ninh Co River, while it could move backward up to Lieu De station (about 28 km from the sea) during the ebb tide period. The Day River, on the other hand, experiences less salinity expansion in comparison to other branches. The research, however, did not take into account the climate change effects.

Tran et al. (2014) studied the saltwater intrusion in the Red River Delta using model MIKE 11 under the effect of upstream water demand with the 85% frequency of exceedance. The research indicates the value of beyond 1 ‰ salt concentration to be found at a distance of 22 km in most of the river branches and 32 km in the Tra Ly River from the estuaries. The longest distance of 1‰ salinity concentration is found in the mainstream Red River (21.9 km) and in the Ninh Co River (22.8 km). Moreover, the threshold of 4‰ salinity concentration is more severe for the mainstream Red River (17.8 km) and the Ninh Co River (18.5 km). Similar conclusions were drawn by Devienne (2006) for the Red River Delta.

As can be seen, a variety of studies were carried out to simulate and assess the seawater intrusion under sea level rise and climate change scenarios. Nonetheless, difficulties in validating the model or setting up the initial conditions are always evident, due to the lack of observations data. However, bearing in mind the uncertainties related to the future world under non-stationary scenarios, the problem is raising along with many questions that still need to be answered in any coastal areas such as: how far the seawater intrusion could occur?; how much of salt concentration could be found at different distances upstream the coastline?; when it could happen and under which circumstances?; how uncertain are our estimates?; at what level could it affect local habitats and ecological systems?; and what could be the actions to be able to control or prevent seawater intrusion?

In general, a number of numerical models and conceptual models exist that were developed and applied, in order to investigate and simulate seawater intrusion processes. The increase in the number of studies over the last decades proves higher attention and awareness towards the problem. In dealing with coastal aquifers, numerical modeling is showing greater advantages as compared to conceptual modeling, despite its heavy computational burden. The numerical model MIKE 11, which was developed by Danish Hydraulic Institute DHI (2014), has been widely applied for river hydraulic dynamics, advection and diffusion processes due to its fast simulation times and user-friendly interface. In addition, some researches (e.g. Toan, 2014; Ha et al., 2016; Hai et al., 2019) used the model packages on seawater intrusion in Vietnam and particularly, in the Red – Thai Binh River Delta (Tran et al., 2014; Cuong et al., 2018 with a coupled 1-2D MIKE model). They proved the goodness of the models in the research areas. The effect of coupled sea level rise and reservoirs regulation scenarios on salinity variation is being examined for the Red River Delta (RRD). Since the growing demand in hydropower and the high flood frequency, the freshwater management plan in the RRD has been solely allocated in serve of flood protection and energy supply and supporting irrigation in downstream areas. In the Red River area, water demands are always high especially for agriculture from January to March, which is the driest period. Therefore, conflicts may arise from these alternative uses, especially during the dry season. These factors have led to a higher probability of an unexpected saltwater intrusion and of water scarcity that will become more severe in the future because of unavoidable sea level rise. Therefore, adaptation measures need to be prepared, including updating of reservoirs regulation. The research focuses on analyzing the saltwater intrusion problem in the Red River Delta by accounting for updated and downscaled sea level rise scenarios and by introducing a statistical characterization of the river flow regulation by Son Tay station using a 1-D model for the future period of 2050 and 2100. MIKE 11 was adopted in the research after consideration from literature review on salinity simulation for the different regions in Vietnam, its wide use in this country and the balance of simulation complexity and capacity to simulate both quantity and quality hydrodynamics. Scenarios of possible adaptation measures assuming an increased release of water from reservoirs in the most critical period for salinity concentration are investigated and the salinity profiles across major river branches in the Red River Delta under both sea level rise and reservoirs regulations are assessed.

2. The Study Area - The Red River Delta

The Red River Delta is located in Northern Vietnam (Fig. 1) and is the final part of the Red River Basin, the second largest river basin in Vietnam after the Mekong River. The Red River network is formed by three main upstream branches, namely the Da River in the western part, the Lo River in the eastern part and the Thao River (called Ha River in China) in the middle. The main river flows in NW-SE direction until the confluence in Viet Tri, (Phu Tho province) just upstream of Son Tay hydrological station, where the river is named more properly Red River. Downstream of Viet Tri, the alluvial delta is formed by six main tributaries, from west to east: Day River, Duong River, Luoc River, Tra Ly River, Dao River and Ninh Co River. Duong River and Luoc River are considered as connections between the Red River and Thai Binh River.

Since the Red River system is a transnational hydrographic network

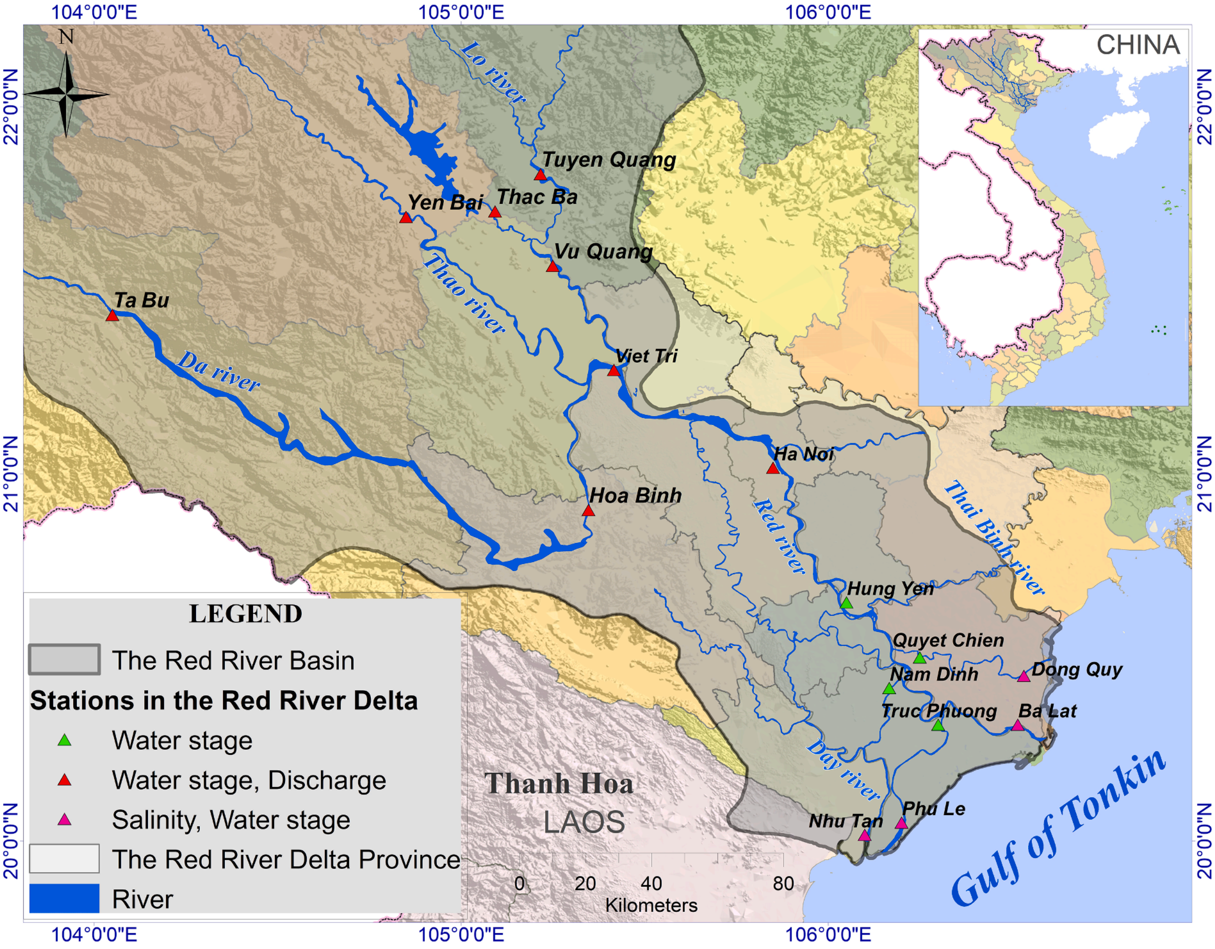

Fig. 1. The Red River system location.

with the upstream catchment basins located in China and a small part in Laos, the hydraulic structure characteristics and operation information for the upstream part are generally scarce. In the river basin several reservoirs were built over the last decades. In Vietnam, the Thac Ba reservoir built in 1972 on Chay River is only able to contribute with a release of nearly 100 $m^3 s^{-1}$ during the low flow season, that is a small contribution as compared to the high downstream hydropower demand. This makes it difficult to satisfy the water demand in the downstream basin. The Hoa Binh reservoir was constructed in 1979, and completed in April 1994, to increase the potential water supply during the dry season by regulating more than 300–400 $m^3 s^{-1}$. The structure was able to manage the demands for hydropower generation, flood protection, and low flow regulation for irrigation (Richaud et al., 2011). Yet, according to the Vietnamese Department of Water Resources Management this still does not fully meet the irrigation demand when severe dry periods occur, such as in 1998, 2001 or in 2003, 2004.

Other main structures are the Son La dam along the Da River (operated since 2012) and the Tuyen Quang reservoir along the Lo River. Son La dam was designed mainly for power supply to foster the economy and social activities, then for flood regulation during rainy season and water supply for the Northern Delta in low flow season (Nguyen, 2011). The Tuyen Quang reservoir was constructed mainly for flood regulation in the Tuyen Quang province (Ranzi et al., 2012), secondly for the Red River delta and to a minor extent to provide water for the dry season. However, water regulation at Tuyen Quang reservoir during the dry season is not yet reasonable, since it is not working in favor of downstream irrigation needs, but only following operation criteria to optimize the water storage to support the hydropower generation.

In recent years, the Red River Delta has faced the risk of extreme drought and saltwater intrusion over all the coastal provinces (e.g., Nam Dinh, Hai Phong, Thai Binh). According to the Institute for Water and Environment (2012), around 20–30% of agricultural areas in the Red River Delta, that represents the most important agricultural zone in Vietnam, are dealing with drought and saltwater intrusion, annually. Although the dry season in the area occurs from December to May, from November 2016 the water levels in the Red River network have decreased continuously, e.g., in 2017 a decrease of about 87 cm in the mainstream Red River was recorded at Ha Noi station, with a 20 cm drop in the tributary Day River at Ben De station. The reduction of water levels in the mainstream Red River affects 6 main tributaries (Day, Duong, Luoc, Tra Ly, Dao and Ninh Co River) as well as all the hydraulic structures placed along those rivers. As a result, the irrigation system in the Delta is not able to function properly, putting more than 233,400 agriculture hectares in danger of drought and saltwater intrusion.

Under the operation of the Hoa Binh and Thac Ba reservoirs, along with Tuyen Quang and Son La reservoirs recently, according to historical records salinity is being pushed seaward due to the effect of higher flow rates from upstream. The salinity threshold of 4 ‰ is exceeded at least 1 km from the sea (Day river) to a maximum of 12 km (Kinh Thay river, Lach Tray). According to the recent observation, a salinity concentration of 1‰ is measured up to Kim Dai along the Day river, at Lieu De along the Ninh Co river, after Duong Lieu on the Red river and at Ngu Thon on the Tra Ly river.

The recent survey from 2010 to 2018 by Thuy Loi University (Vietnam) over the Red River Delta show a variation of salt concentration throughout the river network and different water depths as shown in Table 1. In detail, at KM 32, the maximum salinity of 2.15 ‰ can be found in the mainstream of the Red River while values of 3.75 ‰ and 2.05 ‰ are recorded at Ninh Co and Tra Ly river, respectively. Maximum salt concentration of 8.25 ‰, 10.1 ‰ and 9.1 ‰ could reach up to KM 22 in the Red river, Ninh Co river and Tra Ly river respectively. Noticeably, the highest degree of saltwater intrusion can be seen at KM 10 with the value of more than 30 ‰ in all of the rivers.

Table 1
Salt concentration at different location in the Red River network (2010–2018).

Location	Max (‰)		Average (‰)		Min (‰)	
Water Depth	*0.2 h*	*0.6 h*	*0.2 h*	*0.6 h*	*0.2 h*	*0.6 h*
Red river						
KM32	2.05	2.15	0.12	0.19	0.00	0.00
KM22	6.55	8.25	0.74	0.85	0.035	0.02
KM10	27.95	30.50	9.98	11.46	0.11	0.11
Ninh Co river						
KM32	3.20	3.75	0.14	0.25	0.00	0.01
KM22	8.8	10.1	0.70	0.89	0	0
KM10	28.05	30.00	10.90	14.70	0.20	0.30
Tra Ly river						
KM32	1.60	2.05	0.10	0.12	0.01	0.01
KM22	7.3	9.1	0.47	0.58	0.01	0.02
KM10	25.70	30.65	7.98	10.48	0.05	0.41

The rising problem of saltwater intrusion is thus leaving many consequences on local ecosystems as well as economic burdens which have not been analyzed thoroughly in the Red River Delta, see Nguyen et al. (2020).

3. Dataset and methodology

3.1. Meteo-hydrological data

The water level and discharge data together with salt concentration levels were collected along the river for model boundaries and model validation on hourly and daily basis. A summary of data consistency is reported in Table 2. Salinity and water level observed for four estuaries in 2010 and 2011 are used to calibrate and validate the model, whereas the stations of Ba Lat, Nhu Tan, Phu Le and Dong Quy are adopted as testing stations (see Fig. 1).

The river flow at Son Tay station is collected from 1979 right after the start of the construction of the Hoa Binh reservoir. In 1988 the Hoa Binh reservoir began to impound water, but the operation did not determine a significant impact on water regulation downstream for the first two years, since its management was mainly focused on impounding water in the reservoir. From 1991 to 2004, during the dry season, the reservoir served as power supply with one generating set and maintained environmental flow of around 240 $m^3 s^{-1}$. Since 2005, Hoa Binh reservoir has been operated as the backup hydropower plant, which sometimes caused interruptions in power generation leading to high level of fluctuations in daily releases. This highly affects downstream flow and the lowest water level at Ha Noi continues to decrease. Thus, the values of daily water discharge for the period 1990–2016, after dam operation became more steady, have been analyzed.

Moreover, the two sea level rise scenarios RCP4.5 (2050 and 2100) and RCP8.5 (2050 and 2100) were retrieved from institutional climate change scenarios report by MONRE in 2016. The sea level rise scenarios were estimated and analyzed based on the method applied in IPCC AR5 report and Church et al. (2013). The uncertainties of the SLR scenarios results are estimated from the contributed components uncertainties (glaciers, thermal expansion, Greenland and Antarctic Ice Sheets, Water Storage on Land). Therein, the uncertainty of Greenland and Antarctic Ice Sheets were assessed based on IPCC (2013) method, while the thermal expansion uncertainty was taken into account by using numerical models. Those uncertainties were derived from the CMIP5 (Coupled Model Intercomparison Project Phase 5) ensemble through the normal distribution and assumed the interval 5–95 % for each RCP scenario as the likely range. The results' confidence was analyzed based on the observed data (tidal stations), satellites data and computed data from AOGCMs model (Atmosphere-Ocean General Circulation Models).

The correlation coefficient of the standard deviations of the average water level obtained from the model and from the observed water level along the Vietnamese coast (1986–2014) is about 0.76, whereas that

Table 2
Consistency table of data collected in this research.

River	Station	Parameter	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Red	Son Tay	Water Level	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X		▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X
		Discharge	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓		▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
	Ha Noi	Water Level	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X
		Discharge	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
	Ba Lat	Water Level	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X
		Salt concentration	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X
	Hung Yen	Water Level	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X		▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓	▓	▓
Dao	Nam Dinh	Water Level															░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░	░	░
Day	Nhu Tan	Water Level	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X
		Salt concentration	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X
Ninh Co	Phu Le	Water Level	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓	▓	▓	▓
		Salt concentration	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X
Tra Ly	Dong Quy	Water Level																		▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓	▓	▓	▓
		Salt concentration	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░	░	░
	Quyet Chien	Water Level	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓	▓	▓
Duong	Thuong Cat	Water Level	░ X	░ X	░ X	░ X	░ X	░ X	░	░	░	░	░	░	░ X	░ X	░ X	░ X	░ X	░ X	░ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	▓ X	░	░	░
		Discharge	░ X	░ X	░ X	░ X	░ X	░ X	░ X	░	░	░	░	░	░	░	░ X	░ X	░ X	░ X	░ X	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░

Legend	
▓ X	Data fully available at hourly scale
▓	Data fully available at daily scale
░ X	Data partially available at hourly scale
░	Data partially available at daily scale
🟨	Data of low quality
	Missing data

obtained by comparing model results to satellite data (1993–2014) is 0.80. The sea level trend observed for the Vietnamese coast at the monitoring stations and satellites data along with the uncertainty band (see climate change report by MONRE, 2016), suggests that climatic model projections are consistent with observed data.

In 2050, the estimated SLR along the coastline of Vietnam is 0.22 m (uncertainty range 0.14–0.32 m) for RCP4.5, and 0.25 m (uncertainty range 0.17–0.35 m) for RCP8.5. SLR values estimated for the 2100 scenario are much higher being assessed at 0.53 m (uncertainty range 0.32–0.76 m) for RCP4.5, and 0.73 m (uncertainty range 0.49–0.103 m) for RCP 8.5. The conclusions about the sea level rise of IPCC AR6 are not too different from those of AR5 although they are a little more pessimistic. For instance, AR6 states that "It is virtually certain that global mean sea level will continue to rise over the 21st century. Relative to 1995–2014, the likely (with medium confidence) global mean sea level rise by 2100 is 0.44–0.76 m under the intermediate Greenhouse Gas emissions (SSP2–4.5), and 0.63–1.01 m under the very high GHG emissions scenario (SSP5–8.5)".

3.2. *Topography and river network*

The river network characteristics, including cross sections of each river branch, roughness ranges and hydraulic structures were provided by the Thuy Loi University. The river system to be modeled includes the Thai Binh River, since it is connected to the Red River system through the Duong River. More precisely, the system covers the Duong River (10 cross sections), the main Red (Hong) river from Son Tay (19 cross-sections), the Hoang Long River (5 cross-sections), the Tra Ly River (36 cross-sections), the Ninh Co River (26 cross-sections), the Kinh Mon River (14 cross-sections), the Kinh Thay River (148 cross-sections), the Lach Tray River (25 cross-sections), the Thai Binh River (54 cross-sections), the Van Uc River (22 cross-sections) and some other minor branches. In total, there are 379 cross sections with the interval of around 500 m each that are collected for model simulation.

The downstream boundary conditions are defined at the estuary of each river branch (Day estuary, Red (Hong) estuary, Ninh Co estuary, Tra Ly estuary, Thai Binh estuary, Van Uc, Lach Tray and Cam estuary) as sea levels, whereas the upstream boundary condition are defined at Son Tay station as river flow discharge. The hydraulic structures that are included in the model scheme are (*i*) the control structure of Day dike, (*ii*) 15 pumping stations and (*iii*) the Van Coc culvert equipped with 22 on-line weirs.

3.3. *Study method*

The research methodology algorithm is described in Fig. 2. The discharge values from Son Tay station were collected for the period 1990–2016 (see Table 2) and statistically analyzed by using the Statistical Software Package HEC-SSP (HEC-SSP, 2010). Thus, the best fitting distribution was selected to estimate the discharge values for the model upstream boundary conditions at Son Tay station for fixed frequencies of occurrence.

The collected discharges are analyzed to select the best fitting distribution of the monthly time series data. Consequently, exceedance quantiles (i.e., 25%, 50%, 75% and 95% exceedance probabilities) are estimated and chosen as control discharges in evaluating salinity dynamics in the river network. Such values were coupled with two sea level rise scenarios defining the downstream boundary conditions. The 1-dimensional model MIKE 11 (DHI, 2014) was then used to simulate hydrodynamics (HD module) and salinity dynamics (AD module – Advection) of the river network. The HD module integrates Saint - Venant equations for shallow waters, which express continuity and momentum balances, whereas the advection–dispersion equation models the conservation of mass of a conservative solute (details can be found in DHI, 2014) Water stages, including tidal effects, river flow discharges and salinity concentrations observed in 2010 and 2011 (see

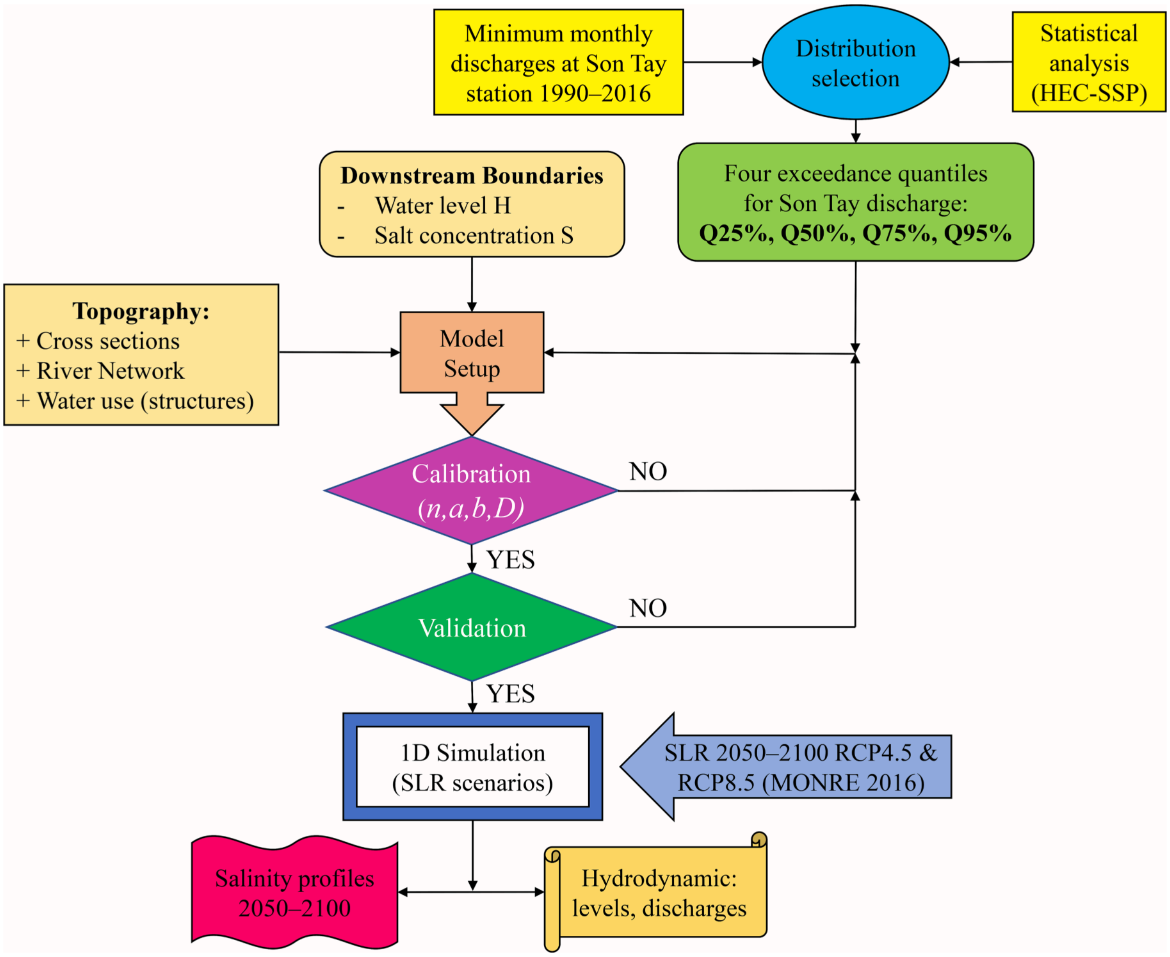

Fig. 2. Research methodology algorithm. (n is roughness; D is dispersion coefficient, a is dispersion factor, b is dispersion exponent).

Table 2) were thus used for model calibration and validation.

The HD model simulated only the part of Red River from downstream of Hoa Binh reservoir in Son Tay to the Gulf of Tonkin through the four estuaries Day, Ninh Co, Ba Lat and Tra Ly. In this study, 8 main river branches featuring 360 cross-sections are simulated. Water levels and flow discharge are the two-primary data for the hydrodynamic module and salt concentration governs the advection–dispersion module. The salinity value is set equal to 0 ‰ at the upper boundaries of the model.

Among the tested distributions, the best fitting distribution was selected by using the Chi-square statistics χ^2 given by Eq. (1).

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{1}$$

where O_i are the observed class frequencies, E_i are theoretical class probabilities and k is the number of classes that the sample is subdivided into. The best solution yields the lowest value of χ^2.

MIKE 11 model performances are evaluated by the Nash Sutcliffe Efficiency indicator NSE (2) and Root Mean Square Error RMSE (3)

$$NSE = 1 - \frac{\sum_{i=1}^{I} \left(X_{cal,i} - X_{obs,i}\right)^2}{\sum_{i=1}^{I} \left(X_{obs,i} - \underline{X_{obs}}\right)^2} \leq 1 \tag{2}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(X_{cal,i} - X_{obs,i}\right)^2} \tag{3}$$

Where $X_{cal,i}$ are the estimated parameters from model simulation, $X_{obs,i}$ are the observed values, $\underline{X_{obs}}$ is the mean of the observation sample (N) and I is the sample size. Model performances are considered to be acceptable when NSE is greater than zero and satisfactory when NSE is near one. Time to peak difference and peak error were also considered in model performance assessment.

4. Results and discussion

4.1. Statistical analysis at Son Tay station

For the purpose of saltwater intrusion dynamics assessment, more attention was paid to the minimum monthly discharge, which was estimated from the daily discharge. The minimum and the mean monthly discharges estimated in the available period are presented in Fig. 3. The collected data illustrates the variation of monthly and minimum discharge over the years with a decline trend from 1995. In general, the lowest minimum discharge is found in the same driest year e.g. 2000, 2010, 2015, and 2016 with the minimum discharge of less than 250 $m^3\ s^{-1}$. These are also the years in which the Hoa Binh reservoir did not meet the normal water level during the dry season. For example, on 21 February 2010 the water level at Ha Noi station dropped at 0.1 m, its lowest level in recorded history.

The annual data of minimum monthly discharge at Son Tay shows the highest discharge observed in 2016 at about 1530 $m^3\ s^{-1}$ while the lowest values were recorded in 1998, 1999 and 2010 with only less than 900 $m^3\ s^{-1}$. Table 3 describes the comparison of observed and estimated quantiles for all selected distributions for the dataset at Son Tay station, focused on the lowest quantiles.

Fig. 4 shows the cumulative distribution function of theoretical

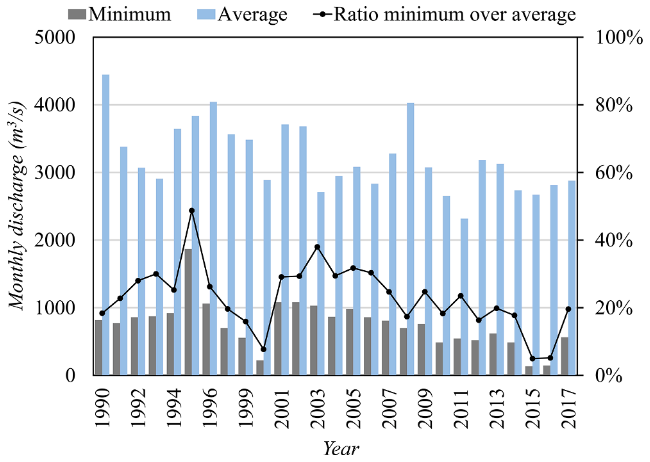

Fig. 3. The average and minimum monthly discharge values observed at Son Tay station between 1990 and 2017.

Table 3

Quantiles of the selected distributions for the lowest quantiles of annual minimum of monthly discharge (m^3/s); best fit is evidenced in boldface.

Distribution	Chi square	Quantiles			
		0.95	0.75	0.50	0.25
Gamma	**2.000**	786	978	1130	1296
Generalized Extreme Value	2.077	849	981	1103	1262
Generalized Pareto	2.462	894	964	1080	1263
Gumbel	3.615	837	979	1107	1270
Normal	3.615	756	987	1146	1306
Pearson III	**1.308**	867	972	1093	1264
Triangular	4.385	837	946	1106	1314
Ln-Normal	**2.077**	815	986	1125	1283
Log10-Normal	2.077	815	986	1125	1281
Log-Pearson III	3.615	836	980	1110	1273

probability distributions commonly used in hydrology (Ln Normal, Pearson III, Gamma) compared to the empirical counterpart for the monthly discharges observed at Son Tay station and the 95% confidence interval.

The analyzed results illustrate a good fit of dataset with Ln-Normal, Gamma and Pearson III distributions for the lowest quantiles. Although, the χ^2 value for the Gamma distribution is not the lowest one, the Gamma quantiles are closer to the observed values in the lowest tail of the distribution which represents the discharge in the driest years, that are more of interest in the study. The research, therefore, selects this distribution to calculate for further simulations the designed discharges of 25%, 50%, 75% and 95% exceedance probability, which are 1296 m^3 s^{-1}, 1130 m^3 s^{-1}, 978 m^3 s^{-1} and 786 m^3 s^{-1} respectively.

4.2. 1D hydrodynamic modelling

According to collected hydrological data, 2010 is considered one of the most concerning dry years in the Red River Delta. From 2004 to 2011, due to the climate and the water storage and reservoirs operation for hydropower upstream, the Red River system experienced an extreme drought with the water shortage up to 45–55% resulting in the reduction of water level measured at Ha Noi. In addition, all the collected data are available in the dry season of 2010 for all the boundaries and testing stations. Therefore, the period from 20 January 2010 to 28 February 2010 was used to calibrate the model and the same period in 2011 was used for model validation. The lack of salinity data for a more extended period prevented the possibility to use a longer calibration and validation period. For the hydrodynamic module, it is necessary to calibrate and validate it using Manning roughness coefficient *n* at different channels and rivers in the network. In addition, the dispersion factor, dispersion exponent and dispersion coefficient *D* are considered to calibrate the AD module (see more about the factors in DHI, User Manual 2014). Then the simulated results of water level and discharge are compared with observed data at the corresponding stations using different criteria (e.g., NSE should be close to 1 and time to peak difference and relative error should be as small as possible). When these conditions are obtained at a reasonable level, the model is considered to be reliable to be used for the simulation purposes. Fig. 5 illustrates the river network implemented in the MIKE 11 modelling scheme for the Red River Delta.

Table 4 presents the model calibration and validation results by comparing observed and simulated water levels, discharges and salt concentrations using criteria NSE, RMSE and relative errors. Calibration results show a satisfactory agreement between the computed values and the observations for both HD and AD modules. Observations and the estimated time-patterns delineate reasonable trends as the peak occurrence time and the time series of computed factors show a close and similar pattern to the observed data.

In general, the peak estimation and NSEs, RMSE of water levels, discharges and salinity concentrations lie in acceptable ranges (RMSE for discharge around 5–10 m^3 s^{-1} and less than 5 cm for water level, NSE more than 70%), confirming the suitability of the model parameterization to be applied in the validation phase.

The model parameter set that is selected is then adopted to validate the model for another dry period from 20 January 2011 to 28 February 2011.

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 Table 4, salt concentration and water levels of simulation and observation differ in a reasonable range, being the NSEs greater than 80% and the RMSE less than 10 m^3 s^{-1}.

Similarly, the salinity dynamics demonstrate comparable patterns between observations and simulations, featuring very close times to peak. Although the data set for salinity was not extended over a long period and the salinity advection and dispersion module is simplified, the model's performances were considered convincing enough to extend the use of the model for different SLR and upstream control scenarios simulations in the river network.

4.3. Salinity dynamics under different designed discharge and sea level rise scenarios

As aforementioned, to understand the seawater intrusion response to the river flow changes, the validated model is used to simulate the four discharge values and two sea level rise scenarios until 2050 and 2100. The results of salinity concentration in the four major branches of the river system – i.e. the Day River, the Ninh Co River, the Red River (mainstream) and the Tra Ly River – are represented in the following sections. Fig. 6 presents the salinity profile in the Red River referred to two sea level rise scenarios. In the main branch of the Red River, it is clear to see that the saltwater intrudes further inland through time with lower discharge values e.g., in 2050, at 20 km distance upstream from the river mouth (KM20), the maximum salt concentration is expected to increase with the discharge quantile 25% (highest discharge) at around 10‰ to approximately 16.75‰ for the discharge quantile 95% (lowest discharge). This could be explained as the result of lower upstream flow (786 m^3 s^{-1}) compared to the larger water discharge (1296 m^3 s^{-1}) from Son Tay station together with the further distance to the sea. Meanwhile, between KM10 and KM15 sections, salinity decreases slightly according to the rate of 0.8 ‰ km^{-1}, then it drops rapidly at the rate of 1.8 ‰ km^{-1} from KM15 to KM25. This salinity dynamic is understandable since the first 15 km from the sea would still be strongly affected by sea level change rather than the change in the freshwater from upstream. Similar trend is expected for the later period until 2100 since the closer to the estuary, the higher the concentration rate could be found.

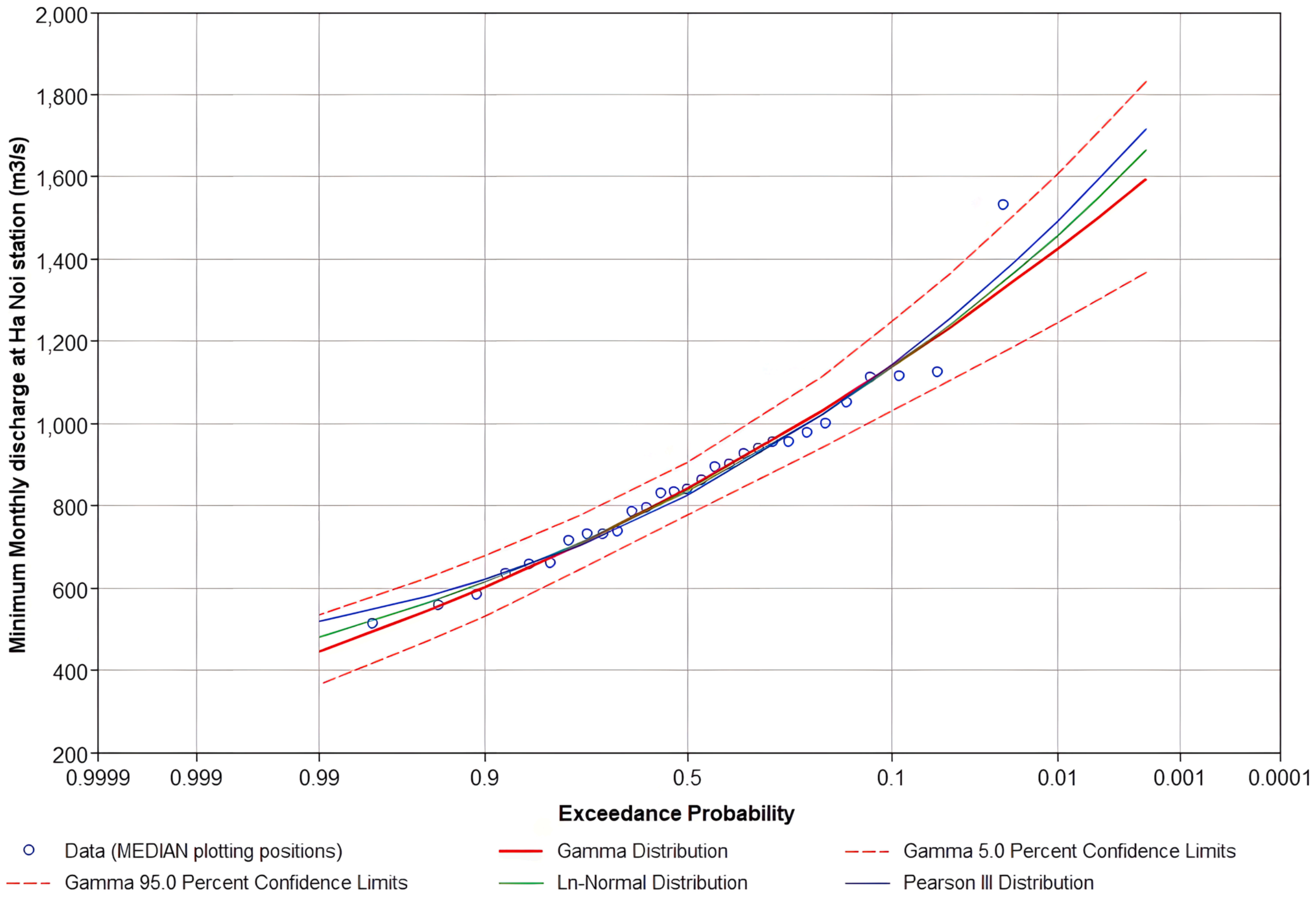

Fig. 4. CDF plotting position of Gamma, Ln Normal and Pearson III distributions (Son Tay station).

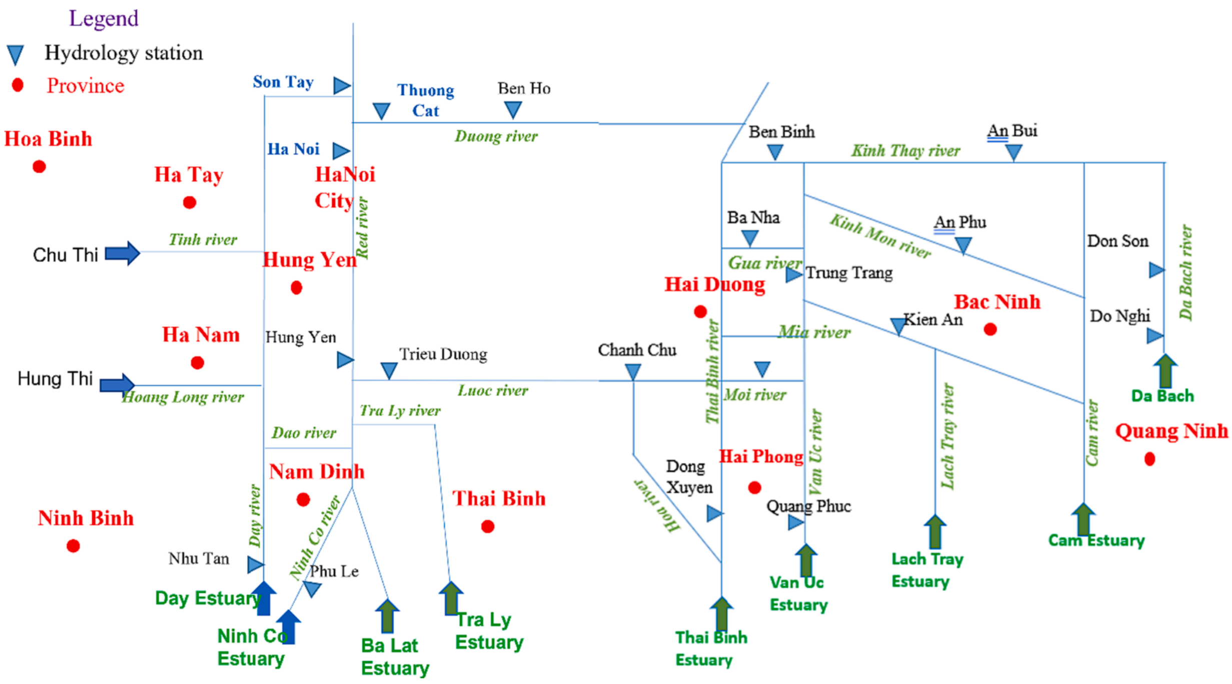

Fig. 5. The river network for modeling.

Table 4
The calibration and validation results of MIKE 11.

No	*Station*	*River*	*Calibration*		*Validation*	
			NSE (%)	*RMSE*	*NSE (%)*	*RMSE*
1	Thuong Cat (H)	Duong	95.1	3.4	96.3	2.7
2	Thuong Cat (Q)	Duong	86.3	7.1	86.7	7.7
3	Ha Noi (H)	Hong	93.2	3.7	86.3	3.3
4	Ha Noi (Q)	Hong	90.3	6.5	91.1	6.1
5	Hưng Yên (H)	Hong	86.3	4.5	85.8	4.2
6	Quyet Chien (H)	Tra Ly	90	3.3	90.8	3.1
7	Nam Dinh (H)	Dao	75.6	3.2	80	3.5
8	Truc Phuong (H)	Ninh Co	78.5	4.3	80	4.1
9	Cat Khe (H)	Ninh Co	91.3	3.4	93.5	3.2
	AD module		*Relative Error (%) Calibration and Validation*			
1	Phu Le	Ninh Co	0.5		4.4	
2	Nhu Tan	Day	0.08		10.7	
3	Dong Quy	Tra Ly	1.6		7.7	
4	Ba Lat	Hong	3.7		7.3	

(Note: RMSE unit in m^3/s for discharge and cm for water level).

In 2100, the effect of upstream discharge could be also observed clearly up to the distance of 30–45 km. For example, in RCP4.5 scenario, the maximum salt concentration at KM30 is simulated to be at around 9.7‰ for discharge quantile 95% (786 m^3 s^{-1}) while it is approximately 5‰ for the discharge quantile 75% (979 m^3 s^{-1}). The concentration continues to reduce gradually to less than 1‰ in the case of the highest discharge value (1296 m^3 s^{-1} with quantile 25%) as evidence of the higher upstream flow effect compared to the downstream sea level change toward saltwater intrusion at the distance of about more than 30 km from the sea.

Fig. 7 illustrates the estimate of the salinity dynamics for the Day River. The variation of salt concentration in the Day River follows the same increasing trend in both RCP4.5 and RCP8.5 over two periods of time 2050 and 2100. Unlike the main stream Red river, in the Day river, a dramatic drop in salt concentrations is predicted to occur at 1.34 ‰ km^{-1} from about 10 to 15 km from the sea. This illustrates a strong effect of SLR in the first 10 km which tends to reduce by the KM15. By comparison, from KM15 to KM20 sections, as a result from the further distance to the sea, sea level change seems to become less dominant towards saltwater intrusion, this decreasing trend is much higher compare to the first 15 km with a value of 3.47 ‰ km^{-1}. Like in the mainstream Red River, the maximum salt concentration in the Day River is also predicted to be lessen as the higher discharge value from Son Tay station is applied for both SLR scenarios. In details, at the KM20, in 2050, the salt concentration is estimated around 5.2‰ with the highest discharge (25%, 1296 m^3 s^{-1}), while it is much higher at about 10.1‰

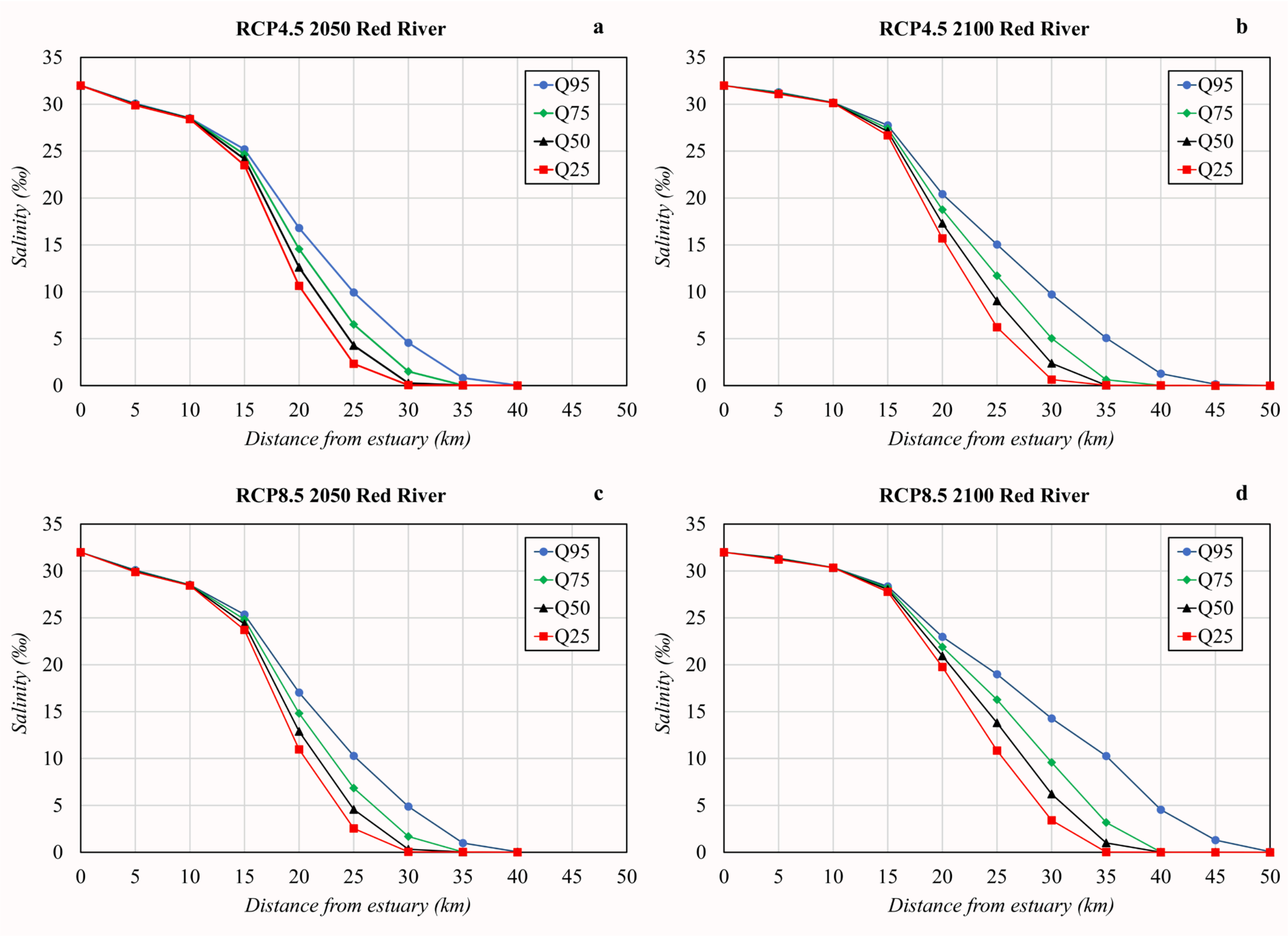

Fig. 6. Salinity profiles in the Red River referred to two SLR scenarios and four flow discharge frequencies: (a): RCP4.5_2050, (b): RCP4.5_2100, (c): RCP8.5_2050, (d): RCP8.5_2100.

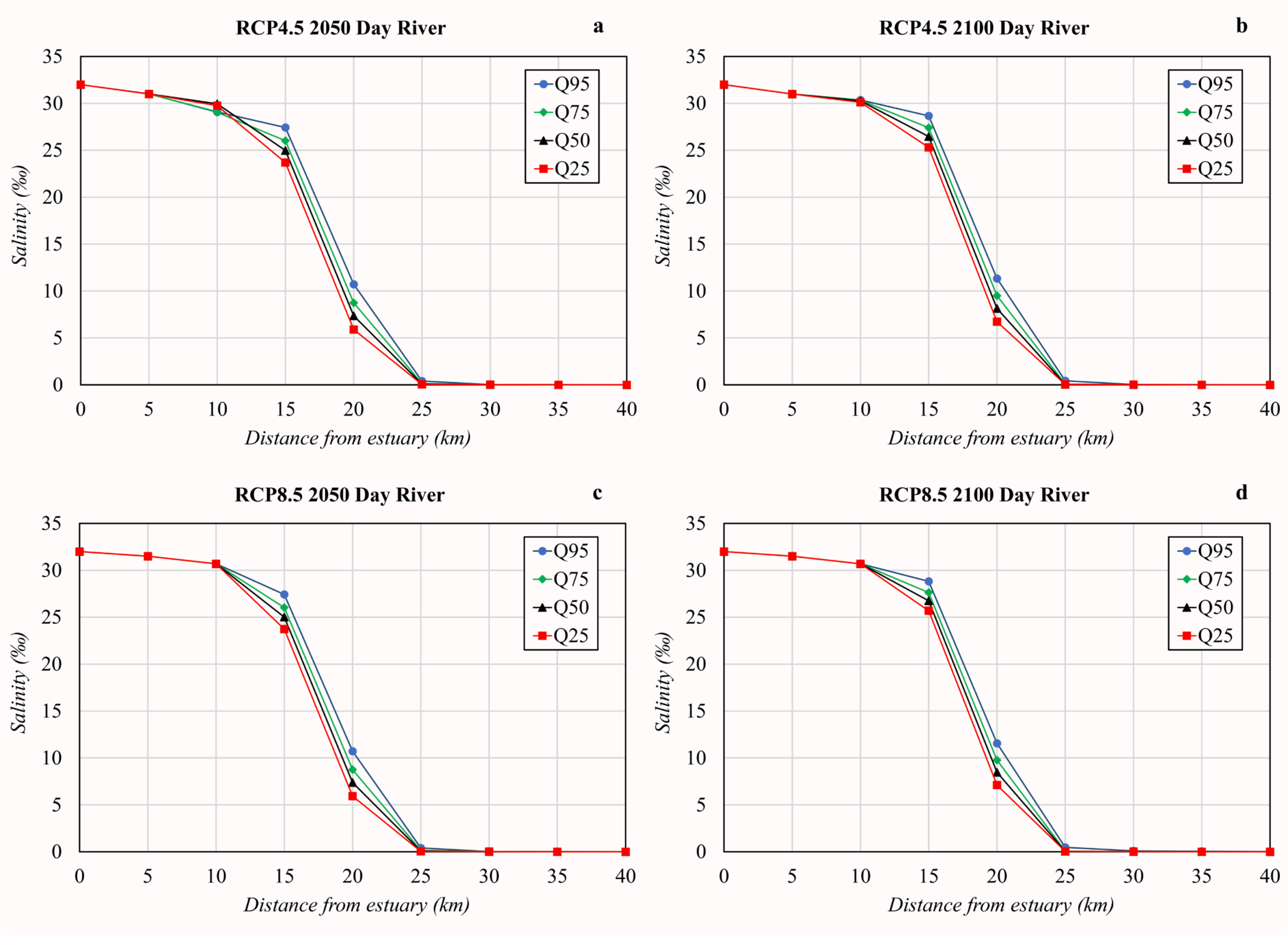

Fig. 7. Salinity profiles in the Day River referred to two SLR scenarios and four flow discharge frequencies: (a): RCP4.5_2050, (b): RCP4.5_2100, (c): RCP8.5_2050, (d): RCP8.5_2100.

for the lowest discharge value (95%, 786 $m^3 s^{-1}$) in the RCP8.5 scenario. The same trend is observed along the whole river in 2100 and with reference to RCP8.5.

Fig. 8 shows the estimate of the salinity dynamics for the Tra Ly River of 4 different discharge levels and sea level rise scenarios. The trend of salinity profile is quite similar for 2050 and 2100 in both RCP4.5 and RCP8.5. Similar to the mainstream Red river, between KM10 and KM15 from the river mouth, the reduction rate of salt concentration remains low at 0.49 ‰ km^{-1}. This indicates that up to about 15 km from the sea, the Tra Ly river would experience a similar seawater intrusion problem with the dominance of sea level rise. While from 15 km to 25 km from the sea, the salt concentration rate sharply drops to 2.56 ‰ km^{-1} due to the higher effect of upstream water discharge coupled with the lessen of tidal contribution. In RCP8.5, in 2100 with higher seawater level, the decrease in salinity level occurs mainly from KM15 to KM30 due to the predominance of sea level rise. It is predicted that up to 24.44 km from the estuary, the water quality is expected not to be suitable for irrigation and domestic water supply in 2050.

The impact of the upstream discharge could be significant in the Tra Ly River between the distance of 15 to 30 km from the sea over the years and scenarios. The noticeable effect is computed to occur at the KM20 where the maximum salt concentration could reduce significantly from about 19‰ with discharge quantile 95% to 10‰ with the highest discharge of 25% quantile in 2050 and according to RCP4.5. This declining trend is also predicted to worsen in 2100 and for the SLR RCP8.5. Nevertheless, in 2100 and according to RCP8.5, a little difference between salinity profiles associated with discharge quantile 50% and 25% is predicted along the river. The Tra Ly River is expected to still experience a strong variation with respect to discharge quantile 95%, according to which the maximum salt concentration is reduced from 13.5‰ (quantile 95%) to 6‰ (quantile 25%).

Fig. 9 finally describes the salinity dynamics in the Ninh Co River which is expected to be highly affected by sea level rise due to its location. The salt concentration is forecasted to drop sharply at a rate of 2.12 ‰ km^{-1} from KM10 (near the estuary) to KM25 as the indication of strong sea level rise impact and lower contribution of the upstream river flow in the estuary area. In the section from KM25 to KM30, the salinity level is smaller than 1‰ then, it increases downstream to the end of the river. This result can be explained by accounting for the influence of the Red River mainstream. Compared to the mainstream Red River, the Ninh Co River appears to be less affected by the upstream condition as the variation of the maximum salt concentration according to different discharge level could be noticed only at the location of between 15 km and 22.5 km from the sea. More precisely, in 2100 for RCP8.5, at KM20, the maximum salt concentration could be declined from about 17.5‰ at the discharge of 786 $m^3 s^{-1}$ to approximately 12‰ for the highest discharge of 1296 $m^3 s^{-1}$.

It is, therefore, agreed that the level of salt concentration in the Ninh Co River could be also mitigated at certain locations with a change in the upstream discharge over the year independently of the different SLR scenario.

In general, all branches of the Red River will be exposed to severe

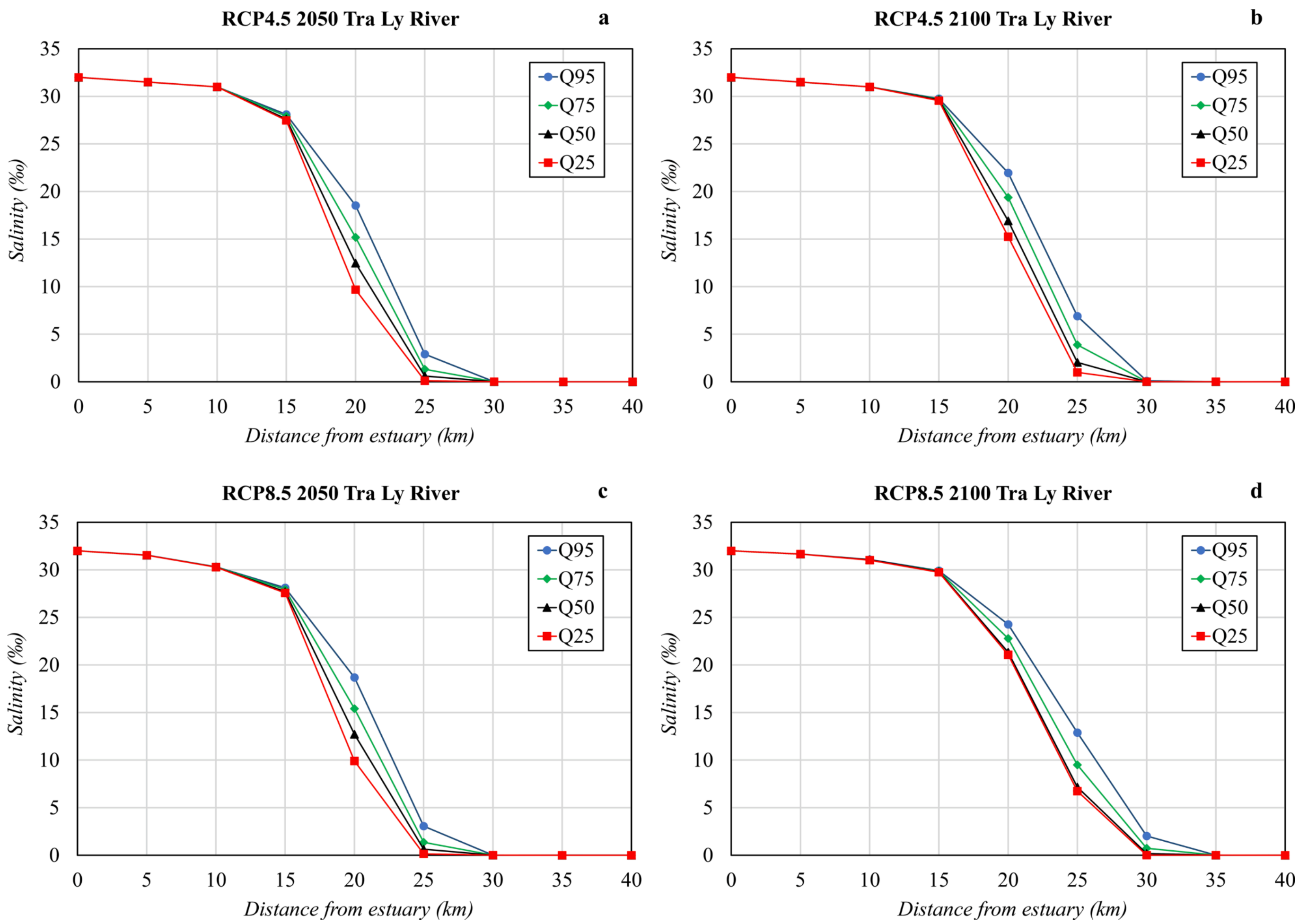

Fig. 8. Salinity profiles in the Tra Ly River referred to two SLR scenarios and four flow discharge frequencies: (a): RCP4.5_2050, (b): RCP4.5_2100, (c): RCP8.5_2050, (d): RCP8.5_2100.

saltwater intrusion by the end of the 21st century, especially in the distance of about 10–15 km from the sea. In addition, the saltwater may intrude up to KM25 or KM30 from the sea. Fig. 10 presents the salinity threshold 1‰ and 4‰ distance from the sea along 4 rivers in RCP4.5 in 2050 and 2100.

As it can be seen, the higher the discharge, the shorter the extent of the saltwater intrusion into the river. In particular, with regard to the discharge quantile of 95%, the salinity in the mainstream Red River is estimated to intrude further inland as the 4‰ salt concentration could be found at the distance of 30.5 km from the sea, while it is predicted to reduce to 23.5 km in the case of the discharge quantile of 25%. The threshold of 1‰ is predicted to occur at 34.6 km in 2050 but at 41.1 km in 2100.

Similarly, in the Tra Ly River, in 2050 with RCP4.5 scenario, the 1‰ salt concentration is estimated to be at the distance of about 24.5 km from the sea if the upstream discharge is at 25% probability while it is predicted to move forward inland up to 28.3 km for the discharge of quantile 95%.

The Ninh Co River and the Day River show the same trend with respect to the shift of around 0.5–1 km in 2050 and 5–5.5 km in 2100 for the threshold 4‰. In the Day River in 2050 the threshold of 1‰ and 4‰ are predicted to occur at 24.1 km and 22.4 km from the sea, respectively. Then, the saltwater is expected to intrude inland in a slightly deeper manner in 2100, for which the salinity level of 1‰ is predicted at 24.2 km and 4‰ at 22.55 km from the estuary.

The Ninh Co River is the most vulnerable to saltwater intrusion over the years. The river is not only affected by sea level rise and low discharge upstream, but also by the high salt concentration water inflow from the Red River mainstream. The threshold of 1‰ is predicted to occur at 23.7 km from the sea in 2050, and all along the river in 2100, while the water from KM 23 to the estuary could not be used for crops.

As a general comment it has to be recognized that a more extensive salinity measurement campaign would be recommended and also further laboratory – as in Crestani et al. (2022) – and modelling efforts would be needed to simulate the dynamics of saline intrusion in river deltas and estuaries.

5. Conclusion

The Red River system in the recent year has experienced a severe saltwater intrusion, especially in the delta area, affecting the local habitat and socio-economic activities, particularly for the coastal provinces e.g., Nam Dinh, Ninh Binh and Thai Binh. Due to high water demand at the downstream together with the conflict between water uses from upstream reservoirs, salinity problem has become a key issue to be addressed in development plans. Our top concern, hence is how to mitigate the seawater intrusion in all of the river branches without causing high conflict between different users. Therefore, in this paper, we have tested the salinity dynamics in the river system with respect to the change in river flow discharges released from upstream reservoirs and under different sea level rise scenarios at the downstream flow into the Gulf of Tonkin, based on IPCC AR5 (2013). The results would shed the light on how the change in the reservoir operation rule could affect and mitigate the seawater intrusion in the river network.

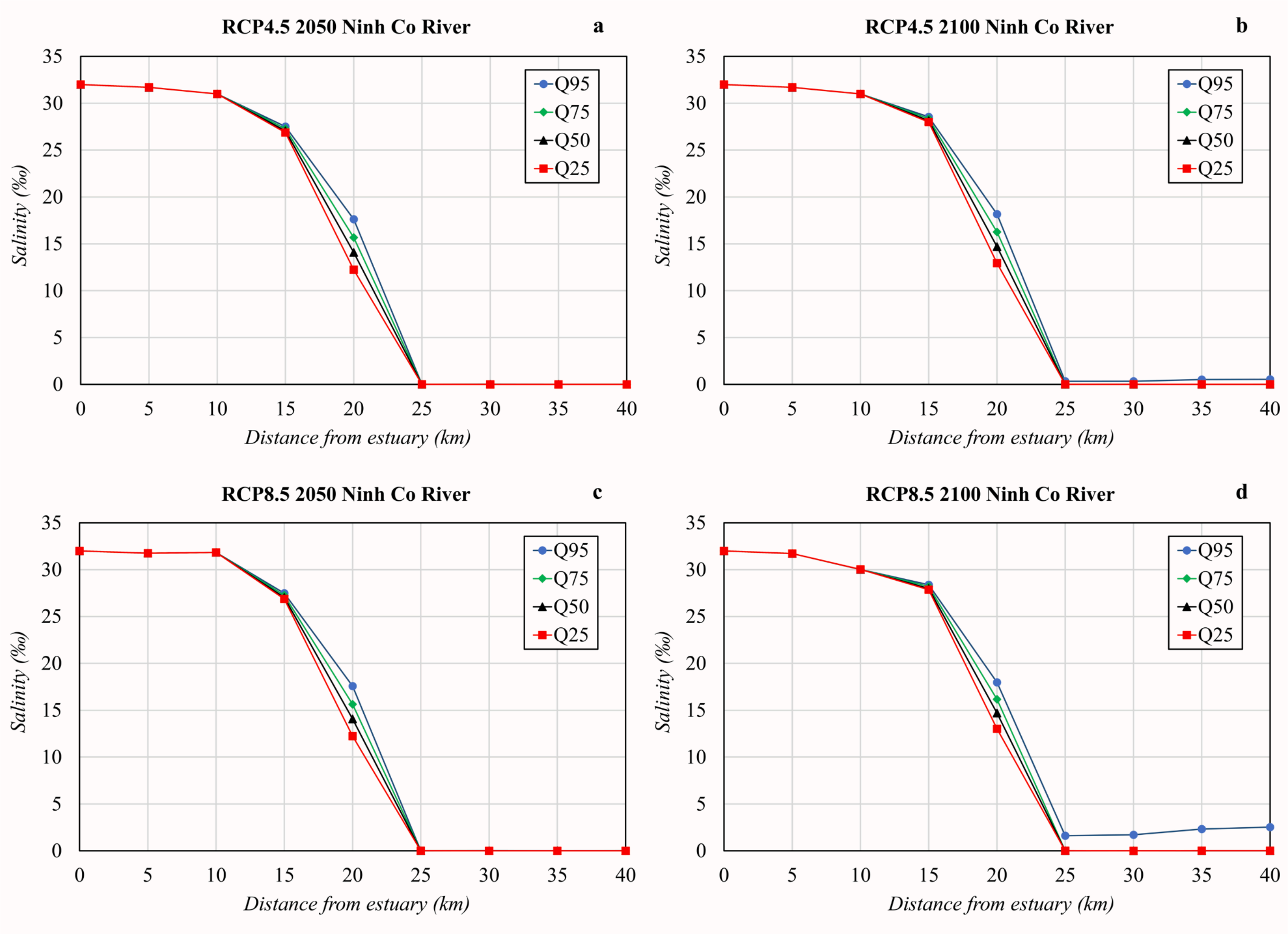

Fig. 9. Salinity profiles in the Ninh Co River referred to two SLR scenarios and four flow discharge frequencies: (a): RCP4.5_2050, (b): RCP4.5_2100, (c): RCP8.5_2050, (d): RCP8.5_2100.

By collecting a series of annual and monthly river flow at Son Tay station (upstream control point) for the period 1990–2016, the study has conducted a statistical analysis focused on the dry period to find the best fit of distribution for the time series data. The results show that the Gamma distribution appears to be a suitable solution among others, in the dry period. In addition, the four Gamma discharge quantiles 25%, 50%, 75% and 95% for Son Tay station have been applied as the change in the upstream conditions with different SLR scenarios at the downstream boundary condition.

A numerical modelling approach is used to assess the saltwater intrusion dynamics in the Red River Delta, considering the effects of reservoir operation upstream and the sea level rise scenarios RCP4.5 and RCP8.5 in 2050 and 2100 downstream. Results obtained by using MIKE 11 hydrodynamic and advection dispersion models in the calibration year of 2010 and in the validation year of 2011 appear to be in satisfactory agreement with observed data, as high Nash Sutcliffe Efficiency coefficients (at least 70%), reasonable RMSE and low error (less than 10%) in both calibration and validation phases were estimated. Thus, the model appears to be suitable for developing the SWI scenarios in future regimes.

The combination of two RCP4.5, RCP8.5 SLR scenarios and four quantile discharges in the two time periods, 2050 and 2100, creates 16 simulation sets for the river system to forecast saltwater dynamics under different conditions from upstream and downstream. Upstream discharge are just hypothetical values: the possibility to release such discharge would depend on the optimization of reservoirs operation considering flow quantity and quality under multiple objectives. Water availability upstream and downstream water demand will depend on climatic, socio-economic changes, land use and agricultural practices and can be the subject of further studies.

The predicted salinity dynamics in the four branches of the Day River, the Ninh Co River, the Red River mainstream and the Tra Ly River, showed an increasing trend in saltwater intrusion over the mid- and end-21st century as the result of sea level rise. Severe saltwater intrusion is expected to be found in all the river branches, particularly at the distance of about 15 km from the estuary if the discharge value is only at the lower quantile of 95% (786 $m^3 s^{-1}$), especially in the Red River mainstream, where the threshold of 4‰ can move to 31.5 km upstream from the sea in 2050 and 41 km in 2100, under RCP8.5 scenario. In the other branches, salt concentration of 4‰ is expected to be found from KM22 to KM28 in RCP8.5 2100, under conditions of critical low discharge released from upstream reservoirs. Salinity level drops very rapidly from KM15 to KM25 in all branches, according to rates varying from 2 ‰ km^{-1} to 3 ‰ km^{-1}. If the high sea level rise combines with critical low discharge upstream, the salt concentration can diffuse from KM50 to KM30 in Ninh Co River, remaining higher than 1‰ all along the river.

The results in the Red river system show that higher sea level and lower discharge could lead to longer seawater intrusion length in all of the branches. From the point of view of upstream reservoir operation, the effect of high inflow discharge is significant. High discharge in the dry season (1296 $m^3 s^{-1}$, discharge quantile 25%) can mitigate the

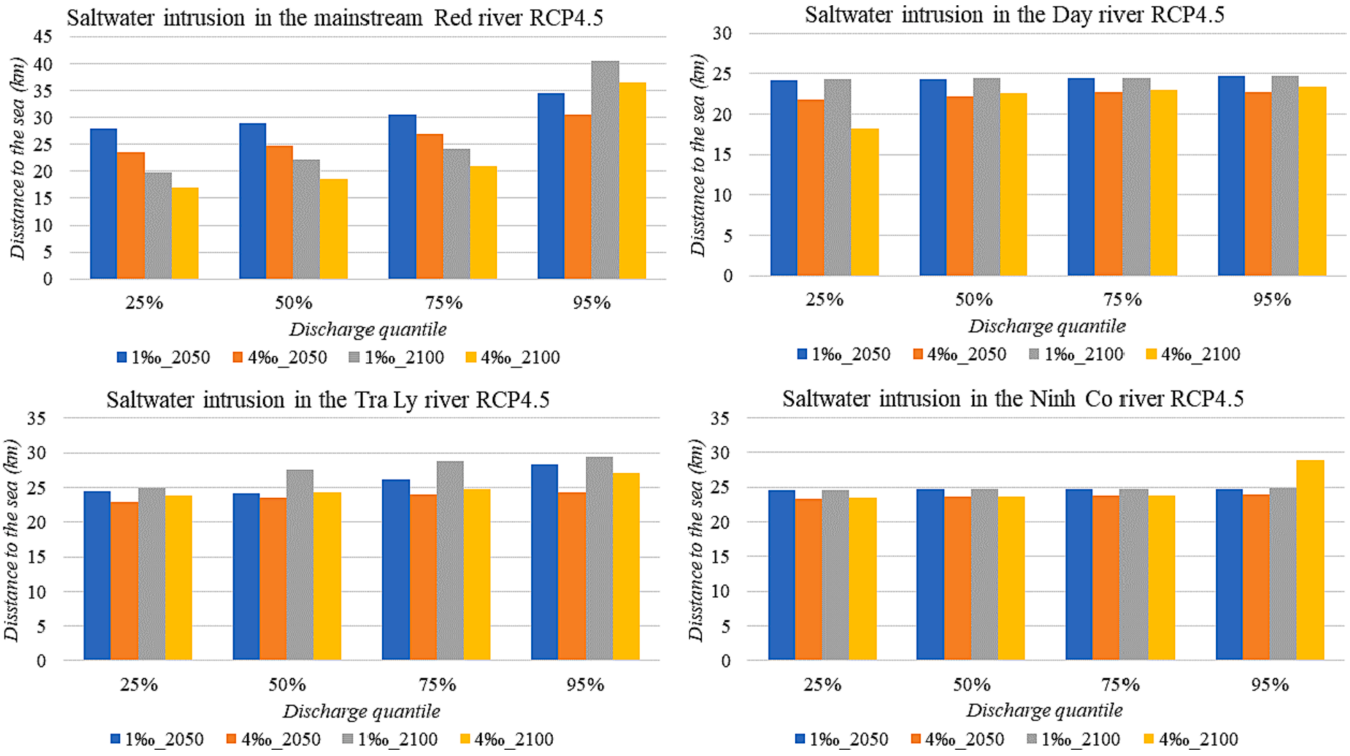

Fig. 10. The 1‰ and 4‰ threshold salt concentration position along the river network in 2050 under SLR scenario RCP4.5.

saltwater in the Red River mainstream downstream from the intersection with the Ninh Co River. This discharge value keeps the salt concentration from KM30 to KM50 in the Ninh Co River lower than 1‰, which means that river flow can be used for irrigation and domestic water supply. Results of this study represent strong evidence that reservoir operations are a potential solution for controlling and preventing saltwater intrusion, provided the reservoir management is optimized considering also this qualitative aspect, generally neglected so far.

This paper is a contribution and an example on how local adaptation measures via reservoir regulations can be implemented to mitigate the salinity problem in the delta area. The research results can provide an important contribution in building a decisions support system for the water management downstream and reservoir operation upstream. As a consequence, the stakeholders could develop skills for the management of multi-purposes reservoirs in mitigating seawater intrusion downstream while maintaining the hydropower supply and irrigation requirements along with flood protection purposes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jher.2023.10.003.

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Nguyen Thi Hien is a researcher assistant at the University of Brescia (UNIBS) since 2020. She got a Ph.D at University of Brescia in 2020, on the saltwater intrusion dynamics under sea level rise context at the Department of Civil, Environmental, Architectural Engineering and Mathematics at University of Brescia. Her main research interests are: hydrology; water resources management; natural disasters early warning e.g flood, debris flow, flash flood; climate change and sea level rise; optimization in reservoir operation regarding different conflicts from irrigation, flood control, and power generation. Her works involve with ArcGIS, MapInfo, hydraulic and hydrology models e.g MIKE, HEC, WEAP.

Nguyen Hai Yen is a second-year PhD student at the University of Brescia at the Department of Civil, Environmental, Architectural Engineering and Mathematics. Her master thesis topic involves the salinity intrusion issues in the estuaries under different climate change scenarios. Her research during doctorate period focus on optimizing the operation of reservoirs located upstream of the Red river basin. The study aims to propose control strategies to balance hydropower generation, irrigation demand and salinity problems.

Matteo Balistrocchi is researcher at University of Modena and Reggio Emilia since 2020, where he lectures on Aqueducts and Sewer systems. Formerly, he lectured on Hydraulic structures at University of Brescia as adjunct professor from 2016 to 2020. He got a Ph.D. in Milan Polytechnique in 2004 with a thesis on analytical-probabilistic methods for the design of storage tanks devoted to capture combined sewer overflows. His research fields mainly cover the application of stochastic multivariate methodologies to the design and safety verification of hydraulic structures such as levees, sewer networks, flood control reservoirs in urban and natural watersheds.

Marco Peli (Brescia, 1985), PhD in Civil and Environmental Engineering, is an Assistant Researcher at the Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM) of the University of Brescia. His major research interests are: (i) soil hydrological properties and water balance, and the influence of annelids on them; (ii) water resources management and optimization with specific attention to irrigation and hydropower; (iii) mitigation of hydrogeological risk with a focus on perched water tables and surface slips; (iv) assessment of the risk of water-driven anthropogenic pollution in surface soils; (v) traditional irrigation techniques and history of hydrology.

Vu Minh Cat is a full professor in hydrology, coastal engineering at Thuy Loi University, Vietnam. He has been the team leader of many research projects funded by Vietnam and international agencies. He obtained his Ph.D in Hydrological and Water Resources Engineering in 1997, on the study of water balance in the dry season. His works cover hydrological engineering, coastal engineering, hydrological and hydrodynamic modelling both in river system and marine, flood and dry flow forecasting, flood risk assessment, river training and coastal protection, as well as design, development and implementation of water system.

Roberto Ranzi is a full professor in Hydraulic Structures and river basin monitoring and restoration at the Department of Civil, Environmental, Architectural Engineering, University of Brescia, Italy since 2005. He got his Ph.D in water engineering at Milan Polytechnic University in 1994. He has been co-authored more than 70 international publications and over 250 publications including conference proceedings and book chapters. His research activities are on hydrology, environmental engineering, water engineering, climate change impact floods, flood forecasting, mountain hydrology, cryosphere, remote sensing.