

Predicting future salinity variability in the Ca Mau Peninsula due to Climate Change

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Abstract. The Ca Mau Peninsula (CMP) in Vietnam's Lower Mekong Delta faces pressing challenges, including sea-level rise (SLR), land subsidence, flooding, and saltwater intrusion. Recent years have witnessed an earlier and more severe dry season, leading to heightened saltwater intrusion. As many CMP provinces rely on the Mekong River for their water supply, they are highly susceptible to prolonged drought and salinization. This study employs the MIKE 11 hydraulic model to project saltwater intrusion scenarios in the CMP up to 2050, based on Vietnam's 2016 Ministry of Natural Resources and Environment (MONRE) SLR projections, considering water regulation from the Cai Lon-Cai Be sluice system. The modelled discharge, water level and salinity were calibrated and validated successfully based on different statistical measures. The projections indicate that saltwater intrusion during the dry season could start 1 to 1.5 months earlier by 2050, with salinity levels exceeding 30 g/l in February. The findings underscore the importance of developing adaptation strategies to address the challenges of climate change and saltwater intrusion, notably in the region's significant agricultural sector.

Keywords. Climate change; Sea level rise; Salinity intrusion; Ca Mau peninsula; MIKE-11

1 Introduction

Salinity intrusion is a pressing issue in numerous coastal areas worldwide because of rising sea levels, particularly in regions with over-abstraction of groundwater due to increasing demand for freshwater [1, 2]. The CMP, located in the Lower Mekong Delta at the southern edge of Vietnam, also faces severe salinity intrusion at the surface through its rivers and canal network [3, 4]. Due to its geographical setup [5], this region experiences salinity intrusion during the dry season, which extends from November to April. The CMP undergoes a scarcity of freshwater input from the Mekong River, making it particularly vulnerable to the challenges posed by climate change and SLR. Therefore, this leads to intricate fluctuations in water levels and currents within river and canal networks, influencing the agriculture and aquaculture sectors, thereby affecting people's livelihoods [4, 6]. Moreover, the CMP suffers from significant coastal erosion problems [7]. The coastline has receded by approximately 50 meters per year, and severe erosion is also occurring along the riverbanks and channel banks [8]. In recent years, the impact of climate change and SLR on seawater intrusion in the Mekong Delta has gained significant interest among researchers. Previous studies have used various models to assess salinity intrusion in the region, including MIKE 11 [6, 9, 10] and MIKE 21 [11, 12]. However, most studies have focused on the Mekong Delta and its primary river systems, i.e., the Hau and Tien Rivers, which flow into the East Sea, except for Nhung et al. [6], who used MIKE 11 to assess salinity in the CMP up to 2030. Additionally, in Sundarbans, Bangladesh, notable research conducted by Wahid et al [13] and Dasgupta et al [14], successfully applied the MIKE 11 model to simulate salinity under various SLR scenarios. This region, similar to the CMP, features a dense network of rivers, and variations in SLR and tidal flow in low-lying areas will bring about changes in spatial and temporal salinity patterns. Therefore, this study uses MONRE's 2016 sea level scenarios for Vietnam [15] to evaluate the consequent changes in saltwater intrusion in the CMP region up to 2050. It thus provides a more detailed understanding of the flow dynamics and the process of saltwater intrusion in the CMP.

2 Methods and Materials

This study models salinity intrusion in the complex CMP river system using a combination of the Hydrodynamic (HD) and Advection-dispersion (AD) modules within the MIKE 11 model developed by the Danish Hydraulic Institute (DHI) [12, 16]. MIKE 11 operates in a 1-dimensional (1-D) unsteady domain. The HD module simulates water levels and

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discharge in the CMP river system, while the AD module accurately replicates salinity propagation. Various data inputs, including meteorological, hydrological, topographic, river network, and river cross-section data, were used for the HD module. After calibration and validation, hydraulic parameters determined the CMP's hydraulic state. The HD module results and salinity data then informed the AD module for salinity propagation simulations, which generated forecasting results combined with climate change and SLR scenarios (Figure 1).

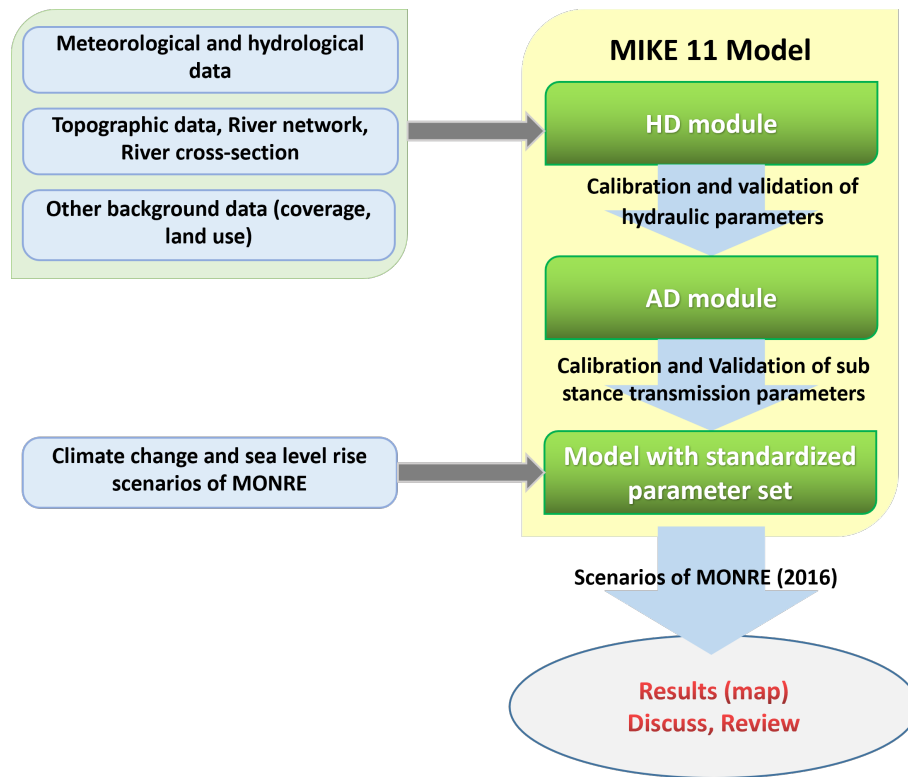


Figure 1. Methodology overview

2.1 Study area

Locating at the southernmost tip of the Vietnamese Mekong Delta, the Cai San Canal bounds the CMP to the north, the Hau River to the northeast, the Western Sea to the west, and the Eastern Sea to the east [17] (Figure 2). The area covers about 1.6 million ha, which accounts for 43% of the total area of the Lower Mekong Delta [6]. This geographical area incorporates the provinces of Can Tho, Soc Trang, Bac Lieu, Hau Giang, Ca Mau, and a segment of Kien Giang [17] (Figure 2). The hydrological system of CMP is governed by the tidal movements of both the East and West Seas, as well as the flow of the Mekong River. The yearly precipitation in this area is approximately 2200 mm, with around 95% of this rainfall occurring during the rainy season. As a result, the freshwater supply for the CMP is a combination of the Hau River's water and rainfall [17]. However, the CMP is currently affected by severe seawater intrusion. Consequently, the water quality during the dry season deteriorates for irrigation purposes [3].

2.2 Input data

This study gathered crucial data from the Southern Institute of Water Resources Research (SWIRR) for CMP, including 1917 branches, river profiles, 10,369 points, and 521 saltwater intrusion control works, notably the Cai Lon-Cai Be sluice. Hydrological data, calibrated and validated, encompass hourly water levels from February to March 2005 at five national hydrological stations (Can Tho, Dai Ngai, Phuoc Long, Vi Thanh, and Nam Can) and hourly discharge data from January to June 2005 at Can Tho station. Salinity measurements at four stations (My Thanh, Ganh Hao, Song Doc, and Xeo Ro) during odd-numbered hours corresponding to the water level time frame were also obtained. Additional updates for salinity control structures up to 2021 were facilitated using Google Earth (Figure 2).

2.3 Boundary condition

The MIKE 11 model defines the Long Xuyen discharge station as the upper boundary and stations on the main rivers (Rach Gia, Song Doc, Ganh Hao, and My Thanh) as the lower boundary. Water level boundaries use data from monitoring

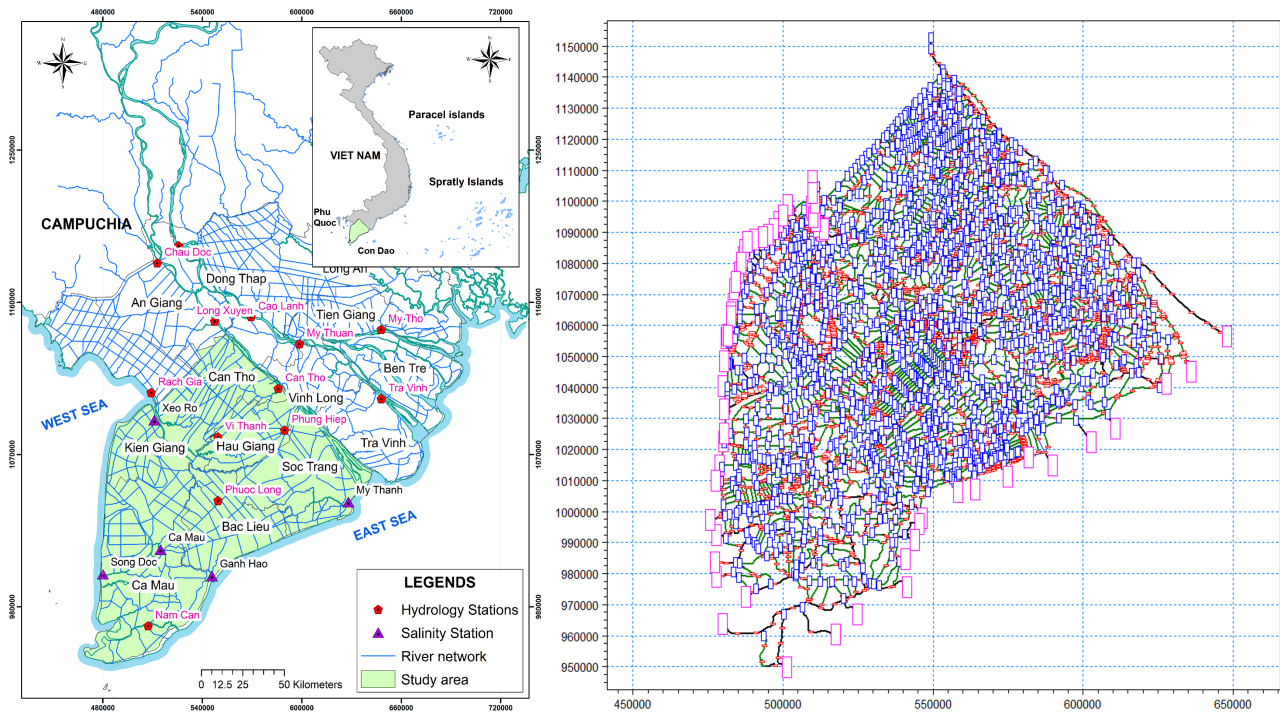


Figure 2. The study area, river network, boundary condition (pink note), and cross-section (red note) in the Ca Mau Peninsula.

Table 1. The statistical indices validated of MIKE 11 HD model

Stations	Factors	River name	RMSE	MAE	R	R^2
Can Tho	Discharge	Hau	5358.3	4363.8	0.79	0.62
Can Tho		Hau	0.155	0.119	0.966	0.935
Dai Ngai		Hau	0.260	0.211	0.964	0.930
Phuoc Long	Water level	Quan Lo - Phung Hiep	0.056	0.043	0.825	0.682
Vi Thanh		Vi Thanh	0.072	0.060	0.849	0.720
Nam Can		Cua Lon	0.391	0.334	0.647	0.419

stations (Ganh Hao, My Thanh, Song Doc, Rach Gia, Xeo Ro, and Nam Can) (Figure 2). As for salinity boundaries, the upper salinity boundaries are set to zero. For the seaward salinity boundaries, a constant value of 35 g/l is used based on the average value over several years. In addition, the time step for stabilizing the model, Δt , must be appropriate for the computational grid. Smaller time steps result in higher model stability, but running with smaller time steps consumes more simulation and computational time. Therefore, this study establishes the computational grid and selects a reasonable simulation time step. It was found that the model runs stably with $\Delta t = 15$ minutes.

2.4 Model validation

The hydrodynamic simulation results were validated with observed discharge data from Can Tho (Figure 3a) (January-June) and water level measurements at multiple stations (Can Tho, Dai Ngai, Phuoc Long, Vi Thanh, and Nam Can) during February-March (Figures 3b-f). Model reliability was assessed through four statistical measures such as RMSE, MAE, R, and R^2 coefficients [18–21]. A comparison of model predictions to actual measurements indicated consistent results, with RMSE values ranging from 0.056 to 0.391, MAE values ranging from 0.043 to 0.334, and R and R^2 coefficients ranging from 0.647 to 0.966 and 0.419 to 0.935, respectively (Table 1). These validated hydraulic modules will be integrated with the AD diffuse load module for saltwater intrusion calculations. Calibrating the AD module’s distributed parameters is a complex task due to factors like monsoon patterns, water flow, demand, wastewater sources, human activities, and salinity control sluice operation. Evaluation of the AD module, using correlation coefficients R and R^2 , demonstrates reasonable agreement between simulated and actual salinity measurements, capturing temporal fluctuations (Figure 4). The simulation model’s performance is deemed acceptable, with R values ranging from 0.794 to 0.978 and R^2 values ranging from 0.632 to 0.958 (Table 2).

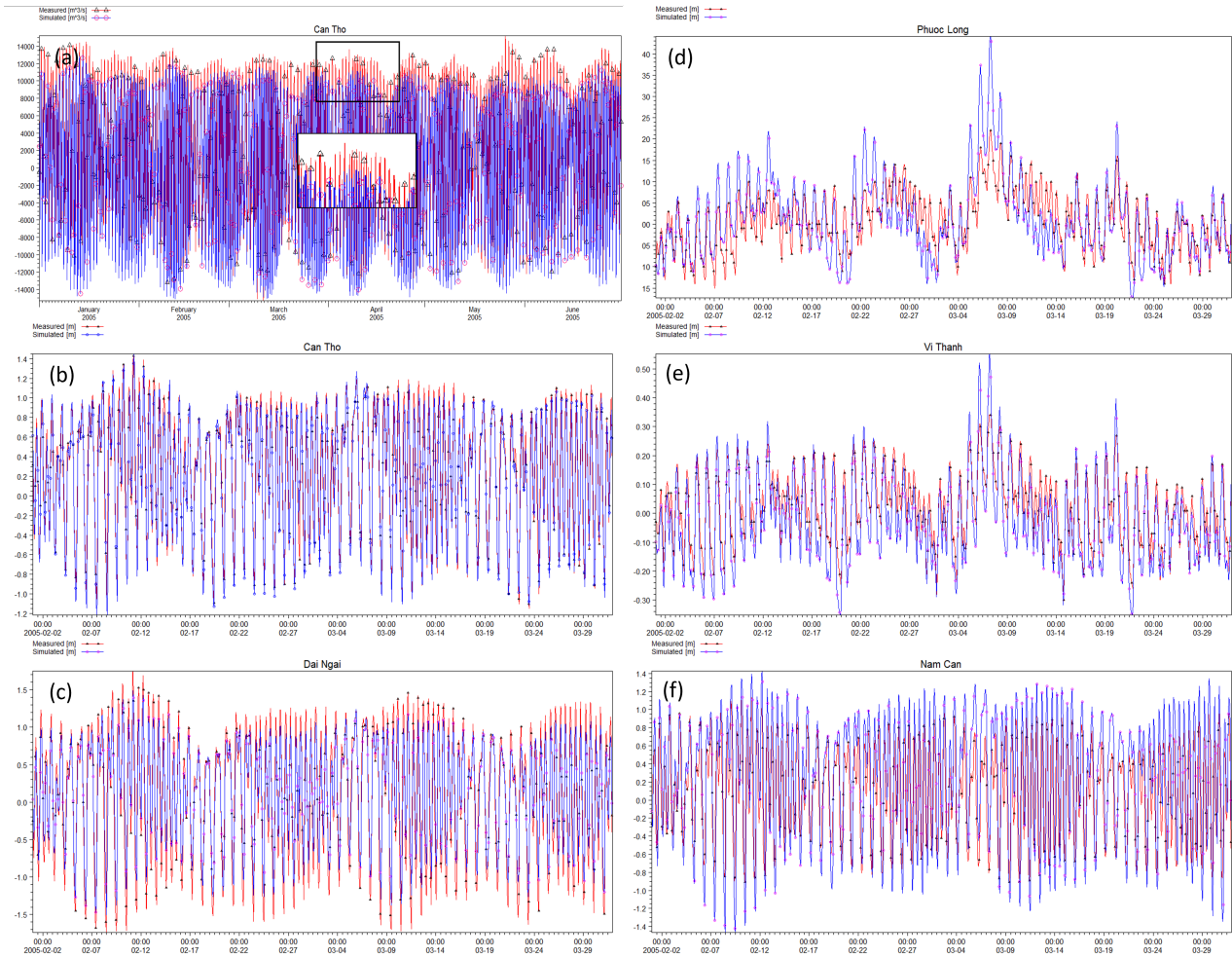


Figure 3. Validation discharge at (a) Can Tho station and water level at (b) Can Tho, (c) Dai Ngai, (d) Phuoc Long, (e) Vi Thanh, and (f) Nam Can stations.

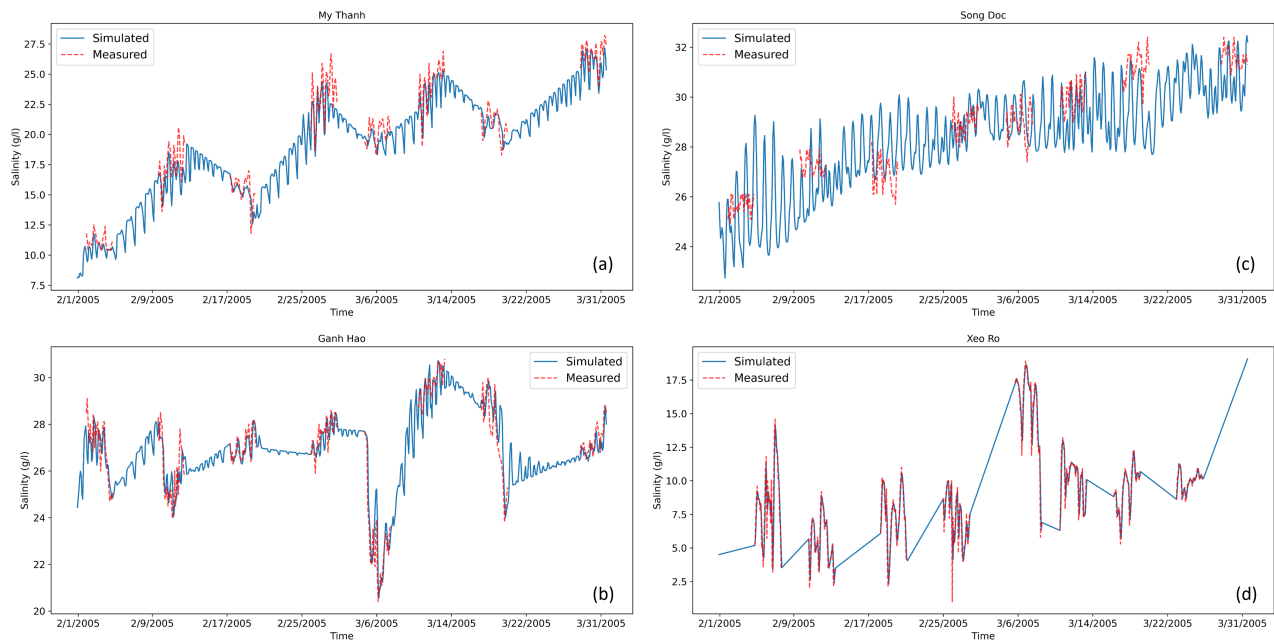


Figure 4. Validation salinity at (a) My Thanh, (b) Ganh Hao, (c) Song Doc, and (d) Xeo Ro stations.

Table 2. The statistical indices validated of MIKE 11 AD model

No	Stations	River name	R	R^2
1	My Thanh	My Thanh	0.978	0.958
2	Ganh Hao	Ganh Hao	0.931	0.868
3	Song Doc	Ong Doc	0.794	0.632
4	Xeo Ro	Cai Lon	0.969	0.940

2.5 Salinity scenarios development

This study developed three scenarios to assess salinity levels in the CMP. The first scenario (S1) is based on data from 2005, incorporating current discharge rates, tidal water levels, and hydraulic work. For the second scenario (S2), SLR projections established by the MONRE in 2016 for Vietnam were used. This scenario includes three sub-scenarios (S2.1, S2.2, and S2.3) with sea level increases of 15 cm (RCP4.5), 25 cm (RCP6.5), and 35 cm (RCP8.5) while assuming a 10% reduction in upstream discharge at the Long Xuyen station. The third scenario comprises three sub-scenarios (S3.1, S3.2, and S3.3) with similar sea level projections (15 cm, 25 cm, and 35 cm) under the RCP4.5, RCP6.5, and RCP8.5 scenarios, respectively. In this case, a greater reduction of 15% in the upstream discharge rate at the Long Xuyen station was assumed (Table 3).

Table 3. Simulation scenarios for salinity at Ca Mau peninsula

Parameters	Simulation scenarios for salinity		
	Baseline (S1)	SLR + Climate change 2050 (S2)	SLR + Climate change 2050 (S3)
Discharge	Current 2005	$Q_{year} - 10\%$ S2.1: + 15 cm (RCP4.5)	$Q_{year} - 15\%$ S3.1: + 15 cm (RCP4.5)
Water level tide	Current 2005	S2.2: + 25 cm (RCP6.5) S2.3: + 35 cm (RCP8.5)	S3.2: + 25 cm (RCP6.5) S3.3: + 35 cm (RCP8.5)
Hydraulic work	Current 2005	Irrigation infrastructure 2021	Irrigation infrastructure 2021

3 Results

Figure 5 depicts salinity levels in February under two scenarios: S1 (Figures 5a) and S2 (Figures 5b, 5c and 5d), which include SLR and a 10% upstream flow reduction. In figure 5a, salinity dominates the CMP, spanning from An Bien District (Kien Giang Province), along the West Sea to Cape Ca Mau, and along the East Sea to Vinh Chau District (Soc Trang Province). Figures 5b, 5c and 5d show deeper salinity intrusion in February, with SLR of 15 cm (S2.1), 25 cm (S2.2), and 35 cm (S2.3), respectively. In Figure 5b, saltwater intrusion extends further than S1, covering nearly 80% of the CMP. Salinity starts in February, affecting Ca Mau and Bac Lieu provinces, with exceptions in some communes in Thoi Binh District and freshwater areas from Tran Van Thoi District to U Minh. Figure 5c, with a 25 cm SLR, shows a deeper intrusion of 10-30 g/l salinity compared to scenario S2.1, as higher sea levels push saltwater further inland through river mouths. Figure 5d, with a 35 cm SLR, reveals 5-7 g/l saltwater intrusion in Tan Hiep District (Kien Giang Province) and My Xuyen District (Soc Trang Province), while other scenarios extend only to Chau Thanh District (Kien Giang Province) and Tran De District (Soc Trang Province). Additionally, for salinity thresholds of 4 g/l, 15 g/l, and 30 g/l, there isn't much difference between scenarios S1 and S2. For instance, with a 4 g/l salinity threshold, measured from the Tran De estuary, saltwater intrudes about 25-27 km inland in both scenarios. For a 15 g/l salinity threshold on the Cua Lon River, from Nam Can station to Cai Nuoc District in Ca Mau Province, saltwater intrusion extends approximately 35-38 km in both scenarios. Regarding a 30 g/l salinity threshold, starting from the Bay Hap River mouth, saltwater intrusion reaches approximately 16-18 km inland in both scenarios. Overall, saltwater intrusion is significant in February, with 10-30 g/l salinity affecting almost 75%.

In scenario S3, where upstream discharge decreases by 15%, and SLR by 15 cm (Figure 6a), 25 cm (Figure 6b), and 35 cm (Figure 6c) correspondence S3.1, S3.2, and S3.3 scenarios, it's evident that when flow reduction is significant and combined with high SLR, salinity fluctuates between 10-30 g/l in February. Within this range, salinity levels of 21-30 g/l cover nearly 60% of the CMP's area. Saltwater intrusion occurs from the East Sea into the southern subregions of South Ca Mau and then into the northern subregions of North Ca Mau. It also intrudes from Bac Lieu along the Quan Lo-Phung Hiep route into the northern subregions of North Ca Mau and from Kien Giang along the Chac Bang channel into the northern and southern subregions of North Ca Mau. Additionally, seaward intrusion from the West Sea occurs in the northern and southern subregions of North Ca Mau and South Ca Mau. In this scenario, saltwater intrusion penetrates deeper into Soc Trang Province compared to scenarios S1 and S2, with salinity levels reaching approximately 6-8 g/l.

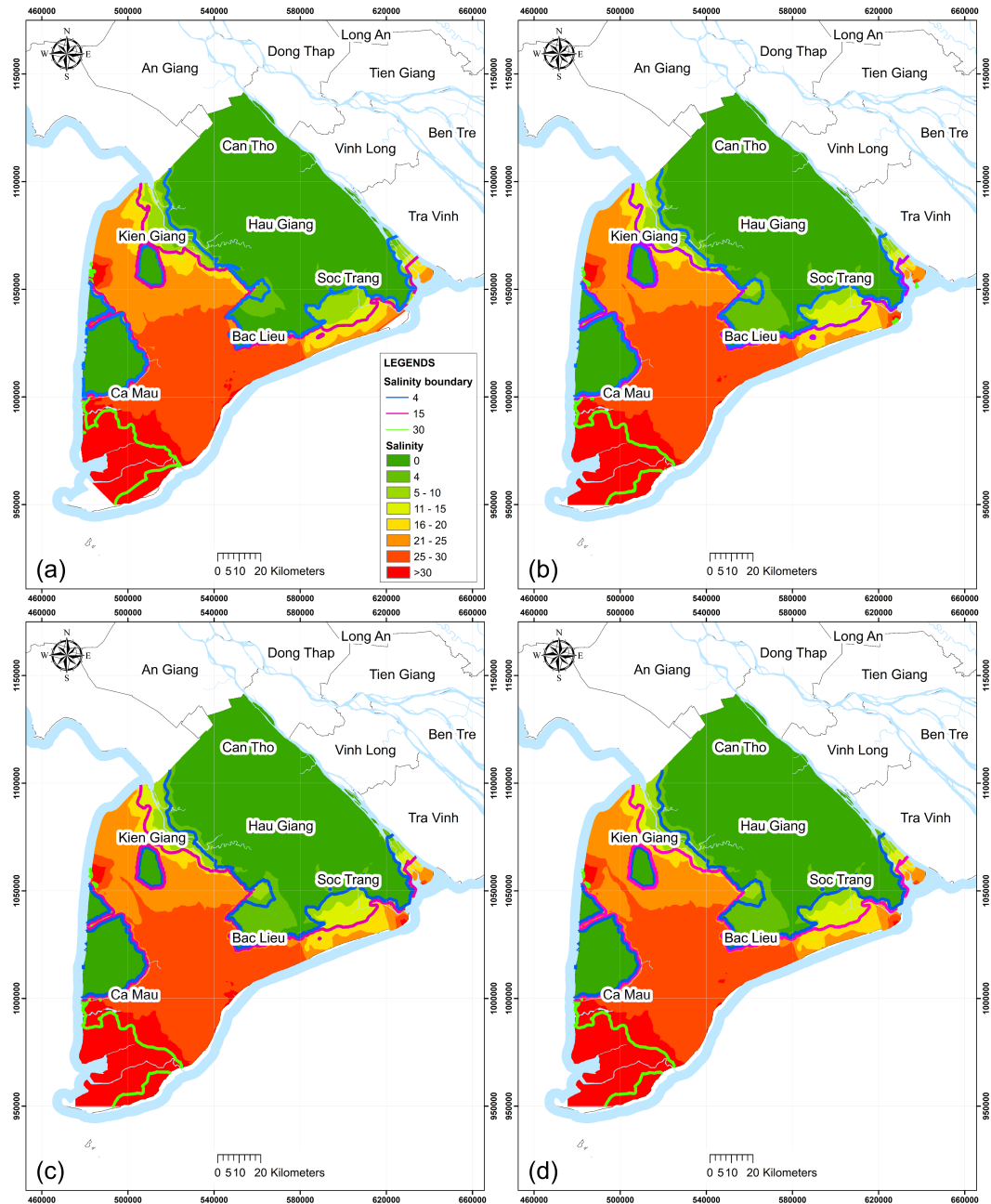


Figure 5. Salinity intrusion area in February of (a) S1, (b) S2.1, (c) S2.2, and (d) S2.3 scenarios.

Coastal areas have salinity levels ranging from 10-20 g/l. Looking at Figure 6a, we observe that a 15 g/l salinity threshold intrudes 38 km from the Cua Lon River to Cai Nuoc District (Ca Mau Province). However, for a SLR of 25 cm (Figure 6b), there isn't much change in the extent of salinity thresholds of 4 g/l and 15 g/l compared to Figure 6a. With a SLR of 35 cm (Figure 6c), the 15 g/l salinity threshold intrudes deeper into the inland areas, reaching approximately 40 km from the Cua Lon River mouth to Cai Nuoc District.

4 Discussion

The simulations show a notable acceleration in saltwater intrusion, occurring 1 to 1.5 months earlier than previously observed (2005), manifesting in February instead of April. This aligns with findings from previous study of Toan [22], suggesting a potential challenge from SLR in CMP. Saltwater intrusion impacts Soc Trang Province, affecting river flows and canal systems. A tidal-saline interface zone near Bac Lieu town exhibits salinity levels exceeding 30 g/l in February. Projections suggest reduced severity at the Tran De estuary, with the 4 g/l salinity threshold retreating seaward. Despite SLR scenarios and reduced upstream flow, salinity is expected to remain less severe, showing a 4-6% reduction along river mouths. Seasonal shifts in saltwater intrusion are driven by dry season flow variations. While March and April witness

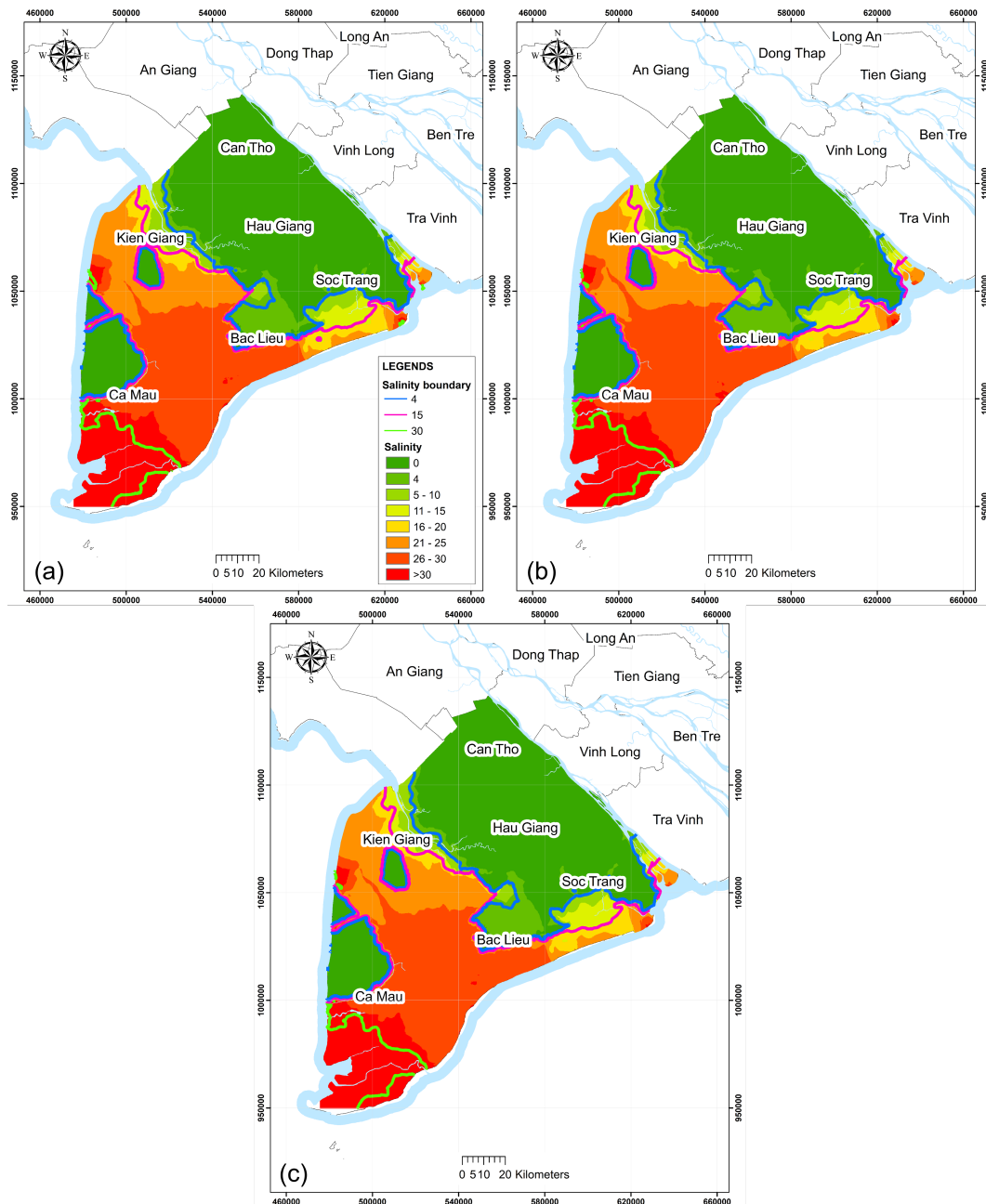


Figure 6. Salinity intrusion area in February of (a) S3.1, (b) S3.2, and (c) S3.3 scenarios.

increased flow and rapid salinity decrease, early dry season experiences elevated salinity due to reduced flow. Limitations include the need for a more comprehensive consideration of climate-induced rainfall changes and evolving water demands in the CMP.

5 Conclusion

This study, utilizing the MIKE 11 hydrodynamic model, analyzed CMP's hydrological conditions in 2005 and projected changes up to 2050 due to climate change. Analyzing reduced upstream flow and SLR scenarios (RCP4.5, RCP6.5, and RCP8.5), the results indicate saltwater intrusion in the CMP is expected 1 to 1.5 months earlier by 2050, primarily through river mouths such as Ganh Hao, Cua Lon, Bay Hap, Ong Doc, and Cai Lon. This intrusion intensifies during high tide periods, notably in February, due to reduced upstream flow and limited off-season rainfall. In scenario S2, with a 10% upstream flow reduction and varying tidal levels, the 10-30 g/l salinity intrusion boundary remains relatively stable for some rivers. However, Ca Mau and Bac Lieu provinces are heavily affected, with nearly 80% of their land experiencing significant salinity intrusion. Under scenario S3, with a 15% upstream flow reduction and varying tidal levels, the salinity intrusion boundary penetrates deeper inland. In S3.3, almost 80% of the CMP, including the Cai Lon River to Bac Lieu province and Vinh Chau district (Soc Trang province), experiences notable salinity intrusion. These findings are crucial for

developing forecasting models and effective coastal management. They offer early warnings for residents and authorities, aiding in adjusting schedules and implementing measures to mitigate saltwater intrusion's impact on livelihoods.

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