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Research Article

Linking hydrological, hydrodynamic models for saline intrusion assessment – Applying for Ve river estuary as a case study

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Abstract: Researches on combinion of hydrological and hydrodynamic models are very important when performing risk assessment and disaster management, including saline intrusion, which is especially important for watersheds, with limited measurement data. The objective of this study is linking two types of hydrological and hydrodynamic models to simulate the scope of salinity intrusion in the Ve estuary, Quang Ngai province. Firstly, SWAT/NAM is applied to calculate flow rate, and then MIKE 21/3 model is applied for hydraulic and salt intrusion simulation. The calibration and validation are also done to show that the acceptable reliability of simulation. Simulation result showed that salinity intrusion depends on water discharge, water level, tidal regime according to dry and wet seasons; the longest distance of saline intrusion from the rivermouth is 5.47 km, occurring in the dry season.

Keywords: Rainfall–Runnoff; SWAT/NAM; MIKE 21/3; Salinity Intrusion; Ve River.

1. Introduction

The development and use of hydrological models has attracted increasing attention in the past two decades [1], and the combination of hydrological and hydrodynamic models has demonstrated is an important tool for the integrated assessment of hydrological processes in basins where measurements are very expensive [2]. Such a combination helps to solve many problems in the area including saline intrusion in the estuary. The hydrological model helps to calculate the discharge of rivers – one of the important factors to simulate the flow [3–4], thereby assessing the scope of salinity intrusion as well as the problems of flooding, bank erosion – which are very typical for many regions bordering the sea [5–6].

With a coastline stretching over 3260 km, along with many socio–economic activities, the coastal zone of Vietnam is a special important one; and saltwater intrusion has always been the subject of national studies [7–22]. In particular, saltwater intrusion in the Mekong Delta is selected in many national researches, projects and programs [23–26] . However, research on saltwater intrusion in the central coastal region is still quite modest in terms of quantity and results [8, 16, 18]. Although there have been studies done, however, when applied to the local scale it is necessary to concretize the dependence as the scope of salinity intrusion on the such factors as upstream discharge, the downstream water level, and the tidal regime. Accurate salinity intrusion forecasting plays a huge role in proactive agro–fishery and land use planning in coastal economic zones, especially in the current climate change situation [7]. Saltwater intrusion prediction would be difficult to do without calculating the water flow entering the river, leading to the need for the application of suitable hydrological models. This shows that the linkage of hydrological – hydrodynamic models play an important role in calculating and predicting saline intrusion [25].

The study selects a typical river in Quang Ngai province as a research case study, following published articles [27–29]. The hydrological coupled models SWAT/NAM combined with the MIKE21 HD to determine the set of hydrological and hydraulic parameters for the Ve river basin was performed [27]. [28] has initially applied a set of hydrological parameters to calculate discharge for the hydraulic model and used it to simulate saline intrusion from the sea to the river. [29] helps to answer the question of how the salinity intrusion mechanism depending on water discharge, water level, seasons have not been shown. In the mentioned articles, the scope of salinity intrusion depending on water discharge, water level, seasonal regimes have not been shown. In this study, the combination of SWAT/NAM coupled hydrological models and MIKE 21/3 HD, AD hydrodynamic models was clarified with the result of determining the scope of salinity intrusion for Ve river. In addition, a number of arguments have been made to argue the dependence of salinity intrusion on the factors of discharge, tidal regime, and flow by 2–D models. The results of this study complement previous studies [28–30].

2. Methods and materials

2.1. The study area

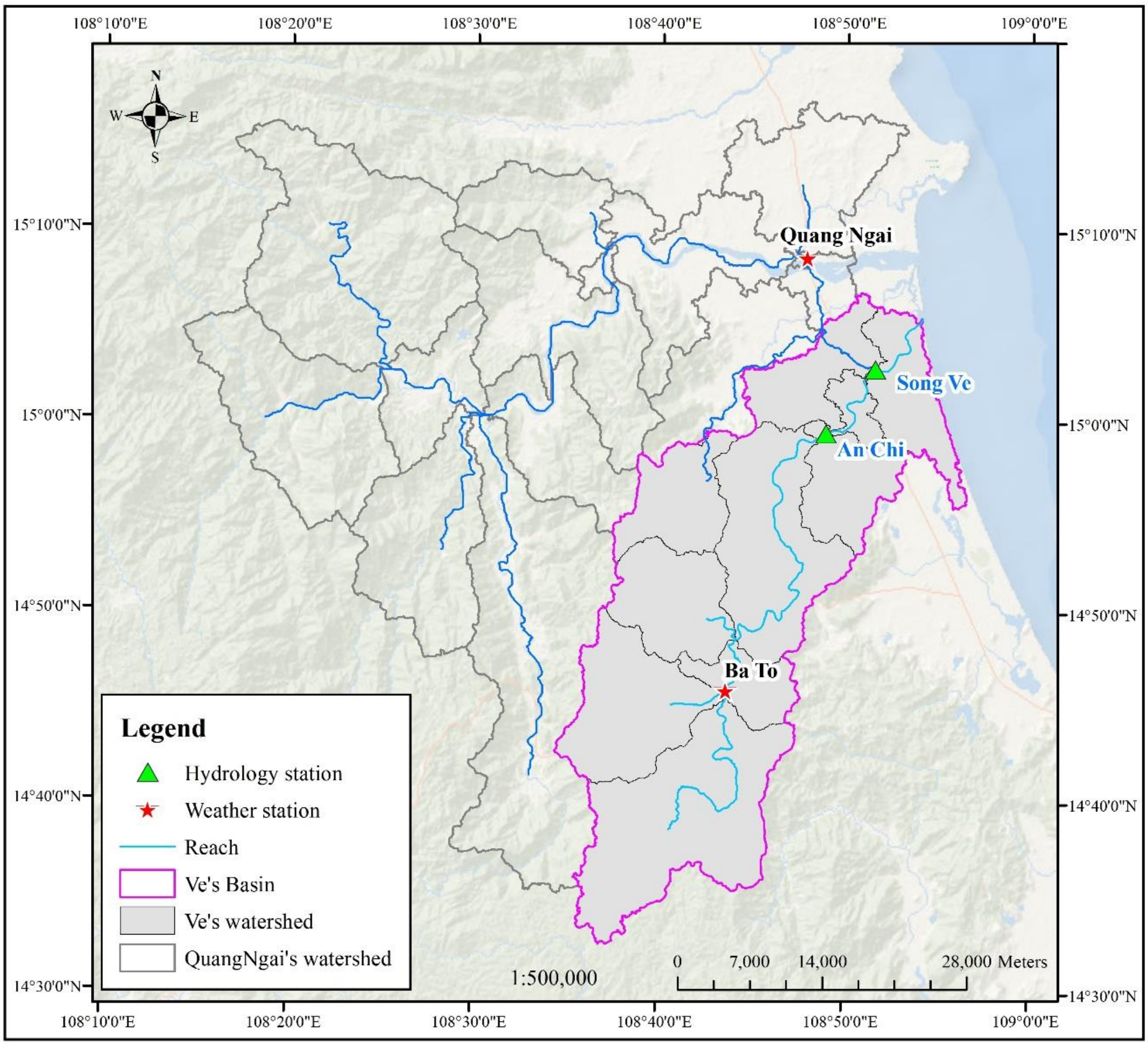


Figure 1. Focus area of the study Ve River basin.

Ve River is one of the largest river systems in Quang Ngai province, covering an area of 1,263 km^2, accounting for 24.51% of the natural area of this province [27]. The study [30], although it mentioned saline intrusion in the Tra Khuc–Ve river basin system, used a 1D hydrodynamic model combined to assess the intrusion salinity in the downstream of Tra Khuc–Ve river system. However, the scope of this study focuses on the Tra Khuc River, not mentioning the Ve River. But, research specifically for the Ve River part, in the last 2 years, has been the subject of some studies [27–29], in which the combination of hydrological and hydrodynamic models has been systematically done.

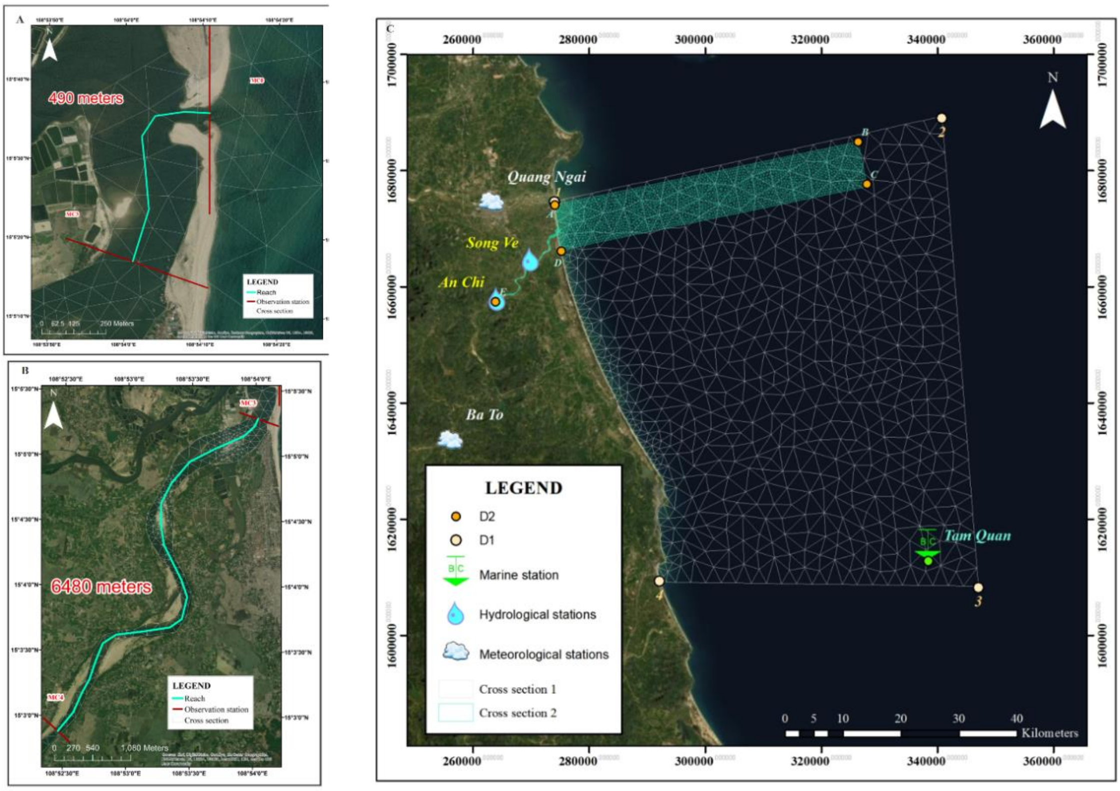


Figure 2. (A), (B) The 3 cross–sectional positions MC0, MC3, MC4 measured water level and salinity; (C) The grid domain D1 includes 4 vertices 1, 2, 3, 4 including marine station Tam Quan, Binh Dinh; The grid domain D2 with 5 peaks A, B, C, D, E was selected to simulate HD and saline intrusion AD, the four measurement stations are shown: meteorology (Quang Ngai, Ba To), discharge (An Chi), water level (Song Ve).

2.2. Hydrological models

To build hydrodynamic scenarios, hydrological models are often used, which involve the use of mathematical modelling techniques of rainfall–runnoff processes in the basins [4, 31]. Analysis of the advantages and disadvantages of these models was carried out in a series of studies [4, 32–33]. For sub–basin division, SWAT is used, input data for the SWAT model includes ASTER digital elevation model data (ASTGTM) with spatial resolution of 30 m, river Ve shapefile (line) and a raster mask layer within Quang Ngai province with 48N UTM coordinate system. Select a flow direction division area of 6838 ha with 72830 cells (default value from SWAT model). An Chi station is added to ArcSWAT using the tool to create an outlet at An Chi station location (Figures 1–2). Thus, using NAM, the discharge data extracted at the outlet of An Chi station will be compared with the actual measured data. In this study, rainfall, temperature, wind, and solar radiation data at Quang Ngai station were used to generate evaporation data. Together with the results of sub–basin division, this dataset is included in NAM to calibrate the set of hydrological parameters for the basin. The set of measured discharge at An Chi is used for the calibration, verification steps. The linking between SWAT and NAM is shown in Figure 3. The results of calibration of the hydrological parameter set for the study basin reflected in the work [27]. To perform the calibration, first, from the initial set of parameters, NAM performs automatic calibration by the gradual trial method to increase the accuracy to a stable level with the allowed error based on the statistical indicators [34].

2.3. MIKE 21/3

The MIKE software package – a product of the Danish Hydraulic Institute – DHI Water & Environment, with modules such as MIKE 11, MIKE 21, MIKE3 HD, AD, ST, MT, SW is used to simulate the one–dimensional, two–dimensional, three–dimensional hydrodynamic processes, the transport and diffusion of dissolved and suspended substances, sediments; propagation of ocean waves, calculation of alluvial sediments in estuaries and coastal areas. Research on the application of MIKE to simulate saline intrusion has been carried out in many studies [7, 10, 17, 21–22]. 2D governing equations and numerical solution of MIKE 21 models (HD and AD) are presented in detail in [35, 37].

2.4. Data

2.4.1. Bathymetry

The MIKE 21 HD running data in this study was divided into 2 groups. The first related to the coastal area was collected, processed and transferred into the module [27–29], the second group related to the mainland and estuary includes: real data measured 19 cross–sections measured, inherited from the previous project. The section of the Ve River considered in this study is limited from the upper reaches of the river to the mouth of the Lo mouth and is 21.47 km long (Figure 1).

2.4.2. Tital factors

Song Ve is influenced by the East Sea with a semi–diurnal tidal regime with 4 main tidal components: M2 = 20h, S2 = 10h, O1 = 30, K1 = 30h, are used to analyze the tidal wave harmonic function to create tidal boundary for the model [29, 38]. This set of parameters plays an important role in the MIKE 21/3 HD and AD modules.

2.4.3. Hydrometeological data

The MIKE 21/3 FM runs for coastal waters requiring hourly data including wind speed and direction. In this study, the Weather Research and Forecasting (WRF) model was used for hourly extraction [29]. [27, 29] show that in July 2018, the average daily discharge is the lowest, and December 2018 has the highest average daily discharge. Besides, in this study, the measured meteorological data at Ba To and Quang Ngai stations, discharge measurement data at An Chi, and water level measurement at Song Ve stations are used. These datasets are used to calibrate NAM hydrological models and hydraulic models. The steps to apply these datasets are shown in Figure 3.

2.3.4. Actual measuring data for water and salinity levels

Within the framework of the thesis, field measurements were carried out with the following equipment: Acoustic Doppler Current Profiler (ADCP); NA2 Leica hydrometer, LEICA (TC805), echo sounder HONDEX PS–7; salinity meter; terrain mia; handheld GPS unit; compass. Hydrological factors were recorded from 0:00 on October 7, to 23h on October 8, 2018 and measured cross–section and elevation conduction from October 9–10, 2018. Simultaneously with measuring the water level, the salinity factor was also sampled and measured in a 24–hour mode from 0:00 on October 7 to 11 p.m. on October 8, 2018 at all 3 cross–sections: section 0, cross section 3 and section 4 [29]. Measurement of water flow by ADCP is performed at 3 cross–sections according to 24/24 mode from 0:00 on October 7 to 23:00 on October 8, 2018. This set of measured salinity data is used to calibrate the AD model.

2.5. Procedural steps

In the study [27], the hydrological – hydrodynamic package SWAT/NAM/MIKE was used to build a set of hydrological and hydraulic parameters for flow calculations.

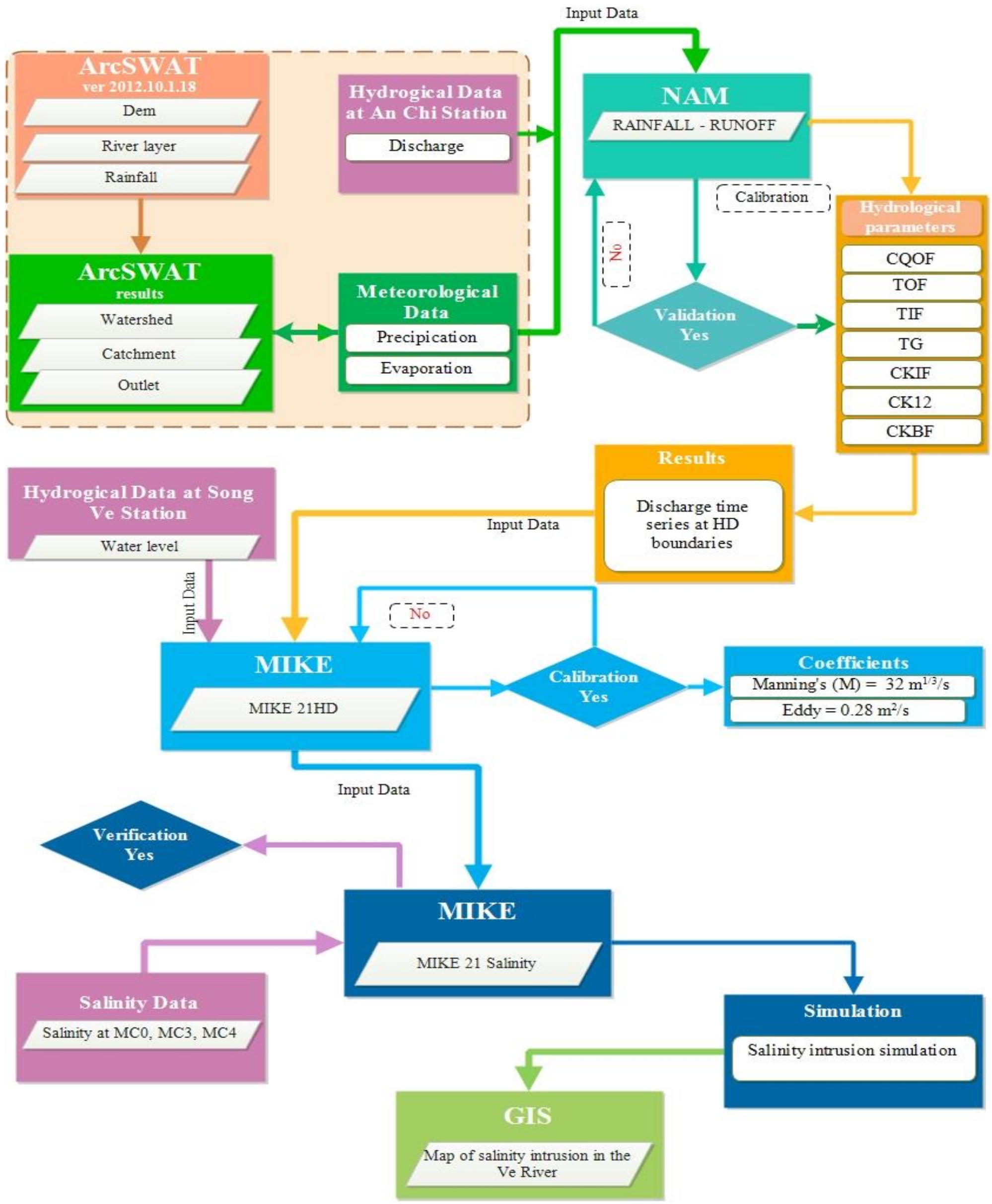


Figure 3. Linking hydrological and hydraulic models to simulate saline intrusion.

The contents and implementation sequence are shown in Figure 3, as follows: first, SWAT is used to divide the basin, determine the outlet as well as create the evaporation, precipitation dataset for NAM. The set of actual discharge measurements at An Chi is used for calibration and validation, the result of the step is the set of calibrated hydrological parameters. The second step–performing calibration and testing of the hydraulic module for the Ve River, using the discharge boundary created by NAM. Measured data of water level at the Ve station is used (Figure 3). The salinity data measured at MC0, MC3, MC4 cross–

sections are used to calibrate dispersion parameter for AD modelling (Figure 3). Third, the MIKE 21/3 AD module is used to simulate saline intrusion from the sea to the land.

The HD module is used on two domain grids D1, D2 (Figure 2). Grid D1(1234) with vertices **1**(108° 53,849'E; 15° 8.245'N), **2**(109° 31,094'E; 15° 16,491'N), **3**(109° 34.907'E; 14° 32,590'N), **4**(109° 4.328'E; 14° 32.776'N) contains Tam Quan station (Figure 2). Grid D2 (ABCDE), where B, E are the vertices located the sea with coordinates **B** (109° 22,973'E; 15° 14.079'N), **C** (109° 23,821'E; 15° 10.165'N); vertices **A** (108° 53,866'E; 15° 7,957'N), **D** (108° 54.421'E; 15° 3,722'N) are located in the coastal area; The vertice **E** (108° 48.130'E; 14° 58.928'N) is located inland and is also upstream of the Ve River (Figure 2). Hydraulic modeling for grid D1 was performed with water level boundaries obtained from the Tide Prediction of Height toolkit in MIKE 21Toolbox(.21t). The set of real data measured at Tam Quan in 2015 was selected for calibration with the result $R^2 = 0.916$; Nash = 0.988; PBIAS = 7.323; RSR = 0.460 and verification with results: $R^2 = 0.919$; Nash = 0.991; PBIAS = 7.933; RSR = 0.490. The result of this step is calibrated parameters: viscosity coefficient 0.28 (m^2/s), roughness coefficient 30 ($m^{1/3}/s$). The hydraulic model that is runs for domain D1 is used to create the water level boundaries for 3 edges AB, BC, CD, belonging to grid D2 (Figure 2). The HD model for grid D2 uses the water level boundary from 3 sides AB, BC, CD, the discharge boundary at the upstream location E, using NAM. Actual data of water level measurement at Song Ve station (Figures 1–2) in 2018 is used for calibration and verification; in which the calibration results are $R^2 = 0.939$; Nash = 0.970; PBIAS = –2.290; RSR = 0.490 and verification results are: $R^2 = 0.901$; Nash = 0.953; PBIAS = –16,763; RSR = 0.490. The result of this step is the set of parameters for the viscosity coefficient of 0.28 (m^2/s) and the Manning roughness coefficient of 32 $m^{1/3}/s$ for the Ve River.

Based on meteorological data in at Ba To station for 2018, the NAM model is applied to create a discharge boundary for the Ve River [27]. From the time series of data for discharge, the month with the smallest and largest average discharge are found, namely the months of July, December. MIKE (21 and 3) HD and AD are applied for hydraulic and saline intrusion modelling in the seleted area. From these results, the relationship between the scope of saline intrusion, the tidal regime and flow discharge has been made.

3. Results and discussions

3.1. Setup the set of hydrological parameters

The discharge data set measured at An Chi station, in the period 2013–2015 is used to calibrate, verify, validate NAM, in which the whole year of 2013 is used for calibration, two years 2014–2015 for verification and validation purposes are determined. The results for the Nash index are 92%, 90% and 93%, respectively, are shown in Figures 3a–3c.

Table 1. Calibrated hydrological parameters set for the selected basin.

Parameters	Meaning	Value
U_{max}	Upper limit of the amount of water in the surface storage (mm)	17
L_{max}	upper limit of the amount of water in this storage (mm)	172
CQOF	Overland flow runoff coefficient, dimensionless	0.185
TOF	Threshold value for overland flow	0.531
TIF	Root zone threshold value for interflow	0.114
TG	Root zone threshold value for groundwater recharge	0.404
CKIF	Time coefficient of surface water flow	655.8
CK12	Constant intrusion time of surface water flow	19
CKBF	Constant intrusion time of groundwater flow	3972

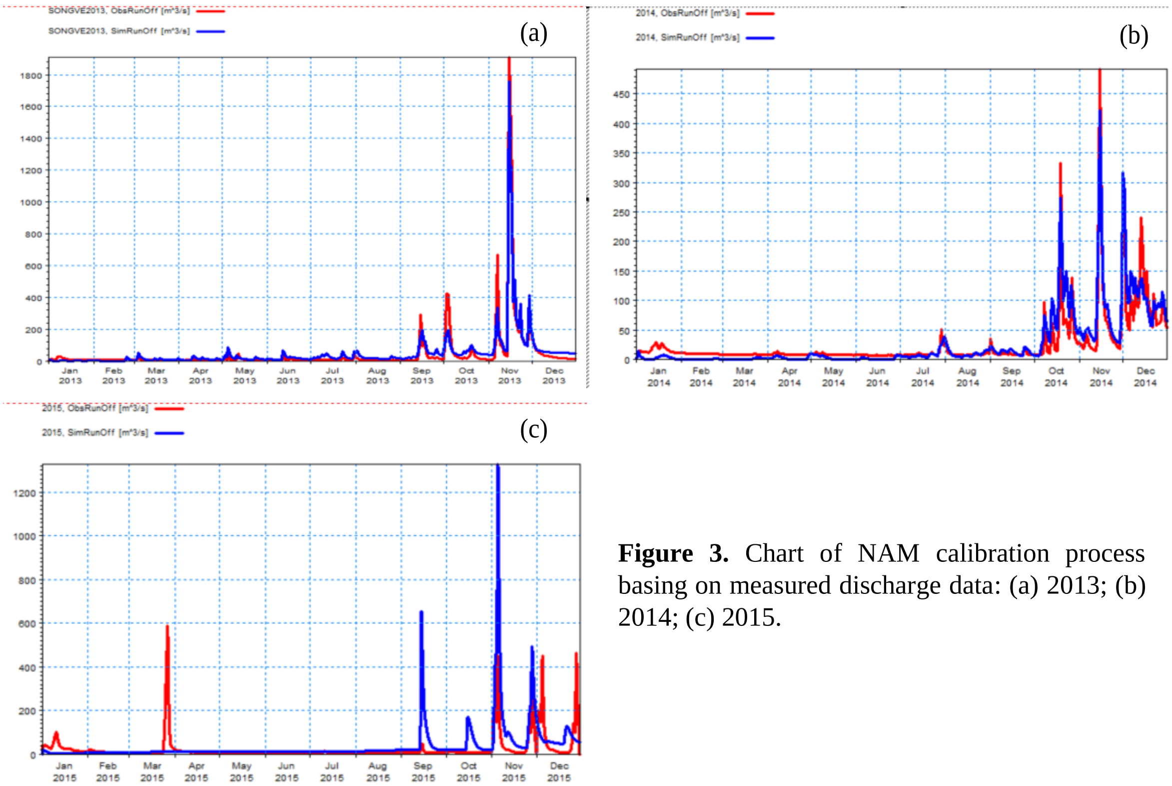


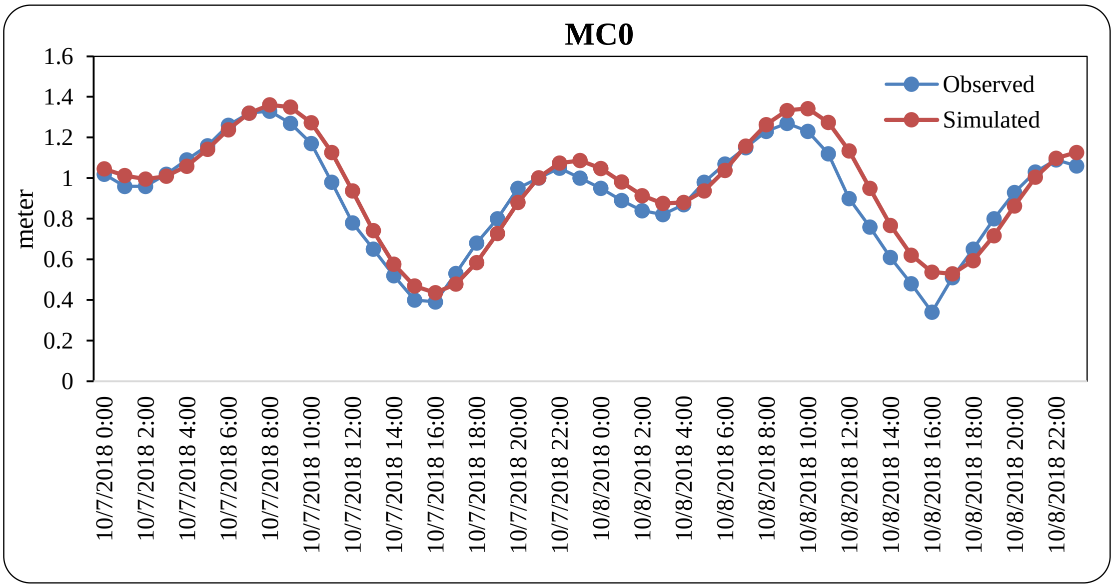
Figure 3. Chart of NAM calibration process basing on measured discharge data: (a) 2013; (b) 2014; (c) 2015.

3.2. HD and AD validation

The time series of water levels selected for validation of the MIKE 21/3 HD hydraulic model is as follows: time series for correction: October 7, 20188 00:00:00 AM – October 8, 2018 11:00:00 PM. Actual measured data of water level is done, described in 2.3.4. The results of validation of the hydraulic model are shown in Table 1 and Figure 4.

Table 1. Verification results of HD module at 3 monitoring sections.

Sections	R^2		Nash		PBIAS		RSR	
MC0	0.9098	Very good	0.8805	Very good	–4.6676	Very good	0.3457	Very good
MC3	0.9027	Very good	0.8929	Very good	–1.0879	Very good	0.3272	Very good
MC4	0.8932	Good	0.8055	Very good	–3.9384	Very good	0.4410	Very good



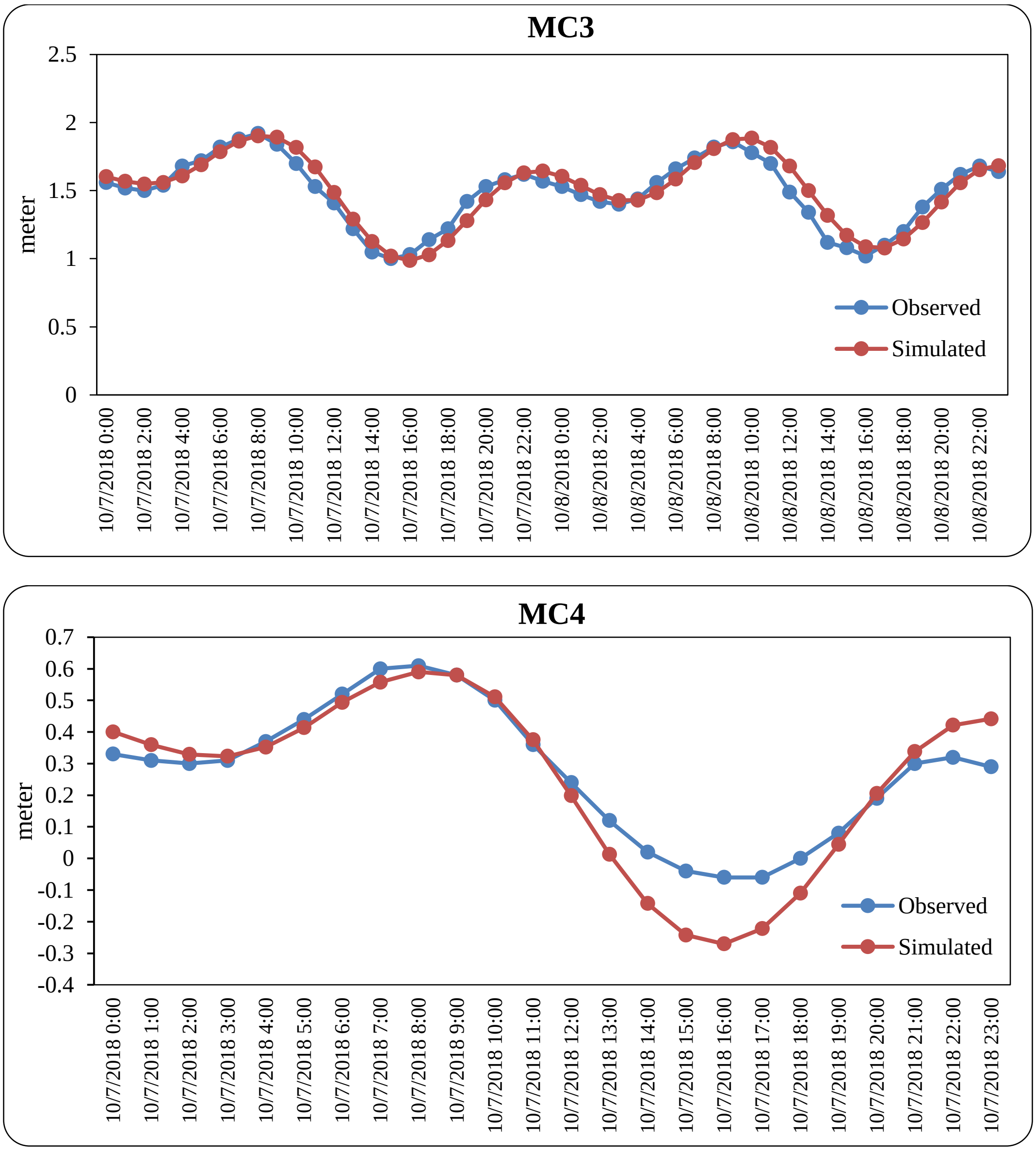


Figure 4. Results of HD verification using real data measured at 3 cross–sections MC0, MC3, MC4.

The results of the MIKE 21/3 AD calibration and verification performed, usingh 48 hours of continuous salinity measurement data for 2 days 7–8 October 2018 at 3 cross–sections MC0, MC3, MC4 (section 2.3.3) are shown in Table 2. This result allows to confirm that MIKE 21/3 AD can be applied to simulate the saline intrusion picture for this study.

Table 2. The results of calibration of the AD module using continuous monitoring data at MC0, MC3, MC4.

Sections	R^2		Nash		PBIAS		RSR	
MC0	0.876	Good	0.704	Good	–18.476	Satisfactory	0.544	Good
MC3	0.725	Good	0.845	Very good	–11.380	Good	0.563	Good
MC4	0.749	Good	0.720	Good	–0.354	Very good	0.539	Good

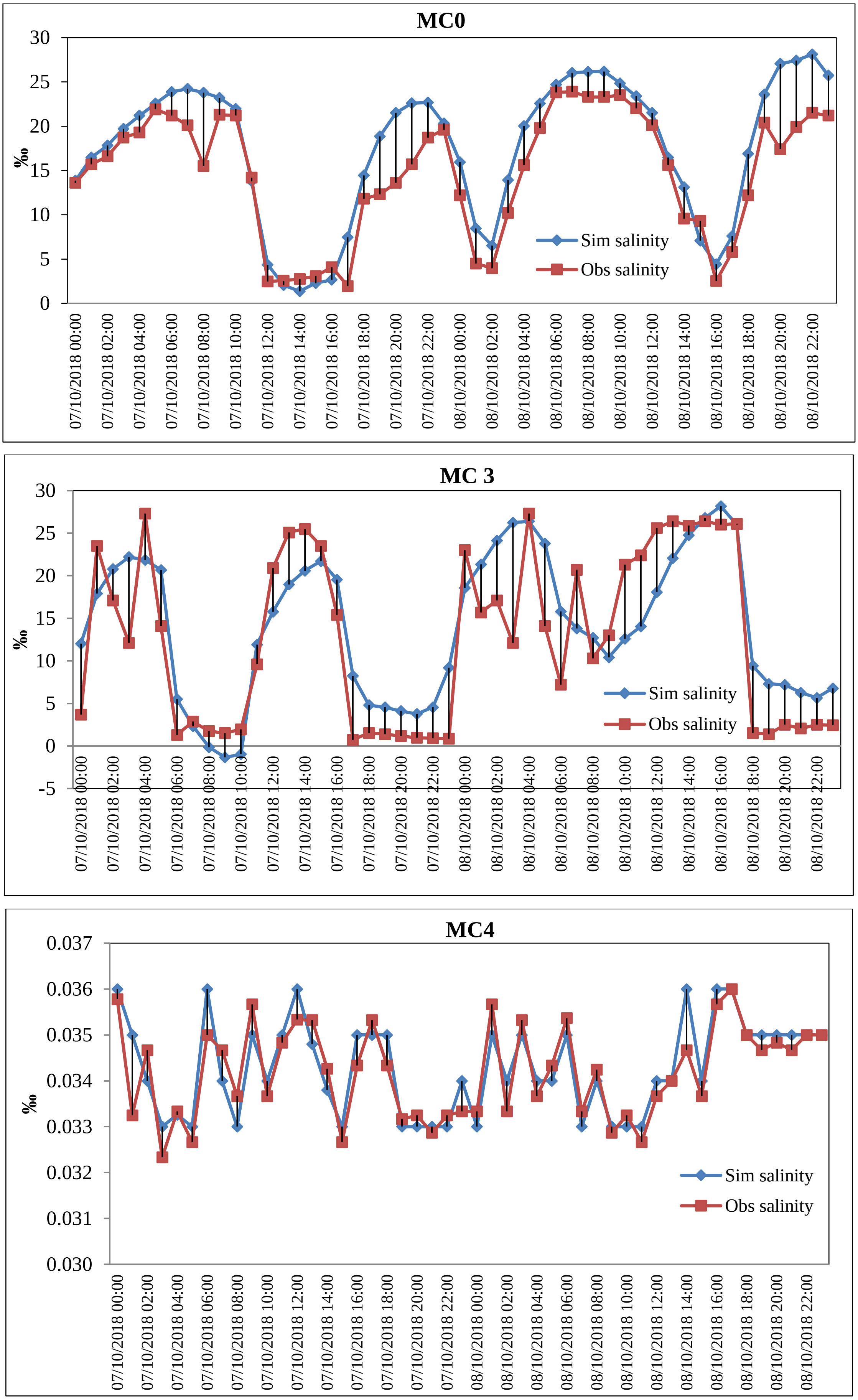


Figure 5. Results of calibration and verification of the AD using the measured data set.

3.3. Simulation of salinity intrusion

The flow discharge in the dry season is small, the selected month July, 2018 has an amplitude ranging from 2.17–13.13 m^3/s. This is the month with the smallest average one of 2018. Salinity amplitude $1^0/_{00}$ and landmark MC0 were selected for discussion. At 0 AM from July 19 to July 20, the tide is falling, the salinity reaches the mark of 5.03 km (Figure 6a), from 0–4 AM, the flow still has a direction from the sea into the river, the salinity reaches the 5.48 km (Figure 6b). This is the time when the salinity intrusion the farthest of the day. From 5 AM, when the tide rises, the flow direction is gradually changing, so the salinity decreases. At 6 AM, the flow direction changed completely from the sea to the river with great speed, the salinity decreased much, until 11 AM, the salinity intrusion slightly down, reaching 5.17 km, which is consistent with low tide in the period of 5–11 AM, currents tendency to go from river to sea (Figure 6c). At 2 PM, the tide is high, the flow is complicated, but the trend of going from the sea to the river, the salinity transmission from the sea to the river reaches the mark of 5.26 km (Figure 6d). Until 10 PM, the range of salinity transmisson is decreased to only 4.99 km (Figure 6e). The time when salinity transmits the least of the day. At 11 PM, the salinity increased slightly and spread to 5.04km (Figure 6f).

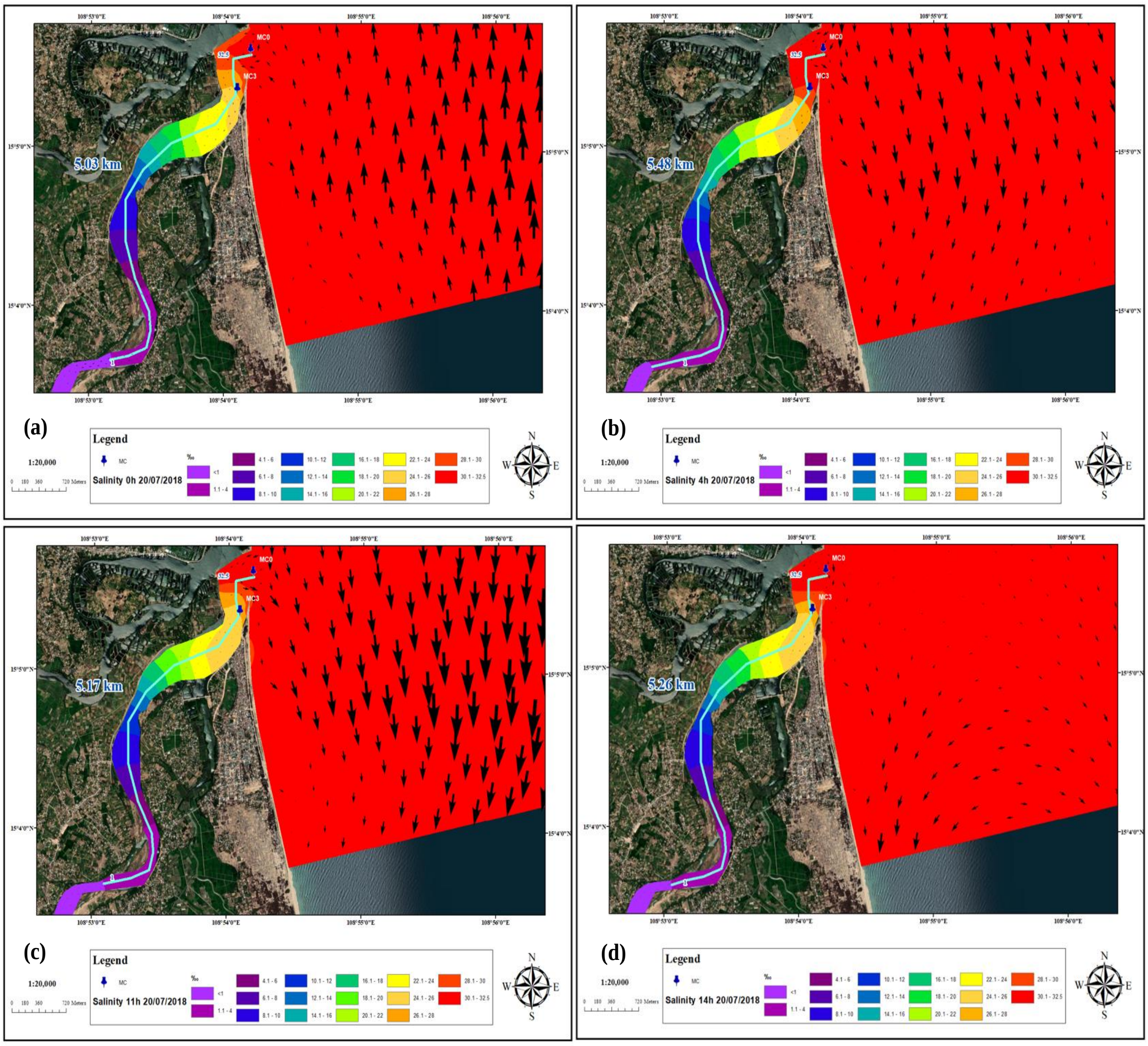


Figure 6. Results of modelling the scope of salinity intrusion in the dry season, simulation results for the day July 20, 2018: (a) At the time of 0 AM, the saline intrusion reaches the mark 5.03km; (b) At the time of 4 AM, the saline intrusion reaches the mark 5.48km; (c) At the time of 11 AM, the saline intrusion reaches the mark 5.17km; (d) At the time of 2 PM, the saline intrusion reaches the mark 5.26 km.

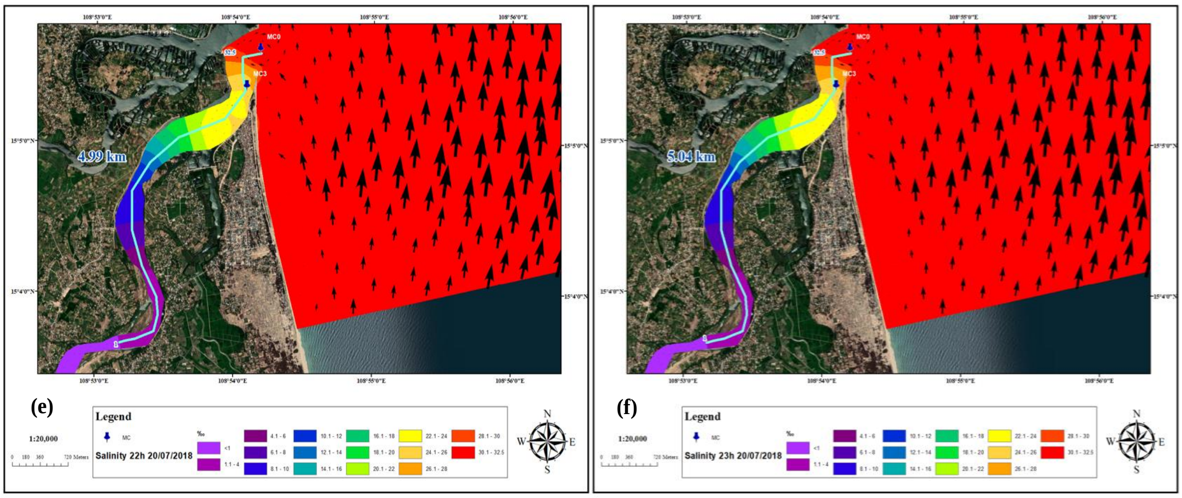


Figure 6. Results of modelling the scope of salinity intrusion in the dry season, simulation results for the day July 20, 2018: (e) At the time of 10h PM, the saline intrusion reaches the mark 4.99 km; (f) At the time of 11 PM, the saline intrusion reaches the mark 5.04km (cont.).

3.4. Discussion

The relationship S = F(Q, H) was built for July 2018, with S being the salinity at the MC3 cross–section. Correlation relationship between salinity depending on flow discharge Q, water level H is following:

$$S = 25.22229 - 0.05313 \times Q + 4.04644 \times H, R^2 = 0.7399, R = 0.8602 \quad (1)$$

The correlation coefficient is R = 0.8602, R^2 = 0.7399, showing that the two factors of discharge and water level explain about 73.99% of the variation in salinity value over time. Based on the results of univariate analysis (Table 3), the correlation coefficient R of water level (0.8563) is much larger than discharge (0.0778).

The results from the p–value show that both the above two factors, H, water level and Q, discharge, are statistically significant, respectively with p–value = 0.000001 < 0.05 and p–value = 0.033805 < 0.05. At the same time, this shows that although both above factors have an influence on the salinity changes in July 2018, the impact of water level H is much larger than the influence of flow Q.

Table 3. Summary of values in single linear regression analysis S = F(Q, H) for July 2018.

Factors	α	β	R	R^2	p–value
Discharge, Q	28.81364	–0.05080	0.0778	0.0061	0.033805
Water level, H	24.98979	4.04484	0.8563	0.7333	0.000001

The relationship S = F(Q, H) is also built for December 2018 – the month with the largest average discharge of the year. Correlation relationship between salinity depending on flow discharge Q, water level H is following

$$S = 6.36848054 - 0.0306469 \times Q + 3.91260007 \times H, R^2 = 0.456827, R = 0.67593099 \quad (2)$$

The correlation coefficient is R = 0.67593099 and both the discharge and water level factors explain about 45.69% of the change in salinity value over time in December at MC3, while based on the univariate analysis results (Table 4) the correlation coefficient R of the discharge (0.6355) is larger than the water level (0.2523). The results from the p–value show that both the above two factors, H, water level and Q, flow discharge, have an impact on MC3 salinity, respectively with p–value = 2.9256E–37 < 0.05 and p–value = 5.4118E–06 < 0.05; At the same time, this shows that although both above factors have an influence on the salinity changes in December 2018, the impact of Q discharge is more, the influence of H water level is lower.

Table 4. Summary of values in single linear regression analysis S = F(Q, H) for December 2018.

Factors	α	β	R	R^2	p–value
Discharge, Q	9.86260676	–0.0310392	0.63548934	0.4038467	2.9256E–37
Water level, H	2.29778936	4.28387584	0.25230199	0.0636563	5.4118E–06

The relationship X_{max} = F (Q, H), where X_{max} is the maximum distance that salinity with the selected value 1 $^0/_{00}$ is reached, is obtained as follows:

$$X_{max} = F(Q,H) = 6.17327 - 0.01612 \times Q - 0.40167 \times H, R^2 = 0.1451, R = 0.3809 \quad (3)$$

In given case, the correlation coefficient is R = 0.3809, showing that the two factors of flow discharge and water level only explain about 14.51% of the change in X_{max} , that is, up to 85.49% due to the impact of other factors. Based on the results of univariate analysis, Table 5, the correlation coefficient R of water level (0.368) is much larger than that of discharge (0.057). The results from the p–value show that only the water level H is statistically significant p–value = 0.041483 < 0.05, which shows that although both factors have an influence on X_{max}, but mainly due to the impact of water level H, the influence of flow rate Q is insignificant.

Table 5. Summary of values in single linear regression analysis Xmax = F(Q, H).

Factors	α	β	R	R^2	p–value
Discharge, Q	5.93374	–0.00940	0.0570	0.0033	0.760634
Water level, H	6.09630	–0.39051	0.3683	0.1356	0.041483

To construct the relationship S = F (X), the driest month of the year (with the lowest average discharge) was chosen, as well as the month of the highest salinity penetration. Landmarks 0, 1 km,…, 6 km are chosen as variable X. The average salinity S is calculated for each day of July. The functional dependence S = F (X) is shown in Figure 7. Results show that salinity gradually decreases with distance from the mouth, although salinity levels differ depending on the day of the month.

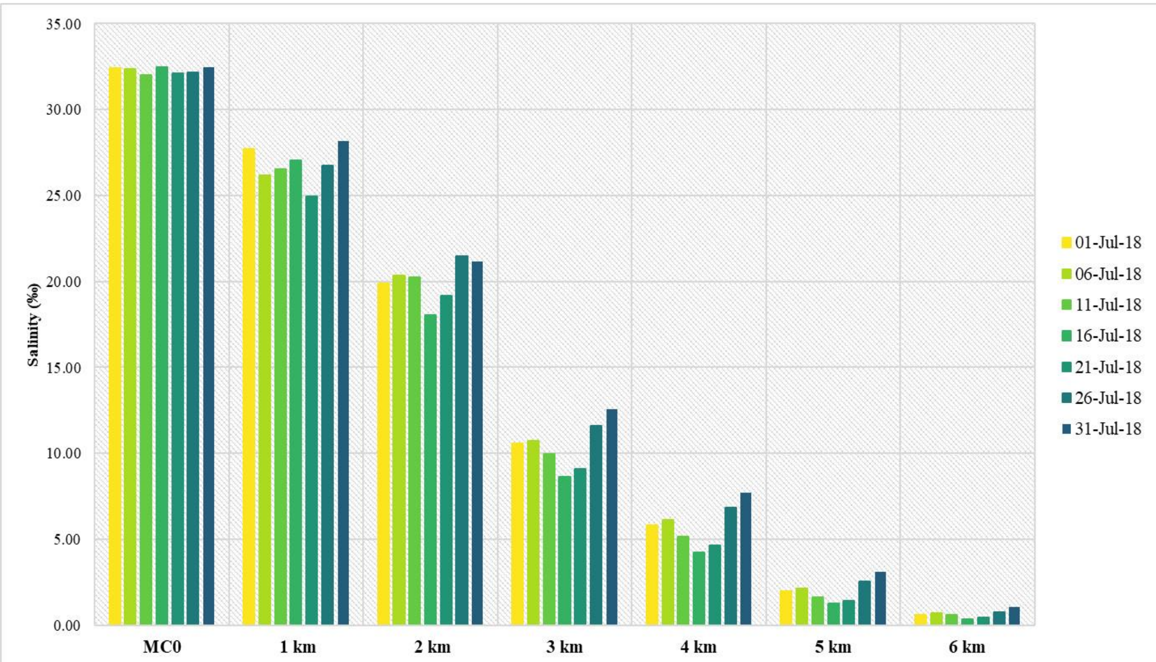


Figure 7. Relationship between salinity S depending on salinity intrusion distance for July, 2018.

4. Conclusion

In this study, the hydrological and hydrodynamic models were performed to simulate saline intrusion for the Ve estuary, Quang Ngai. The results obtained include:

First, the salinity intrusion in a specific day in July 2018 is shown. The results showed that salinity penetrated the farthest distance up to 5.47 km. A two–dimensional map of saline distribution was built for the time of change in the intrusion state: from the sea and from the river.

Second, the relationship between the salinity in the MC3 cross section and the flow rate and water level is built. The typical dry season month serves as an example. The results show that in section MC3 the effect of the water level is much greater than the comparison of the flow discharge factor.

Third, the relationship has been established between the furthest salinity intrusion distances depending on Q,H. The results show that the two factors of discharge and water level have not significantly impact on this relationship, however, the water level factor still has a larger impact.

Fourth, the relationship between salinity level and intrusion distance shows that salinity decreases with distance from the estuary, although salinity at landmarks varies by day.

Note that this study is still limited, as actual measurement data, including salinity, are limited by a 48–hour measurement sequence over 2 days October 7–8, 2018, so further monitoring of salinity is required for a longer time to improve the accuracy of the salinity intrusion modelling. In addition, due to the lack of data on the amount of water pouring in from the Tra Khuc river side, this study did not take into account this effect on saline intrusion.

Author contribution statement: Conceived and designed the experiments; Analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the draft manuscript; manuscript editing: B.T.L.; Performed the experiments; contributed reagents, materials, analyzed and interpreted the data,: L.T.M.D.

Competing interest statement The authors declare no conflict of interest.

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