Journal of Science and Technology in Civil Engineering NUCE 2020. 14 (2): 1–16

RESPONSE OF SALINITY INTRUSION TO THE HYDRODYNAMIC CONDITIONS AND RIVER MOUTH MORPHOLOGICAL CHANGES INDUCED BY THE 2011 TSUNAMI

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Article history:
Received 07/03/2020, Revised 29/03/2020, Accepted 31/03/2020

Abstract

The 2011 Tohoku Earthquake and tsunami were one of the most devastating natural disasters in history. It caused significant ground subsidence and erosion along the Japan coastline. The Natori river mouth which is a habitat for both fishes and bivalves, as an important fishing ground, has been damaged by the tsunami because of the change of the process of salt transport in an estuarine system. In general, salinity intrusion into the river mouth can be affected by many factors such as river water discharge and tidal level, as well as estuarine morphology. In this study, the response of salinity intrusion to the river mouth morphological changes induced by the 2011 Tsunami is investigated. The topographical changes caused by the tsunami are mainly divided into two stages. The first is the direct action of the tsunami, which caused the severe scouring of the coast and the widening of the river. The results have clearly indicated that after tsunami the salt water can intrude much further upstream compare to the condition before the tsunami event. Another changes occurred during the restoration process after the tsunami. The sediment accumulation in the river channel prevented the saltwater from entering the river channel, which reduced the salt intrusion degree. However, the effect of the morphology change caused directly by the tsunami is far greater than the sedimentation of the river.

Keywords: salinity intrusion; river morphology; tsunami impact; numerical simulation; EFDC model.

https://doi.org/10.31814/stce.nuce2020-14(2)-01

1. Introduction

Salt intrusion is one of the important problems in estuaries because it affects the quality of surface water and groundwater as well as the aquatic habitat. Salinity has been used as an indicator of the water quality for organism distribution [1, 2]. The Natori River is an important fishing ground both for bivalves and fishes in central Miyagi prefecture. It is important to figure out the salinity distribution in this area, as it will prove invaluable in the maintenance of fishery resources in Miyagi. The effects of the Great East Japan Tsunami on fish populations and ecosystem recovery has been studied, which indicates that the distribution and abundance of bivalve can be affected by variations of salinity and depth of the water. The brackish area has extended upstream after the tsunami, presumably caused by

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ground subsidence in this area [3]. The extension of brackish water area may increase the operation cost for the desalination processes such as using the nanofiltration technique for the drinking water treatment in the lower Thu Bon River Basin [4].

Based on this background, discussion about the salinity distribution in the Natori River mouth will be conducted. This research will reveal the spatial and temporal variations in salinity and the roles of river discharge, tidal period as well as morphology changes in regulating salt transport.

Many kinds of complex processes such as tidal variation, hydrological flux, wind stress reflect changes in salinity. Numerous efforts have been made to understand the spatial and temporal distributions of salinity under the external influences of these factors. The distribution depends on the estuarine response to river discharge, wind and tidal mixing over time scales from days to weeks and months. There is a consensus that salt intrusion is inversely correlated to river discharge. A high river flow results in a decreased salinity intrusion. The relationship between salt intrusion length and river discharge follows a power law with an exponent of n, which varies in different estuaries [5, 6]. And the response of salt intrusion to tidal mixing has also been studied extensively, while the relationship between salt and tidal mixing differs largely. For a well-mixed or salt wedge estuary, salt intrudes more landward during spring tides than during neap tides [7]. On the other hand, observations, analytical and numerical model results have indicated that larger upstream salt flux or salinity intrusion happens during neap tides in partially mixed estuaries. The difference has been attributed to the different salt transport mechanisms for different estuaries [5, 6, 8].

In addition, the salt transport process can be also affected by changes in some geometric characteristics. Such changes can alter both the hydrodynamics and the rate of mixing in the coastal ocean, thereby having a profound effect on salt transport in estuaries. Salt intrusion is generally caused by an imbalance between river and tidal flows but variation in seawater intrusion is also attributable to estuarine geometry. Morphological changes during tidal variation drastically affect the longitudinal salinity distribution [9, 10].

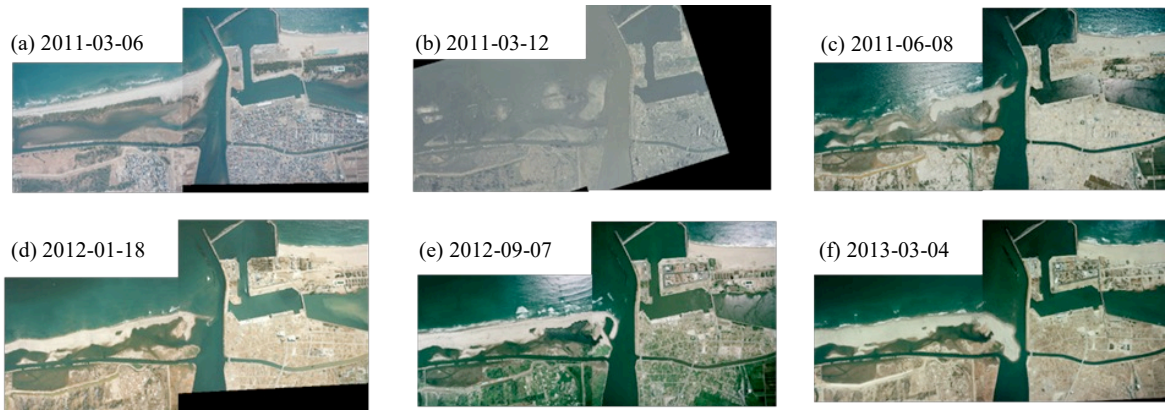


Figure 1. Aerial photographs of the Natori estuary morphological changes after the 2011 tsunami

Because of the Great Tsunami which occurred on 11 March 2011, many coastlines and river mouths has been greatly damaged. The serious coastal and estuarine morphological changes due to the 2011 tsunami in Tohoku region has been reported in the study by [11]. In addition, a detail study of the morphological characteristics of Natori River mouths after the 2011 tsunami and recovery process have carried out by [12]. Fig. 1 shows the aerial photos of the river mouth taken between March 6, 2011 and March 4, 2013. Comparing Figs. 1(a) and 1(b), it can be found that the tsunami

severely washed away the estuary's lagoon area and the river channel was also greatly expanded. After this event, the estuary has entered a slow recovery phase, and the washed and broken coastline has gradually become complete again, after 2013, the shape of the river mouth maintaining a relatively stable state. However, comparing Figs. 1(f) with 1(a), there is still a large difference between the form of the estuary and that before the tsunami: a clear sediment accumulation inside the river can be observed in 2013.

As indicated above, the general understanding of estuarine dynamics and salt intrusion has advanced greatly in recent decades. However, for a specific estuary, such as Natori Estuary in particular, which was under the severe impact of the tsunami, the morphology changed in a short period of time and continued to change in the subsequent recovery process, the changes in salt transport have not been quantitatively evaluated so far. Therefore, several observation datasets (topographic survey data before and after tsunami, river discharge, water elevation, tidal level) are collected in this study. The verified model is used to investigate the impacts of morphology change, river discharge, and tidal level on salt transport in the Natori River Estuary. The purpose of this study is to quantitatively evaluate the changes in salinity distribution induced by factors with different time scales, from weeks (spring-neap tide) to months (seasonal river discharge change) and years (morphology change), then identify the extent to which each factor affects changes in salinity. The results obtained provide significant implications for the sustainable development of the estuarine system and the local fishery revival.

2. Materials and methods

2.1. Study area

The Natori River is located in central Miyagi prefecture, in the Tohoku region of northern Japan, which is listed as a first-class river according to the River Act of Japan (Ministry of Land, Infrastructure, Transport and Tourism (2013)). The Natori River is approximately 55 km in length, and has 13 branches. The basin area is about 939 km^2, yearly averaged discharge is 16.32 m^3/s. The Natori River Estuary is located on Japan's east coast, and faces the Pacific Ocean (Fig. 2). The river divided into two branches about 5.5 km upstream from the river mouth, one of which is the Hirose River, which

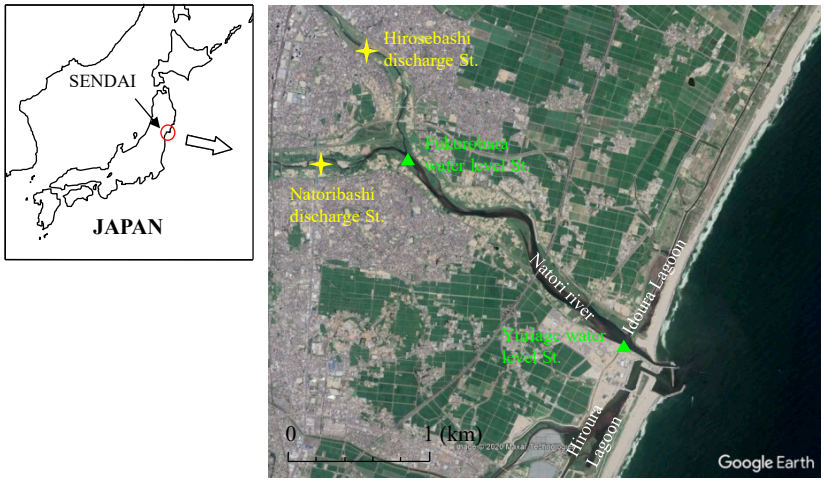


Figure 2. Location of the study area

passes through the city of Sendai. In the downstream close to the coast, there is the Idoura Lagoon on the north coast and Hiroura Lagoon on the south coast.

The Great East Japan Earthquake and Tsunami in March 2011 were one of the most devastating natural disasters in history, affecting the society, economy, coastlines, infrastructure, and housing. In addition to affecting human life, the subsequent tsunami also struck organisms living in the water. Miyagi Prefecture is the second largest fishery landing region in Japan and as a result of the tsunami this fishery was heavily affected: many ships were lost; ports and jetties were destroyed [13]. The Natori River is an important fishing ground both for bivalves and fishes, various fish species live in brackish water areas, which are very important for the maintenance of fishery resources [3]. The tsunami resulted in significant ground subsidence and deposition of rubble and mud in the Natori River.

2.2. Data collection

In this study, to achieve the above objectives, the required data sets are the bathymetry data in different years before and after the tsunami, river discharge and tidal elevation were specified as boundaries, water level and salinity were used for model calibration and verification. Table 1 is the list of all data available from 2009-2016.

Table 1. Summary of the data collection from 2009-2016 (Black dots indicate the data availability) [14]

	Morphology	Water level	Tidal	River discharge	Salinity
2009	•	•	•	•	
2010			•		
2011	•		•		
2012	•	•	•		
2013	•	•	•	•	
2014	•	•	•	•	•
2015	•	•	•	•	•
2016	•	•	•	•	•

a. Bathymetry data

The topographic map of 2009 was used as the bottom elevation before the tsunami. From 2011 to 2015, the bottom elevation of shallow coastal terrain was measured every one kilometer along the coast of the Sendai Bay with the survey line which is perpendicular to the coastline, which was carried out by the Geospatial Information Authority of Japan. On the other hand, the Tohoku Regional Bureau, Ministry of Land, Infrastructure and Transport (MLIT) provided the bottom topography data of 4 sections, with the survey line which is perpendicular to the channel, within a distance of 0.6 km from the ocean side to the Natori River mouth as shown in Fig. 3. By combining these two data sets, the detailed topograpthic maps of the Natori estuary can be determined for each year by an interpolation process.

b. Hydrodynamic data

There are two river discharge measurement stations located in the upstream of the study area which are Hirosebashi station located on the Hirose river branch and Natoribashi station on the Natori river. These river discharge stations are located far enough to avoid the impacts by the tidal motion. In

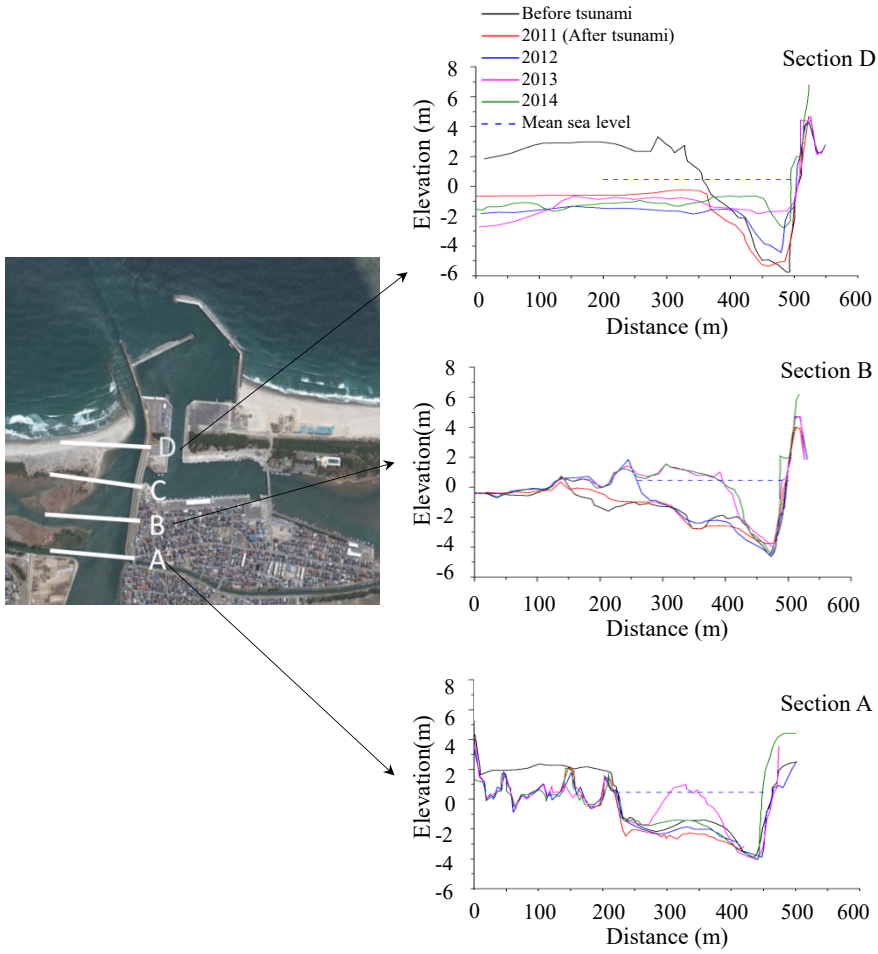


Figure 3. Natori river mouth transection measurement data before and after the 2011 tsunami [MLIT]

addition, there are two water level stations where Fukurobara station is located upstream and Yuriage station is located downstream near the estuary respectively. Annual, monthly and hourly river discharge and water level data for 4 hydrodymanic stations are provided by the Japan Meteorological Agency (JMA) website [14].

The tidal levels used in this study are obtained from hourly measured data at Sendai Port station, provided by the JMA [14] The distribution of tidal phases in the Natori River estuary is mixed tide and the tidal range is from about 0.8 m to 1.6 m. The tidal amplitudes decrease gradually when the tide propagates upstream.

c. Salinity data

In this study, measured salinity data for the three years from 2013 to 2015 were used. This salinity data was provided by the College of Agriculture, Tohoku University. As shown in Fig. 4, there are three salinity measurement points, St.A, St.B., and St.C respectively. St.A as the basic setting point, located under the Yuriage Ohashi Bridge, with coordinates of 38°10.949N, 140°8.850E. St.B is located downstream which is very close to the estuary, St.C is located upstream of the Yuriage Ohashi Bridge, in the deep waters near the right bank. All of the measurement point is set 10-20 cm from the bottom of the river bed elevation.

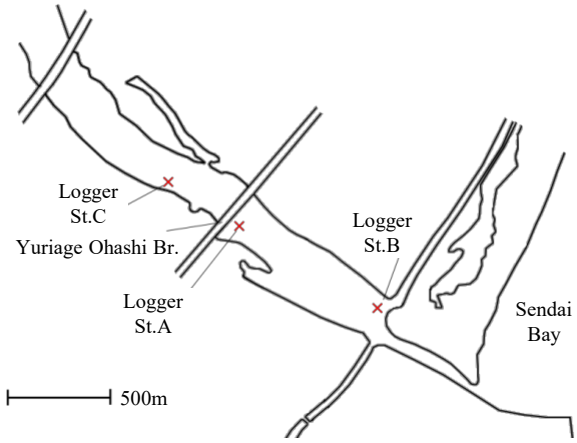


Figure 4. The location of salinity measurement stations

The salinity measurement is divided into two periods. From 2014 to 2015, a salinity sensor named the YSI 6920V2 multi-item water quality meter was used. The measurable items include salinity, water temperature, turbidity, water depth, pH, etc. The salt measurement range is 0-70 ppt, with the resolution 0.01 ppt. On these two years, the measuring interval is 10 minutes, and the salinity changes at measurement points St.A and St.B were mainly measured, besides, in a few months, the salinity data at St.C was also measured. From 2016, the salinity measuring instrument was changed to the small memory water temperature and salt meter INFINITY-CT, the measurable items include salinity and water temperature. This salinity sensor employs a 7-electrode in-tube method for the electrical conductivity sensor with a high-precision. The observation interval is 1 minute, and the salinity is converted by measuring the conductivity of the water body, the measurement range is 0.5-70 mS/cm, and the resolution is 0.001 mS/cm, the precision is ±0.05 mS/cm. In 2016, only the salinity data of measurement point St.A was measured. An example of the time variation of salinity data at three station is shown in Fig. 5.

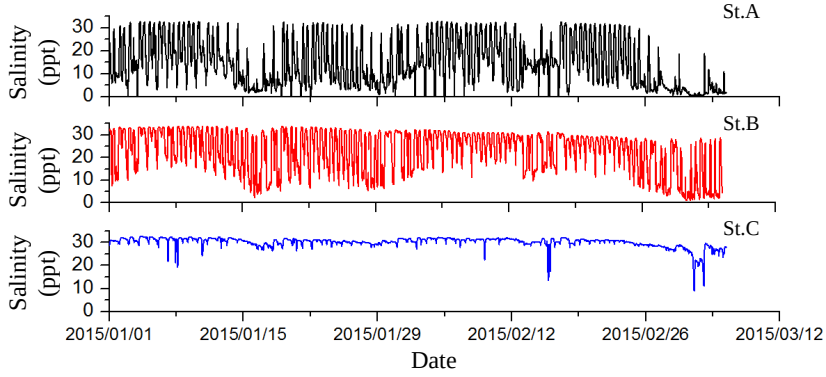


Figure 5. Time variation of the measured salinity data at the St.A, St.B and St.C from January to March in 2015

2.3. Numerical model and model setup

a. Numerical model

In this study, a three-dimensional numerical EFDC+ (Environmental Fluid Dynamics Code Plus) model is used [15]. This is an open-source code model that can be downloaded from the website at https://github.com/dsi-llc/EFDCPlus. In recent years, this model has been widely used in the study of estuarine hydrological environment and salt distribution. Through the model results after verification, it can provide more accurate and clear temporal and spatial changes of salinity in different estuaries. The study by [16] predicted the hydro-environmental impacts of a renewable energy structure, including sluice gates and turbines, across the Severn Estuary by refinements to the EFDC model. In particular, a comparison between salinity concentration distributions predicted by the 2D and 3D models indicated that near the barrage site, the salinity levels predicted slightly different both on the upstream and downstream. Hence, it is preferable to use a 3D model for more detailed and accurate hydrodynamic and solute concentration distributions. Gong and Shen [17] studied salt intrusion in the Modaomen Estuary, one of the estuaries in the PRD area, China. The EFDC model was calibrated and verified for water elevation, water current, and salinity. Their result indicated that the estuary gains salt during neap tides and loss salt during spring tides and a river discharge pulse suppresses the salt intrusion greatly. Yoon and Woo [18] applied EFDC model in tidally-dominated Han River Estuary, South Korea to understand the along-channel salinity distribution and its response to river discharge. Although in a tidally-dominated estuary, freshwater discharge is still the primary environmental factor controlling the salinity.

The model solves the three dimensional continuity and free surface equations of motion [19]. The Mellor and Yamada level 2.5 turbulence closure scheme is implemented in the model [20]. The model also solves the three dimensional continuity and free surface equations of motion. The model uses stretched vertical coordinates and curvilinear, orthogonal horizontal coordinates. It simulates density and topographically induced circulation as well as tidal and wind-driven flows, and spatial and temporal distributions of salinity, temperature, and conservative/non-conservative tracers. The model has a flexible grid network structure, which is capable of linking multiple tributaries to the main channel through grid linkage between upstream and downstream grid cells, including dam structures. The model has been successfully applied to a wide range of environmental studies [16–18, 21].

b. Numerical setup

Fig. 6 shows the model grid, bottom elevation of the Natori River Estuary, and the location of each measurement stations. The EFDC model domain covers the Natori River Estuary and upstream to the Hirose River and the Natori River, where two hydrological stations, Hirosebashi and Natoribashi, are located. To ensure that the study area was fully covered by the model, the boundary with the open sea was extended approximately 4 km to the offshore. A curvilinear and orthogonal grid was used over the entire domain, and this refined grid was utilized for the Natori River Estuary. The horizontal spatial resolution ranges from about 300 m at offshore to 10 m in the area near the river channels. Several sensitivity tests were conducted for the vertical resolution using 5, 10, 15, and 20 sigma layers in the vertical. It was found that using 15 layers improved model results considerably compared to 5 and 10 layers, whereas 20 layers did not improve results further. Thus, the use of 15 sigma layers was adopted in the vertical direction. Sufficient grid resolution was provided to adequately schematize the bottom elevation of the Natori River Estuary.

At the two upstream boundaries of the two hydrological stations, Hirosebashi and Natoribashi, Hourly river discharges were specified as the inflowing boundaries with an inflowing salinity of

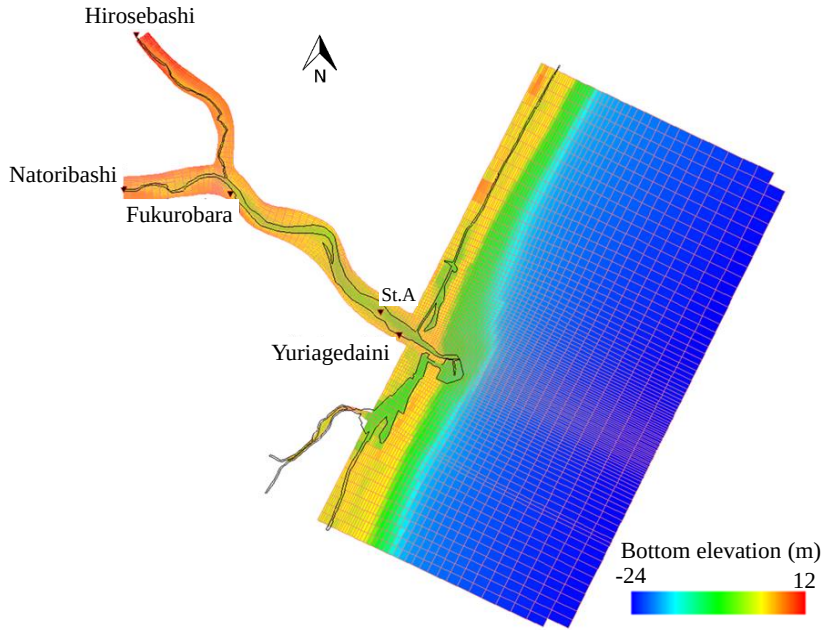


Figure 6. Model grid showing bottom elevation and the locations of the upstream boundaries

zero based on statistical result of observation data. The upstream boundaries were set with sufficient distance from the Natori River Estuary to ensure that any effects from morphology changes were negligible. The water levels were specified for offshore open boundary conditions, allowing the tidal flow to freely propagate across the model domain. In this study, one coastal open boundary was set at the east boundary, which was forced by water elevation obtained from the hourly observation data in Sendai Bay station. References to the average salinity of the world's oceans and the measured data of salinity in this study, the incoming salinities at the offshore open boundary were specified as 35 ppt. With regard to the initial hydrodynamic conditions, the water elevation was set as zero over the domain. To obtain the initial conditions for salinity, the model was run iteratively for approximately 30 days using the forced boundary conditions. The resulting salinity distribution at the end of the simulation was used as the initial salinity condition in all cases.

3. Model calibration and validation

In this study, the bathymetry data input to the model adjusted the topography for each year after the tsunami, considering the possible impact on the accuracy of the estuary salt distribution results simulated by the model, and the feasibility of verifying this method, the model calibration and verification were done in 2014-2016, all of the three years that have available salinity data. The simulation period for the model calibration was from December 1 to 31 in 2014, January 1 to 31 in 2015, and April 1 to 30 in 2016 respectively; and the model verification was from August 1 to 31 in 2014. The available boundary conditions during the period were implemented into the model.

3.1. Calibration of water level

The modeled water elevations were compared with the observations data. The root–mean–square error (RMSE) and Nash–Sutcliffe Efficiency coefficient (NSE) were used to assess the model accu-

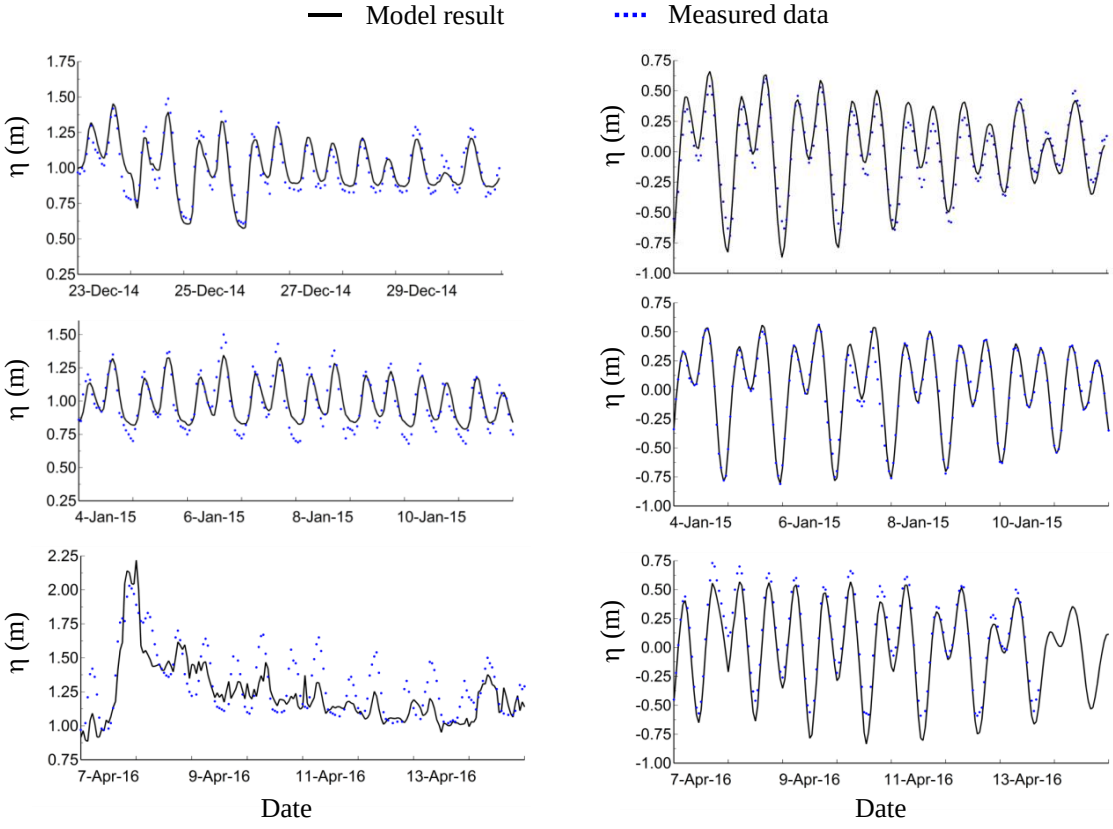
racy of the model. These criteria are defined as following:

$$\text{RMSE} = \sqrt{\frac{\Sigma(M-D)^2}{n}} \tag{1}$$

$$\text{NSE} = 1 - \frac{\Sigma(M-D)^2}{\Sigma(D-\bar{D})^2} \tag{2}$$

where D is the observational data, $\bar{D}$ is the mean of the observational data, and M is the corresponding modeled data.

As shown in Fig. 7, the modeled water levels agreed well with the observations at the two hydrological stations in the Natori River Estuary, and the model evaluation index values of water elevations are shown in Table 2. In each year, the results of downstream station (Yuriagedaini) are generally better than the upstream station (Fukurobara). The averaged RMSE between the modeled and observed data was 0.117 m. The NSE values for the results at different stations varied from 0.527 to 0.945, indicating that the modeled water levels achieved very good performance.



(a) Time variation comparison of water level at Fukurobara station in 2014, 2015, 2016

(b) Time variation comparison of water level at Yuriage station in 2014, 2015, 2016

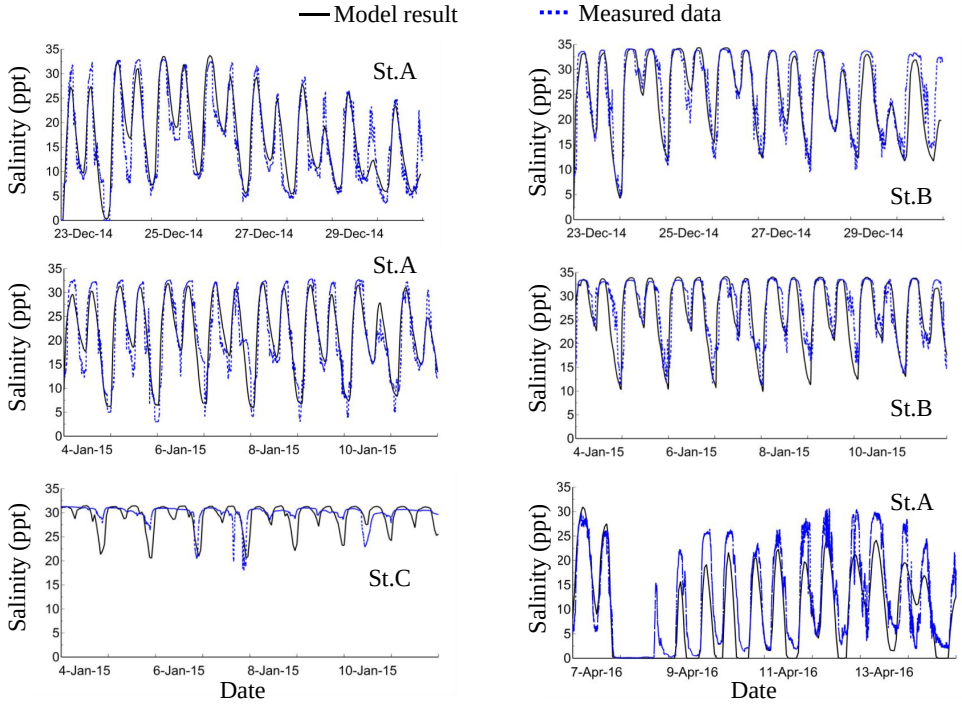
Figure 7. Water level calibration results

Table 2. The model evaluation index values for calibration of water level in 2014, 2015 and 2016

Year	Station	RMSE (m)	NSE
2014	Fukurobara	0.133	0.726
	Yuriagedaini	0.122	0.849
2015	Fukurobara	0.086	0.798
	Yuriagedaini	0.081	0.945
2016	Fukurobara	0.165	0.527
	Yuriagedaini	0.114	0.907
Average		0.117	0.792

3.2. Calibration of salinity

Fig. 8 shows comparisons between the modeled and observed salinities in the estuary, and the model evaluation index values for calibration of salinity shows in Table 3. The model results were particularly accurate when reproducing the salinity of St.A and St.B in 2014 and 2015, with the RMSE less than 3.9, and NSE over 0.64. Although the trough of salinity variation did not capture well in the St.C, but the evaluation index values in most stations are showing a good performance, suggesting that the model is capable of accurately simulating the process of salt transport. Although



(a) Time variation comparison of salinity in 2014, 2015, 2016

(b) Time variation comparison of the salinity in 2014, 2015, 2016

Figure 8. Water level calibration results

the discrepancies between the modeled and observed salinities were significantly greater than those for simulations of the water level, the salinities modeled in this study are generally considered to be acceptable.

Table 3. The model evaluation index values for calibration of salinity in 2014, 2015 and 2016

	Station	RMSE (ppt)	NSE
2014	A	3.628	0.836
	B	3.900	0.748
2015	A	3.585	0.815
	B	3.701	0.641
	C	2.453	0.805
2016	A	5.129	0.729
Average		3.733	0.762

4. Results and discussion

4.1. Numerical simulation scenarios

In order to evaluate the different extent of the three factors (river discharge, tide, and morphology changes) impact on the salinity transport mechanism of the Natori River Estuary, after obtaining the ideal calibration result, at the stage of analysis, different scenarios were designed and simulated to quantify the salinity distribution in estuary under different conditions. In order to assess the salinity intrusion into the estuary under different flow conditions throughout the year, three different inflowing boundary conditions such as high discharge, normal discharge and low discharge were set at the two upstream boundaries at the Hirosebashi Station, and the Natoribashi Station respectively. High river discharge is defined as 95 days of river discharge in a year not less than this value; normal river discharge is 185 days of river discharge in a year not less than this value; low discharge is 275 days of river discharge in a year not less than this value. The specific values are calculated based on the information provided by the Japan Meteorological Agency website [13] from year of 1969 to 2016 and shown in Table 4. Specifically, in Hirosebashi station, the high discharge is: 11.73 m^3/s; the normal

Table 4. The determine the high-, normal-, and low-mean river discharges based on the data collected between 1969 and 2016

	Hirosebashi (m^3/s)	Natoribashi (m^3/s)
High discharge	11.73	15.17
Normal discharge	6.26	7.81
Low discharge	3.62	4.67

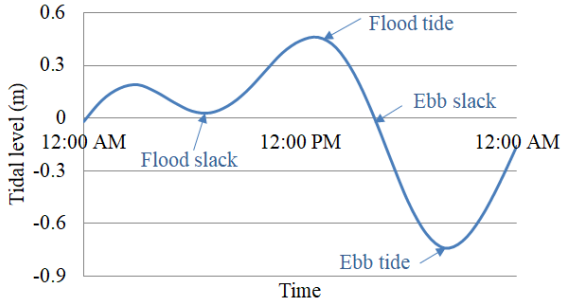


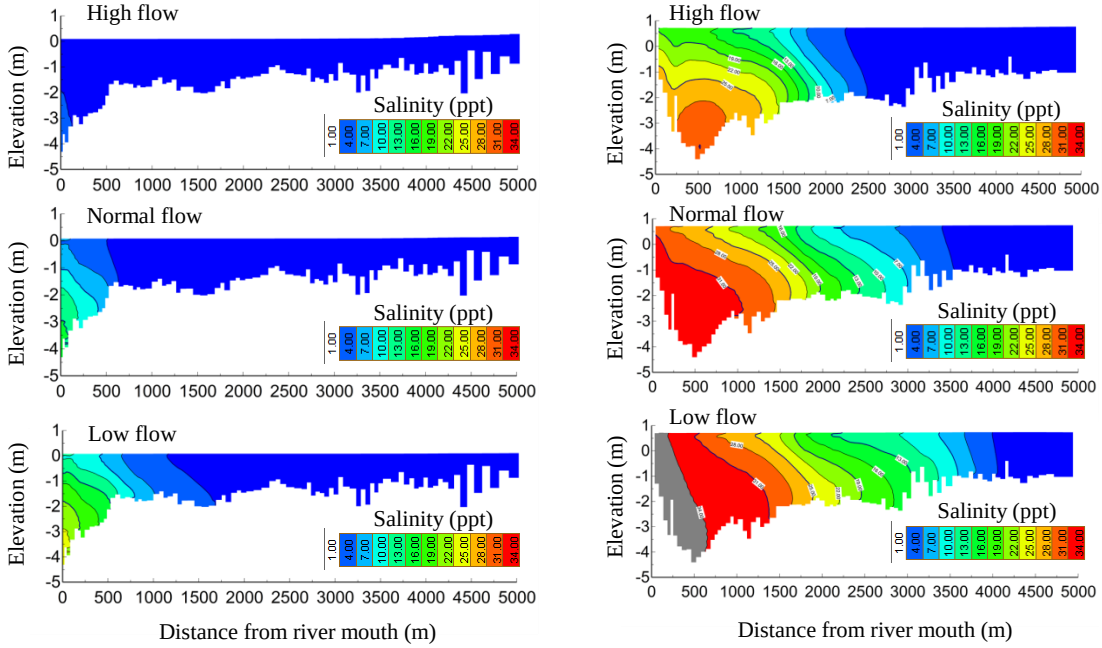
Figure 9. Description of the tides on the example of one day

discharge is: 6.26 m^3/s; the low discharge is: 3.62 m^3/s. In Natoribashi station, the high discharge is: 15.17 m^3/s; the normal discharge is: 7.81 m^3/s; the low discharge is: 4.67 m^3/s.

In total, there 9 simulation scenarios were set up which consisted of three typical river discharges over three different bathymetries in 2009, 2013, and 2014. The models were simulated over one month tidal cycle to cover the spring tide and neap tide effects. The analysis of simulation results will focus on the salinity distribution during the high, normal, and low river discharge, as well as during the different tidal stages as shown in Fig. 9.

4.2. Effect of river discharge and tidal level on salinity instrusion length

In order to quantify salt transport and to analyze the controlling mechanisms, the distributions in salinity along the longitudinal section from the river mouth at the Section A (Fig. 3) to the river upstream. Fig. 10 is the numerical simulation results of the longitudinal distribution of salinity corresponding to the actual bathymetric conditions in the years of 2009 and 2014. These two simulation cases represent to the situation before and after the 2011 tsunami event. The results were compared under the high, normal and low river discharge during a whole spring-neap tidal cycle to detect changes in the vertical stratification of salinity in the Natori River Estuary. As a result, the longitudinal and vertical distributions of salinity before and after the 2011 event are distinctly different. More salinity intrusion after the tsunami during 3 stages of river flow, it is mainly due to the river mouth morphological changes. Under high river discharge conditions, no significant salt intrusion was observed in 2009. While as the river discharge decreases, the salt intrusion in the estuary become very obvious. Under the conditions of normal and low discharge, near the river mouth, salinity in the bottom water



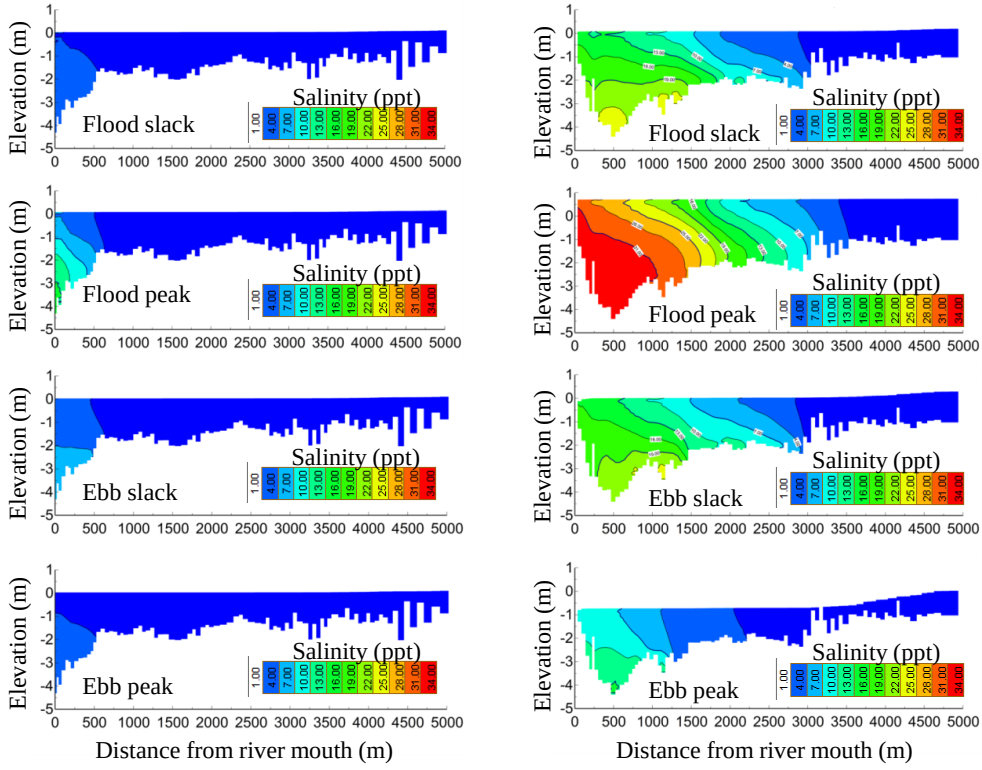
(a) Longitudinal distribution of salinity during the high-, nomal- and low-flow in 2009

(b) Longitudinal distribution of salinity during the high-, nomal- and low-flow in 2014

Figure 10. Longitudinal distribution of salinity during the high, normal and low river flow (a) in 2009 (before the tsunami event) and (b) in 2014 (after the tsunami event)

layer almost always changes within the range of more than 20 ppt in the year of 2014 and the salinity intrusion length has also greatly increased.

In addition, short-term changes in salinity are also very sensitive to the tide periods. As shown in Fig. 11, salt is intruded into the estuary during the flood-tide periods; the salinity thus increases, and the maximum salt intrusion occurs at flood slack. However, salt is expelled from the estuary during ebb-tide periods; the salinity decreases, and the minimum salt intrusion occurs at ebb slack. During the same tidal period, due to the effects of high tide and low tide, the difference between the maximum salt intrusion length in the estuary varies from 300 to 2000 meters, with the increased tidal range in the spring tide, the salt intrusion length at its high tide level is always longer than that of neap tide.



(a) Longitudinal distribution of salinity due to the effects of tidal level in 2009

(b) Longitudinal distribution of salinity due to the effects of tidal level in 2014

Figure 11. Longitudinal distribution of salinity during different stages of tidal cycle (a) in 2009 (before the tsunami event) and (b) in 2014 (after the tsunami event)

4.3. Effect of river mouth morphological change on salinity

Fig. 12 shows a comparison of the maximum salinity intrusion length during the high tide and low tide period for three different years of 2009, 2013 and 2014. The previous analysis suggests that the topographic subsidence caused by the tsunami and the severe erosion of the beach near the estuary resulted in more seawater pouring into the river and the salinity concentration increased significantly. Due to the limited range of traceability of seawater under high river discharge conditions, this change in salinity distribution caused by topographic differences is more pronounced at low and normal river discharge. Comparing the situation before and after the tsunami, there is a significant difference in

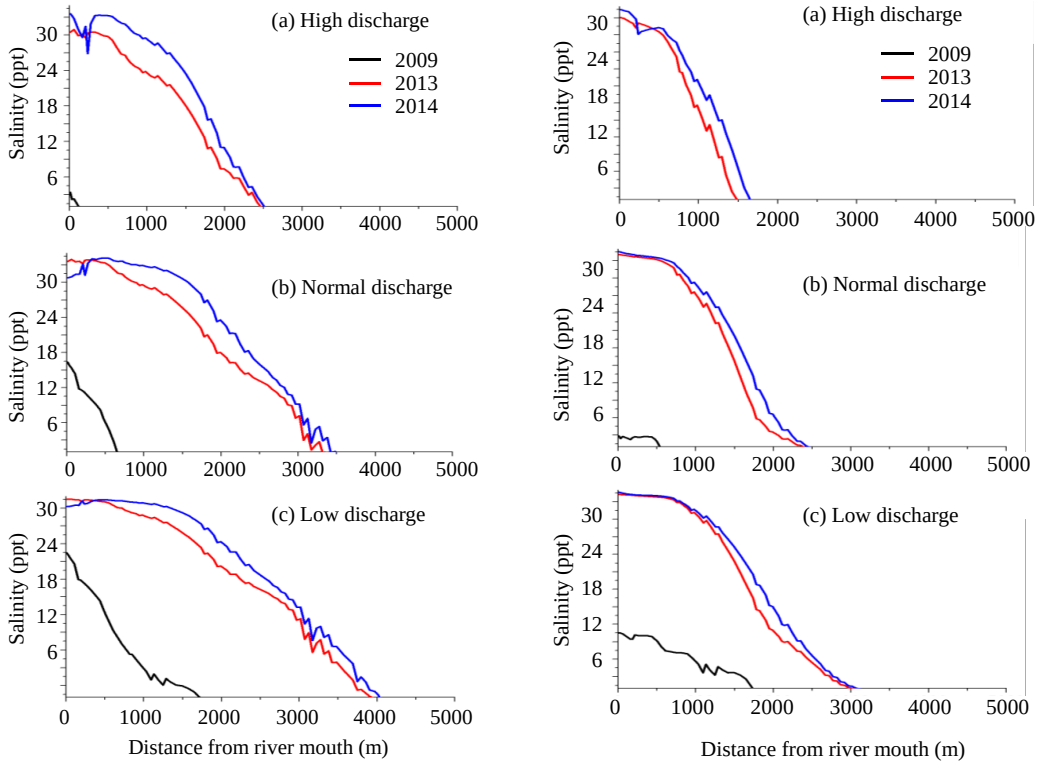


Figure 12. Maximum salinity intrusion length before and after the 2011 tsunami

the maximum salt intrusion length before and after the tsunami event. Here, the maximum intrusion length is defined as a distance from the 0.0 km of the river to the 1 ppt contour in the upstream. Table 5 summarizes all maximum salinity intrusion length during the different conditions of river flow and tidal periods. The salinity intrusion length and concentration before the tsunami event in 2009 are much shorter and smaller compare to the situation after tsunami in 2013 and 2014. By comparing the results of 2013 and 2014, it can be found that, due to the obvious sediment deposition inside the river channel in 2013, which prevented seawater invasion to a certain extent, the salt intrusion in the estuary in that year was weaker than in 2014, but the increase in salt transport caused by tsunami is significantly stronger than the weakening effect from sand deposition. In addition, by comparing the longitudinal distribution of salinity before and after the tsunami, the vertical stratification has

Table 5. The Maximum salinity intrusion length – Unit is meter

Year	High discharge		Normal discharge		Low discharge	
	High tide	Low tide	High tide	Low tide	High tide	Low tide
2009	120	0	630	510	1700	1680
2013	2410	1480	3360	2360	3850	3010
2014	2490	1680	3480	2480	4060	3060

also changed significantly. In 2009, the estuary was mainly in a highly stratified state, the salinity isohaline is nearly horizontal. However, because the topographic changes increase the mixing effect of freshwater and saltwater at the estuary area, the stronger tidal mixing effect generally weakened the stratification of the water column and destroyed the salt wedge in the corresponding cases after the tsunami.

5. Conclusions

In this study, the EFDC model was used to quantitatively evaluate the impacts from river discharge, tidal and the morphology change caused by tsunami on salt transport in the Natori River Estuary. The model calibration and validation using observed data collected from 2014 to 2016 indicate that the model successfully simulated the dynamic processes and salinity distribution in the estuary. The simulation results of salinity distribution in the river mouth were compared under different conditions.

The modeled results indicate that the river discharge greatly affects the change of salinity, and it directly determines whether the salt intrusion occurs in the estuary. At the same time, the salt distribution also responds to the cyclical changes in the tide level during a short term period. Due to the impact of the 2011 tsunami, the increase of river month width and water depth caused more salt water to enter the river mouth, exacerbating the salt intrusion, and the sediment accumulation during the estuary restoration after the tsunami reduced the salinity in the estuary, but with the effect far less dramatic than the effects of the tsunami. The expansion of the Natori estuary is not only caused by the tsunami but also caused by a river flood. Therefore, a similar salinity intrusion mechanism might also be happened. Thus, the findings from this study will be very useful for the river authority to find the best countermeasure plans for the sustainability development of the fishery activities and agricultural purposes in the future.

Acknowledgements

This study supported by the "Tohoku Ecosystem-Associated Marine Sciences (TEAMS)" project funded by MEXT.

References

[1] Jassby, A. D., Kimmerer, W. J., Monismith, S. G., Armor, C., Cloern, J. E., Powell, T. M., Schubel, J. R., Vendlinski, T. J. (1995). Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications*, 5(1):272–289.

[2] Lewis, R. E., Uncles, R. J. (2003). Factors affecting longitudinal dispersion in estuaries of different scale. *Ocean Dynamics*, 53(3):197–207.

[3] Ito, K., Katayama, A., Shizuka, K., Monna, N. (2016). Effects of the Great East Japan Tsunami on fish populations and ecosystem recovery. The Natori River; northeastern Japan. In *The Natori River; Northeastern Japan. Tsunamis and Earthquakes in Coastal Environments*, Springer, 201–216.

[4] Ha, T. D., Hien, D. T. T., Hoa, N. Q., Tinh, N. T. H. (2017). Brackish water treatment research in pilot scale using dual-stage nano filtration for domestic/drinking water supply in Thu Bon river basin. *Journal of Science and Technology in Civil Engineering (STCE)-NUCE*, 11(6):149–155.

[5] Bowen, M. M., Geyer, W. R. (2003). Salt transport and the time-dependent salt balance of a partially stratified estuary. *Journal of Geophysical Research: Oceans*, 108(C5).

[6] Banas, N. S., Hickey, B. M., MacCready, P., Newton, J. A. (2004). Dynamics of Willapa Bay, Washington: A highly unsteady, partially mixed estuary. *Journal of Physical Oceanography*, 34(11):2413–2427.

[7] Uncles, R. J., Stephens, J. A. (1990). Computed and observed currents, elevations, and salinity in a branching estuary. *Estuaries*, 13(2):133–144.

[8] Prandle, D. (2004). Saline intrusion in partially mixed estuaries. *Estuarine, Coastal and Shelf Science*, 59(3):385–397.

[9] Gay, P. S., O'Donnell, J. (2007). A simple advection-dispersion model for the salt distribution in linearly tapered estuaries. *Journal of Geophysical Research: Oceans*, 112(C7).

[10] Ralston, D. K., Geyer, W. R., Lerczak, J. A. (2008). Subtidal salinity and velocity in the Hudson River estuary: Observations and modeling. *Journal of Physical Oceanography*, 38(4):753–770.

[11] Tanaka, H., Tinh, N. X., Umeda, M., Hirao, R., Pradjoko, E., Mano, A., Udo, K. (2012). Coastal and estuarine morphology changes induced by the 2011 Great East Japan Earthquake Tsunami. *Coastal Engineering Journal*, 54(01):1250010.

[12] Roh, M., Mitobe, Y., Tanaka, H. (2016). Morphological Characteristics of River Mouths After the 2011 Tohoku Tsunami in Miyagi Prefecture. In *Tsunamis and Earthquakes in Coastal Environments*, Springer, 137–152.

[13] Watanabe, K., Shoji, M., Sasaki, K. (2013). Impact on the bivalve Fisheries in the middle-south area of Sendai Bay brought by the Great East Japan Earthquake. *Miyagi Pref Res Fish Sci.*, 13:23–29.

[14] Japan Meteorological Agency (JMA). *http://www.jma.go.jp/jma/indexe.html*. Website for downloading the river discharge, water level, and tidal level data.

[15] DSI (2017). *The Environmental Fluid Dynamics Code: Theoretical & Computational Aspects of EFDC+*. Dynamic Solutions – International, LLC, Edmonds, WA, USA.

[16] Zhou, J., Falconer, R. A., Lin, B. (2014). Refinements to the EFDC model for predicting the hydro-environmental impacts of a barrage across the Severn Estuary. *Renewable Energy*, 62:490–505.

[17] Gong, W., Shen, J. (2011). The response of salt intrusion to changes in river discharge and tidal mixing during the dry season in the Modaomen Estuary, China. *Continental Shelf Research*, 31(7-8):769–788.

[18] Yoon, B. I., Woo, S.-B. (2015). The along-channel salinity distribution and its response to river discharge in tidally-dominated Han River Estuary, South Korea. *Procedia Engineering*, 116:763–770.

[19] Hamrick, J. M. (1992). *A three-dimensional environmental fluid dynamics computer code: Theoretical and computational aspects*. Special Report in Applied Marine Science and Ocean Engineering. No. 317. College of William and Mary, VIMS 63 pp.

[20] Mellor, G. L., Yamada, T. (1982). Development of a turbulence closure model for geophysical fluid problems. *Reviews of Geophysics*, 20(4):851–875.

[21] Liu, C., Yu, M., Jia, L., Cai, H., Chen, X. (2019). Impacts of physical alterations on salt transport during the dry season in the Modaomen Estuary, Pearl River Delta, China. *Estuarine, Coastal and Shelf Science*, 227:106345.