Responses of Hydrodynamics and Saline Water Intrusion to Typhoon Fongwong in the North Branch of the Yangtze River Estuary

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1. Introduction

Saline water intrusion is a common phenomenon in estuaries, which is affected by different spatial-temporal hydrodynamic forces such as river discharge, sea level rise, tides, waves and cyclonic conditions [1]. Severe saline water intrusion, which may be caused by low river discharge and sea level rise (SLR), can impair fresh water supplies in local regions and threaten aquatic plants and animals [2]. Occasionally, estuaries are exposed to meteorological forces. The perturbation of winds and the fluvial flow interacting with tides increase the complexity of the dynamics and salinity distributions in the estuary system.

River discharge is one of the dominant forces used to control saline water intrusion in estuaries [3–6]. Generally, saline water intrusion is inversely correlated to river discharge, i.e., a low river discharge results in an increased saline water intrusion. For example, in the dry season, low river discharge can result in the salinity front shift about 20 km toward upstream in the Bengal delta [7]. The relationship between saline water intrusion, length and river discharge follows a power law with an exponent of n, which varies in different estuaries [8–11]. The asymmetries of saline water intrusion responding to increasing and...
decreasing river discharge were observed in the Modaomen estuary by Gong and Shen [11]. River discharge also affects water vertical mixing. For example, the Hong Kong coastal water is stratified or has a large salinity gradient in the vertical direction in the wet season due to the large runoff from the Pearl River [12,13]. In contrast, it is fully mixed in the vertical direction in the dry season due to low river discharge [14,15].

Salinity distribution in an estuary depends not only on river discharge, but also wind and tidal mixing. The relationship between saline water intrusion and tidal mixing is complex [5,6] and depends on different estuary types due to the different salinity transport mechanisms. For a well-mixed or salt wedge estuary, larger saline water intrusion occurs during the spring tides [16–18]. However, for a partially mixed estuary, larger saline water intrusion happens during neap tides [3,10,17,19]. Compared with the extensive literature on saline water intrusion variability induced by the spring–neap tidal cycle and seasonal variations in river discharge [17–22], studies of climate events, such as wind-induced salt transport are surprisingly lacking, and the mechanism of salt transport is not sufficiently documented.

Wind increases the complexity of dynamics and saline water intrusion in the estuary [23,24], which has long been considered to cause a decrease in stratification. Several field surveys conducted during summer have shown that a change in wind direction to the E or NE can cause the vertical mixing of Hong Kong coastal water, and it may also change the spatial distribution of phytoplankton biomass [25]. Kuang et al. [26] studied in detail effect of wind speed and direction on summer tidal circulation and vertical mixing in Hong Kong waters using a 3D numerical model. They revealed that a strong NE wind pushed the river plume westward away from eHong Kong waters and more saline coastal waters entered Hong Kong waters; the water only became vertically well mixed after a 10 m/s NE wind blew for 5 days, but wind speeds of 5 and 7.5 m/s did not result in the same extent of mixing. Chen and Sanford [27] summarized the wind’s effect on stratification and suggested the two mechanisms of direct wind mixing and wind straining on stratification and salt transport. They used a horizontal Richardson number modified to include wind straining/mixing to reasonably represent the transition, and a regime diagram to classify the wind’s effect on stratification. The variability of salt transport ultimately affects exchange flow because it governs the variability of salt intrusion, and thus the large-scale salt gradient that drives gravitational circulation.

Typhoons or hurricanes are the most energetic atmospheric force acting on coastal and estuarine waters, which certainly cause significant changes in water level, dynamics and mixing [28–31]. For many years, the study of storm surges has been largely focused on the extreme water level variations. Observations and numerical simulations have indicated a strong salinity variation during hurricanes and storm surges induced by cyclones [32,33]. From a post-disaster survey, Tajima et al. [34] reported that higher water levels in the inundated area, or runup heights, were found on the coast facing north due to the super typhoon, Meranti, which migrated toward the WWN direction. Pan et al. [35] studied two opposite dynamic effects (east-path and west-path typhoons) on saltwater transport and stratification in the Modaomen waterway of the Pearl River Estuary, and discovered that the east-path typhoon led to the set-down of the coastal sea level, and increased the oceanward advective flux, while the west-path typhoon resulted in the set-up of the coastal sea level, which promoted the landward advective flux and caused more serious saltwater intrusion. Li et al. [36] investigated two cases of different hurricanes and concluded that the stronger wind force clearly alters the pattern of salinity intrusion. Besides, salinity stratification is also an important phenomenon in the estuary as illustrated by Knudsen’s kinematic estuarine salt balance, stratification determines the volume transport of oceanic water into an estuary. Both observations and modelling work testified to the stratification change induced by storm events in many estuaries [37–39], but the typhoon-induced salinity intrusion and horizontal distribution were rarely popular topics when comparing larger estuaries.
The Yangtze River is the longest river in China, with a length of 6380 km, spanning 19 provinces and with a catchment area of $1.8 \times 10^6$ km$^2$. The Yangtze River Delta is one of the most developed economic areas in China. The YRE (Figure 1) is divided into the NB and the South Branch (SB) by the Chongming Island, while the Changxing Island and Hengsha Island divide the lower SB into the North Channel (NC) and the South Channel (SC). Finally, the lower SC is divided into the North Passage (NP) and the South Passage (SP). The YRE has a complicated topography with third-order bifurcations and four outlets into the East China Sea, and the salinity intrusion can significantly impact the four large-size drinking-water reservoirs that supply drinking water to about 50 million people. Many studies investigated the YRE: its plume characteristics [40,41], impacts of river discharge [42,43], SLR [44,45] and Three Gorges Reservoir [46,47]. However, little information, which focused on coastal inundation [48] and dynamical responses of river plumes [49], is available about the influence of short-lived episodic events such as storms and typhoons, which may significantly influence the vertical mixing processes. The NB is the first bifurcation; it has the lowest river discharge in the four branches and is mainly dominated by tidal force, which is vulnerable to typhoons.

In this study, we aim to investigate responses of hydrodynamics and saline water intrusion in the NB of the YRE to Typhoon Fongwong, which landed in Shanghai, using a process-based numerical model based on MIKE3. Firstly, a three-dimensional hydrodynamic and salinity transport numerical model, with a high-resolution unstructured mesh and spatially varying bottom roughness, was developed and validated quantitatively against hydrodynamic and salinity measurements. Secondly, the spatio-temporal hydrodynamic characteristics and salinity in the NB during Typhoon Fongwong were analyzed. Finally, we discussed the effects of the typhoon on hydrodynamics and salinity through the comparison with a scenario of normal wind force action. Several studies showed the significance of wind on water mixing and column stratification [30,42], and we focused on the mechanism of the salinity distribution, which was altered by Typhoon Fongwong along the NB of the YRE. The distinctive features of this study, which make it different from existing studies are: (1) the investigation of a specific typhoon with a unique path; and (2) more discussions and investigation of the horizontal distribution of salinity affected by the typhoon, tide, current and wind. Salinity intrusion is a significant event which affects the ecosystems of many animals and plants in the estuaries and, due to the location of the reservoirs in the YRE, the security of the water supply is mostly threatened by low river discharge and a stronger saltwater intrusion. All findings are made for a better understanding of saline water intrusion, which plays a vital role in the government strategies in mitigating its effects.
typhoon-induced salinity intrusion and horizontal distribution were rarely popular topics when comparing larger estuaries. The Yangtze River is the longest river in China, with a length of 6380 km, spanning 19 provinces and with a catchment area of \(1.8 \times 10^6\) km\(^2\). The Yangtze River Delta is one of the most developed economic areas in China. The YRE (Figure 1) is divided into the NB and the South Branch (SB) by the Chongming Island, while the Changxing Island and Hengsha Island divide the lower SB into the North Channel (NC) and the South Channel (SC). Finally, the lower SC is divided into the North Passage (NP) and the South Passage (SP). The YRE has a complicated topography with third-order bifurcations and four outlets into the East China Sea, and the salinity intrusion can significantly impact the four large-size drinking-water reservoirs that supply drinking water to about 50 million people. Many studies investigated the YRE: its plume characteristics \([40, 41]\), impacts of river discharge \([42, 43]\), SLR \([44, 45]\) and Three Gorges Reservoir \([46, 47]\). However, little information, which focused on coastal inundation \([48]\) and dynamical responses of river plumes \([49]\), is available about the influence of short-lived episodic events such as storms and typhoons, which may significantly influence the vertical mixing processes. The NB is the first bifurcation; it has the lowest river discharge in the four branches and is mainly dominated by tidal force, which is vulnerable to typhoons.

Figure 1. (a) The computational area of the YRE and the path of Typhoon Fongwong. The red circles and arrows are the typhoon center and moving direction. Purple cross-shapes are locations of six tidal gauge stations. Three black triangles mark the tidal current measurement locations in February 2014. Colored star symbols signify the cruising survey stations in July 2014. (b) The focused investigational area of the NB with two selected cross-sections of the NB and the SB at separation point, and talweg of the NB. Two black solid triangle points NB1 and NB2 are located at the mouth and the middle of the NB, respectively. (c) The map of the study area is downloaded from the Google Earth.

2. Numerical Model

The MIKE3 developed by DHI Group is applied to simulate saltwater intrusion in the YRE. The model is based on a flexible, unstructured mesh approach and is widely used in coastal and estuarine environments. The system is based on the numerical solution of the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations with the Boussinesq assumption and hydrostatic pressure distribution. The spatial discretization of the primitive equations is performed using an element-centered finite volume method. The spatial domain is discretized by the subdivision of the continuum into non-overlapping
The MIKE Flow Model is used in many studies and governing equations and details of this model can be found in the MIKE User Manual [50].

2.1. Model Setup

The spatial extent of the model ranges from 26.9° N to 34.4° N with a length of 810 km in the N-S direction and from 120.2° E to 125.6° E with a length of 500 km in the W-E direction. The model covers the entire YRE and Hangzhou Bay (HB) in order to present the complete typhoon track (shown in Figure 1) and to better express the hydrodynamics and saltwater exchange between the two estuaries. The horizontal computational domain is composed of an unstructured triangular mesh with 18,887 nodes and 33,656 elements, with the coarsest mesh at the east ocean boundary and the finest in the NB. The mesh size generally decreases from the sea toward the coast and estuary when considering both computational time and accuracy. A non-uniform 10-layer grid is adopted in the vertical direction, and the relative water depths are 0.05, 0.05, 0.1, 0.1, 0.2, 0.2, 0.1, 0.1, 0.05 and 0.05 from the surface to the bottom, which better reflect the impacts of wind, surface water level fluctuation and the bottom roughness (Figure 2).

The real daily river discharges at Jiangyin and Cangqian at the upstream of the YRE and Hangzhou Bay were taken as river boundaries, respectively. The initial tidal level and velocity are set as 0. Because of the big computational domain and the open sea boundaries are very large, the open sea boundaries are specified as time-varying tidal levels derived from a harmonic model covering the entire China Sea and its adjacent seas, whose open boundary is driven by the Global Tidal Model [50], which accounts for 8 main astronomical components (M2, K2, S2, N2, K1, P1, O1, Q1). A non-slip condition is used on riverbanks and islands. To reproduce the intermittent appearance of the tidal flat, wet-dry moving

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**Figure 2.** The bottom roughness ($k_s$) of this model.
boundaries were adopted. The depth thresholds in each element were used to classify each element as drying, flooding and wetting, with threshold depths of 0.005 m, 0.05 m and 0.1 m, respectively. The 6-hourly wind and air pressure (10 m above sea level) data in 2014, were downloaded from the ECMWF (European Centre for Medium-Range Weather Forecasts, http://apps.ecmwf.int/datasets/data/interim-full-daily, 1 September 2020) and were employed to determine the wind stress and atmospheric pressure. The bottom stress is determined by a quadratic friction law as follows:

$$\vec{\tau}_b = \rho_0 c_f \vec{u}_b |\vec{u}_b|$$

(1)

where $c_f$ is the drag coefficient defined as (2), $\rho_0$ is the density of the water, $\vec{u}_b$ is the flow velocity at a distance $\Delta z_b$ above the seabed, and the drag coefficient is determined by assuming a logarithmic profile between the seabed and the point at the distance $\Delta z_b$ above the seabed:

$$c_f = \frac{1}{((\frac{1}{k})ln(\frac{\Delta z_s}{m}))^2}$$

(2)

where $k = 0.4$ is the von Karman constant, and $m$ is approximately $1/30$, $k_s$ is the roughness height varying in a range from 0.00027 to 0.0016 m [46].

The salinity at the upstream boundaries (Jiangyin and Cangqian) was set as zero. At the open sea boundary, the salinity is interpolated based on the measured data with a value of 32 psu in the whole vertical direction. The dispersion coefficient is one of the key calibration parameters for the Salinity Model. This model determines the dispersion coefficients as the horizontal and vertical eddy viscosity, used in the flow equations, multiplied by scaling factor. When the $k$-$\varepsilon$ turbulence model is used, the scaling factor is estimated by $\frac{A}{\sigma_T}$, where $\sigma_T$ is the Prandtl number. The turbulent viscosity was obtained from a standard $k$-$\varepsilon$ turbulence model [51]. The horizontal ($D_h$) and vertical ($D_v$) diffusion coefficients can be related to the eddy viscosity:

$$D_h = \frac{A \sigma_T}{\sigma_T}, D_v = \frac{\nu_t}{\sigma_T}$$

where $A$ is the horizontal eddy viscosity; $\nu_t$ is the vertical eddy viscosity. According to the previous research in the YRE, a dispersion coefficient in the range of 10–1000 m$^2$/s could make the salinity distribution stable [52]. A sensitivity study revealed that the horizontal and vertical dispersion coefficients of 300 and 200 m$^2$/s, respectively, could be chosen as the optimal dispersion coefficients in this study, which were successfully used in our previous study [46].

The bathymetry is derived from the Navigation Guarantee Department of the Chinese Navy Headquarters (China Navigation Publications Press). The scale of bathymetry map is 1:120,000 with varied survey times in different areas. The bathymetry was surveyed in 2009 and 2012 for the SB and Hangzhou Bay, in 2008 for the NB, in 2010 for the NC, in 2011 and 2012 for the SC, in 2011 for the NP and the SP and in 1999 for the open seas.

The hydrodynamic and salinity transport model apply a hot start, which is the result of running for 2 months from a cold start (the initial tidal level, velocity and salinity are defined as 1 m and 0 m/s, respectively) to get relatively realistic salinity distribution. The time step is controlled by the Courant-Friedrich-Lévy (CFL) number with the requirement that $CFL < 1$, in order to keep the computational stability, where $CFL = (\sqrt{gh} + |u|) \frac{\Delta t}{\Delta x} + (\sqrt{gh} + |v|) \frac{\Delta t}{\Delta y}$. The time step interval can self-regulate, ranging from 0.01 to 30 s to meet the CFL restriction as the velocity changes with time at all computational nodes and time steps.

2.2. Model Verification

Typhoon Fongwong is the strongest typhoon to land directly in Shanghai during the past 25 years through the YRE, with a maximum wind speed of 14.2 m/s and an air pressure
of 998 hPa, approaching a gale force of 10 at Sheshan station and landing in Shanghai in September 2014. Figure 3 shows the process of wind speed and direction at Sheshan station. The speed and direction exhibit complex changes because of the exceptionally rare typhoon phenomenon: it derived from the East China Sea and moved west. The typhoon progress can be divided into three stages: from 20:00 on 19 September to 22:00 on 21 September; 22:00 on 21 September to 19:00 on 23 September; and 19:00 on 23 September to 00:00 on 26 September, as the rising (the wind speed has an increasing trend), the stable (the wind speed reaches a maximum and remains strong, but suddenly reduces in speed and changes direction around 0:00 on 23 September) and the falling stage (the wind speed establishes a decreasing trend), respectively, according to the measured wind speed.

![Wind process demonstrating the manifestation of Typhoon Fongwong at Sheshan station from 19 to 27 September 2014. The upper vectors are the wind speed and direction change phenomenon.](image)

Water level measurements from tidal gauges at Sheshan, Luchaogang, Dajishan, Daishan, Tanhu and Zhenhai (Figure 1) in the study area are used to verify the modeled water elevation affected by Typhoon Fongwong. As shown in Figure 4, the comparisons of the time series of computed and observed water elevation at six tidal gauges from 18–24 September in 2014 show good agreements in both magnitudes and phases. Figure 5 is the difference between the measured tide and astronomic tide, which shows a significant increase around 23 September. The surges during the typhoon period are well reproduced, which indicates the effects of the wind on water level that was captured by the model. The period of current velocity simulation for validation spanned from 28 February 2014 to 1 March 2014 at three stations (positions shown in Figure 1). The computed current profile and direction are also well matched with the measured data, and Figure 6 shows the comparison of the surface and bottom current velocity and direction at one selected point NGN4SD. We use the cruising survey data collected in July 2014 by the State Key Laboratory of Marine Geology of China for salinity verification. In this survey, 45 measurement points located at the different branches, and their positions, are shown in Figure 1. Figure 7 is the comparison of computed and measured salinity along the selected profiles, A4 and A5, on the surface, middle and bottom layer, which show that the general trend of salinity is well captured.
Verification of surface and bottom current velocity and direction in 2014.

Figure 4. Verification of tidal level during typhoon period in 2014.

Figure 5. Difference in tidal level (DTL) between measured tide and computed astronomical tide at the six stations.

Figure 6. Verification of surface and bottom current velocity and direction in 2014.
Moreover, the skill model [53] is used to quantitatively assess the model performance. The skill model is demonstrated below:

\[
\text{skill} = 1 - \frac{\sum_{i=1}^{N} |M - D|^2}{\sum_{i=1}^{N} (|M - \overline{D}| + |D - \overline{D}|)^2}. \tag{3}
\]

where \(\overline{D}\) is the mean value, in situ, of the observed data; \(M\) and \(D\) are the computed result and in situ observed data, respectively; \(N\) is the number of data entries. A skill value of 1.0 indicates a perfect performance of the model: skill between 0.65 and 1 is considered excellent, skill in the range of 0.5–0.65 is considered very good, skill in the range of 0.2–0.5 is considered good, and skill of less than 0.2 is considered poor.

Table 1 summarizes the skill values to assess model performance. For the tidal level, the skill values at six stations present an excellent performance with skill = 1.00. For the current velocity, the computed current velocities agree well with the in situ data (Table 1 and Figure 4), such as at the surface layer, with skill = 1.00 and 0.97 at station NGN4SD and CS3SD and skill = 0.95 and 0.96 at the bottom layer. All skill values for tidal level, current speed and direction are larger than 0.9, which indicate that the performance of the hydrodynamic model is excellent. For the salinity, the average skill values of all profiles are shown in Table 1. Except for the profile, A6, on the middle layer, other skill values are over 0.5, which indicates that the performance of the salinity transport model is good. The verification generally supports the applicability of the hydrodynamic and salinity transport model in the YRE.
Table 1. Summary skill values of the assessment model performance.

| Quantity        | Station  | Skill | Performance |
|-----------------|----------|-------|-------------|
| Tidal level     | Sheshan  | 1.00  | Excellent   |
|                 | Luchaogang | 1.00  | Excellent   |
|                 | Dajishan | 1.00  | Excellent   |
|                 | Daishan  | 1.00  | Excellent   |
|                 | Tanhu    | 1.00  | Excellent   |
|                 | Zhenhai  | 1.00  | Excellent   |

| Current velocity | Stations   | Surface | Bottom | Surface | Bottom |
|------------------|------------|---------|--------|---------|--------|
|                  | NGN4SD (speed) | 1.00    | 0.95   | Excellent | Excellent |
|                  | NGN4SD (direction) | 1.00    | 1.00   | Excellent | Excellent |
|                  | CS3SD (speed)   | 0.97    | 0.96   | Excellent | Excellent |
|                  | CS3SD (direction) | 1.00    | 1.00   | Excellent | Excellent |
|                  | NC6D (speed)    | 1.00    | 0.93   | Excellent | Excellent |
|                  | NC6D (direction) | 1.00    | 1.00   | Excellent | Excellent |

| Salinity         | Profile | Surface | Middle | Bottom | Surface | Middle | Bottom |
|------------------|---------|---------|--------|--------|---------|--------|--------|
|                  | A3      | 0.82    | 0.63   | 0.70   | excellent | very good | excellent |
|                  | A4      | 0.95    | 0.92   | 0.97   | excellent | excellent | excellent |
|                  | A5      | 0.97    | 0.90   | 0.95   | excellent | excellent | excellent |
|                  | A6      | 0.51    | 0.32   | 0.78   | very good | good | excellent |
|                  | A7      | 0.98    | 0.91   | 0.89   | excellent | excellent | excellent |
|                  | A8      | 0.79    | 0.68   | 0.63   | excellent | excellent | very good |

3. Results

This section mainly presents the spatial-temporal distribution of the tidal level, current velocity and salinity in the NB due to Typhoon Fongwong. For comparison, two scenarios of no-wind force action and normal wind action (5.8 m/s in 75°) since 0:00 on 15 September 2014, instead of the typhoon with a hot start, are also computed. Figure 8 is the salinity distribution before the typhoon landed which is simulated for over 2 months and is also the initial distribution of the hot start.

Figure 8. The salinity distribution at 00:00 on 15 September 2014.

3.1. Tidal Level Changes by the Typhoon

Figure 9 shows the time history of tidal levels and their difference under Typhoon Fongwong and the no-wind force action at NB1 (positions shown in Figure 1b) located at the mouth of the NB. It indicates the storm surge caused by the typhoon achieves...
a maximum value at 7:00 on 23 September. Although the typhoon caused abnormal changes, the tidal level process showed a semi-diurnal tidal type, and its change also had a semi-diurnal pattern. During the typhoon rising period, the tidal level has an increasing trend, and this increase reaches a peak during the first half of the typhoon stable stage. An obvious negative storm surge appeared around 24 September 2014 due to the wind direction changing from S/SW to W/NW (shown in Figure 3). During the typhoon falling stage, the storm surge becomes weaker as the time passes Figure 10a shows the time history of the hydrodynamics, surface salinity, wind speed and atmospheric pressure at NB1 and NB2 located at the middle of the NB (positions shown in Figure 1b). For the tidal level, both NB1 and NB2 have the similar semi-diurnal pattern, but the tidal level rising time at NB1 began earlier than that at NB2. Another interesting phenomenon is that the high water (HW) at NB2 is higher than that at NB1; the former has a maximum value of 2.36 m while the latter is 2.10 m. Similarly, the low water (LW) at NB2 is lower than that at NB1. The higher high water at HW and the lower high water at LW at NB2 causes the tidal level range at NB2 to be larger than that at NB1. In general, the tidal level and its range increase toward the upstream area in the NB due to the combined effects of the funnel-shaped plane geometry of the NB and the typhoon (see Figure 9b).

Figure 9. (a) Time history of typhoon-induced and astronomic tidal levels; (b) the difference in tidal level (DTL) under Typhoon Fongwong and no-wind force action at NB1.

Figure 10. Time history of surface salinity (SS), tidal level (TL), current speed (CS), wind speed (WS) and air pressure (AP) at NB1 and NB2 in 2014: (a) with typhoon; (b) without typhoon.
To obtain the spatial distribution of the tidal level in the YRE, we present the tidal level contours (Figure 11) at 7:00 on 23 September with the strongest storm surge and at 5:00 on 19 September with the same tidal phase during the typhoon rising period. Both have a similar tidal level distribution pattern; however, the tidal level in the YRE is much higher than that in the HB, which indicates that they have different tidal phases. The tidal level in the YRE during the typhoon stable period is much higher than that during the typhoon rising period due to the strong storm surge. The tidal level in the upstream is also much higher than that in the downstream of the YRE, because the main wind direction is SE/S in the typhoon, which pushes water toward the NW. To explain the change more clearly, the contours of the difference of tidal level between the typhoon, and without the typhoon are shown in Figure 12. With the typhoon moving and the wind speed changing, the tidal level change in the north part of the YRE significantly increases which indicates that a large amount of water is pushed northwestward, causing the tidal level to increase significantly.

Figure 11. Tidal level contours and surface current velocity vector fields at 5:00 on 19 September (a) and at 7:00 on 23 September 2014 (b) with the strongest storm surge.

3.2. Spatial–Temporal Distribution of Current Velocity

The surface current velocity vector fields at 5:00 on 19 September and at 7:00 on 23 September with the strongest storm surge are also shown in Figure 11. Both have a similar flood current pattern. The typhoon clearly increases the surface flooding velocity in the offshore area due to the strong wind stress and low bottom roughness in deeper water. From Figure 10a, both current velocity magnitudes at NB1 and NB2 have a similar semi-diurnal pattern, such as the tidal level type. The start time of flooding current at NB1 began earlier than that at NB2, which corresponded to the tidal level change. However, the flooding current at NB1 is much higher than that at NB2, i.e., the typhoon strengthens the current more at the mouth than in the upstream area due to both the typhoon being weaker after landing and increasing bottom roughness toward the upstream. The maximum value that the current velocity magnitude can achieve is 1.19 m/s at NB1, while it is 0.87 m/s at
NB2. Meanwhile, the typhoon changes the current velocity more during the flood period than the ebb period.

![Contours of difference of tidal level (DTL) between typhoon and without typhoon and surface current velocity vector fields at 5:00 on 19 September 2014 (a) and at 7:00 on 23 September 2014 (b) with the strongest storm surge.](image)

**Figure 12.** Contours of difference of tidal level (DTL) between typhoon and without typhoon and surface current velocity vector fields at 5:00 on 19 September 2014 (a) and at 7:00 on 23 September 2014 (b) with the strongest storm surge.

### 3.3. Salinity Structure Change by the Typhoon

Figure 13 is surface salinity distribution with and without the typhoon at 5:00 on 19 September in the rising period, 7:00 on 23 September in the stable period and 9:00 on 25 September 2014 in the falling period of Typhoon Fongwong. Those three different times are at the same tidal phase. The six surface salinity distributions have similar patterns, i.e., high salinity in an offshore area and a salinity reduction towards the upstream area, except for shoal areas with high salinity. The main differences at three typical times of the typhoon focus on the area around the mouth. Compared with the scenario without the typhoon, the salinity distribution at the mouth area has a significant difference. Figure 3 shows the wind directions are NW, SW and NW on 19, 23 and 25 September, respectively, which indicate that the wind drives the saline water more to the open sea, making the salinity decrease at NB1.

According to Figure 10a, salinity variations have significantly different styles that, at the surface salinity at NB2, have a semi-diurnal changing cycle, while this becomes irregular at NB1. Meanwhile, the surface salinity at NB1 is much higher than that at NB2, which means the effect of the typhoon on salinity at the mouth is much stronger than that in the upstream area of the NB. The surface salinity at NB1 also clearly presents a decreasing trend around 24 September 2014 due to the wind direction changing from S/SW to W/NW, which corresponds to the varying storm surge. The wind speed and air pressure also has a decreasing trend around 24 September, which indicates that the salinity variation is also related to the atmospheric pressure due to the wind speed having a direct relationship with the pressure gradient. Hence, the wind is a key influence factor on salinity change. A high surface salinity is maintained during the typhoon falling period (the wind speed is below 6 m/s), which shows that salinity change does not synchronize with the typhoon process and the impacts of the typhoon on salinity can be longer lasting.
Figure 13. With typhoon and without typhoon. Surface salinity distribution at (a) 5:00 on 19 September in the rising period; (b) 7:00 on 23 September in the stable period; (c) and 9:00 on 25 September 2014 in the falling period of Typhoon Fongwong, and the same time-surface salinity distribution (d–f) without typhoon.

Figure 10b is the time history of surface salinity, tidal level, current speed and air pressure without the typhoon. Compared with Figure 10a, the surface salinities under the scenarios with the typhoon and without the typhoon at NB1 have significant differences during the period from 22 September to 25 September due to different dominant factors. The former is dominated by wind with a low salinity, while the latter is dominated by tide with a high salinity. It also indicates that the salinity in the mouth area of NB is more sensitive to the impact of the typhoon.

Water column stratification was determined by estimating the stratification parameters from each salinity profile. To better explain the salinity vertical distribution during the typhoon period, a stratification parameter $n_s$, defined by Haralambidou et al. [54], was given by:

$$
n_s = \frac{S_{\text{bott}} - S_{\text{surf}}}{\frac{1}{2}(S_{\text{surf}} + S_{\text{bott}})}$$

where $S_{\text{surf}}$ and $S_{\text{bott}}$ are the surface and bottom salinity, respectively. If $n_s < 0.1$, the water column is well mixed; if $0.1 < n_s < 1.0$, the water column is partially mixed and if it is above 1.0, stratification with the presence of the salt wedge is evident. Table 2 is the $n_s$ at points along the talweg on 19 and 25 September, respectively. Before the typhoon, except for point 1, point 3 and point 4, the $n_s$ value is entirely above 0.1 and the maximum value reaches 0.528, which means that the salinity stratification exists. However, after the typhoon, the $n_s$ value is entirely below 0.1, which indicates that the water column is well mixed.
Table 2. Summary $n_s$ values of the points along the talweg.

| $n_s$        | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Point 7 | Point 8 | Point 9 | Point 10 | Point 11 |
|--------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|
| 19 September | 0.050   | 0.011   | 0       | 0.003   | 0.381   | 0.240   | 0.510   | 0.528   | 0.390   | 0.263    | 0.231    |
| 25 September | −0.025  | −0.015  | −0.003  | 0.003   | −0.007  | −0.005  | −0.002  | −0.002  | −0.001  | 0        | 0        |

Figure 14 is the salinity vertical distribution along the talweg of the NB at 5:00 on 19 September in the rising period and 9:00 on 25 September 2014 in the falling period of Typhoon Fongwong. Both have significant different vertical structures, the former is a typical salt wedge reflecting partial mixing, while the latter is totally mixed in the vertical direction. Moreover, compared to the salinity stratification at the two different times, it is obvious that the water movement was not only synchronized from the surface to the bottom but also from the upstream area to the mouth. Combined with the $n_s$ and the simulation result, the typhoon changes the estuarine mixing type and enhances water mixing and matter exchange in the vertical direction, which means that the strong winds can create sufficient mixing energy to destroy this stratification [39]. Figure 14 also shows the isohaline of the 1 psu, 2 psu and 4 psu shift upstream at 500 m, 1000 m and 19.5 km, respectively, in the NB due to the typhoon and this result can have important implications for the water quality.

Figure 14. Salinity vertical distribution along the talweg of the NB at (a) 5:00 on 19 September in the rising period; (b) and 9:00 on 25 September 2014 in the falling period of Typhoon Fongwong.
4. Discussion

In this section, we further discuss the impacts of Typhoon Fongwong, including the tidal level, current velocity and salinity in the NB of the YRE through comparison with a scenario of normal wind force (5.8 m/s in 75° at 0:00 of 15 September 2014) compared to the wind force of Typhoon Fongwong after 0:00 of 15 September 2014. Figure 15 is the time history of the difference in tidal level between the two scenarios of Typhoon Fongwong and a normal wind force action at NB1 and NB2 in the NB. To clearly reflect the typhoon function impact on the estuary, Figure 16 shows the close-up view from 22 to 26 September (covering the whole stable stage and part of the falling stage) of the differences in tidal level, the current speed and surface salinity between the two scenarios of Typhoon Fongwong and the normal wind force action at NB1 and NB2 in the NB. The change processes in the difference of tidal levels at NB1 and NB2 have similar trends, while the change starting time at NB1 begins earlier than that at NB2, which corresponds to the tidal level change. The maximum tidal level difference at NB2 is 0.61 m at 9:00 on 23 September, which is higher than the maximum value of 0.46 m at NB1. The tidal level difference increases toward the upstream area in the NB corresponding to the tidal level range change (shown in Figures 9 and 11a), which is controlled by the funnel-shaped plane geometry of the NB and the typhoon action.

![Figure 15](image1.png)

**Figure 15.** Time history of difference in tidal level (DTL) between the two scenarios of Typhoon Fongwong and normal wind force action at NB1 and NB2 in the NB in 2014.

![Figure 16](image2.png)

**Figure 16.** Difference in tidal level (DTL), current speed (DCU) on the surface and surface salinity (DSS), from 22 to 26 September, between the two scenarios of Typhoon Fongwong and normal wind force action at NB1 and NB2 in the NB in 2014.

For the current speed, the difference in the typhoon stable period is much larger than that in the typhoon rising and falling period. The maximum current velocity difference is 0.13 m/s during the flood tide, while it is 0.12 m/s during the ebb tide at NB1; it has a similar characteristic at NB2 with smaller change values. Table 3 shows that the typhoon enhances the flood current and weakens the ebb current, and this effect is obvious at the
mouth of the NB. It implies that the typhoon has a stronger impact on the mouth than the upstream area of the river, due to both the typhoon becoming weaker after landing and an increasing bottom roughness toward the upstream area. Li et al. [39], who studied the current induced by a hurricane in a semi-enclosed bay, found that after the storm’s passage, the bay relaxed with a rapid movement of the entire water column in the opposite direction, which could explain the difference in current wind speed after 25 September in our study.

Table 3. Flood and ebb discharge of the NB and the SB, and the flow split ratio of the NB under two scenarios of Typhoon Fongwong and normal wind force.

| Scenario          | NB Flood Discharge/m³ | NB Ebb Discharge/m³ | SB Flood Discharge/m³ | SB Ebb Discharge/m³ | Split Ratio of the NB |
|-------------------|----------------------|--------------------|----------------------|--------------------|------------------------|
| Typhoon           | 39,908,656.93        | 19,885,622.09      | 845,086,196.6        | 3,673,630,447      | 4.51% 0.54%            |
| Normal wind force | 28,182,935.52        | 36,591,983.35      | 823,104,668.9        | 3,673,645,087      | 3.31% 0.99%            |

We computed the flood and ebb discharge of the NB and the SB through two selected cross-sections in the NB and the SB at the separation point (positions shown in Figure 1b) under two scenarios of Typhoon Fongwong and a normal wind force; the results and the flow split ratio of the NB are also shown in Table 3. The typhoon slightly increases flood discharge and decreases ebb discharge in the SB, but a significant change happens in the NB, i.e., the flood discharge increases by 29.38% and ebb discharge decreases by 84.01%, respectively. This changes the flow split ratio of the NB, that is, the flood flow split ratio increases from 3.31% to 4.51% with an increase ratio of 26.61%, while the ebb flow split ratio decreases from 0.99% to 0.54% with a decrease ratio of 83.33%. This further supports that the typhoon enhances the flood current and weakens the ebb current in the NB of the YRE.

For the surface salinity, this difference in the change process is similar to the change trend of salinity shown in Figure 8. The change range of the surface salinity difference at NB1 is much larger than that at NB2. For example, the maximum surface salinity difference at NB1 is 1.40 psu, while at NB2 it is 0.50 psu, which demonstrates that the effect of the typhoon on the salinity at the mouth of the river is much stronger than in the upstream area of the NB. The surface salinity difference at NB1 has a sharp decrease around the 24 September, due to the wind direction changing from S/SW to W/NW, which corresponds to the negative storm surge and the atmospheric pressure reduction. Chen and Sanford [27], in their study of the axial wind effect, found that increasing down-estuary wind could make both the stratification and the exchange flow show a transition of an increase and then a decrease, and a strong down-estuary wind could decrease the flow exchange and overcome the wind straining. Our result of salinity distribution change around 24 September can be well explained by a downwind in the NB.

Figure 16 also shows that the typhoon enhances salinity in the flood tide and weakens salinity in the ebb tide in the NB of the YRE, which correspond to the influence of the typhoon on current. Wang et al. [55] described the estuary mixing as “a mixing machine that combines high salinity water from the ocean with fresh water from the river to form intermediate-salinity water” and Lange et al. [24] investigated the mixing in the estuary by the transport of inflow and outflow water volume, which emphasized the interaction of current and salinity. However, the impact of the typhoon on salinity is much more prolonged than that on current, i.e., a high salinity can remain in the typhoon falling period, which greatly influences water intake from the NB in the YRE in the typhoon period and the post-typhoon period. The salinity distribution and well-mixed water gradually recovered to the normal salt wedge pattern in 3 days after the typhoon, which was similar to the situation in Chesapeake Bay [39]. Overall, the typhoon significantly increases the tidal level, current speed, and water mixing.
5. Conclusions

A process-based, three-dimensional, hydrodynamic and salinity-transporting, numerical model based on MIKE3, with a high-resolution of unstructured mesh and spatially varying bottom roughness, is applied to investigate the effects of the historical Typhoon Fongwong, which landed in Shanghai, on the hydrodynamics and saline water intrusion in the NB of the YRE. The model covers the entire YRE and the HB to present the complete typhoon track and to better express the hydrodynamics and saltwater exchange between the two estuaries. This numerical model is well validated quantitatively against tidal level, current velocity and salinity measurements. Three scenarios of Typhoon Fongwong, no wind force action and normal wind force were computed and analyzed to describe the influence of the typhoon on the NB of the YRE, and the main findings could be concluded as below.

Although the tidal level process in the NB kept a semi-diurnal tidal type during Typhoon Fongwong, the tidal level had an increasing trend in the typhoon rising period, reaching the highest increase during the first half of the typhoon stable stage, then appearing as an obvious negative storm surge around 24 September 2014 due to the wind direction changing from S/SW to W/NW, the storm surge diminished in the typhoon falling stage and vanished at the end of the typhoon. In general, the tidal level and its range, and the tidal level difference caused by the typhoon, increased toward the upstream area in the NB due to the combined effects of the funnel-shaped plane geometry of the NB and the typhoon.

The typhoon clearly increased the surface flooding velocity in the offshore area of the YRE due to a strong wind stress and low bottom roughness in deeper water. During a tidal cycle, the typhoon enhanced the flood current with a maximum increase by 0.13 m/s and weakened the ebb current with a maximum decrease by 0.12 m/s in the NB, and the typhoon changed the current more at the mouth than in the upstream area, due to both the typhoon becoming weaker after landing and increasing bottom roughness toward the upstream. The typhoon significantly increased the flood discharge and decreased the ebb discharge in the NB, i.e., the flood discharge increased by 29.38% and ebb discharge decreased by 84.01%, respectively. This led to a large change in the flow split ratio of the NB, that is, the flood flow split ratio increased from 3.31% to 4.51% with an increase ratio of 26.61%, while the ebb flow split ratio decreased from 0.99% to 0.54% with a decrease ratio of 83.33%.

The surface salinity distributions during the typhoon’s three periods had similar patterns, i.e., the high salinity in offshore areas and the salinity towards the upstream area both reduced, except for shoal areas with a high salinity. The effect of the typhoon on the salinity at the mouth of the river was much stronger than that at the upstream in the NB. The salinity at the mouth had a clear decrease around on 24 September 2014 due to the negative storm surge. A high surface salinity was maintained during the typhoon falling period, which indicated that the typhoon impact on salinity could last much longer than the tidal level and current. The typhoon changed the estuarine mixing type and enhanced water mixing and matter exchange in the vertical direction. The isohaline of 1 psu, 2 psu and 4 psu shifted upstream at 500 m, 1000 m and 19.5 km, respectively, in the NB due to Typhoon Fongwong. The salinity distribution gradually recovered to the normal salt wedge pattern in 3 days after the typhoon.

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