Integrated flow-wave-sediment modeling at Tamsui Estuary with SRH-2D Coast

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Abstract

Large cities have been built at river mouths where rivers meet the ocean. Such estuary and near-coast areas are subject to high wind, heavy precipitation, severe tides and storm surges, and high waves during a storm event. Storm-induced hazards are numerous, such as flood, shoreline erosion, beach and bay sediment movement, and infrastructure damage. An understanding of the water and sediment characteristics in the estuary and near-shore coastal areas is critical in protecting the coastal infrastructure and ecosystem. Often, numerical models are used to predict the water flow, wave behavior and sediment dynamics.

In this study, a newly developed SRH-2D Coast model is demonstrated by applying the model to the Tamsui River Estuary, Taiwan, under three typhoon events. The objective is to introduce the model, demonstrate its capability, and verify its usefulness for a practical case. A new third-generation wave model is developed with several novel features; a special sediment transport module is implemented, taking into account the combined flow and wave actions; and they are then integrated into the existing flow and sediment transport model SRH-2D. The model application to the Tamsui River Estuary is presented, along with verification results compared and model performance discussed. Satisfactory comparison of the model results with the field data is demonstrated.

Introduction

There exist a number of numerical models developed for coastal and estuary applications. Such models may be generally classified into process-based and behavior-based. Whereas the former describes the underlying physics using the deterministic governing equations, the latter utilizes parameterized relations to deduce general behaviors (Amoudry and Souza 2011). In terms of the temporal scale, the process-based models simulate time scales ranging from hours to years, while the behavior-based counterparts are in decades to centuries (Ding et al. 2017).

Processed-based models may be further classified as conceptual model, coastal-line evolution model, coastal profile model, and coastal area model – with the last the most comprehensive and in the form of two-dimensional (2D) or three-dimensional (3D). The SRH-2D Coast model, developed at the U.S. Bureau of Reclamation (Lai 2022), belongs to the 2D coastal area model; that is, the current flow, wave propagation and sediment transport are all governed by the depth-averaged partial differential equations representing the first principles of conservation laws. In addition, most important physical processes are incorporated in the model such as tidal forcing, wind forcing, wave-current interactions, bed friction forcing, and morphodynamic forcing. A major challenge of a coastal area model is the proper formulation of the mathematical equations for these physical processes, along with the adoption of a reliable and efficient numerical method. In general, the computational cost associated with the spatial and temporal sizes required to resolve the underlying processes is an important consideration, especially for large domains or longer-time simulations. Different models may develop different strategies to reduce the computational time, leading to various formulations and numerical algorithms.

There are only a few integrated wave-current-sediment models for general use that is freely available, though there are plenty of research models. Commercial models have also been used such as Mike 21. Three popularly used non-commercial 2D area models are briefly reviewed below.

SWAN (Simulating WAves Nearshore) is probably one of the mostly used 2D coastal area models for simulating the wave propagation processes. Various documentations of SWAN are available (e.g., Booij et al. 1999 and SWAN Team 2019) and may be consulted. SWAN solves the full spectral wave action balance equation that incorporated various source and sink terms corresponding to various physical processes such as wind generation of waves, whitecapping, depth-induced wave-breaking, bed friction damping, and wave-wave interactions. SWAN can simulate processes such as wave shoaling, refraction, diffraction, wave blocking, reflection, or transmission. The current SWAN model is often called "third-generation," referring to the fact that it explicitly represents all relevant physical processes for the development of the sea state in two dimensions. In applications, SWAN is often coupled to other current solver and sediment module to achieve an integrated wave-current-sediment modeling. For example, Lesser et al. (2004) presented the coupling of SWAN with the Delft3D suite; and Warner et al. (2008) reported the coupling of ROMS and SWAN using a special procedure named Model-Coupling Toolkit.

CMS-Wave is an integrated wave-current-sediment model developed at the U.S. Army Corps of Engineers (Lin et al. 2008). The flow model was based on CMS2D - Coastal Modeling System two-dimensional (Buttolph et al. 2006), the wave model was developed and documented by Lin et al. (2008), and the sediment module was developed by Sanchez et al. (2016). CMS-Wave is a 2D area model based on the solution of the 2D spectral wave action balance equation formulated by Mase (2001). Similar to SWAN, most physical processes may be simulated such as wave generation by wind, wave shoaling, refraction, diffraction, reflection, depth-induced wave breaking, wave-current interaction, and whitecapping. The structured finite difference model version has been verified and validated (Lin et al. 2011) and are available for public use. For example, recent use of the model includes the wave-structure-land interaction simulation by Nassar et al. (2019) and effect of coastal structures by Mera and Chrisnatilova (2021).

CCHE2D-Coast is another integrated wave-current-sediment model developed at the National Center for Computational Hydroscience and Engineering (NCCHE), the University of Mississippi (Ding and Wang 2010; Ding et al. 2016). The model has been applied to coastal and estuary cases for engineering planning and design of coastal flood and erosion protection (e.g., Ding and Wang 2008; Ding et al. 2013a; 2017; Hsieh et al. 2020). A unique feature of CCHE2D-Coast is the inclusion of a nonlinear parametric hurricane cyclonic wind module that may compute the cyclonic barometric pressure and wind fields along storm tracks (Ding et al. 2013b). The wave module adopts similar mathematical equation and formulation to CMS-Wave. A key difference is that CCHE2D-Coast adopted the finite element method in the discretization of the governing equations, although quadrilateral mesh cells are used. Ding et al. (2016) reported that the wave processes included refraction, diffraction, shoaling, wave breaking, wave transmission through structures, bottom friction, wave-current interaction, vegetation effect, wind-induced waves, and whitecapping.

In this paper, the current-wave-sediment integrated model SRH-2D Coast is reported which belongs to the 2D area model. This model category allows most physical processes being incorporated, although some are based on simplifying assumptions and/or empirical relations. The current solver is based on the finite-volume model of SRH-2D (Lai 2010); the wave module follows the third-generation formulation for various physical processes as described in SWAN Team (2019) and Lai and Kim (2020); and the sediment module solves the coupled system of sediment transport equations of single or multiple size classes (Lai 2020). A unique feature of SRH-2D Coast is the adoption of the flexible polygon-based mesh. Moreover, the one-mesh approach is adopted for all three modules. In terms of numerical method, new numerical methods and algorithms are developed and implemented to solve the wave equation, using a unique mixed finite-difference and finite-volume method (Lai 2021; 2022).

Tamsui Estuary Description

Case Description

Taiwan is an island surrounded by oceans; there are many bays and infrastructures along the shoreline. Each year, an average of three to four typhoons may hit the island, which has induced numerous hazards. An understanding of the water and sediment characteristics in the estuary and coastal shorelines during typhoon is critical in protecting the coastal infrastructure and ecosystem. Often, numerical models may be adopted to predict the water movement (current), wave behaviors and sediment dynamics. In this study, the newly developed SRH-2D Coast is applied to the Tamsui River Estuary, Taiwan, under multiple typhoon events, along with results presented and discussed.

The aerial photography of Tamsui River estuary is displayed in Fig.1; the study area is located at the northwest of Taiwan Island and is marked in the figure. Tamsui River is the largest river in northern Taiwan; its upstream has two large reservoirs – Shihmen Reservoir and Feitsui Reservoir. The river flow, tide and current, wave dynamics, and sediment processes are very complex at Tamsui Estuary. Coupled and highly nonlinear interactions among these processes only exacerbate the complexity. Continuous studies have been carried out in the last 50 years, involving mostly field and laboratory studies (Hsieh et al. 2020).

The model domain is also shown in Fig.1 and has a size of 40 km in the north and 30 km in the west. In the south, Tamsui River flows into the estuary at the Guandu Bridge. The northern offshore boundary is placed far enough away from the estuary in the deep water (about 100 m deep) and free from impact of the near-shore processes. The west boundary is located near the Zhuwei Fishing Port station and the east boundary is at the Linshanbi station; at these two stations, tidal data are available and used as the boundary conditions. Along the shore, approximately 21 km in length, the coast is composed of mostly sand and rock with many concave bays and beaches.

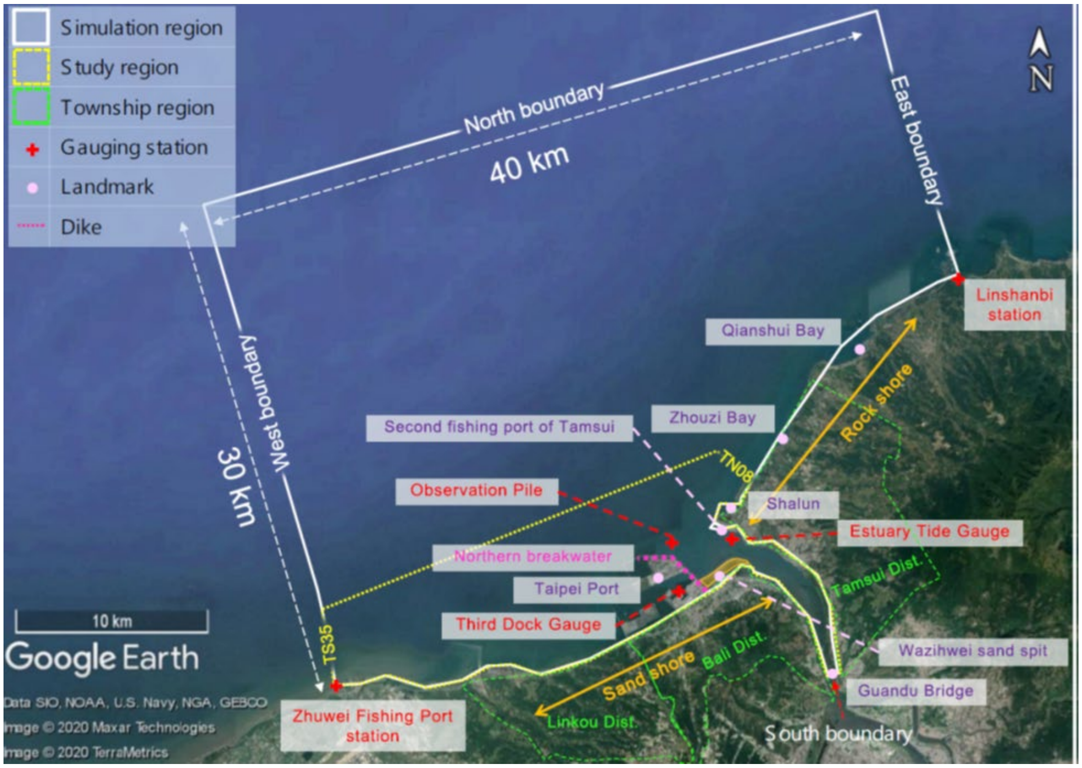


Figure 1. Aerial map, model domain and relevant monitoring stations of the Tamsui River Estuary study area (source: Hsieh et al. 2020).

Terrain and Mesh

The terrain data were measured by the Institute of Harbor and Marine Technology, Ministry of Transportation and Communications, using the single-beam echosounders. The bed elevation contours of the measured terrain in May 2008 are displayed in Fig. 2; these data are used as the initial terrain for the simulation.

A hybrid 2D mesh consisting of both quadrilaterals and triangles is adopted within the model domain – it is also displayed in Fig.2. The total number of mesh cells is 18,569 (10,914 quadrilaterals and 7,655 triangles). The mesh size ranges from 40 m near the river inlet, to 100 m in the bay and near-shore areas, to 500 m in the offshore areas.

The simulation includes two time periods: July 26-30, 2008 during Typhoon Fung-Wong and September 12 – October 1, 2008 during Typhoon Sinlaku and Jangmi. The numerical simulation is carried out in several steps. The initial step focuses only on flows forced by river entry, tidal and wind forcing. In the second step, wave-current interaction is simulated by adding the wave dynamic processes. In the third and final step, the sediment module is activated and simulated together with the current and wave solvers.

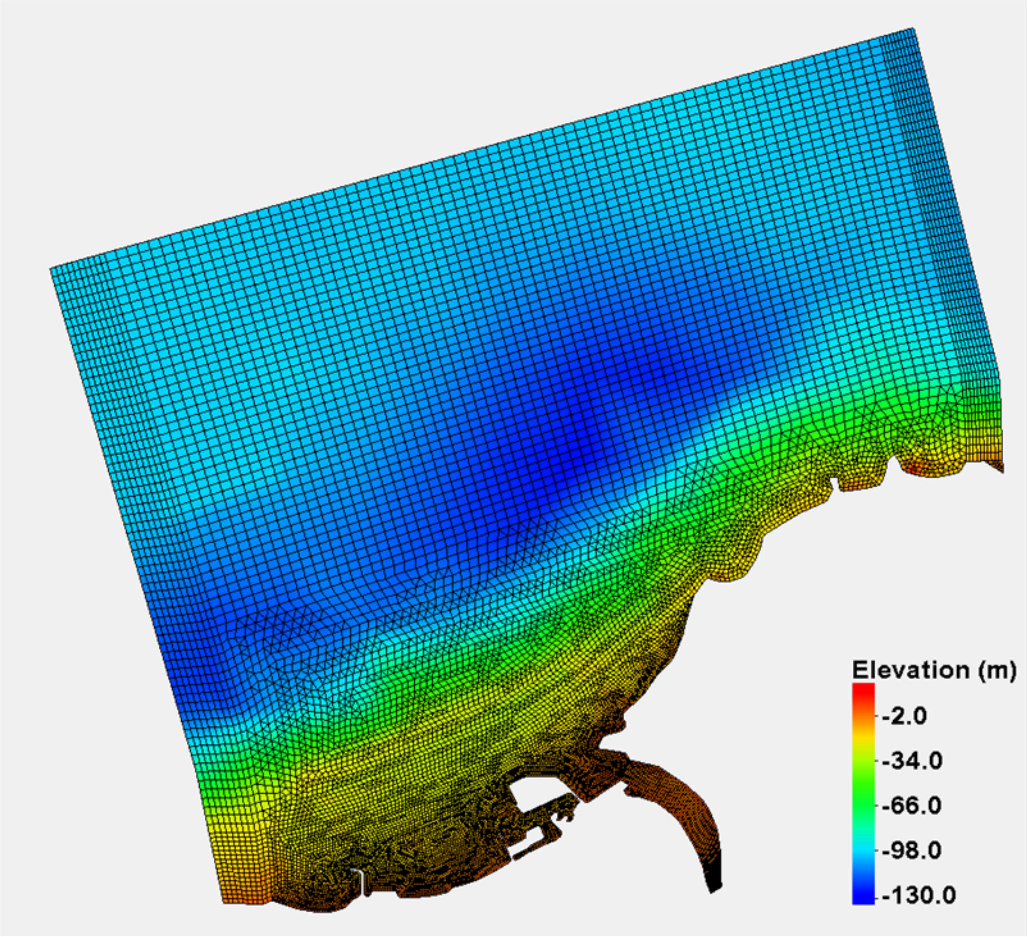


Figure 2. Terrain (bed elevation) in May 2008 and the hybrid 2D mesh for simulation at the Tamsui River estuary.

Model Results and Discussion

Current Flow Results

In the first step, we focus on the current flow modeling influenced by river inflow, tidal and wind forcing. The simulation is between 17:00 July 23 to 0:00 October 1, 2008 - a total of 1,663 hours (70 days). The period included three typhoons: Fung-Wong, Sinlaku and Jangmi. Quiescent assumption is assumed as the initial condition at 17:00 July 23 - that is, both water elevation and velocity are zero initially. The boundary conditions for the tidal forcing are as follows. At the east and west boundaries, measured tidal elevation data are imposed as in Fig.3. It is noted that the tidal amplitude is different at Zhuwei and at Linshanbi. This difference in water elevation would induce strong along-shore current flow. Moreover, the flow is oscillatory between west and east although the dominant flow is from west to east. Such tidal driven along-shore current flow is unique at the Taiwan Strait, and it makes the numerical simulation challenging. The remaining boundary conditions are as follows. At the north office boundary, the symmetry condition is imposed for water elevation. At the south Guandu Bridge, the river flow from Tamsui River is specified; as shown in Fig.4; note that three high flow periods may be identified reflecting the three typhoons. The rest of model boundaries are treated as solid walls. The impact of the wind field is activated; the wind data were measured at the Taipei Harbor meteorological station 10 m above the sea level. The data included the time series values of wind speed and angle.

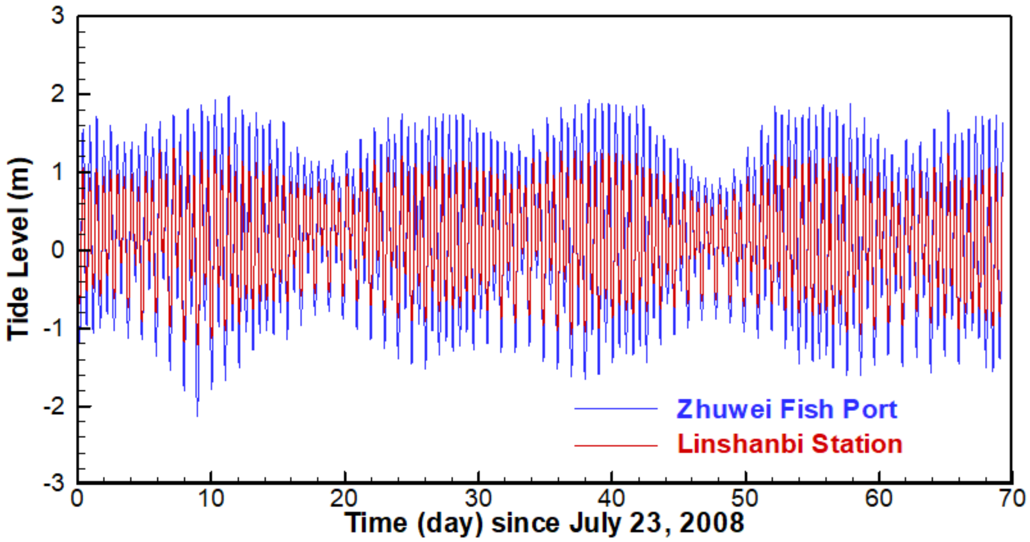


Figure 3. Tidal elevation data measured at Linshanbi station and Zhuwei Fish Port during the simulation period.

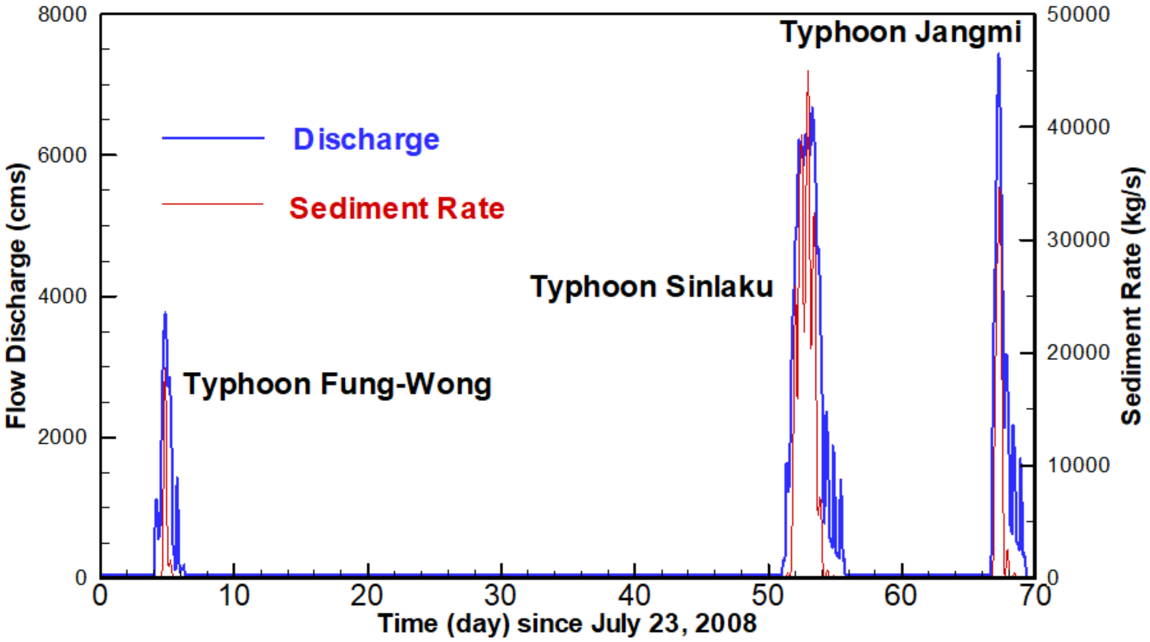
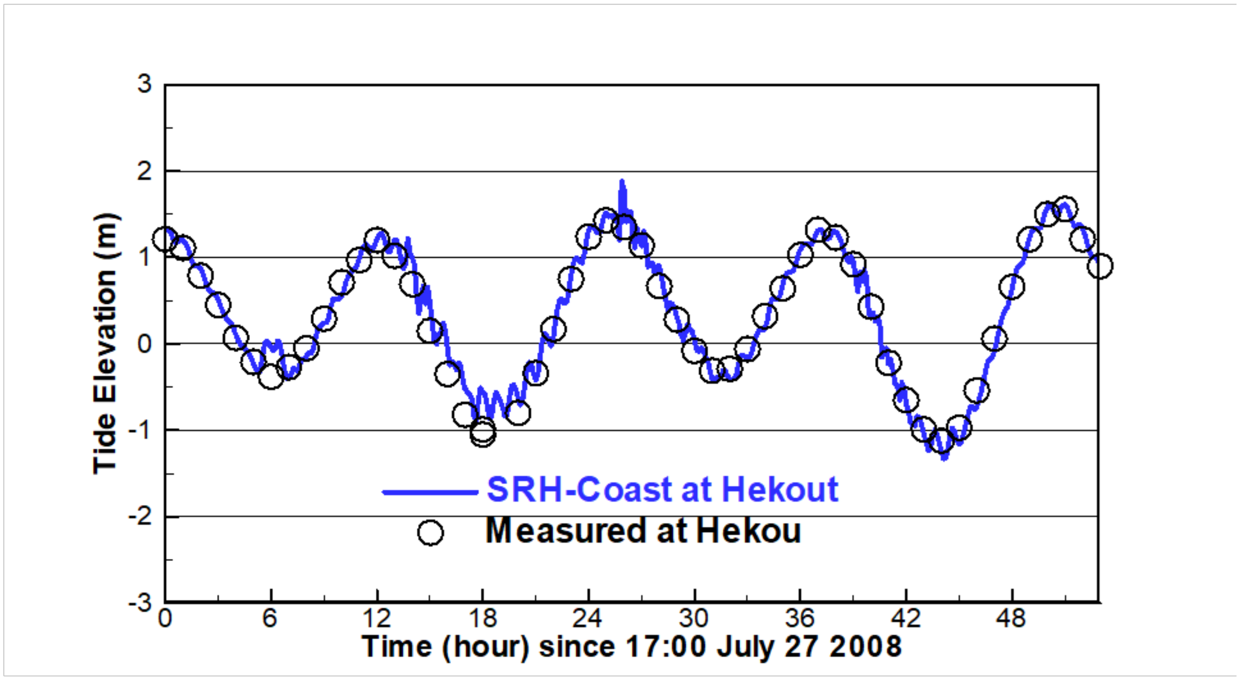


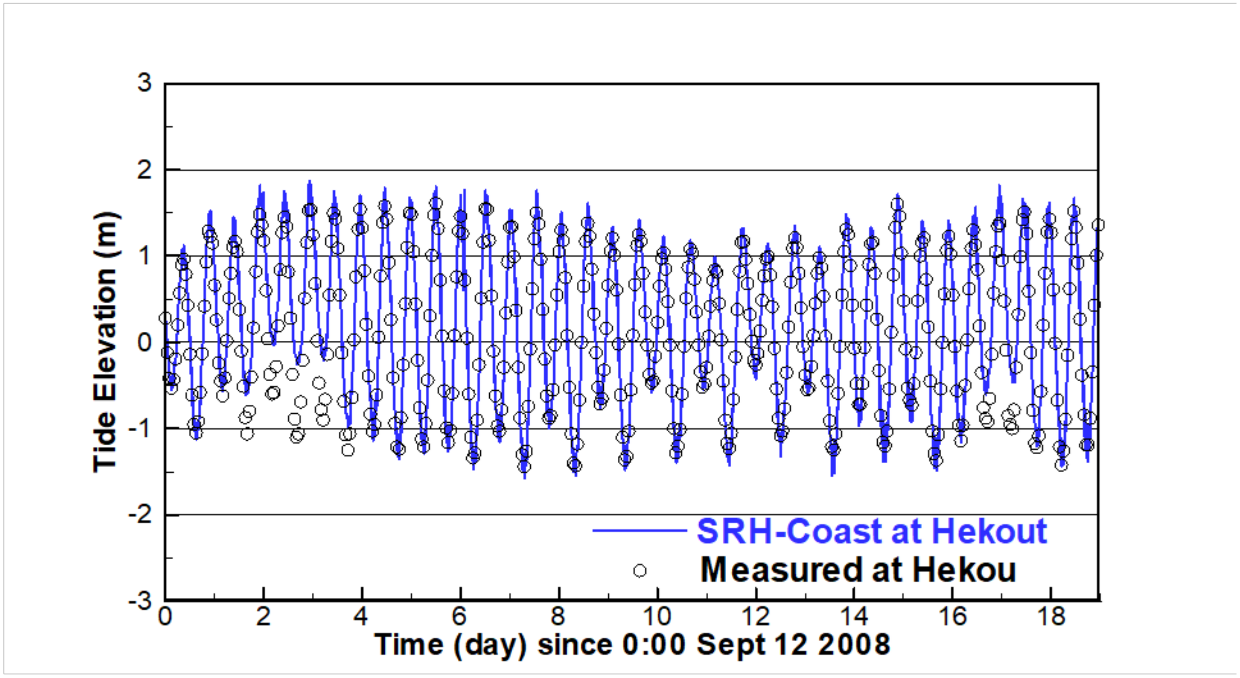
Figure 4. Flow discharge and sediment rate at the Guandu Bridge of the Tamsui River.

The model predicted water elevation at Hekou tidal station is compared with the measured data in Fig.5. The model results agree with the measured elevation well, considering that the flow processes were very complex during typhoons. The tidal elevation is not constant offshore and it also varies spatially. To appreciate the complexity of the longshore current setup by the tidal difference and wind forcing, predicted flow patterns at two times are displayed in Fig.6. On

August 9, the flow is predominantly from west to east; on August 16, an eddy is formed with current flow from east to west near the shore and west to east offshore.

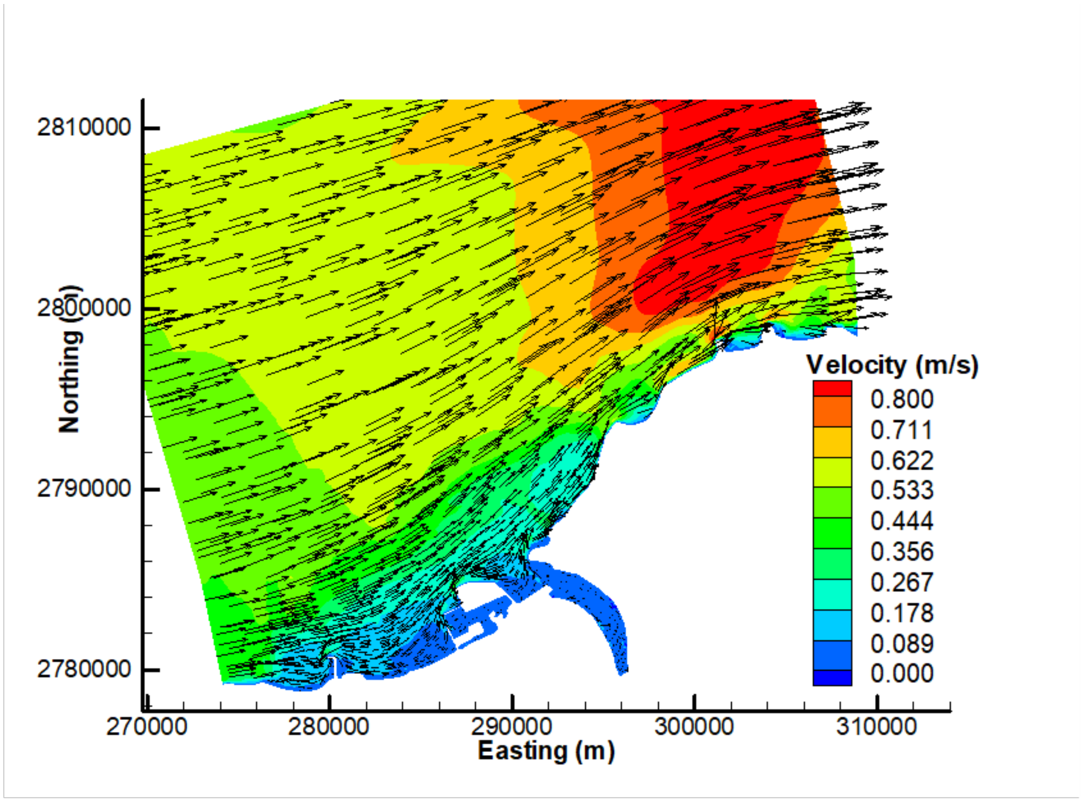


(a) During Typhoon Fung-Wong

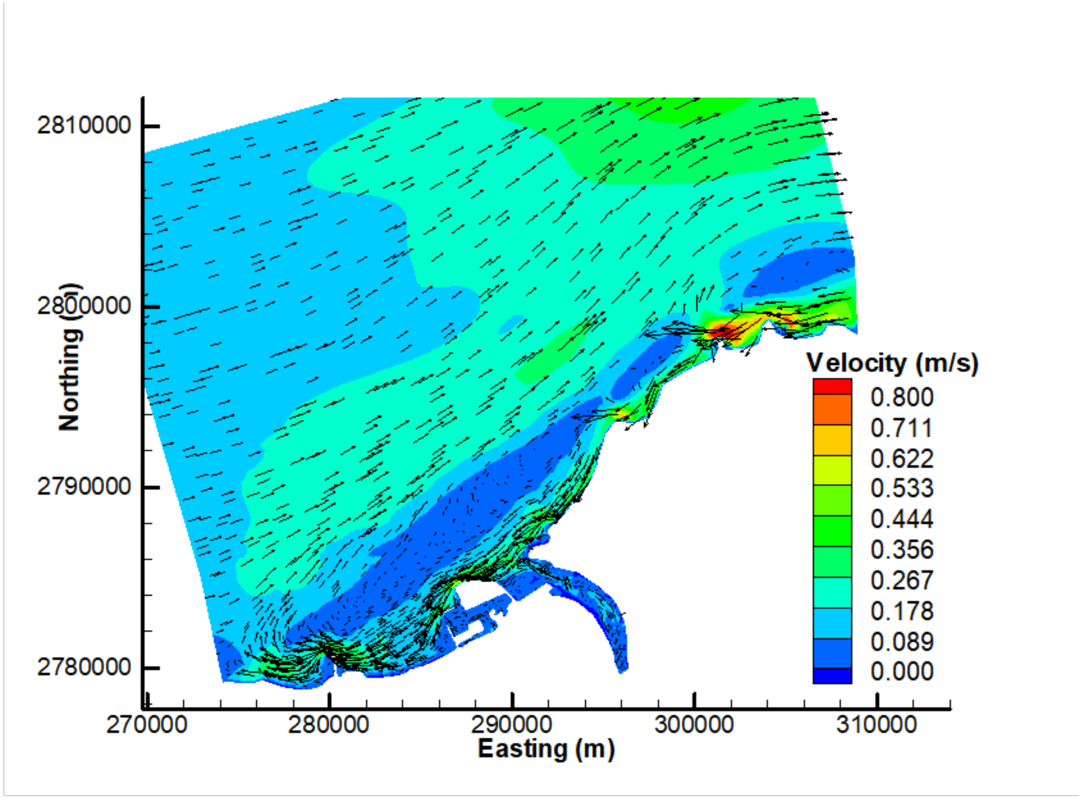


(b) During Typhoon Sinlaku and Jangmi

Figure 5. Comparison of simulated and measured water elevation at Hekou station.



(a) August 9, 2008



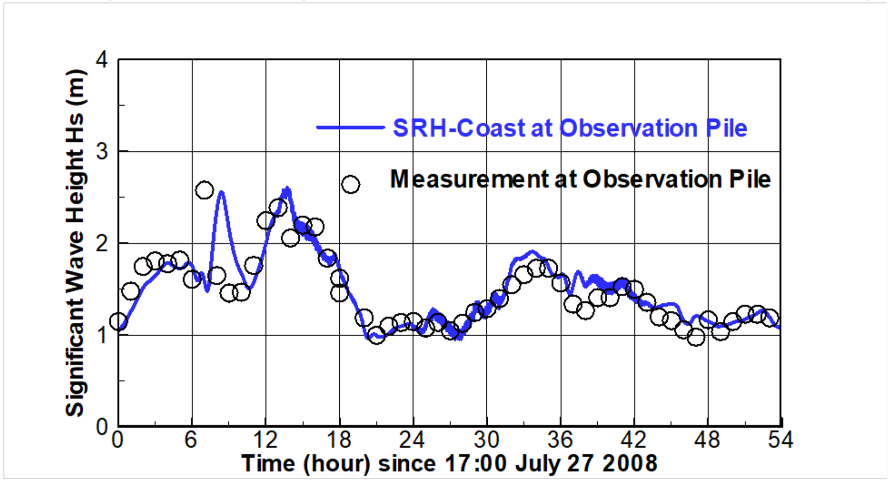
(b) August 16, 2008

Figure 6. Simulated current flow velocity field at two times.

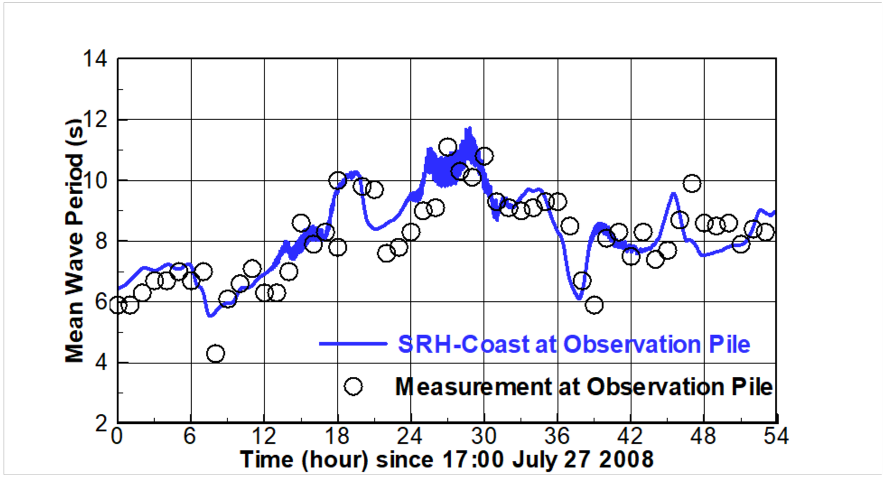
Wave-Current Interaction

In the second step, wave-current interaction simulation is carried out with the wave module activated. The calibration model included the Typhoon Fong-Wong period, while Typhoons Fung-Wong and Sinlaku-Jangmi serve as the model validation. The simulation starts from 17:00 July 26, 2008 and the initial condition is the quiescent-flow assumption. In the wave directional space, 37 points are used, covering the half-plane from -1350 to 450 (zero is along the East and the wave angle is positive counter-clockwise). In the wave frequency space, the frequency range is set up between 0.01 Hz and 2.0 Hz, with the corresponding wave period between 0.5 s to 100 s, and 21 frequency bins.

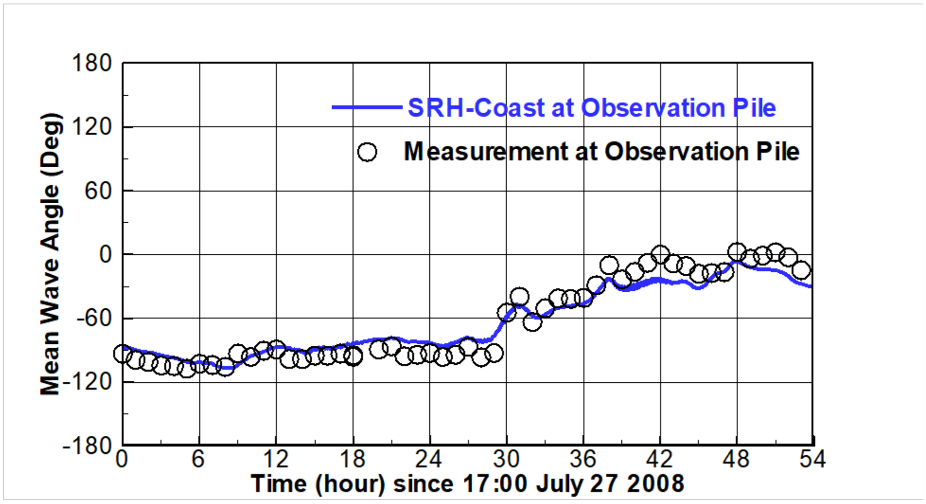
The simulated wave results are compared with available data at a buoy installed near the Taipei Port (named Observation Pile outside the harbor in Fig.1). Comparisons of the simulated and measured wave parameters at the Observation Pile are shown in Fig.7 for Typhoon Fung-Wong, while the same comparison is displayed for the other two typhoons in Fig.8. Overall, it is seen that the agreement is good, indicating that the current-wave interaction modeling is good.



(a) Significant Wave Height

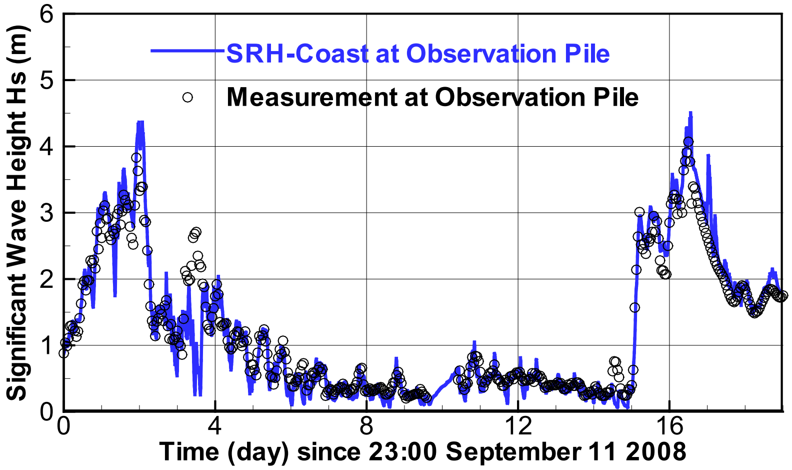


(b) Mean Wave Period

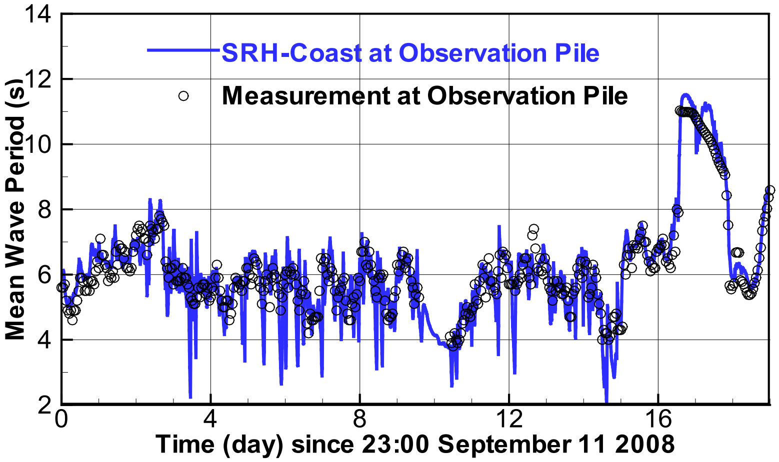


(c) Mean Wave Angle

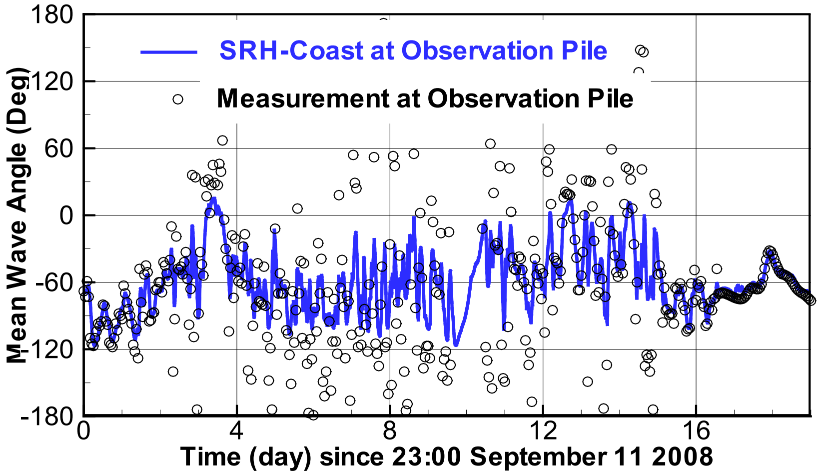
Figure 7. Comparison of wave parameters at the Observation Pile station during Typhoon Fung-Wong.



(a) Significant Wave Height



(b) Mean Wave Period



(c) Mean Wave Angle

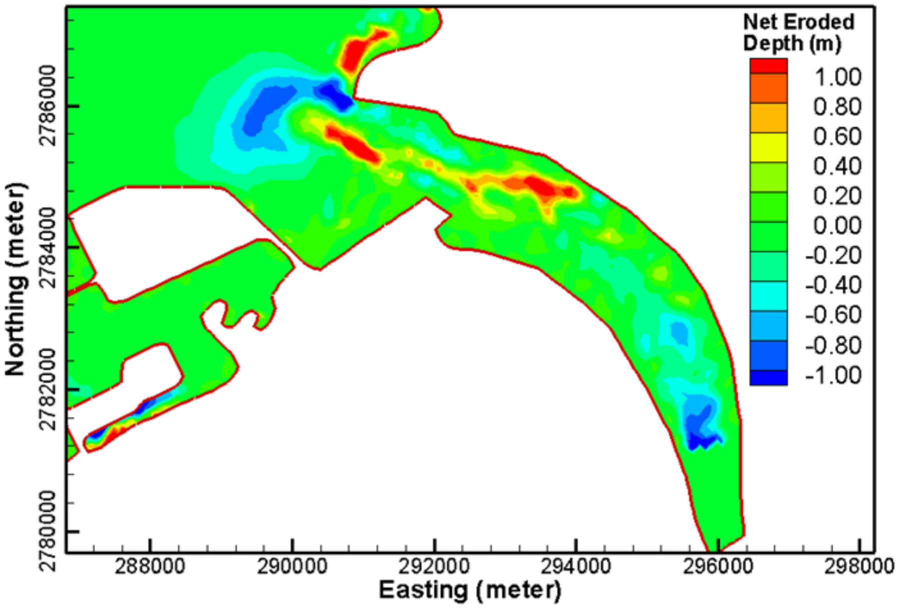
Figure 8. Comparison of wave parameters at the Observation Pile station during Typhoon Sinlaku-Jangmi.

Sediment Transport Simulation

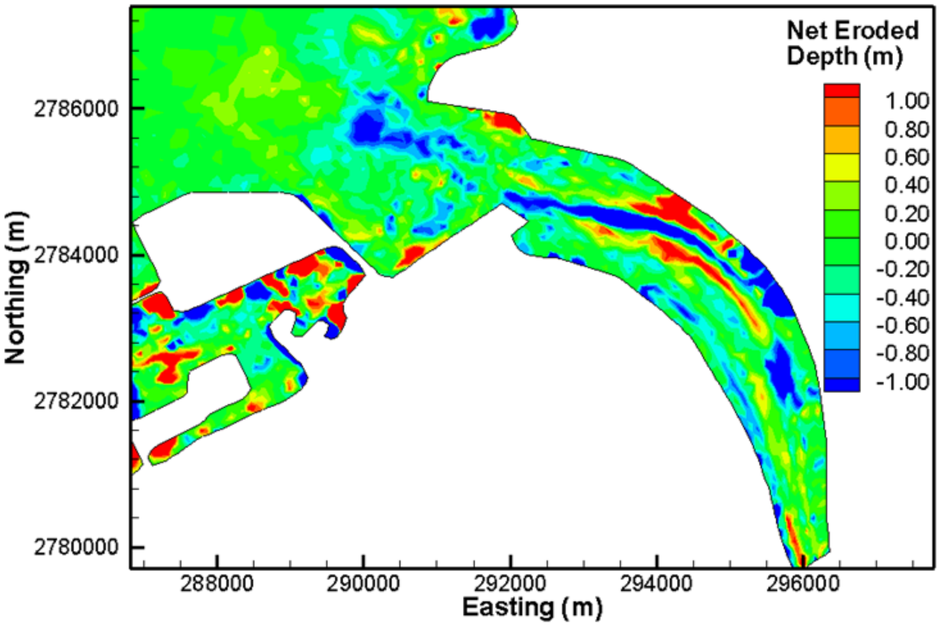
Sediment processes at the Tamsui River Estuary are very complex. Large amount of sediment supply from the upstream, primarily Shihmen and Feitsui reservoirs, may occur under typhoon events; there exist strong tide-induced current flows along the shore – a unique situation at the Taiwan Strait; potential flood flows into the estuary from the river; and the existence of many infrastructures.

The sediment solver adopts the uniform sediment size of 0.2 mm based on an estimate of the measured sediment size and gradation. The sediment is simulated as non-cohesive with a porosity of 0.4 and specific gravity of 2.65. The sediment movement is governed by the non-equilibrium sediment equation and the exchange rate is related to the 2007 van Rijn capacity equation (See Lai 2022 for details). The key parameter of the van Rijn equation is the percentage of wave orbital velocity used for sediment movement and it is set as 0.4. The primary sediment input is at the south boundary, the Guandu Bridge, where the time series sediment rate into the Estuary from the Tamsui River is imposed (see Fig.4).

The wave-current-sediment coupled simulation is carried out over the three typhoon periods. The only data available for comparison is the measured terrain difference, or bed changes, from June 2008 to October 2008, and this difference is visually compared in Fig. 9. Overall, the comparison is not satisfactory in terms of the spatial distribution details; however, the general trend is in agreement in the averaged sense.



(a) SRH-2D Coast Result



(b) Measured Data

Figure 9. Simulated and measured net eroded depth (positive for erosion) after three typhoon events.

Concluding Remarks

The integrated wave-current-sediment modeling using SRH-2D Coast is carried out at the Tamsui Estuary, Taiwan during July-October, 2008 when three large typhoons occurred (Fung-Wong, Sinlaku and Jangmi). The current flow modeling focuses on the forcing by river flows, tide and wind; the wave-current interaction simulation considers the wave dynamic processes; and sediment module is activated and simulated together with the current and wave solvers finally to simulate the current-wave-sediment interactions.

The model results are compared with the available measured data at the Tamsui Estuary, Taiwan. It is found that the tidal elevation and the wave variables, such as the significant wave height, wave angle and period, are predicted reasonably well by the integrated model. The predicted erosion-deposition, however, is less satisfactory. The causes of the mismatch between the model and field erosion-deposition data are unknown. The results point to further investigation. For example, it may be necessary to incorporate additional sediment capacity equations targeted for coastal applications, re-examine the wave-induced sediment processes, and carry out more sensitivity studies. Importantly, better field data need to be collected for model comparisons.

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