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Mechanisms of Rapid Flow caused by Tidal–Fluvial Flow Interaction in Inland Waterways of the Mekong Delta

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Abstract. The present study investigates the river flow intensifications in the urban areas of the Mekong Delta, which are characterized by tributaries, channels, and low-lying lands in addition to the main stream of the Mekong Delta system. A hydraulic model is used to simulate velocities under the influence of both ocean tide and river discharge. A series of numerical simulations estimate that a rapid flow occurs along the tributary in flood season, reaching up to 1.8 m/s during the 2013 historical flood, which can be reproduced by assigning the net downstream river discharge of 9200 m³/s as well as tidal current. A unique mechanism of flow intensification caused by “tidal blockage”, which occurs in the flood tide phase during the flood season, is also identified. Such locally intensified flows could be further strengthened particularly during abnormal high water events such as storm surges and tsunamis, resulting in ship handling difficulties or a risk of overturning small ships.

1. Introduction

The Mekong River flows southward, traversing a distance of approximately 4,800 km from its source to the sea, draining a total catchment area of 795,000 km² that falls within six different countries: China, Myanmar, Lao People’s Democratic Republic, Thailand, Cambodia, and Vietnam. On the basis of its mean annual flow at the river mouth, the Mekong River ranks 10th amongst the world’s great rivers [1]. The Mekong Delta begins at Phnom Penh, Cambodia, where the river divides into its two main distributaries (Figure 1): Tien River and Hau River. The flow of the Tien River is much greater than that of the Hau River, where the annual discharge at Tan Chau accounts for about 83% and the annual discharge at Chau Doc accounts for about 17%. These distributaries trend roughly parallel to each other for most of their journey to the sea (Figure 1). The Tien River then divides into six main channels and the Hau River divides into three channels. These river systems form the Mekong Delta, which is made up of a vast triangular plain with an area of approximately 55,000 km² [1]. There is a noticeable difference between the channel network morphologies of the Tien and Hau branches; the former divides into a number of smaller distributaries before discharging into the sea, whereas the latter more or less maintains a single straight course to the sea [2].

The hydrological regime within the Mekong Delta is a product of the interaction among river discharge, tides, the landform, and configuration of the delta [2], [3]. Therefore, it is generally difficult to obtain a reasonable estimate of the discharge distribution over the branches [3]. Nevertheless, the hydrology of the Mekong Delta has been studied by many researchers [4]-[10] and an understanding



of the flood inundations or sea-level rise impacts and their mechanisms have been substantially improved over the last couple of decades. Flood, inundation, and increasing sea-levels draw significant attention of authorities as well as researchers mainly because they would have direct and visible impacts on local communities [11], [12].

On the other hand, it appears that the river flow characteristics and patterns in the delta system have been overlooked and have not been sufficiently studied in the previous flood risk studies. Given the importance of oceanic influences on deltaic regions, the authors developed a tidal model and investigated the mechanisms of tidal propagation and its influence on flooding in the urban areas of the Mekong Delta [13]. Their model indicates that the flow velocity largely varies depending on the location, which exceeded 1 m/s in the tributary. However, the model can only be applied to simulations during the dry season because it cannot reproduce an abnormal water level rise induced by a high river discharge. In addition to tidal current, it is important to consider a rapid flow induced by a high river discharge during the flood season because small ships are likely to encounter handling difficulties or risk being overturned owing to the unexpectedly rapid flows.

The present study attempts to extend the tidal model [13] to enable application to both flood and dry seasons and thereby investigates the influence of combined flow characteristics of oceanic and fluvial flows on the development of a rapid flow in the complex waterway. The developed model is expected to be useful for identifying the locations subjected to unusual rapid flows in the Mekong Delta.



Figure 1. The close-up image of Can Tho, the largest city in the Mekong Delta, which is located in southern Vietnam. The yellow rectangle in the satellite image shows the computational domain dealt with in this study. The study area encompasses the main river (Hau River), the tributary (Can Tho River), and several small canals.

2. Methodology

The present study focuses on Can Tho City, which is the regional capital and has the highest population in the Mekong Delta (around 1.2 million). Can Tho is characterized by the main river (Hau River), tributary (Can Tho River), and many canals, demonstrating a complex river system that appears to create complicated hydraulics in its system (Figure 1). Although Can Tho is located 80 km inland from the river mouth, the ocean tides predominantly determine the water elevation [14], [15].

This study applied Delft3D-FLOW to reproduce ocean tides propagating upstream of the Hau River, which is one of the main streams of the Mekong system. This model is a multi-dimensional (2D or 3D) hydrodynamic simulation program which calculates non-steady flow that result from tidal and/or meteorological forcing on a rectilinear or a curvilinear grid. Although the model is applicable to a much wider region, this study limits the computational domain to encompass only Can Tho and its surrounding area in order to reduce the computational cost and enable a detailed analysis, which considers the local topography and bathymetry characterized by tributaries, channels, and low-lying lands in addition to the main stream. The present study extends the model [13] in order to incorporate river discharge upstream of Hau River as well as the tidal forcing downstream.

Figure 2 illustrates two different boundary conditions according to tropical seasons: one for the dry season and the other for the flood season. Ocean tides can be generated by assigning the boundary condition with a total of 60 tidal constituents [13]. Amongst all tidal components, the semidiurnal tidal constituent with a period of around 12 h appears to have the strongest influence. In the case of the dry season condition, when the pluvial and fluvial runoff can be negligible, the upstream boundary as well as the other tributaries was set as the Riemann condition, which enables progressive ocean tides to pass through with less reflection (Figure 2). In the case of the flood season condition, the upstream river discharge is determined by a trial method, which finds the discharge that best describes water levels observed by the Mekong River Commission (MRC) and the Southern Regional Hydro-Meteorological Centre, as discussed in the following section.

In March 2015, the author measured the river bathymetry using an echo sounder [13]. The computational grid size is set to be as small as 10 m throughout the domain with 442,704 nodes, while a sufficiently short time step of 0.6 s is assigned to run the simulation as stably as possible. The Manning's n value was set as 0.02 for the water and 0.05 for the land area [16]. The simulation is run for two seasons, which considers the days of 10–11 March 2012 as a typical dry season and 20–21 October 2013 as a typical flood season. The former period is chosen because the author performed the field survey (Figure 3 (left)), while the latter period is selected because a historical flood occurred during this period (Figure 3 (right)). Velocity changes with time are outputted at four locations (points a to d in Figure 2) in order to examine a wide area of the river system including both the main stream (Hau River) and the tributary (Can Tho River). The point referred to as MRC indicates the location of the water-elevation monitoring station.

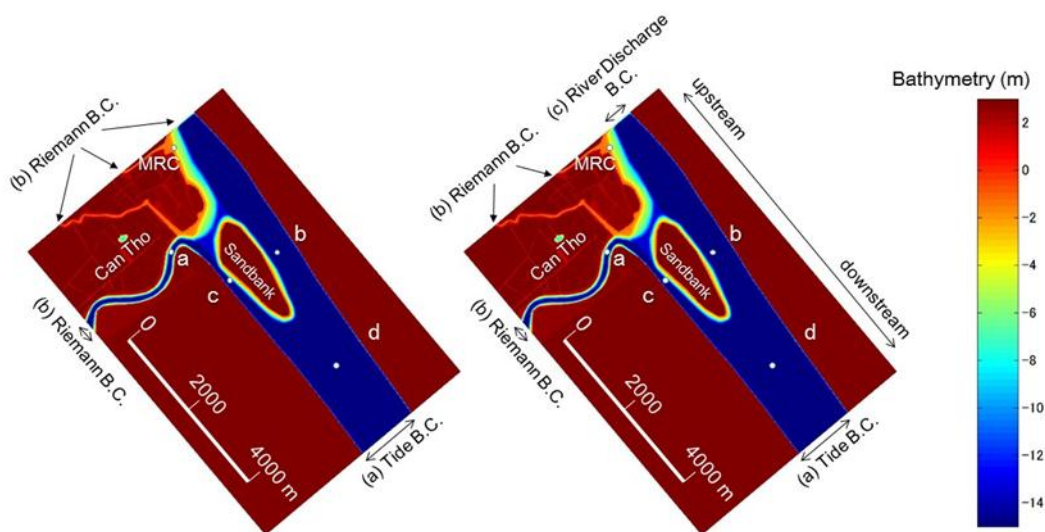


Figure 2. Boundary conditions assigned in the numerical simulations for the dry (left) and flood seasons (right).



10 March 2012



20 October 2013

Figure 3. Photos taken near point a in Figure 2 during dry (left) and flood seasons (right). In October 2013, many local communities across the Mekong Delta suffered from a historical flood [17].

3. Results and Discussion

3.1. Dry season analysis

Given that March lies in the midst of the dry season, the river discharge is typically very small [14]. Therefore, the simulation for the dry season only deals with tides and neglects the river discharge generated by fluvial and pluvial influences. Figure 4(a) shows the tidal fluctuations at one of the output points indicated as MRC in Figure 2, which demonstrates that the simulated and observed water levels are in good agreement in terms of both amplitude and phase. Figure 5(a) depicts the simulated depth-averaged velocities at four different locations in the river basin (Figure 2). The depth averaged velocity significantly varies depending on the location in the river basin. In particular, the flow velocity at point *a*, which reaches a maximum of 1.1 m/s, was almost three times that at point *d* in the main stream. It is obvious that the flow intensification that occurs as tidal current downstream of the river enters into the narrower channels and vice versa, causing a rapid flow. Figure 6a demonstrates that flow intensifications occur during both ebb and flood tides in the dry period. In the ebb tide phase, a strong flow developed in the tributary (Can Tho River) first impinges on the sandbank and then splits into two streams, merging again about 2.5 km downstream (Figure 6a (i)). In the slack tide phase when the tidal current almost ceases, two whirlwinds develop near the edge of the sandbank, indicating that the tide is about to reverse its direction (Figure 6a (ii)). In the flood tide phase, the tide from the sea propagates upstream and a part of the water departs from the main stream and flows into the narrower tributary, causing a rapid flow (Figure 6a (iii)).

3.2. Flood season analysis

It appears that the treatment of the boundaries is more difficult for simulating the hydraulics in the flood season than that in the dry season. Although the Southern Regional Hydro-Meteorological Centre measures river velocity with a current meter in Hau River, it is inevitable that gross discharge rates are substantially influenced by tidal currents. Thus, the net downstream river discharge on the dates studied needs to be estimated by some other method. In this study, the rate is determined by repeating the simulation with a number of different river discharge rates in order to identify the condition which best reproduces the observed water levels at the MRC observatory.

Figure 4(b) demonstrates that the maximum water level up to 2 m on 20 October 2013 cannot be accounted for by only tidal fluctuations, showing about a 60 cm difference between the actual observed levels and tide levels derived by tidal harmonic analysis [14] or the present numerical simulation. The water level abnormally rises above the predicted tidal levels, implying significant pluvial and fluvial influences in addition to tidal influence. The numerical simulation with the boundary condition for the flood season shown in Figure 2 has been repeatedly performed until this gap becomes sufficiently small; the optimal river discharge rate is determined to be 9200 m³/s. The red continuous line in Figure 4(b) indicates the best fitted water level calculated by inputting a river discharge rate of this volume, demonstrating that the model can reproduce water levels during the flood season with a reasonable accuracy.

Figure 5(b) presents the simulated flow velocities in the flood period, including the points *a* at the tributary, *b* and *c* at the narrower strips in the main stream, located on both sides of the sandbank, and *d* at the main stream of the Hau River, where the river is the widest in the computational domain. Numerical simulations were repeated for three different assignments of boundary conditions. While the maximum flow velocity is estimated to be only about 0.6 m/s for (iii) the river discharge condition, it reaches up to 1.3 m/s and 1.8 m/s for (ii) the tide condition and (i) the tide and river discharge combined condition, respectively. This observation corroborates that the tidal regime is generally more predominant than the fluvial regime in the lower Mekong Delta, such as in Can Tho [14].

Given that the tidal regime in this delta is typically semi-diurnal, both ebb and flood tides occur approximately once in the course of half a day, producing the flow velocity peak that occurs twice a half day, as shown in Figure 5b (ii). In the flood tide phase, the flow at point *a* in Figure 2 becomes remarkably fast owing to the influence of tides (Figure 5b (ii)), which is further excited by the fluvial inflow (Figure 5b (i)). In contrast, in the ebb tide phase, it appears that the flow at point *a* reduces to the lowest owing to an opposite flow direction between the tide and river discharge.

The stagnation of flow in the tributary can also be observed in the contour and vector maps (Figure 6b (i)), which are snapshots taken when the tide is at the lowest level. The flow in the tributary is not stagnated even in the slack tide phase (Figure 6b (ii)) because of a constant inflow of river discharge. A unique mechanism that could be found in the flood tide phase (Figure 6b (iii)) is that the tidal current interferes with the fluvial downflow at the confluence of the main stream and tributary. This phenomenon, which could be referred to as *tidal blockage*, forces a combined water flow of tidal and fluvial waters to rush into the narrower tributary. In this way, the diverted river discharge from the main stream of the Hau River exclusively flows into the tributary, Can Tho River, owing to the tidal–fluvial flow interaction. On the other hand, in the ebb and slack phases, it splits into two flows: one towards the tributary and the other towards downstream.

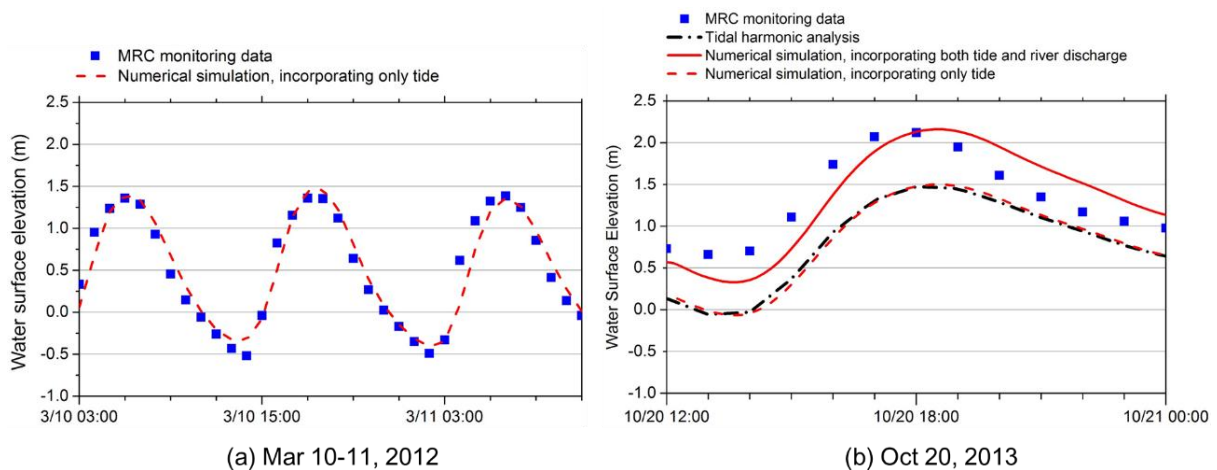


Figure 4. Comparison between the numerically simulated and measured water levels at the observatory, indicated by MRC in Figure 2, covering a typical dry period (a) and flood period (b).

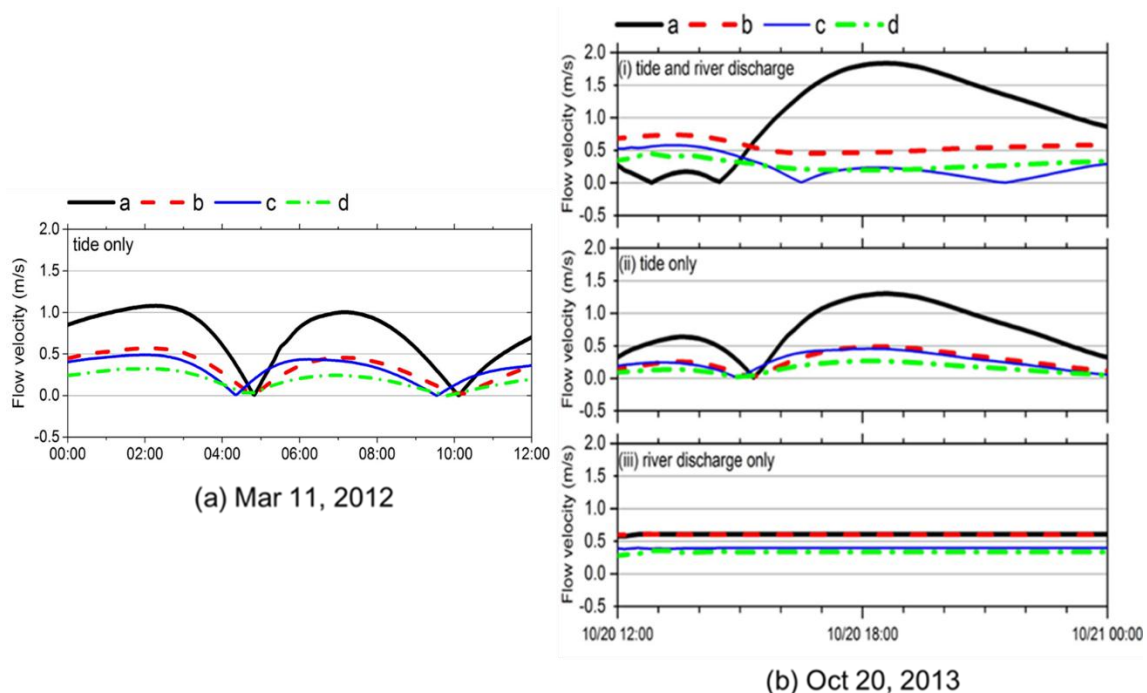


Figure 5. Simulated depth averaged velocity during a semi-diurnal cycle in a typical dry period (a) and a flood period (b). The outputs correspond to the four locations indicated in Figure 2.

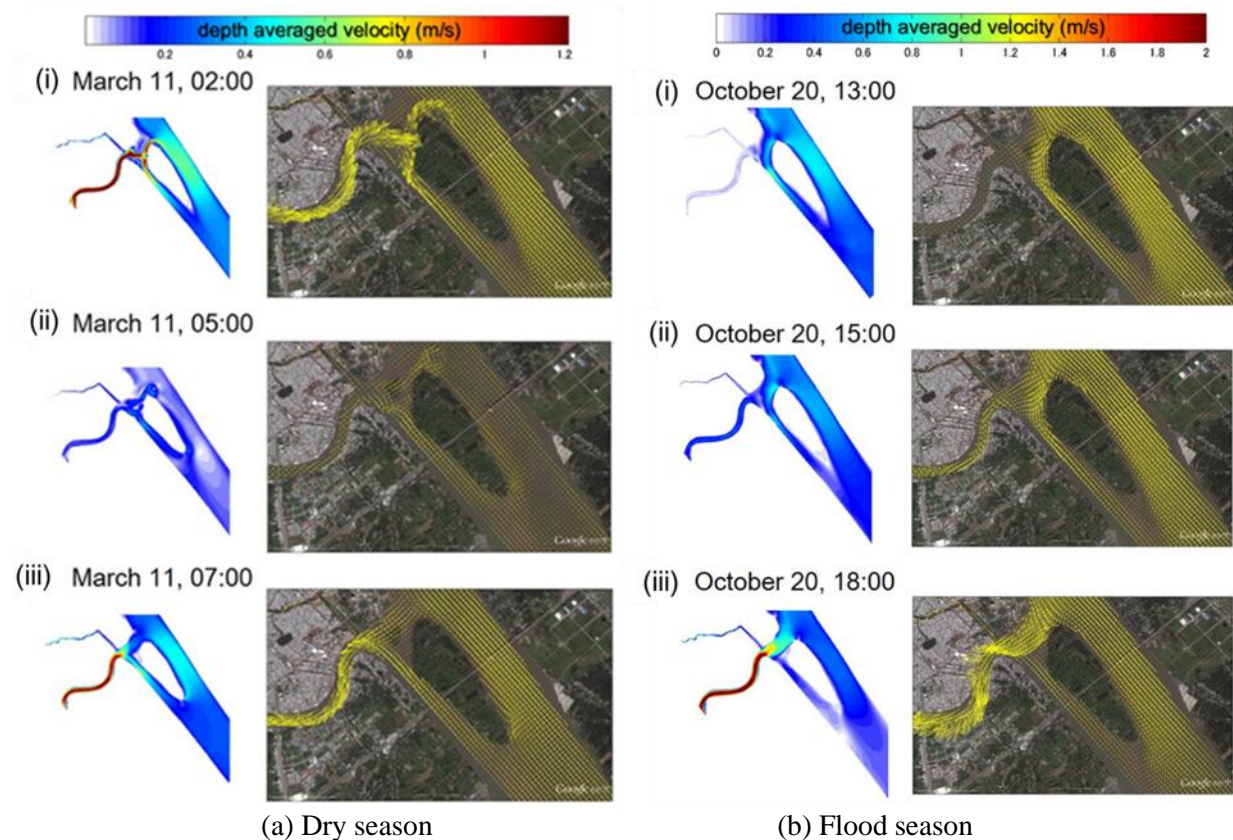


Figure 6. Tidal flow intensifications observed in the numerical simulation. (i) ebb tide phase, (ii) slack tide phase, and (iii) flood tide phase.

3.3. Flow classifications

A rule of thumb suggests that the maximum tidal velocity of the spring tide may not exceed more than 1 m/s in estuaries [18]. Indeed, this rule is also applicable to the main stream of the Mekong Delta system, as found in Figures 5. However, this study corroborates that this is the case for the main stream (point *a*), but not the case for narrower tributaries or channels which connect to a wider main stream (points *b*, *c*, *d*). This kind of complex waterway may create flow intensifications due to a contraction of the waterway, causing unusual rapid flows which sometimes exceed 1 m/s.

To sum up, Figure 7 illustrates how flow intensifications can be developed according to different seasons and different tidal phases. Flow intensification occurs along the tributary under all these conditions. As already discussed, the most intensified flow can be induced when the tidal and fluvial flows meet at the confluence of the main stream and tributary, induced by tidal blockage.

Although the phenomena found in this study may not be simply generalized, it is considered that such flow intensifications could occur at many other waterways in deltas or estuaries. Urban development increases flood risk in cities owing to local changes in the hydrological and geological conditions that increase flood hazard as well as urban concentrations that increase vulnerability e.g. [8], [19].

Furthermore, the rapid economic developments appear to have complicated the river system as a result of construction of man-made channels. It is feared that while comprehensive flood control measures will reduce flooding, the developed embankments could cause more severe riverbank erosion due to increased flow speeds in the rivers. Although the proposed model focuses on a specific area in the Mekong Delta, this methodology can also be applied to other stretches of the delta by assigning appropriate river conditions such as bathymetry, river discharge, and tidal regime.

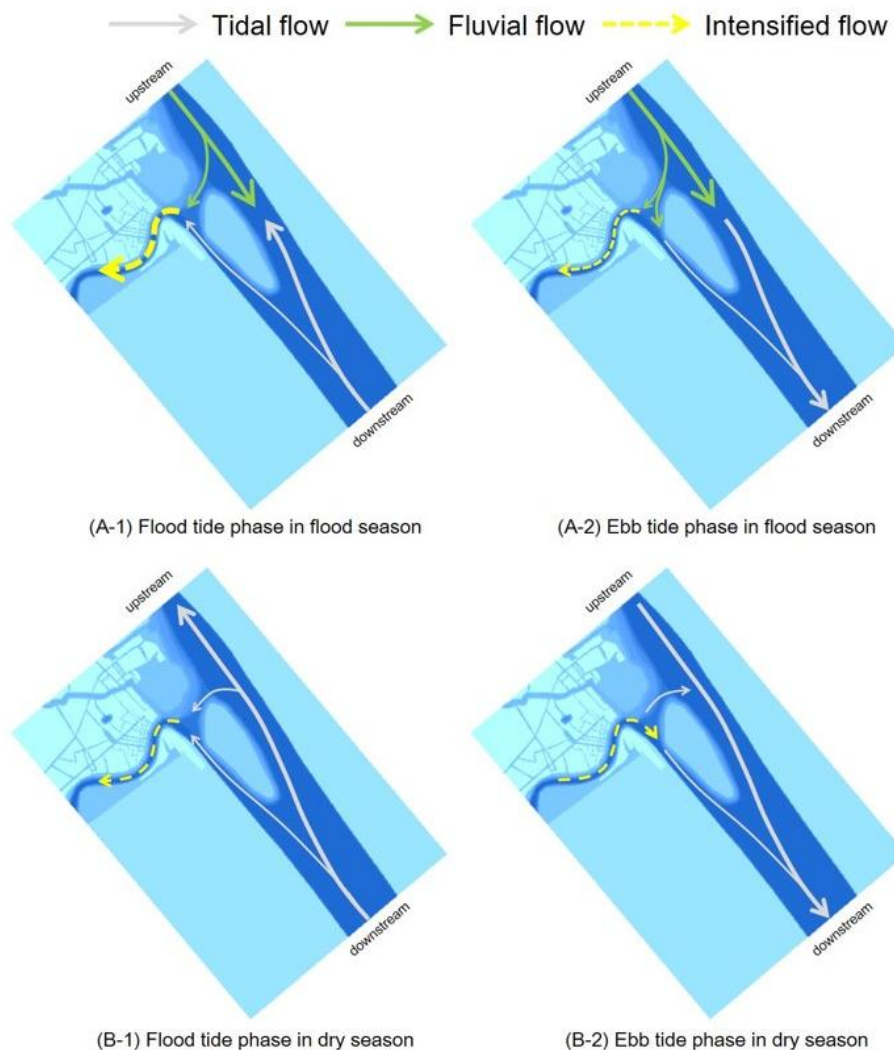


Figure 7. Classification of flow intensification induced in accordance with two seasons and two tidal phases.

4. Conclusions

The hydraulic model was used to simulate velocities in the most populated city of the Mekong Delta, Can Tho, under the combined influence of ocean tides and river discharge. The computational boundaries were differently modelled for the flood and dry seasons to identify unique flow characteristics in the two distinctive seasons. The results from the numerical simulations suggest that a very rapid flow likely occurs along the tributary in both flood and dry seasons. In particular, a unique mechanism of flow intensification, *tidal blockage*, was observed during the flood tide phase in the flood season. Tidal blockage is a phenomenon wherein the tidal current interferes with the fluvial flow at the confluence of the main stream and tributary and causes a rapid flow up to 1.8 m/s in the study river. This local intensification of the flow velocity could be an important characteristic when considering the flood risks in the urban areas of the Mekong Delta or other deltas, which could be further amplified during unusually high tides or typhoon-induced storm surges. Because a large number of local fishermen, tourist guides, and floating market merchants use small wooden ships, there is a considerable risk that they may encounter ship handling difficulties or risk being overturned owing to these unexpected unusually rapid flows. Although the present study only deals with a small area of the Mekong Delta, the proposed model is expected to be applicable to other stretches of the delta in order to identify inland waterways subjected to rapid flows caused by the tidal–fluvial flow interaction.

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