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Key Points:
- Wave strengths during both periods of high and low flows as well as sediment grain size control mouth bar formation
- Three regimes for mouth bar formation, namely, stable, ephemeral, and absent, were observed in numerical experiments
- The mouth bar formation regimes exhibit cascading effects on the evolution of deltaic distributary networks

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3

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Combined Effects of Unsteady River Discharges and Wave Conditions on River Mouth Bar Morphodynamics

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Abstract River mouth bar formation, a key process in fluvial-deltaic morphodynamics, is subject to both river discharge and waves. Given the increasing variability of both forcings under continuous climate change and human interventions, assessing their combined effects on mouth bar formation is an imperative issue. In this study, an extensive set of combined high and low river flows coupled with varying wave conditions and sediment grain sizes was assumed for numerical experiments conducted in Delft3D-SWAN. The results suggested that three regimes existed for mouth bar formation, namely, stable, ephemeral, and absent. These regimes corresponded to consistently weak, initially-weak-then-strong, and initially strong relative wave strengths, respectively, during the onset and reworking stages. Suppression of mouth bar formation further led to the inhibition of deltaic distributary networks. These findings have important implications for water and sediment management strategies, such as water diversion and dam regulation, in estuaries and deltas to prevent coastal erosion.

Plain Language Summary River discharge and waves are important forces that shape the morphology of deltas. Under continuous climate change and human interventions, both forces tend to be more variable, and predicting their combined effects on the formation of river mouth bars, a key morphological unit in a delta front, becomes important. To address this issue, we carried out extensive numerical experiments to reproduce the formation of river mouth bars under hypothetical unsteady river discharges and wave conditions and explored the inherent patterns of mouth bar formation. Based on the numerical results, we found that mouth bars may form or be suppressed from the start, and the formed mouth bar may subsequently persist or diminish as it continuously evolves, all dictated by the wave strength relative to the variable river discharge. We further showed that the different patterns of river mouth bar formation have cascading effects on the evolution of deltaic distributary networks, another prominent morphological feature of deltas. Our findings have important implications for water and sediment management strategies, such as water diversion and dam regulation, in estuaries and deltas to prevent coastal erosion.

1. Introduction

Deltas are the most populous areas in the world and are among the most productive ecosystems on the planet (Giosan et al., 2014). Understanding the deltaic morphological evolution is of crucial importance to coastal management and restoration as well as habitat protection in the face of combined natural and anthropogenic stresses (Edmonds, 2012). As a key morphological unit in the delta front, the formation of mouth bars further leads to channel bifurcation and hence the formation of new distributaries (Edmonds & Slingerland, 2007); therefore, mouth bars have been extensively studied (Fagherazzi et al., 2015; Wright, 1977).

It is well recognized that wave conditions play a vital role in the formation of mouth bars and deltaic distributary networks. In general, the effects of waves on mouth bar formation are manifested in two contrasting facets (Nardin & Fagherazzi, 2012). On the one hand, the presence of waves enhances the spreading of the river jet, resulting in sediment deposition at the river mouth that favors mouth bar formation (Nardin et al., 2013; Nardin & Fagherazzi, 2012). On the other hand, the presence of high wave energy increases the maximum bed shear stress at river mouths, which causes sediment resuspension and hence suppresses mouth bar formation (Geleynse et al., 2011; Jerolmack & Swenson, 2007; Soulsby et al., 1993).

Nardin and Fagherazzi (2012) adopted the ratio between wave- and current-induced bed shear stress to quantify the relative strength of the waves. Further assuming that waves propagate perpendicularly to the shoreline, the authors found that relatively weak waves (with an abovementioned ratio of less than 0.9) favor the formation of mouth bars, while relatively strong waves (a ratio greater than 0.9) tend to transport the sediment to the sides of the river mouth and suppress mouth bar formation.

Given the contrasting effects of waves on mouth bar formation, the cascading effects on the evolution of deltaic distributary networks are also complex. Jerolmack and Swenson (2007) showed that relatively strong waves suppress the formation of mouth bars and, thus, smaller-scale (i.e., bifurcation-induced) distributaries in natural deltas. Nardin et al. (2013) stated that the presence of relatively weak waves favors the formation of mouth bars closer to the bifurcation point, and therefore, the resultant distributaries should be shorter after several bifurcations. On a global scale, Syvitski and Saito (2007) showed that river discharge and waves exert opposing effects on deltaic distributaries. Based on their analyses of deltas worldwide, the authors found that the number of deltaic distributaries correlated positively to the maximum monthly river discharge and negatively to the maximum monthly wave height.

Notably, the existing studies on mouth bar formation, including those mentioned above, all make the assumption that most of the sediments are delivered to the ocean during periods of bank-full discharge, so is the most significant deltaic morphological evolution. Therefore, periods of relatively low flow are *safely* neglected, disregarding the effects of unsteadiness of river discharge on fluvial-deltaic morphodynamics altogether (Fagherazzi et al., 2015; Shaw & Mohrig, 2014). However, the neglect of the period of low flow and the unsteadiness of the river discharge altogether is worth reviewing in the context of combined fluvial and marine forcing, as relative wave strength has been repeatedly considered a critical parameter in fluvial-deltaic morphodynamics (Anthony, 2015; Chatanantavet et al., 2012; Geleynse et al., 2011; Nardin & Fagherazzi, 2012; Swenson et al., 2005), dating back to Galloway's (1975) classic tripartite delta classifications. Evidence from field studies also suggested that mouth bars tended to form during periods of high flow when river discharge was dominant, and yet waves could prevail and destroy the formed mouth bar during periods of low flow (Cooper, 1990; Giosan et al., 2005; Maillet et al., 2006; Rodriguez et al., 2000). When waves were sheltered, the mouth bar could persist and keep evolving throughout periods of high and low flows (Esposito et al., 2013). Moreover, alternate hydrodynamic behaviors of river flow associated with varying jet stability have been found for different flow regimes, which in turn affect mouth bar evolution (Canestrelli et al., 2014; Esposito et al., 2013). In natural deltas, the period of high river discharge may or may not coincide with the occurrence of maximum wave strength, which further complicates their combined effects (Anthony, 2015; Wright & Coleman, 1973).

As a first step toward assessing the complex combined effects of unsteady river discharges and wave conditions on river mouth bar morphodynamics, numerical experiments were carried out in this study with an extensive set of combined high and low river discharges associated with varying wave conditions. Additional scenarios were simulated to explore the effects of various sediment grain sizes on river mouth bar morphodynamics. Our study focuses on addressing the following: (1) the initial formation and reworking of mouth bars under unsteady river discharges and wave conditions; (2) the ways in which the combined forcing dictates the regime of river mouth bar formation; and (3) the implications of the combined effects on deltaic distributaries.

2. Methodology

2.1. Model Setting

In this study, we adopted schematized numerical experiments with idealized geometry and modeling parameters assuming generic values as the main methodology. Delft3D, which is a process-based numerical model that solves hydrodynamics including waves, sediment transport, and morphodynamics in a coupled fashion (Booij et al., 1999; Lesser et al., 2004), was used as the modeling tool. The model adopted in this study is a 2-D depth-averaged model. The computational domain (7,500 × 3,750 m) is rectangular, and the grid size is 25 × 25 m (see Figure 1a). The *x* and *y* directions are parallel and perpendicular to the shoreline, respectively, with the origin of the coordinates located at the center of the mouth where the channel meets the basin. The cross section of the initial river channel is rectangular and measures 250 m in width and 2.5 m in depth.

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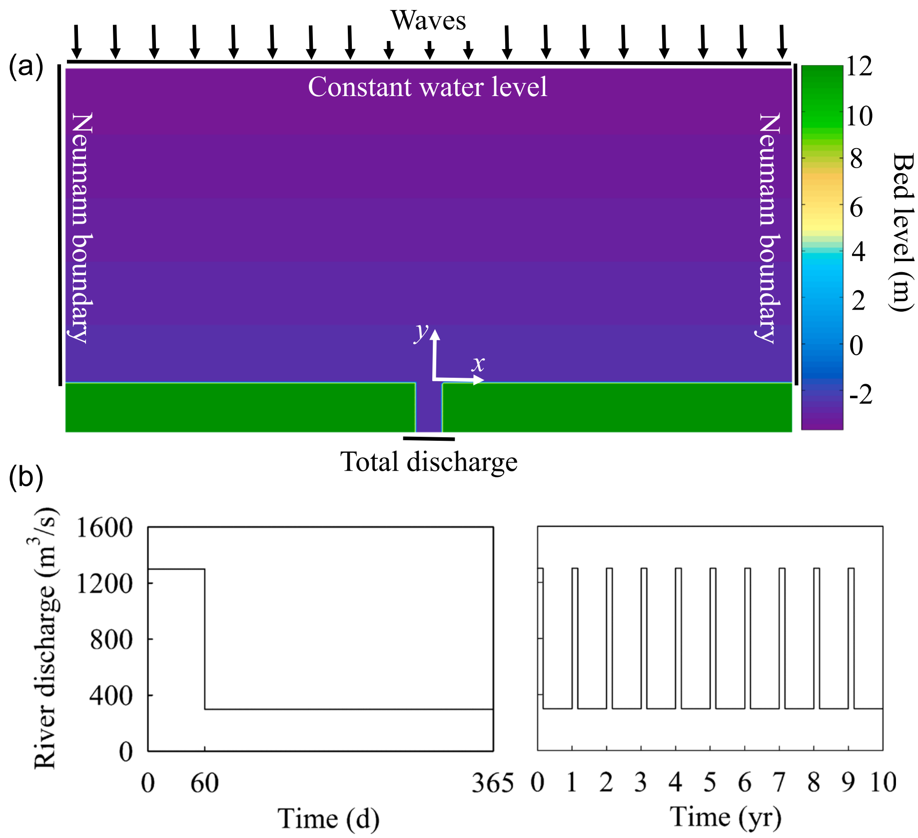

Figure 1. (a) Configurations of the computational domain and boundaries. (b) Hypothetical unsteady river discharges at the upstream river boundary.

Constant water level boundary conditions and wave conditions were prescribed at the offshore boundary, and zero-gradient water level conditions were imposed at two lateral boundaries. Total discharge with a combination of high and low flows (Figure 1b) was imposed at the upstream river boundary, along with noncohesive suspended sediment with uniform grain sizes (D_{50}) of 100, 150, and 200 μm and a density of 2,650 kg/m^3. A baseline sediment concentration at the upstream river boundary was set at 0.1 kg/m^3 (Caldwell & Edmonds, 2014) during periods of high flow for a sediment grain size of 200 μm, and that for the other sediment grain sizes was set in proportion to $1/D_{50}$. The sediment concentrations during periods of low flow were set at 1/10 of those during periods of high flow. The sediment transport formula of van Rijn (1993) was adopted in this study. The morphological scale factors were set to 20 and 100 during periods of high and low flows, respectively. These factors were determined by a series of sensitivity tests in which the maximum values that ensured sufficient computational accuracy were selected. Other modeling parameters are summarized in Table S1 in the supporting information.

2.2. Scenarios for Mouth Bar Formation

A stepped hydrograph that combines high and low river discharges (left panel of Figure 1b) to mimic the variability of natural river flow regimes was adopted in this study. The high and low river discharges were set to 1,300 and 300 m^3/s, respectively, which consistently corresponded to stable jet conditions (Canestrelli et al., 2014). We first ran the model with high flow for 60 days, which acted as the onset stage of the mouth bar. The bathymetry at the end of the periods of high flow was used as the initial bed level for modeling the subsequent periods of low flow. The simulation periods were set to 305 days for the reworking stage. Following Edmonds and Slingerland (2007), we recognized the formation of mouth bars if the bed elevation reached 60% of the initial local water depth above which the flow tends to bifurcate. Representative wave conditions following those adopted in Nardin and Fagherazzi (2012) were imposed during periods of high and low flows, resulting in different combinations of relative wave strengths.

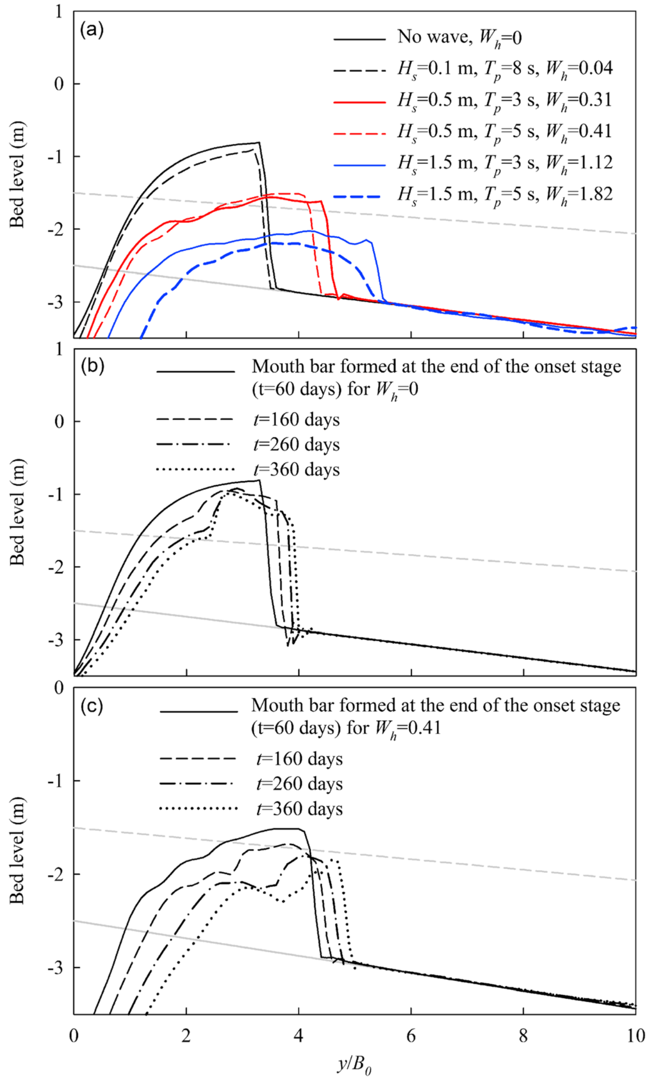

Figure 2. (a) Longitudinal cross-sectional profiles along the centerline of the river mouth at the end of the onset stage for some representative scenarios; longitudinal cross-sectional profiles along the centerline of the river mouth during the reworking stage for scenarios where (b) H_s = 0.5 m and T_p = 3 s and (c) H_s = 1.2 m and T_p = 3 s. The gray solid and dashed lines mark the initial bed level and 60% of the initial local water depth. B_0 is the width of the initial river channel.

Significant wave height and peak period range from 0 to 1.8 m and 0 to 8 s, respectively. To avoid undesired bed distortion induced by the augmented relative wave strength near the boundary due to reduced river discharge, the wave period was fixed at 3 s during periods of low flow. The calculation of relative wave strength following Nardin and Fagherazzi (2012; see also Fredsøe, 1984; Swart, 1974) is documented in the supporting information, which is defined as the ratio between wave-induced bed shear stress at the offshore boundary and bed shear stress induced by current at the river mouth. As such, wave-induced bed shear stress is calculated at the offshore boundary, resulting in a domain-dependent value. Relative wave strengths during periods of high and low flows are denoted as W_h and W_l, respectively, in this study.

2.3. Scenarios for Deltaic Distributary Evolution

Ten water years with recurrent annual flood pulses (the right panel of Figure 1b) were also simulated to explore the effects of unsteady river discharges and wave conditions on the evolution of deltaic distributary networks (termed *large-scale simulations* hereinafter). The duration of high flow is 60 days. The transition between low and high discharges is linear within 2.5 morphological days, allowing the adjustment of hydrodynamics during the periods of transition and minimizing the sediment mass imbalance caused by the transition. Scenarios assuming constant bank-full discharge were also run for comparison with the unsteady discharge scenarios. The constant bank-full discharge assumed high flow in the unsteady discharge scenarios, that is, 1,300 m^3/s. Significant wave height for the large-scale simulations ranged from 0 to 1 m, and wave period was fixed at 3 s. Distributary networks were extracted following the procedures described in Tejedor et al. (2016). The average number of deltaic distributaries were further calculated from the results of the distributary networks. The details for the extraction of the distributary network and the calculation of the average number of distributaries are documented in the supporting information.

3. Evolution of Mouth Bars

The simulation results of bed level for all simulation scenarios are shown in Figure S1. The effects of waves on the evolution of mouth bars were examined at the end of both the onset and reworking stages. As shown in Figure 2a, mouth bars form at the end of the onset stage with relatively small W_h. With increasing W_h, the bed elevation decreases due to the dispersion of sediment from the river mouth (Nienhuis et al., 2015; Swenson et al., 2005) and gradually falls short of the threshold, leading to the suppression of mouth bar formation (Geleynse et al., 2011; Jerolmack & Swenson, 2007). The mouth bars that formed during the onset stage are subject to reworking by waves during the ensuing period of low flow (reworking stage), which again drives the evolution in two opposite directions. The initially formed mouth bar can persist when waves are relatively weak during the reworking stage (Figure 2b) or diminish below the 60% threshold with relatively high W_l (Figure 2c).

Based on the simulation results of the evolution of mouth bars during the onset and the following reworking stages presented above, the process of the mouth bar formation subject to the combined forcing of unsteady river discharges and waves can be summarized by three different regimes (Figure 3a) as follows:

R1. Formation of stable mouth bar. For regime R1, wave strength remains weak relative to river discharge throughout the entire hydrologic period. Therefore, a mouth bar that formed during the onset stage persists during the subsequent reworking stage.

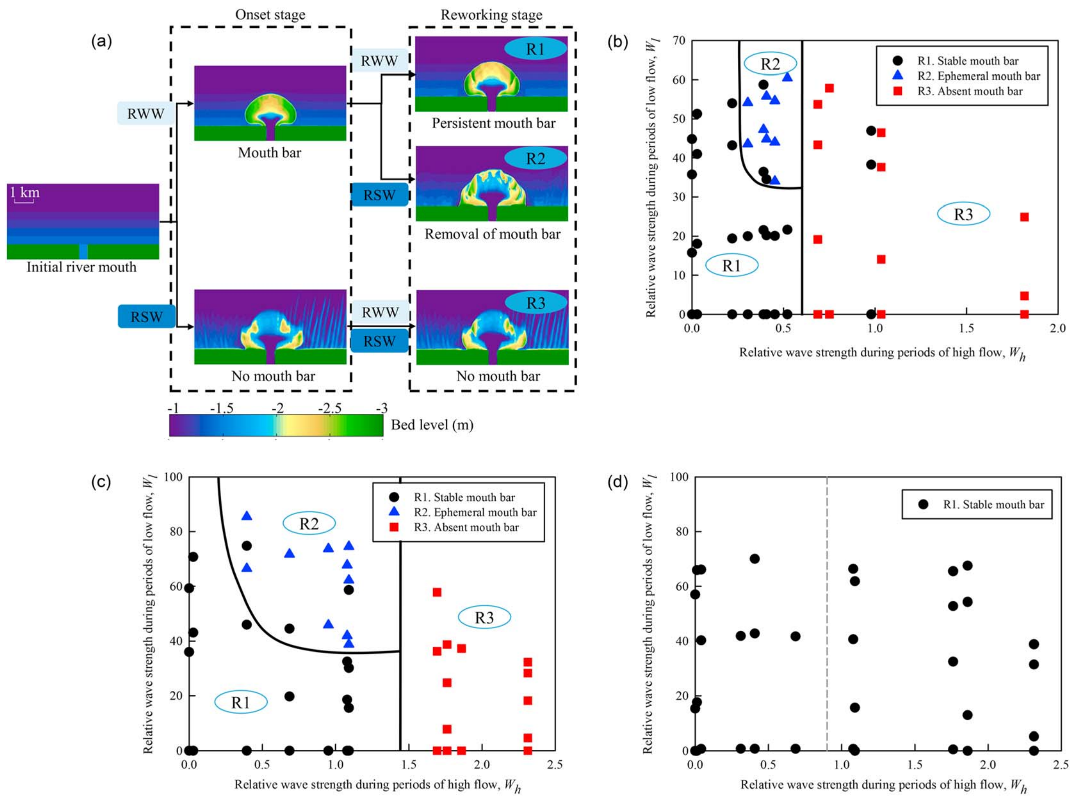

Figure 3. (a) Schematic of the three regimes for mouth bar formation subject to the combined forcing of unsteady river discharges and waves. RWW and RSW are abbreviations for relatively weak and strong waves, respectively. The distribution of the regimes for mouth bar formation as a function of the relative wave strengths during periods of high and low flows for sediment grain sizes (D_{50}) of (b) 100, (c) 150, and (d) 200 μm. The gray dashed line represents the boundary between mouth bar formation and wave-dominated regimes in Nardin and Fagherazzi (2012) assuming bank-full discharge and a sediment grain size of 200 μm.

R2. Development of ephemeral mouth bar. For regime R2, high river discharge is coupled with relatively weak waves during the onset stage, leading to the initial formation of the mouth bar. During the subsequent reworking stage, waves transform the mouth bar significantly as the relative wave strength becomes much greater.

R3. Absence of mouth bar. For regime R3, waves are relatively strong despite the high river discharge during the onset stage, and the mouth bar fails to form from the start.

The distribution of the regimes for mouth bar formation was further plotted in Figures 3b–3d, which suggests the existence of a threshold of W_h above which the mouth bar tends to be suppressed from the start (regime R3). The threshold of W_h lies within the ranges of 0.5–0.7 (Figure 3b) and 1.1–1.7 (Figure 3c) for scenarios assuming D_{50} = 100 and 150 μm, respectively. In particular, only regime R1 was recognized for the scenarios covered in this study with D_{50} = 200 μm (Figure 3d). However, when we extended the simulation period of the reworking stage to 350 days, both regimes R1 and R2 were recognized, which suggests that a longer reworking period is required to remove the initially formed mouth bar with increasing sediment grain size.

The existence of a threshold of W_h for initial mouth bar formation is consistent with the numerical simulation results of Nardin and Fagherazzi (2012), which assumed D_{50} = 200 μm and constant bank-full river discharge, and showed that the central bar formed when relative wave strength was below ~0.9. The threshold of W_h is presumably greater than 2.3 for scenarios assuming D_{50} = 200 μm in this study (Figure 3d), and the disparity can be attributed to the larger computational domain adopted here to simulate the evolution of deltaic distributary networks compared with that in Nardin and Fagherazzi (2012) with a primary focus of mouth bar formation, that is, 7,500 × 3,750 m versus 900 × 2,160 m, respectively. Wave energy dissipates when propagating from the boundary toward the river mouth, which results in a larger threshold of W_h in this study. Further checking the relative wave strength using the wave-induced bed shear stress at 2,000 m

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away from the river mouth for scenarios assuming D_{50} = 200 μm showed that the threshold decreased to 1.3, which is closer to that reported by Nardin and Fagherazzi (2012). Moreover, the trend of the increase in the threshold of W_h and thus the rightward movement of the left boundary of regime R3 with increasing sediment grain size (Figures 3b–3d) presumably occur because greater wave-induced shear stress is required to prevent coarser sediments from being deposited on the bed and forming a mouth bar (van Rijn, 1993).

During the periods of low flow, further development of the initially formed mouth bar when W_h is below the threshold is subject to reworking by waves. Mouth bars tend to persist when W_l is relatively weak (regime R1) and can otherwise be removed when W_l is relatively strong (regime R2). The boundaries between the two regimes are delineated in Figures 3b and 3c as well. Notably, our results suggest that the threshold of W_l between regime R1 and R2 is correlated with the respective W_h. A larger W_h tends to render a smaller threshold of W_l, resulting in boundaries with steep decreasing slopes. Presumably, lower wave energy is required to remove the slender mouth bar formed in stronger waves during the onset stage and vice versa (Figure 2a). In addition, similar to the effect of sediment grain size on the boundary between regime R1/R2 and R3, as D_{50} increases, the boundary between regime R1 and R2 tends to move upward and rightward, as shown in Figures 3b and 3c.

4. Comparison to Natural River Mouth Bar Formation

The regimes for mouth bar formation proposed in this study can be recognized in principle in natural river mouths. For sheltered river mouths with limited wave intervention, the mouth bar keeps aggrading and persists during periods of low flow, which is exemplified by the evolution of a mouth bar in a crevasse splay in the Mississippi River Delta reported in Esposito et al. (2013), following the pattern of regime R1. In wave-dominated coasts, such as the Natal coast of Southeast Africa (Cooper, 1990) and the modern Brazos Delta in Texas (Rodriguez et al., 2000), river mouth bars formed during river floods could be ultimately removed by waves, largely following a cycle of formation, temporal morphological changes, and ultimate destruction consistent with regime R2. At the same time, the Nile River Delta, which has very strong wave energy, demonstrates how waves entirely inhibit mouth bar formation and suppress bifurcation-induced distributaries (Jerolmack & Swenson, 2007), that is, regime R3.

5. Implications for Deltaic Distributary Networks

For unsteady discharge scenarios (Figures 4a and 4c), fewer distributaries form when waves are imposed. The number of distributaries decreases with increasing wave strength until the significant wave height reaches 0.2 m, after which the number of distributaries levels off. For constant bank-full discharge scenarios (Figures 4b and 4d), the correlations between number of distributaries and significant wave height exhibit some nonlinearity. The number of distributaries could increase slightly with relatively weak wave strength (significant wave height ≤ 0.2 m) compared with a situation with no waves (Figure 4b). However, the number of distributaries is considerably reduced with higher wave strength compared with a situation with no waves.

This disparity can be related to the contrasting mouth bar formation regimes. For unsteady discharge scenarios, the relative wave strength is weak during periods of high flow and becomes stronger during periods of low flow, and the formation of mouth bars tends to follow regime R2. As such, mouth bars and bifurcations formed during periods of high flow can be removed by the reworking of waves during periods of low flow, resulting in fewer distributaries (Geleynse et al., 2011; Jerolmack & Swenson, 2007). With increasing significant wave height and, hence, relative wave strength, the number of distributaries decreases as the reworking ability of waves increases. On the other hand, for constant bank-full discharge scenarios, waves coincide with high river discharge, and when wave strength is weak, the relative wave strength remains weak throughout the simulation period, and the evolution of mouth bars tends to follow regime R1. Therefore, mouth bars persist throughout the simulation, and the position of the mouth bar moves toward the river mouth (Nardin et al., 2013), such that more distributaries tend to form given the same amount of sediment input (Figure 4b). With further increasing wave strength, the suppression of mouth bar formation by waves (Jerolmack & Swenson, 2007) could be dominant, leading to a decreasing number of distributaries with increasing wave strength.

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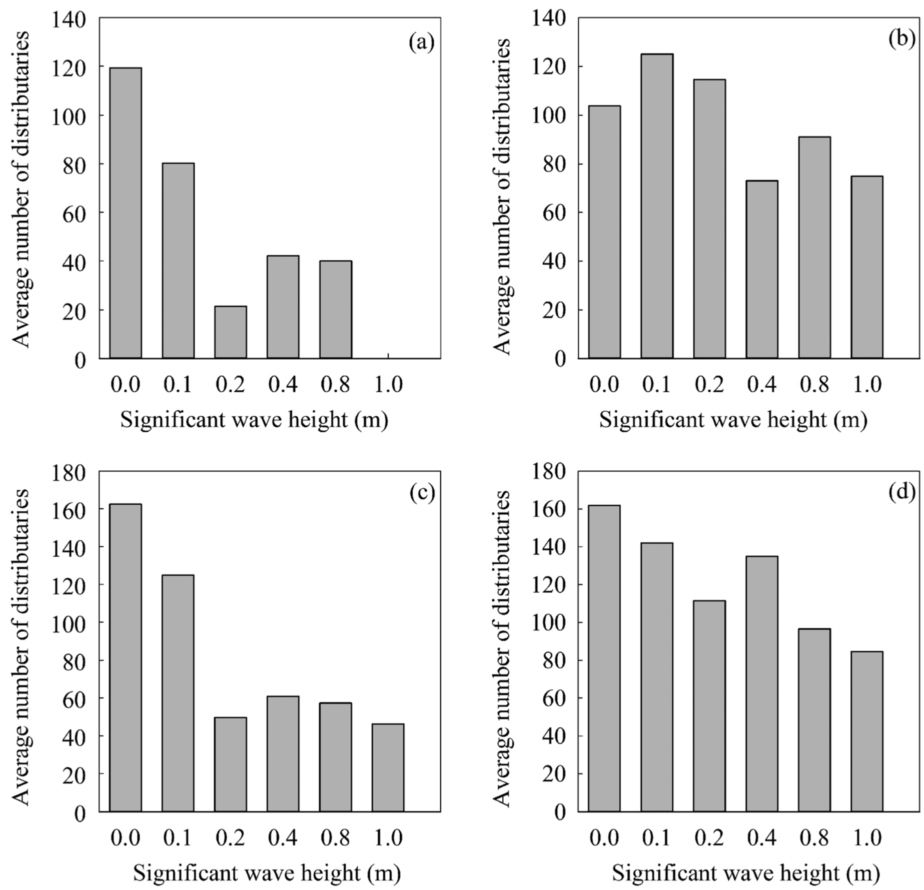

Figure 4. Average number of distributaries for different large-scale simulation scenarios: (a) and (b) D_{50} = 150 μm, and (c) and (d) D_{50} = 200 μm. The left and right panels are scenarios with unsteady and constant bank-full discharges, respectively.

6. Discussion and Conclusion

In this study, three regimes for mouth bar formation, namely, the formation of a stable mouth bar (R1), development of an ephemeral mouth bar (R2), and absence of a mouth bar (R3), were determined from the numerical simulation results. Our results further showed that the suppression of river mouth bars could be due to the following reasons: (1) the relative wave strength during periods of high flow is above the threshold of W_h, and therefore, the mouth bar fails to form from the beginning, or (2) the mouth bar is removed during periods of low flow with excessive relative wave strength. On the other hand, the formation of a mouth bar requires consistently low relative wave strengths during periods of high and low flows. The results of scenarios with varying sediment grain size also confirm its effects in shifting the boundaries between different regimes. Regarding the cascading effects of mouth bar formation on the evolution of deltaic distributary networks, while regimes R2 and R3 can result in the suppression of a mouth bar and, hence, distributaries in the delta, regime R1 can cause the opposite effect.

In essence, our results provide extensive numerical evidence indicating that the whole spectrum of relative wave strength over the entire hydrologic period should be considered when studying the morphodynamics of a river mouth, a point repeatedly mentioned in previous studies (Anthony, 2015; Fagherazzi et al., 2015; Nienhuis et al., 2016; Swenson et al., 2005; Wright & Coleman, 1973). This point is compounded by the fact that the mouth bar formation of many rivers around the world may undergo potential regime shifts under altered hydrographs and wave conditions induced by climate change and human intervention. For instance, with increasing dam regulations, many rivers have been subjected to reducing flooding and peak discharges (Milliman et al., 2008; Nilsson et al., 2005). As a consequence, the initial formation of a mouth bar during periods of high flow could be suppressed, leading to potential regime shifts from regime R1 to regimes R2/R3 or from regime R2 to regime R3.

In conclusion, numerical experiments using Delft3D-SWAN were conducted in this study to assess the combined effects of unsteady river discharges and wave conditions on mouth bar formation. The mouth bar formation regimes proposed in this study provide the first quantitative reference for this issue and have important implications for water and sediment management strategies for estuaries and deltas to prevent coastal erosion.

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