Original Paper

Numerical forward Modelling of River-dominated Deltas

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Abstract

A delta is a type of sedimentary system that is closely related to oil and gas. Shallow-lake delta deposits in the Mesozoic-Cenozoic strata of China are of particular interest. This delta has significant oil and gas reserves that are developed widely. Based on a numerical simulation of the sand body of the shallow-lake delta, this study analyzes the influence of various sediment conditions on the sand-body development. The formation and distribution rules of the sand body are concluded and verified, and the results can effectively guide the exploration and development of oil and gas resources. Unlike traditional flume experiments, this study adopts sediment numerical simulation technology. This approach is borrowed from the advanced achievements of computational fluid dynamics, and Delft3D is used to establish a three-dimensional numerical model of the delta. The calculation field was 20.5 km in length by 10 km in width. With the Mor-Factor set to 60, the simulation time was 45 days. The formation and the avulsion of the mouth bar, as well as the extension, migration and bifurcation of distributary channels, have been observed and studied through analysis of the simulation results. The vertical cross-section shows that the distributary channel was filled multiple times. According to distributary channel evolution characteristics combined with quantitative methods, the terminal distributary channels can be extremely developed under ideal conditions. Due to the cross-cutting and reform effort of distributary channels, sediments were spread widely and continuously. The results show that the numerical model works well in explaining the process of evolution in fluvial-dominated delta distributary channels. This study not only enables us to quantitatively understand the dynamic processes of terminal distributary channels in fluvial-dominated delta systems, but also provides a reference model for numerical simulation of hydrodynamics in sedimentology study.

Keywords

quantitative sedimentology, numerical simulation of sediment, fluvial-dominated delta, distributary channels

1. Introduction

Currently, river-dominated deltas have attracted extensive attention mainly owing to their significance to oil and gas exploration. As described in modern sedimentology, the morphology and distribution of deltas are primarily subject to the control of hydrodynamic force. According to the controlling effects of rivers, waves and tides on the formation of deltas, the modern deltas can be classified based on three-terminal element, which is a classical classification scheme on deltas in sedimentology (Galloway, 1975). In subsequent studies, the particle size distribution of sediments was taken into account in the classification framework based on three-terminal element. Accordingly, the classification methods for deltas were enriched (Orton & Reading, 1993). The numerical geomorphic model based on physical processes is proved to be feasible in the studies on the formation of river-dominated deltas (Geleynse et al., 2010). Moreover, the effects of the flocculation of sediments on the morphology of river-dominated deltas were revealed (Edmonds & Slingerland, 2009). The sedimentary response can be fully investigated only when the source system is known. The controlling effects exerted by source system on sedimentary response have been demonstrated by a large number of delta classification schemes (Nemec, 2009). Previous studies imply that, in numerical simulations on three-dimensional hydrodynamic force, the hydrodynamic conditions in the upper reaches determine the planar distribution of deltas, while the hydrodynamic conditions in the lower reaches dominate the migration of river dikes and distributary channels (Geleynse et al., 2010). Additionally, the total number of distributary channels depends on the variations of discharge (Edmonds et al., 2010; Geleynse et al., 2011). The numerical simulations considering the hydrodynamic force are widely applied in geological investigation of deltas (Flores, 2011; Hanegan, 2011; Koolen, n.d.).

River-dominated deltas are formed under the following conditions: the sediments flowing into the river are large in quantity, the wave and tidal actions are weak and the constructive effects of river far exceed the destructive effects of wave and tides. According to the traditional viewpoints, the morphology of river-dominated deltas can be further divided into two types, namely, bird-foot deltas and lobate deltas (Zhu, 2008). The bird-foot deltas are the typical high-constructive deltas, with developed natural levees and fixed distributary channels. Comparatively, the lobate deltas are semi-circles or lobes protruding towards the sea. In the lobate deltas, the finger-shaped sand bodies whose leading edges reach towards the sea form the sheet-like sand layer as they are gradually washed away by the sea (Zhu, 2008). The river activities at each stage can give rise to continuous bifurcation in the estuary, leading to complex distributary systems (Busch, 1971). The researchers have conducted many studies on the relationship between estuary sandbars and distributary channels (Olariu & Bhattacharya, 2006). By means of numerical simulations on hydrodynamic force, the distribution characteristics of the distributary channels in the delta were investigated in depth in the present work. The relevant findings can provide guidance for oil and gas explorations.

2. Hydrodynamic Properties of the Estuary

The formation of distributary sandbars and the development and evolution of distributary channels are two distinct features related to estuary sediments. According to the traditional view, in the estuary where the river flows into the sea (or the lake), the flow velocity decreases dramatically due to the broadened flow and uplifting effects of tides. The bottom load of the river sinks and accumulates, forming the underwater shoal. Finally, after being aggraded and enlarged, the shoal rises above the water and form a crescent-shaped estuary sandbar (He & Wang, 2007), i.e., the blocking sandbar.

After flowing into the sea (or the lake), the river exhibits significant variations in hydrodynamic properties compared with that on the land. On the land, the driving force generated by gravity, the frictional resistance at the bottom of estuary and the air resistance in river-air interface all produce an impact on the river. The driving force generated by gravity and the frictional resistance induced by topographic slope play the decisive roles. After flowing into the sea (or the lake), the static water appears at the front of the river, which acts as a resistance on the river flow. Due to the obstruction by the impounding water of sea (lake), there are three mixed flowing modes according to the difference of density between river water and sea (or lake) water, namely, the bottom density current in high-density river, the upper flowing current in low-density river and the rapid mixed current in the river with a similar density. The propulsion performances and the patterns of the river flowing into the sea (or the lake) are significantly different in these three modes (Bates, 1953). Nevertheless, in all these three modes, the sea (or the lake), as the stable water, imposes a strong blocking effect on the river. As a result, both the flow velocity and the sediment carrying capacity decrease rapidly. Accordingly, a large amount of sediments accumulate in the estuary, forming sedimentary bodies in the estuary (Zhang et al., 2010).

As the delta moves gradually towards the center of the basin, the distributary channels bifurcate continuously. The further the river extends towards the basin, the narrower the river becomes and the greater the amount of the distributary channels will be. On the whole, delta forms a triangular network. Moreover, the upper and lower rivers are interconnected with each other. The underwater distributary channels and estuary sandbars are the most active sedimentary bodies in the delta. The underwater distributary channels are the extension of the distributary channels under the water. With the gradual progradation of the delta, these underwater distributary channels evolve into distributary channels (Duan et al., 2014). In the same delta system, the scale of the distributary channels varies greatly. However, the variations of distributary channels of different scales are continuous and exhibit temporal connections. Based on the scale, the distributary channels can be classified into the following three levels (Olariu & Bhattacharya, 2006):

2.1 Main Distributary Channel

The main distributary channel is formed at an earlier time, and its size is the largest in the river network of the delta. Generally, it is already formed at the initial stage of the delta and extends gradually towards the basin with the progradation of the delta. The main distributary channel can be regarded as

the skeleton of the delta.

2.2 Distributary Channel in the Middle

The size of distributary channels in the middle is lower than that of the main distributary channel but higher than the distributary channels at the tail end. In some modern deltas, as the river extends towards the basin, the flow velocity decreases further, while the main distributary channel is divided into several distributary channels in the middle, whose size is smaller. In some large-scale delta systems, the distributary channels in the middle converge again, forming the sedimentary structures similar to braided streams or anastomosed streams. The distribution of these distributary channels in the middle determines the morphology of the delta. For example, in the bird-foot delta (the Zhangtian River Delta, as shown in Figure 1), the main distributary channel moves toward the sea (or the lake) rapidly, with a long extension distance. The distributary channels and the finger-shaped sand bodies vary greatly in distance and resemble the bird's claw, which can be considered as due to the absence of the distributary channels in the middle.

2.3 Distributary Channels at the Tail End

The distributary channels at the tail end are the rivers at the ends of the whole delta distributary system. Starting from the distributary channels in the middle, the distributary channels at the tail end extend towards the front edge of the delta. The flow velocity is generally low in the distributary channels in the middle.

Figure 1. Zhangtian River Delta, from Google Earth

3. Model Configuration

3.1 Grid Generation and the Initial Bottom Configurations

During the simulations, the grid quality directly affects the convergence performance and accuracy (Deltares, Delft3D-FLOW User Manual, in Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments, 2013).

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In the present simulations, the model size was determined abstractly based on the scale of the actual estuary in natural world. Specifically, the river was rectangular, whose length, width and depth were 5 km, 500 m and 3 m, respectively. Considering the discharge, sediment quantity and the distribution range of the deltas composed of the distributary channels, a wedge-type water channel was designed, with the storage capacity and slope of 20.5 * 10 km and 0.01 deg, respectively. As shown in Figure 2, the water channel presents a flat bottom and tilts towards the basin. The computational grids were generated using the RGFGRID module of Dleft3D software. According to the aforementioned geometric requirements, the river and the lake basin regions were divided into 100*10 and 200*410 grids, respectively, with the total number of grids of 83000. In ξ and η, the grid scale was 50 m. The underwater topography required in the calculations was simulated under QUICKIN module of Delft3D. The depths of water at certain points in manually configured model were first used, while the interpolation was performed on the underwater topography at each grid using triangular interpolation.
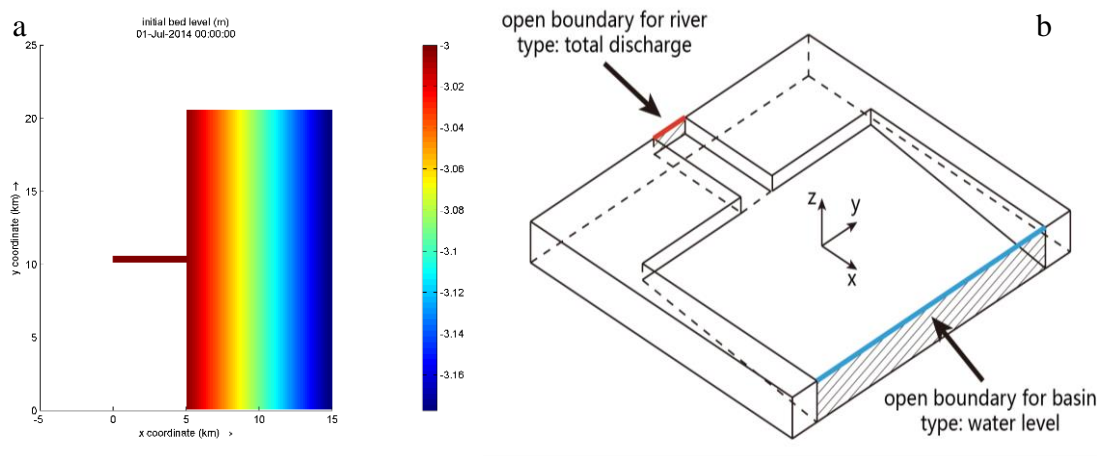

Figure 2. a. Initial Bed Level in Plane Graph; b. the Three-dimensional Figure. Stream Channel 5 km in Length, 500 m in Width and 3 m in Depth, Maximum Depth is 3.18 m, Average Slope is about 0.01 Degree

3.2 Boundary Conditions of the Model and Configuration of Other Parameters

In hydrodynamic models, the most important parameter is the boundary conditions, which can be simply interpreted as the driving force in the models.

In the present work, we focus on the river-dominated deltas. With regard to the geological agents, the effects of the rivers occupy a large proportion, while the wave and tides impose weaker effects. Therefore, aiming to explore the role of rivers in the evolution of deltas, the model was configured as the shallow river-dominated deltas without tectonic subsidence and wave and tidal effects. In the models, no wave and tidal fields were configured, and only the boundary conditions were configured, with the location shown in Figure 2b. In the regions near the river, the total discharge was used as the boundary conditions (marked by blue line), while in the regions near the impounding basin, the water

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level was used for the boundary conditions (marked by red line).

To further investigate the development and distribution characteristics of the distributary channels of river-dominated deltas, two scenarios, Scenario 1 and Scenario 2, were adopted. Except discharge, the other parameters in these two scenarios were identical. In Scenario 1, the flow was set as slowly increasing in order to simulate the flood season of natural river; while in Scenario 2, the flow was set to be constant. With reference to 2011 Bulletin of Sediments of China's Rivers, published by the Ministry of Water Resources of the People's Republic of China, the discharge and sediment yields of the model were configured by making an analogy with the annual runoff volume and annual sediment yields of the Yangtze River. Moreover, the measured data at Gaochang Hydrometric station along the Min River, one of the main tributaries of the Yangtze River, were taken into account (Ministry of Water Resources of the People's Republic of China, (2011). The discharge in Scenario 1 increased gradually within the range from 1200 m^3/s to 2200 m^3/s, while the discharge in Scenario 2 was set to be a fixed value, 2000 m^3/s. With respect to the sediments, the parameter configurations were identical. The compositions of the sediments were classified into three types, i.e., sand-basin, sand-river and mud-river. To be specific, these three sediment compositions represent the sands at the bottom of basin, the sands carried by the river and the mud carried by the river, respectively. The sand content and mud content in the river were set to be identical. Both values increased with the increasing discharge within the range from 0.05 kg/m^3 to 0.15 kg/m^3. These results agree well with the tendency that the sediment quantity increases with the discharge in the flood season (Ministry of Water Resources of the People's Republic of China, 2011).

The parameters were configured in accordance with the actual conditions in the estuary and the requirements of the calculations. Specifically, the roughness coefficient was 0.03; the computation time was set as one and a half month; the mor-factor and time step were set as 60 and 1 min, respectively. The details of parameter configuration are listed in Table 1.

Table 1. Summary of Model Parameters

Parameters	Symbol	Scenario 1	Scenario 2
Simulation time		45 Day	45 Day
Time Step	Dt	1 min	1 min
Morphological scale factor	Morfac	60	60
Flow grid resolution	-	50m×50m	50m×50m
Flow grid size	-	302×412	302×412
Sediment Characteristics			
Spin-up interval time before morphological changes	MorStt	720min	720min
Sediment fractions		3	3
Specific density (all fractions)	ρ	2650kg/m^3	2650kg/m^3

Type of sediment (Fraction 1) - coarse sand, Basin	Basin-sand	Non-cohesive	Non-cohesive
Median grain size (Fraction 1)	D50	350μm	350μm
Dry bed density (Fraction 1)	ρ	1600kg/m^3	1600kg/m^3
Type of sediment (Fraction 2) - Fine sand, River	River-sand	Non-cohesive	Non-cohesive
Median grain size (Fraction 2)	D50	135μm	135μm
Dry bed density (Fraction 2)	ρ	1600kg/m^3	1600kg/m^3
Type of sediment (Fraction 3) - Mud, River	River-mud	Cohesive	Cohesive
Dry bed density (Fraction 3)	ρ	500kg/m^3	500kg/m^3
Settling velocity (Fraction 3)		1.5mm/s	1.5mm/s
River Forcing			
River length		5km	5km
River width		500m	500m
River depth		3m	3m

4. Calculation Results of the Models

With the calculation results, the dynamic evolution process of two river-dominated deltas and the variation tendency of various sedimentary elements over time is revealed. Figure 3 presents the typical time slices during the evolution of the model, which briefly demonstrate the construction processes of the two deltas. S1a-d in the first row presents the morphology of the delta in Scenario 1 (in which the total discharge varied), while S2a-d in the second row presents the morphology of the delta in Scenario 2 (in which the total discharge was fixed). By comparisons, it was concluded that the variations of discharge affect the morphology evolution of deltas to a certain degree. The extension distance of sediments in Scenario 1 towards the basin is shorter than that in Scenario 2. Since the initial discharge in Scenario 1 was lower than that in Scenario 2, the effects of river on the construction of delta in Scenario 1 were weaker (1200 m^3/s under a smaller discharge. By comparing S1-a with S2-a in Figure 3, it can be observed that the front edge of the delta in Scenario 2 has moved towards the basin by 2.6 km, while the moving distance in Scenario 1 was only 1 km. Another important finding is that the delta in Scenario 1 was distributed asymmetrically along the axis. Additionally, the mechanisms of how the specific variations of discharge, such as increase, decrease and periodic variations, determine the formation of deltas will be further investigated in future work. In the following sections, river diversion, river channel migration, river filling and the development of sedimentary bodies during the evolutionary course of river channel will be discussed in detail.
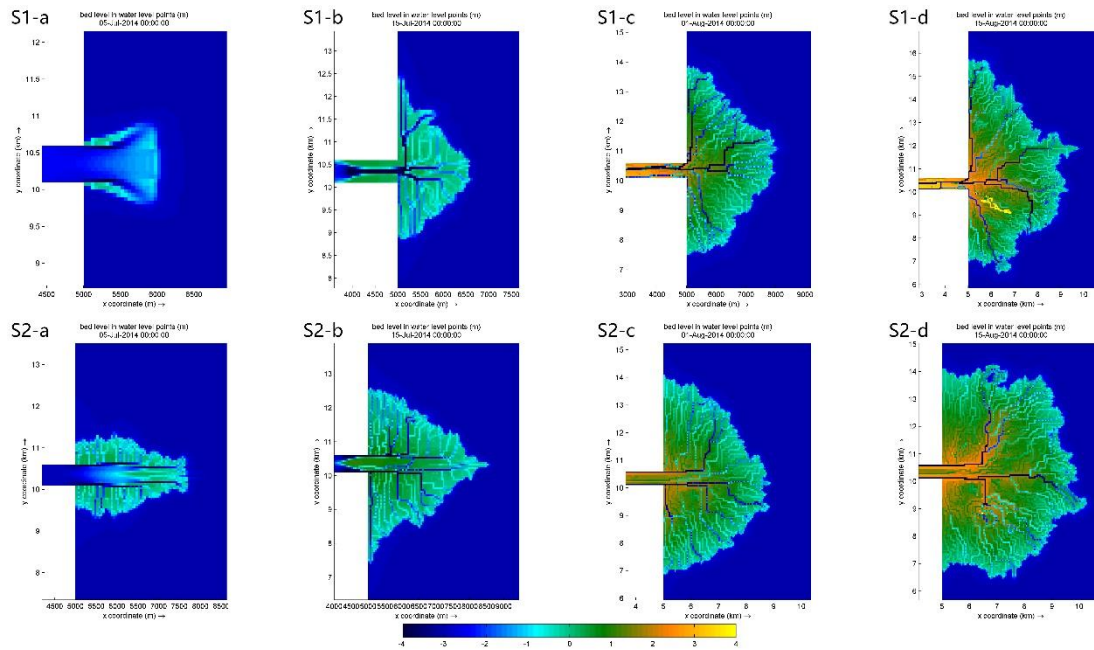
Figure 3. a-d. The Time Snap of Delta Evolution in Each Typical Stages. S1- Scenario 1, S2-Scenario 2

4.1 Evolution of Rivers

In both Scenario 1 and Scenario 2, the evolution tendencies of rivers were similar. In the following section, the evolution process of the river in Scenario 1 will be described in detail. As indicated by the simulation results, the flow velocity in the estuary decreases rapidly in the absence of wave and tidal effects (the vertical cross-section along the river is shown in Figure 4, in which the blue line and yellow line denote the variations of flow velocity and riverbed topography with the distance. It can be observed that the flow velocity decreases rapidly in the estuary after reaching the open water environment). Moreover, the sediment carrying capacity of the river decreases correspondingly, leading to huge accumulation of sediments (as shown in Figure 4). As a result, the initial estuary sandbar is formed. The river flow is then divided into two distributary channels extending outward (Figure 5a shows the planar maps of the bottom topography, in which the color gradually varying from blue to yellow denotes the fluctuations of distance between the points on the plane and the elevation of the datum plane, i.e., the bottom topography after sedimentations and denudation, the same below). As the water washes steadily, the estuary sandbars are destroyed by the rush of water, which gives rise to crevasse channels, i.e., four distributary channels (as shown in Figure 5b). With the gradual extension of distributary channels towards the sea (or the lake), secondary sandbars appear, and the distribution area of the sediments is enlarged steadily. In other words, the number of distributary channels increases. Due to the imbalance between the discharge of river and the sedimentation rate, the distributary channels sing laterally during their gradual propulsion and expansion. As shown in Figure 5c-d, the distributary channels migrate constantly. The sedimentary bodies in the original distributary channels

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are incised by the distributary channels that are formed later. On account of the aggradation and expansion of the sandbars, the rivers migrate towards the two sides. As shown in Figure 5f, the distributary channels with low discharge and low flow velocity are filled and dried up until being finally abandoned. The distributary channels with great discharge scour the sandbars and new distributary channels are formed in the crevasse. During the evolution of deltas, it is because of the repeated process as described above, the interlaced distributary channels are formed, which finally results in the lobate delta (Figure 5e).
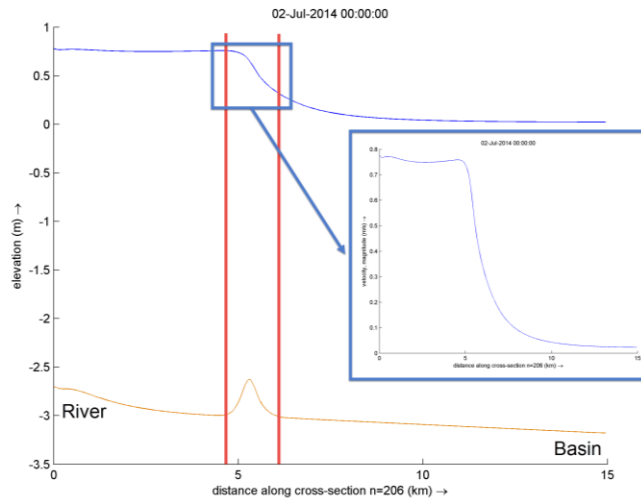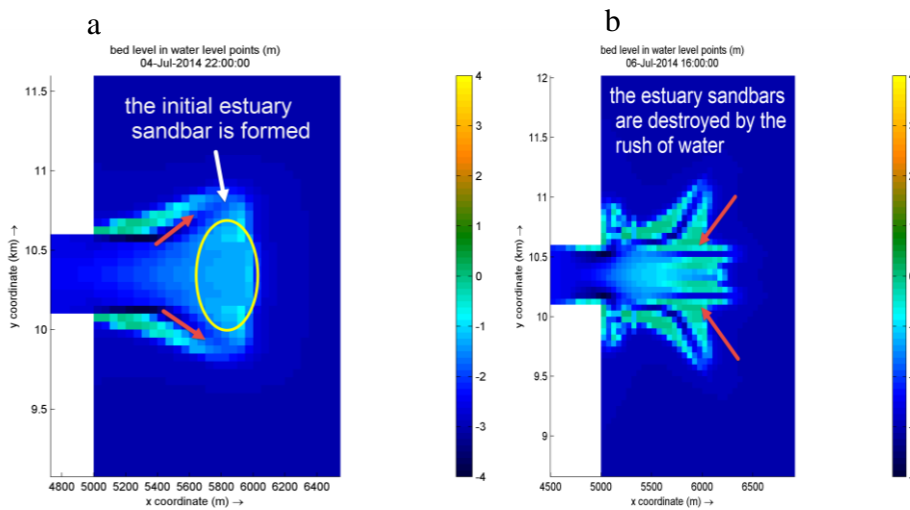

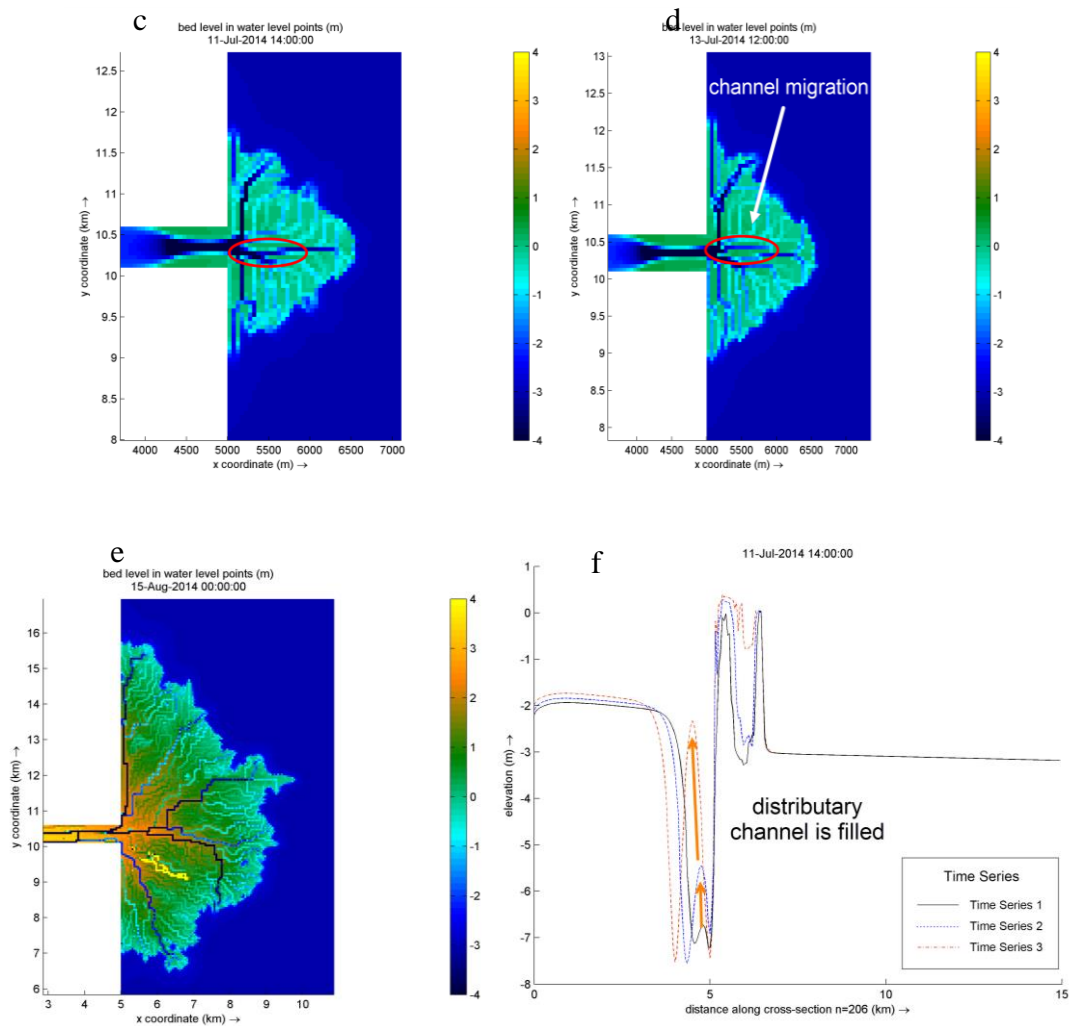**Figure 4. the Cross-sectional View of Velocity and Bed Level**

Figure 5. The Process of Distributary Channels Evolution. a. the Formation of River-mouth Bar; b. the Formation of Crevasse Channel; c~d. the Channel Migration; e. the Final Form of Delta; f. the Cross-sectional View of a Distributary Channel

4.1.1 Variation in the Number of Distributary Channels

In Scenario 1, with the extension towards the lake (or the sea), the initially one distributary channel has evolved to several channels, exhibiting a fan-shaped pattern. These distributary channels constitute the basic skeleton of sediments in the delta. Starting from the initial bifurcation point, the concentric circular lines were drawn with the same intervals (500 m) towards the basin, as shown in Figure 6a. The number of the distributary channels along the measuring lines was recorded, and the relationship between the extension distance and the number of distributary channels was constructed, as shown in Figure 6b. Obviously, it can be observed that, along with the extension, the absolute number of the distributary channels increases significantly. Similarly, the vertical cross-sections of the delta were intercepted at the interval of 500 m along the basin direction. The relative number of distributary channels per unit width of the cross section was recorded. Then the variation tendency of the relative

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number of distributary channels with extension distance was established, as shown in Figure 7. It was found that both the relative number and absolute number of distributary channels increase remarkably with the progradation of the delta. The same variation tendency can be also noted from the results in Scenario 2. Combining with the evolutionary mechanisms of the river channels, it can be predicted that, if the space is large enough and the time is long enough, numerous distributary channels can be developed in the absence of waves and tides.
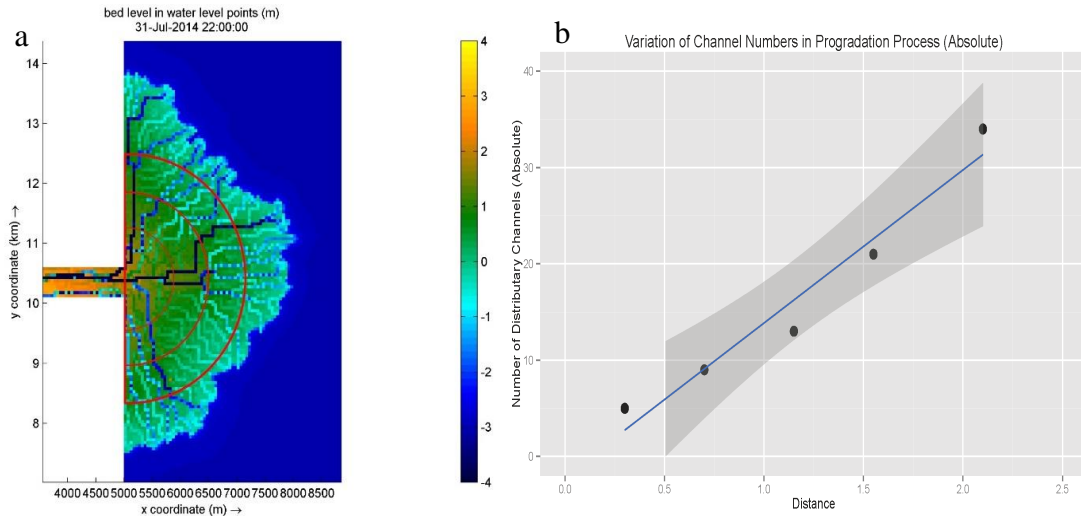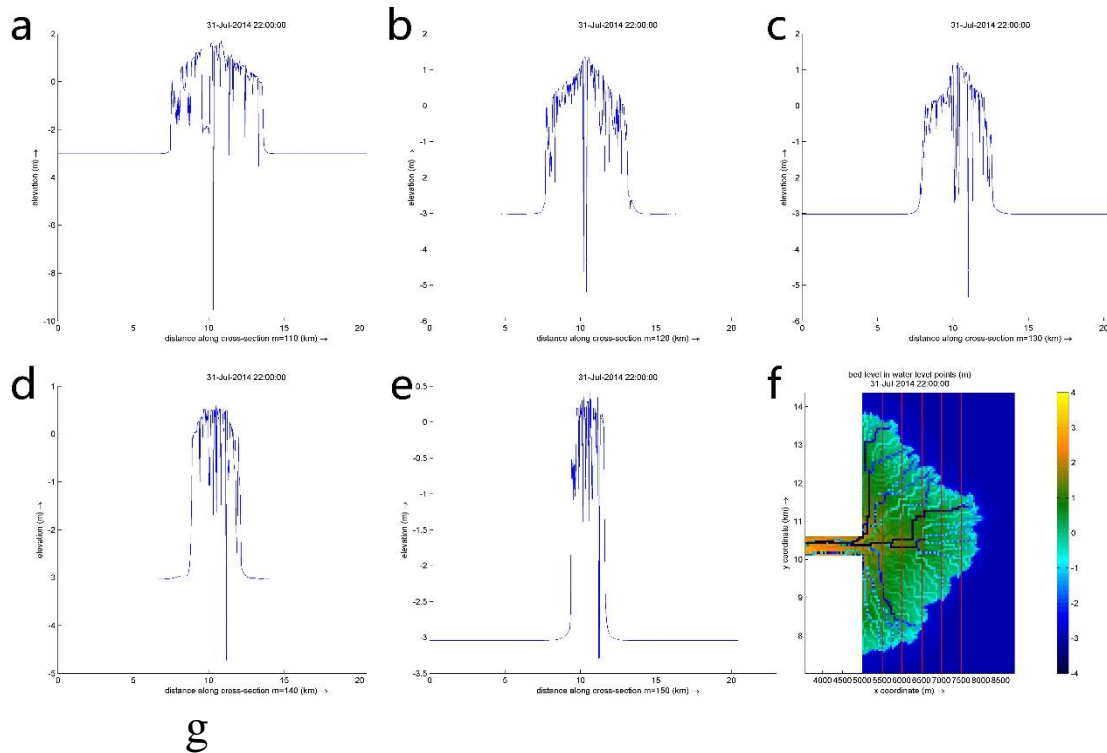

Figure 6. a. Survey Line Location, b. Variation of Channel Numbers in Progradation Process
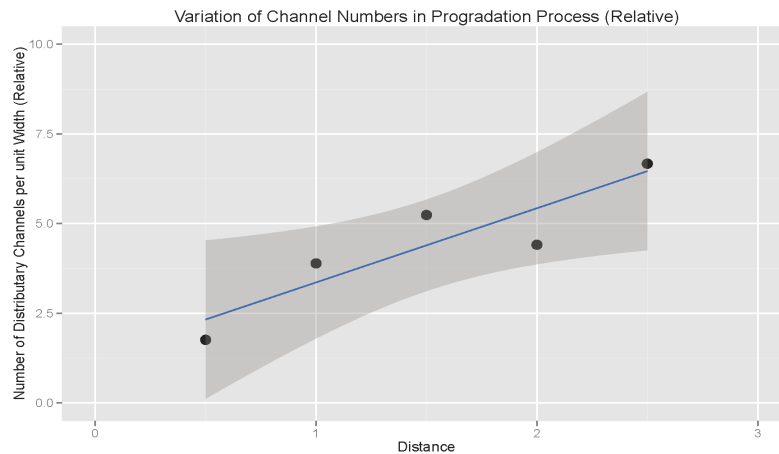
Figure 7. a-e. Vertical Cross-section f. The Location of Vertical Cross-sections in Plain View g. Variation of Channel Numbers in Progradation Process

4.2 Distribution of Sedimentary Bodies

As stated above, the front edges of the deltas in the two scenarios exhibit a lobate shape. Moreover, the total discharge of the river directly controls the morphology of the deltas. In Scenario 1 where the total discharge varies, the delta moves slowly towards the basin and develops laterally along the banks. In Scenario 2 where the total discharge is fixed, the extension distance of the delta towards the basin is very long. Using QUICKPLOT, the planar graphs of bottom topography (as shown in Figure 8 S1A-C; S2A-C) and the distribution of flow velocity (as shown in Figure 8, S1a-c; S2a-c) were drawn, respectively. In the planar graph of the bottom topography, the fluctuations of distance (i.e., the bottom topography after sedimentations and denudations) between the points on the plane and the elevation of the datum plane were marked by colors gradually varying colors blue to yellow. Similarly, in the planner graph of the flow velocity distribution, different colors were used to represent different flow velocities on the plane. The relationship between the flowing water and the sediments can be depicted by comparing the two graphs in the same time slice. As shown in Figure 8 S1C-c and S2C-s which are marked by red boxes, in the flow velocity distribution graphs at the same spatial locations, the regions with the flow velocity of 0 m/s corresponds to the regions with a certain thickness of sediments in the planar graphs of the bottom topography. By comparing these two graphs, it can be found that the planar graph of the flow velocity distribution clearly depicts the morphology of the river channel. This is due to the fact that the water only flows along the river channel and the flow velocity at this point is not equal to zero in the planar graph of flow velocity distribution. The colors in these two graphs were compared in order to investigate the flow velocity along the distributary channel. At the early stage of the evolution of the delta (as shown in Figure 8 S1-a), the flow velocities vary from 0.8 to 1.2 m/s, i.e., the flow velocity of the rivers in this period is slow and uniformly distributed. Due to the increasing flow velocity, the flow velocity increases, and the downcutting effects of the river are enhanced, which are intensified with the increase of the composition of fine-particle sediments (Geleynse et al., 2011).

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The newly formed distributary channels cut the earlier formed sedimentary bodies in a crisscrossed manner. However, at the later stage of the evolution of deltas, some distributary rivers are abandoned or converge into several main distributary rivers with high discharge and flow velocity. Extensive sedimentary bodies appear (Figure 8 S1C-c and S2C-c). Under the appropriate topographic conditions, when the wave and tidal effects are weak, the lobate delta with favorable connectivity is formed due to the migration and cutting of the distributary channels. This is quite different from the formation mechanism of the continuous lobate deltas under the effects of waves and tides. It is conventionally believed that the continuous sedimentary bodies are the products of transformation by external force such as waves and tides (Zhu, 2008; He & Wang, 2007). However, when only the action of river is considered, the lobate river-dominated deltas with continuously distributed sedimentary bodies can be also formed. In previous studies, the researchers have observed the similar tendencies in the southern region of the Poyang Lake by carrying out physical simulation experiments on sediments (Zhang et al., 2010; Zhu, Zhang, & Yin, 2013).
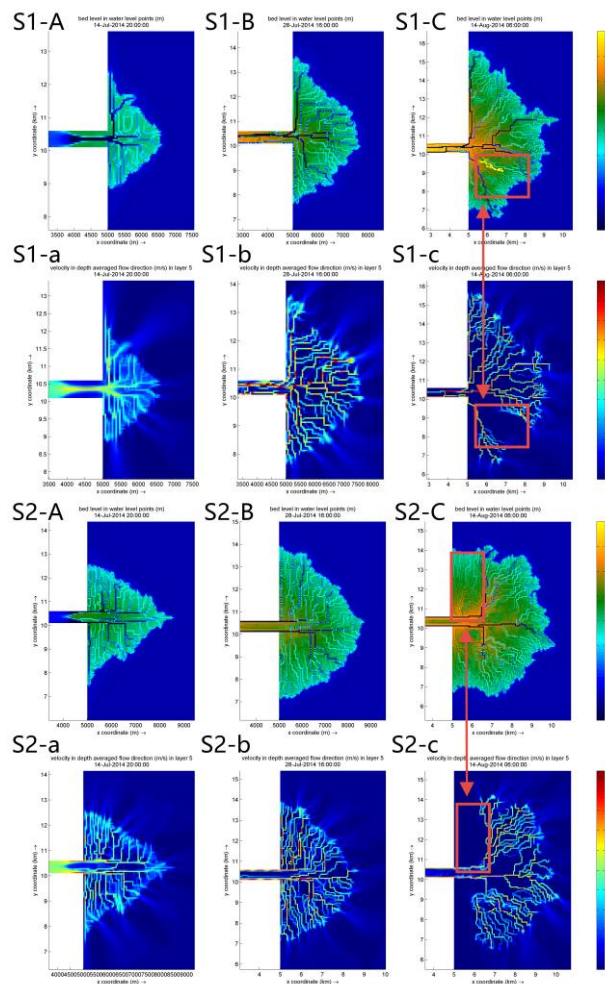

Figure 8. The Distribution of Sidement in River Dominated Delta System. S1-Scenario 1, S2-Scenario 2, A-C. Bed Level in Plane Graph. A-c. Velocity in Depth Averaged Flow Direction

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5. Conclusion and Discussion

In the present work, numerical simulations were performed on deltas. Though the deltas in simulations were highly abstracted and simplified from the deltas in natural world, the present work still has a great significance in scientifically investigating the complex delta systems in real world. By analyzing the evolution and distribution characteristics of the distributary channels, the following conclusions are reached:

1.   For the sedimentary bodies in deltas, the locations which are beneficial for the development of sand bodies are not necessarily concentrated in the distributary channels. Since the distributary channels migrate sharply and frequently, the accommodating space is filled up quickly, and then the river channel migrates to the new regions with favorable conditions where the sediments are deposited. After several repeated processes, the system of interlaced distributary channels is formed. The transformation of the distributary channels results in the sheet-like distribution of the sedimentary bodies. Rather than the stripe-like distribution as expected, the sand bodies can be developed intensively in certain regions. The early form of the sand body is the sandbar, which will evolve to natural levees or shallow swamps at the later stage.

2.   The numerical simulations on sedimentation considering the hydrodynamic force will be of great significance on the studies of the principles of sedimentology. Numerical simulation on sedimentation proves to be a powerful tool for facilitating the progress from qualitative studies on sedimentology to quantitative studies. By numerical simulations, the process of sedimentation of deltas can be described in detail, and the migration and evolution of distributary channels and the filling processes of mild slopes and sharp slopes will be characterized.

However, this system is not applicable for the simulations on the geological time scale (approximately tens of thousands years or even several million years). Therefore, the numerical simulation with low physical complexity still remains as a powerful tool (Deltares, Delft3D-FLOW User Manual, in Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments, 2013; Coulthard, Hicks, & Van De Wiel, 2007; Murray & Paola, 1997).

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