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# A reduced-complexity model for river delta formation – Part 2: Validation of the flow routing scheme

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## Abstract

In a companion paper (Liang et al., 2014) we introduced a Reduced-Complexity Model (RCM) for river delta formation, developed using a parcel-based "weighted random walk" method for routing water and sediment flux. This model (referred to as "DeltaRCM") consists of a flow routing scheme as the hydrodynamic component (referred to as "FlowRCM") and a set of sediment transport rules as the morphodynamic component. In this work, we validate the flow routing scheme (FlowRCM) via a series of hydrodynamic tests by comparing the model outputs to Delft3D and theoretical predictions. These tests are designed to reveal the capability of FlowRCM to resolve flow field features that are critical to delta dynamics at the level of channel processes. In particular, we focus on (1) backwater profile, (2) flow around a mouth bar, (3) flow through a single bifurcation, and (4) flow through a distributary channel network. We show that while the simple rules are not able to reproduce all fine-scale flow structures, FlowRCM does capture flow field features that are essential to deltaic processes

<sup>15</sup> such as bifurcations and avulsions. Finally, we discuss advantages and limitations of FlowRCM and identify environments most suitable for it.

#### 1 Introduction

In the past decades we have seen significant development and applications of reduced complexity models (RCMs) in the field of geomorphology. These models cover a wide
range of landscapes and governing processes, including braided rivers (e.g. Murray and Paola, 1994, 1997; Thomas and Nicholas, 2002), upland and alluvial fans (e.g. Coulthard et al., 2002), deltas and fan deltas (e.g. Sun et al., 2002; Seybold et al., 2007), alluvial channel processes and architecture (e.g. Jerolmack and Paola, 2007; Kassenberg and Bridge, 2008), shoreline evolution and continental shelf (e.g. Ashton et al., 2001; Murray and Thieler, 2004), aeolian landscapes (e.g. Anderson, 1988; Werner, 1995) and wetlands (Larsen and Harvey, 2011). Although all models resolving



coupled fluid flow and sediment transport are simplified to a certain degree, RCMs gain their name in comparison to more detailed reductionism models, sometimes referred to as "high-fidelity" models, typically based on rigorous Computational Fluid Dynamics (CFD) solutions (e.g. Lane et al., 2002; Lesser et al., 2004; Nicholas et al., 2013; Duan

- and Julien, 2010; Siviglia et al., 2013). The most common RCMs in geomorphology are in the form of cellular models, in which topography is represented by a lattice of cells with elevation information and wherein flux is calculated by cellular rules abstracting governing physics. This intuitive yet quantitative approach serves as a great tool to study the interaction of key processes of a system in a self-organized manner (Murray,
- 2007; Paola et al., 2011). Moreover, RCMs can be the analysis and synthesis engines at the geomorphology–ecology interface by incorporating existing knowledge into deterministic, probabilistic, or expert rules (rules using "IF-THEN" statements) (Fonstad, 2006).
- The growing usage of RCMs brings up the issue of validation of these models. Validation is defined as a consistency between RCM model results and other systems such as CFD simulation, field observations, and theory. We see validation as a test of model plausibility (Hardy et al., 2003), or the credibility of the processes represented in the model. Some argue that validation of numerical models in earth science is impossible and model confirmation by the demonstration of agreement between observation
- and prediction is inherently partial (Oreskes et al., 1994). Still, approaches at different levels have been defined and applied (Martin and Church, 2004) to compare a simulated landscape and a real landscape in terms of: (i) the behavior of governing processes (e.g. Tucker and Bras, 1998), (ii) qualitative consistency (e.g. Howard, 1997), (iii) full quantitative comparison (e.g. Ferguson et al., 2001), (iv) statistical properties
   (e.g. Willgoose, 1994).

For RCMs, however, model validation poses extra difficulties due to several reasons. First of all, RCMs in general put emphasis on "explanation" rather than "prediction", and validation methods usually focus on whether the interaction of processes in the model captures important aspects of the natural system's behavior (Murray, 2007). Due to



the wide spectrum of purpose and complexity of RCMs, standards for model validation are still poorly defined. Statistical methods offer quantitative metrics for validation, but the identification of the most revealing and discriminating statistics of a certain system is a challenge in itself. Examples of on-going efforts in developing better metrics for

- <sup>5</sup> the quantitative description of river deltas include the work by Wolinsky et al. (2010), Edmonds et al. (2011), and Passalacqua et al. (2013). Second, a large portion of RCMs are built for geological time scales, such as models for studying channel avulsions and alluvial architecture (e.g. Jerolmack and Paola, 2007; Karssenberg and Bridge, 2008). Validation of such models requires intensive stratigraphic data which are not easily
- available. This issue has been addressed by many researchers, calling for a combined effort of model development and field observations (Overeem et al., 2005; Hajek and Wolinsky, 2012). Third, for cellular models, model validation (whether the model correctly represents physical processes) and verification (whether the numerical solutions are in agreement with the given equations) are sometimes mixed. For example, achieving a grid-independent solution is inherently more difficult than for other types of
- numerical models as the grid structure represents an implicit element of the process parameterization (Nicholas, 2005).

After recent improvement of reduced-complexity (RC) modeling techniques, especially in flow routing schemes, it is possible to develop RCMs that are capable of pre-

- dicting flow patterns with accuracy comparable to CFD-based models (Nicholas et al., 2012). In the validation work by Nicholas et al. (2012), an inter-comparison of a relatively simple RCM with two CFD models shows that all the three models are able to replicate patterns of depth-averaged velocity and unit discharge evident in ADCP cross-sectional surveys.
- Motivated by the points mentioned above, in this work we design a series of tests for the RC flow routing scheme – referred to as "FlowRCM" – of the delta formation model introduced in Part 1 (Liang et al., 2014). With the proposed validation tests we aim to examine to what extent FlowRCM is able to reproduce hydrodynamic details, in comparison to higher fidelity CFD-based models such Delft3D (Lesser et al., 2004). We



propose the following test cases because each case represents a critical hydrodynamic process essential to delta morphology at the scale of channel dynamics: (1) backwater profile, (2) flow around a mouth bar, (3) flow through a single bifurcation, and (4) flow through a distributary channel network.

<sup>5</sup> The paper is organized as follows. In Sect. 2, we briefly describe the key steps in FlowRCM, based on a parcel-based weighted random walk method. In Sect. 3, we present the design and setup of the test cases and their relevance to delta formation. Results from the validation tests are presented in Sect. 4. We discuss our results and ideas for future research in Sect. 5. Finally, we present our conclusions in Sect. 6.

#### **2** Review of the flow routing scheme

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Here we give a brief review of our reduced-complexity flow routing scheme "FlowRCM", focusing on the key steps and parameterizations (for a complete description refer to Part 1, Liang et al., 2014). In this section, we assume a non-deformable topography (i.e. no morphodynamic processes), over which the flow routing scheme resolves the depth-averaged flow field and the water surface profile given appropriate initial and boundary conditions.

The topography is represented by a lattice of square cells. At each cell, quantities such as bed elevation  $\eta$ , water surface elevation H, and water unit discharge q are recorded (Fig. 1). Water depth h can be calculated by taking the difference between <sup>20</sup> water surface elevation and bed elevation (with H and  $\eta$  both relative to a reference datum). Water flux is represented by a large number of small water parcels, typically hundreds to a few thousands. The solution is reached in an iterative fashion: first, parcels are routed individually from cell to cell based on a probability field, then the flow field and water surface elevation are updated. This process is repeated until the 25 calculated flow field and water surface elevations still occur after convergence of the calculation is reached, while the mean values remain stable. A demonstration of the oscillation



process is given in the discussion section based on the results of test 4a. Therefore we run the code over a large number of iteration steps, typically 500 to 1000, which is more than what is needed to achieve convergence.

The key step is calculating the probabilities for routing water parcels, based on rules
<sup>5</sup> abstracting the governing physics – hence the name "weighed-random-walk". As the detailed procedure is explained in Part 1, here we only revisit the main idea. The like-lihood of a neighbor cell to receive a water parcel is determined by a combination of local quantities including water surface gradient, the direction of flow inertia, and flow depth at the cell. In other words, if a cell is more aligned with the local "downstream"
<sup>10</sup> direction and has greater water depth, then its probability of receiving water parcels from nearby cells is higher.

The steps for calculating the routing probability field are:

## 2.1 Step 1: define a routing direction at each cell

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The routing direction (F) is essentially an estimate of local downstream direction for the purpose of directing the water flux. In our model, it is a combination of the estimated local water surface gradient and direction of flow inertia:

$$F^* = \gamma F_{\text{sfc}} + (1 - \gamma) F_{\text{int}},$$

$$F = \frac{F^*}{|F^*|},$$
(1)
(2)

<sup>20</sup> where  $F_{int} = \frac{q}{|q|}$  is a unit vector indicating inertia, and  $F_{sfc} = \frac{\nabla H}{|\nabla H|}$  is a unit vector indicating surface gradient. Both q and  $\nabla H$  take value from the latest iteration step.  $\gamma$  is a dimensionless coefficient, which is set to 0.05 in our runs if not indicated otherwise (Liang et al., 2014).



#### 2.2 Step 2: calculate relative routing weights for the neighbors at each cell

With the routing direction F specified, the relative routing weights ( $w_i$ ) for neighbors around each cell (8 neighbors in the case of square lattice setup) are determined as follows:

$$w_i = \frac{h_i \max(0, \boldsymbol{F} \cdot \boldsymbol{d}_i)}{\Delta_i}, \ i = 1, \dots, 8.$$

The cellular direction vector,  $d_i$ , is a unit vector pointing to neighbor *i* from the given cell;  $\Delta_i$  is the cellular distance (taking a value of 1 for cells in main compass directions and a value of  $\sqrt{2}$  for corner cells), and  $h_i$  is water depth and neighbor *i*.

#### 10 2.3 Step 3: calculate routing probabilities $(p_i)$

The weights above are then processed according to the wet-dry status of cells. The model considers cells with flow depth greater than a threshold value (typically 1–5% of the characteristic flow depth of the system) as "wet" cells, and the opposite as "dry" cells. The weights for dry cells are then converted to the value of 0. The routing probabilities ( $p_i$ ) are calculated as:

$$p_i = \frac{W_i}{\sum_{nb=1}^{8} W_{nb}}, i = 1, \dots, 8,$$

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where *nb* is the numbering of neighbors around a given cell (1 to 8 for a 3-by-3 square grid). With the routing probabilities calculated, water parcels are released one by one from the upstream inlet cells and each of them does a "directed-random-walk" based on the probability field. The cumulative movements of parcels are summed in terms of vectors at each cell to obtain an estimation of flow unit discharge.

The calculation of the water surface profile is based on a 1-D scheme along the water parcel paths, rather than the solution of a system of partial differential equations. The



(3)

(4)

basic assumption is that the water surface profile along a streamline can be approximated by a 1-D equation. In the morphodynamic results in Part 1, this 1-D equation takes the simplest form that water surface slope on the delta equals a constant value – the "reference slope". In this hydrodynamic validation work, we formulate the 1-D s equation such that (i) it satisfies the backwater equation if the local Froude number is low ( $Fr^2 \le 0.5$ ) and (ii) the water surface slope (*S*) is equal to the friction slope (*S*<sub>f</sub>) if the Froude number is high ( $Fr^2 > 0.5$ ):

$$\frac{\partial h}{\partial l} = \frac{S - S_{\rm f}}{1 - Fr^2}, \text{ if } Fr^2 \le 0.5,$$

$$\frac{\partial H}{\partial l} = S_{\rm f}, \text{ if } Fr^2 > 0.5,$$
(5)
(6)

where  $C_f$  is the coefficient of friction,  $S_f = C_f F r^2 = C_f \frac{U^2}{gh}$  is the friction slope and / is the distance along an arbitrary flow streamline.

This calculation is done along each water parcel path via a finite difference scheme. An average value is taken for cells belonging to multiple paths. The obtained surface profile is then smoothed with numerical diffusion to remove bumps and ditches caused by the gaps between different 1-D paths. In addition, an under-relaxation is applied for numerical stability between iterations (see Part 1 for details).

#### 3 Validation cases

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The validation cases are designed to illuminate two important aspects in the RCM. First, we target the "reduced-complexity" features in our flow routing model, i.e. the rules and parameterizations that represent governing physics; second we want to capture critical hydrodynamic processes affecting the overall delta morphology. The hydrodynamics of river deltas involve a hierarchy of processes occurring at a wide range of scales, from flow structures behind individual ripples on the bed to channel avulsions

that change the distribution of water flux across the entire delta surface. We focus on hydrodynamic processes at the channel scale, which are essential to creating, maintaining and modifying a distributary channel network. The proposed validation tests are: (1) backwater profile in a straight channel, (2) flow around a mouth-bar, (3) partitioning of flow at a single bifurcation, (4) partitioning of flow in a distributary channel network with submerged islands. A description of each test case is given below.

## 3.1 Test 1: backwater profile in a straight channel

River deltas have subtle topography and water surface gradients and flow is typically subcritical. Nevertheless, the gradient in the surface profile is essential to water motion in deltaic environments (Edmonds and Slingerland, 2008). As mentioned in the previous section, FlowRCM estimates the water surface based on the assumption of a 1-D surface profile along flow streamlines. As the movement of water parcels on the grid is in both *x* and *y* direction, the calculations along these paths involve projecting each step a parcel makes to the estimated flow streamline. Thus, in the first test we use a straight channel of constant width with no variation in cross-stream direction, whose surface can be described by the 1-D backwater equation. The model performance is compared to the theoretical backwater profile.

The domain is 2000 m wide and 15000 m long with a rectangular cross-section (Fig. 2). The bed has a constant slope  $S = 10^{-3}$  and a constant friction coefficient  $C_{\rm f} = 0.01$ . A constant discharge of  $2 \times 10^4$  m<sup>3</sup> s<sup>-1</sup> is fed into the upstream inlet. The downstream outlet has a fixed water surface elevation as boundary condition. The discharge is chosen so that the flow remains subcritical in normal flow conditions. By varying the downstream water surface elevation relative to that of the normal flow, different backwater profiles can be achieved, such as M1, M2 and normal flow (Chow, 1959) (Fig. 2). As the flow does not have cross-stream variation, the surface profile

<sup>25</sup> 1959) (Fig. 2). As the flow does not have cross-stream variation, the surface profile can be resolved using the 1-D backwater equation (Eq. 5).



For the FlowRCM calculation, we use a grid of  $20 \times 150$  cells, with cell size of 100 m. The water surface elevation calculated from FlowRCM is averaged in the cross-stream direction and compared to the numerical solution of Eq. (5).

## 3.2 Test 2: flow around a mouth bar

- <sup>5</sup> The formation of channel bifurcations is essential to the formation of the distributary channel network on river deltas (Edmonds and Slingerland, 2007; Kleinhans et al., 2013). Therefore the ability of a numerical model to represent the bifurcation process is of great importance. As shown by the work of Edmonds and Slingerland (2007), mouth bar development is critical to bifurcation. Particularly, one key feature in this process is
- the transition from flow acceleration to deceleration over the top of the mouth bar as the bar height grows and the bar top approaches the water surface (Fig. 3). Here we design a similar test with variable bar heights. The mouth bar topography is represented by a Gaussian-shaped bump in a straight channel. The bump does not deform and its height is varied from 10 to 99 % of the normal flow depth.
- <sup>15</sup> The domain is a straight channel section, 100 m wide and 200 m long with rectangular cross-section. The bed has a constant slope  $S = 2.5 \times 10^{-3}$  and a constant friction coefficient  $C_f = 0.1$ . A constant water discharge of  $50 \text{ m}^3 \text{ s}^{-1}$  is fed into the upstream inlet. The downstream outlet has a fixed water surface elevation as downstream boundary condition. The Gaussian-shaped bump has a diameter equal to approximately one
- third of the channel width. The side walls of the channel have a no flow boundary condition. FlowRCM uses a 40 × 80 grid with cell size of 25 m. Both FlowRCM and Delft3D are setup in exactly the same manner.

We compare the outputs from FlowRCM and Delft3D in terms of water surface elevation and flow velocity, focusing on: (i) the location of "hot spots" of high and low velocity

(ii) the deformation of the water surface in proximity of the bump, and (iii) the transition of flow velocity right over the top of the bump as the bump height increases from 10 to 99 % of the normal flow depth.



## 3.3 Test 3: flow through a single bifurcation

Bifurcations control the partitioning of water and sediment in the deltaic system and affect the stability of the whole network (Edmonds and Slingerland, 2008; Edmonds et al., 2010; Kleinhans et al., 2008, 2013). Our goal here is to use simple and idealized <sup>5</sup> bifurcation topography to test the response of FlowRCM to bifurcation asymmetry, e.g. changes in width and/or depth ratio of the two downstream branches.

There are three groups of tests, referred to as group A, B and C. In all groups the main channel splits into two branches that open at an angle of 60°, and both branches enter a basin with constant depth (Fig. 4). Channel banks are no-flow boundaries so that the water flux stays in the channel and there is no flooding onto the bank. For all tests FlowRCM uses a 100 by 100 grid. Group A and B have smaller domain size which is 2500 m by 2500 m with 25 m grid size, and total input discharge of 3000 m<sup>3</sup> s<sup>-1</sup>. Group C have larger domain size of 5000 m by 5000 m with 50 m grid size, and total input discharge of size, and total input discharge of 5000 m<sup>3</sup> s<sup>-1</sup>.

- keeping the two branches at same width; group B explores the effect of asymmetry in width alone, keeping the two branches at same depth; group C explores the effect of asymmetry in cross-sectional area, by keeping the summation of the cross-sectional areas constant and all channels at the same width-to-depth ratio. Detailed channel geometries are shown in Fig. 4.
- <sup>20</sup> The output of FlowRCM is compared to Delft3D in terms of: (i) the spatial pattern of flow velocity and water surface elevation and (ii) the ratio of fluxes between the two branches.

#### 3.4 Test 4: flow through a distributary channel network

In the last test, we evaluate the performance of FlowRCM at the scale of a complete deltaic distributary channel network. Specifically, we are interested in assessing whether the "inaccuracy" of the flow field at finer scales accumulates as the flow propagates through the whole channel network. The topography setups used to run



FlowRCM and Delft3D are: the synthetic topography of a natural river delta (Test 4a) and a DeltaRCM simulated topography (Test 4b).

## 3.4.1 Test 4a: synthetic Wax Lake Delta (WLD) topography

Wax Lake Delta (WLD) is a modern river-dominated delta in the coast of Louisiana, part of the Mississippi River Delta system (Roberts et al., 1980; Wellner et al., 2005; Shaw et al., 2013). We constructed a synthetic bathymetry (Fig. 5) from satellite images and bathymetry measurements along 9 transects (USACE survey, 1999). We used an image processing software (Adobe Photoshop CS6) to integrate the planview of islands and channels from the satellite imagery and obtain a smooth profile between neighboring transects. FlowRCM and Delft3D are given the same initial and boundary conditions: an upstream inlet channel discharge of 2490 m<sup>3</sup> s<sup>-1</sup> and a water surface elevation at the downstream boundary of 0 m. The friction coefficient is set to 0.01. Both FlowRCM and Delft3D use a 200 by 200 grid with cell size of 60 m.

## 3.4.2 Test 4b: bed topography generated by the DeltaRCM

For this test, delta topography is taken from a snapshot of the mixed grain size delta simulated by DeltaRCM. The delta is composed of 70% fine grain and 30% coarse grain, and has a very well-defined distributary channel network (Liang et al., 2014) (Fig. 5). The rectangular domain is 6 km wide and 3 km long. The inlet channel has a discharge of 1250 m<sup>3</sup> s<sup>-1</sup>, and the delta is formed in a basin with a constant depth of 5 m. Both FlowRCM and Delft3D use a 60 by 120 grid with cell size of 50 m.

The Delft3D simulations in both Test 3 and Test 4 were done in depth-averaged mode. The time step is 30 s and we use a constant horizontal eddy viscosity  $(1 \text{ m}^2 \text{ s}^{-1})$  and a constant Chezy coefficient (65 m<sup>1/2</sup> s<sup>-1</sup>).



## 4 Validation results

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## 4.1 Test 1 results: backwater profile in a straight channel

The results show that in all three scenarios FlowRCM is able to successfully reproduce the backwater profile solution (Fig. 6). The predicted cross-stream averaged water surface elevation, in fact, matches the solution of the 1D backwater equation. The simple scheme used in FlowRCM is thus able to produce realistic water surface profiles.

## 4.2 Test 2 results: flow around a mouth bar

The maximum flow velocity over the top of the bump occurs when bump height is around 60% of the flow depth (Edmonds and Slingerland, 2007). Therefore, we compare FlowRCM and Delft3D results with bump heights at 20, 60 and 90% of the flow 10 depth in Fig. 7 in order to capture this transition. The results show that (i) both FlowRCM and Delft3D reproduce the transition from flow acceleration to deceleration over the top of the bump as the height of the bump increases (Figs. 7 and 8), (ii) both models show that higher velocity occurs in a "bow-shape" over the bump and curved into the downstream direction, while lower velocity occurs behind the bump and slightly in front of 15 the bump (Fig. 7), and (iii) both models show that the water surface is super-elevated in front of the bump and is drawn-down behind the bump. FlowRCM thus captures the key hydrodynamic features, although their magnitude and shape does not exactly match the results from Delft3D (Fig. 7). The irregularities in the FlowRCM output are caused by the "randomness" inherent in the weighted-random-walk scheme. As seen 20 in Figs. 4 and 5 such irregularities do not affect the ability of the model to reproduce key hydrodynamic features.



#### 4.3 Test 3 results: flow through a single bifurcation

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To evaluate the effects of channel geometry asymmetry on flow partitioning between the bifurcations, we calculate two values from each test result for both FlowRCM and Delft3D: the asymmetry of discharge  $\psi_Q$  and the asymmetry of cross-sectional area  $\psi_A$ :

$$\psi_Q = \frac{|Q_L - Q_R|}{Q_L + Q_R},$$

$$\psi_A = \frac{|A_L - A_R|}{A_L + A_R},$$
(7)
(8)

where Q<sub>L</sub> and Q<sub>R</sub> are the water discharge in the left and right branch respectively; A<sub>L</sub>
 and A<sub>R</sub> are the cross-sectional area (calculated with bed elevation and resolved water surface elevation) of the left and right branch respectively.

The asymmetry values defined in Eqs. (7) and (8) are plotted in Fig. 9. FlowRCM captures the same trend of flow discharge partitioning predicted by Delft3D: the amount of water flux into the two branches is proportional to the cross-sectional area of the branches. This means that despite the variation in the ratio of depth and/or width, the flow tends to have the same mean velocity in both branches. Also, both FlowRCM and Delft3D predict a water surface gradient in the shallower branch that is significantly higher than the one in the deeper branch, consistent with field observations by Edmonds and Slingerland (2008). In quantitative terms, FlowRCM tends to over-predict

- <sup>20</sup> surface elevation by up to 12 centimeters, and predicts a discharge asymmetry within 7 % difference compared to Delft3D (Table. 1). An example of flow field and water surface elevation (test C3) is plotted in Fig. 10. Also, within each test group both FlowRCM and Delft3D predict the same behavior of upstream water surface elevation in response to the discharge asymmetry: in group A and C the upstream water surface elevation
- <sup>25</sup> decreases as discharge asymmetry increases; in group B the upstream water surface elevation increases as discharge asymmetry increases.



One qualitative difference in the observed flow plan-view pattern produced by FlowRCM and Delft3D is what we call "local effects". In the results of FlowRCM there is significant concentration of flux right upstream of the island, where flow bifurcates directly against the tip of the island (in this case, the no-flow condition at the boundary

of the islands does not allow any water flux to escape the channels) (Fig. 10, dashed square region). The water surface elevation calculated by FlowRCM does not show super-elevation right at the tip of the island as in the Delft3D results; instead, there is a draw-down. We believe that the super-elevation creates a gradient that causes the flow to divert around the island much further upstream.

## 10 4.4 Test 4 results: flow through a distributary channel network

## 4.4.1 Test 4a: synthetic Wax Lake Delta (WLD) topography

The results show that the two models have strong agreement on the flow distribution among channels and islands, for example "hot spots" of higher flow velocity occur at the same locations (Fig. 11). Delft3D shows a more "diffused" velocity map while FlowRCM gives a more "noisy" map. The flow pattern on the islands predicted by 15 FlowRCM seems to respond to island topography, exhibiting a converging stream in the low elevation area towards the lower center of the islands (Fig. 11). In Delft3D results, flow is more evenly distributed across each island, thus not revealing much island topographic detail (although higher resolution Delft3D modelling would, while constraints exist in its drying-flooding algorithm). The depth-averaged mode and the 20 choice of horizontal eddy viscosity might also add to the relatively smooth outputs from Delft3D. The "local effects" in FlowRCM that we demonstrated in the previous section cause the appearance of a high velocity zone right along the tip of the islands rather than a low velocity zone caused by flow diversion starting upstream of the island as in the Delft3D results (Fig. 12). 25



## 4.4.2 Test 4b: bed topography generated by the DeltaRCM

These results show that similar to the synthetic WLD topography test, FlowRCM and Delft3D show strong agreement in the flow distribution through the network, e.g. the partitioning among channels and islands (Fig. 13). Moreover, the water surface profile calculated by FlowRCM is smoother than the one from Delft3D, and FlowRCM is in fact

- <sup>5</sup> Calculated by FlowRCM is smoother than the one from DelitsD, and FlowRCM is in fact able to handle discontinuities in the domain represented by frequent alternation of "wet" and "dry" cells. Also note that in this test "local effects" are not pronounced. A possible reason is that this simulated topography has already adapted to the features of the flow field calculated by the FlowRCM, such that at the tip of the island, local topography creates a smooth transition from deep channels to shallow islands that divert the flow
- <sup>10</sup> creates a smooth transition from deep channels to shallow islands that divert the now gradually. At the same time, as the islands are mostly submerged and flow can get onto the islands, the calculation of free surface allows a more accurate surface construction compared to merely using a no-flow boundary condition for the edge of the islands. More discussion is given in the next section.

### 15 **5** Discussions

In this work, we validated FlowRCM in terms of its ability to reproduce plausible hydrodynamics of deltaic systems. We presented the direct outputs from FlowRCM in several setups designed to mimic hydrodynamic scenarios characteristic of river deltas. The computed flow fields are compared to theoretical and numerical simulation results ob-

- tained with a higher-fidelity hydrodynamic model (Delft3D) which has been previously validated for similar purposes (Lesser et al., 2004). From the comparison to analytical solutions and Delft3D, we address the goal stated in our introduction: what level of hydrodynamic physics does our FlowRCM capture? In terms of water surface profile modelling, FlowRCM is able to replicate (i) the backwater profile along a simple straight channel matching the solution of the theoretical backwater equation, (ii) the lo-
- <sup>25</sup> straight channel matching the solution of the theoretical backwater equation, (II) the local surface deformation around submerged bumps, including a super-elevated region



upstream of the bump and a draw-down region downstream of the bump, (iii) the difference in surface gradients between two competing bifurcation branches, and (iv) the outward surface gradient from channels to floodplains. In terms of flow discharge and velocity field, FlowRCM is able to replicate (i) the non-linear response of flow velocity to the height of the submerged bump structure, (ii) the discharge partitioning between

- two competing bifurcation branches in a single bifurcation, and (iii) the discharge partitioning through a whole distributary network of channels and floodplains. The results also show that FlowRCM falls short with respect to Delft3D in terms of detailed hydrodynamic features. For example, in the single bifurcation test, the RCM results show
- strong "local effects" resulting into the flow splitting right in front of the island. Also, occasional irregularities appear due to the probabilistic approach of routing water parcels. Overall, compared to higher-fidelity models, FlowRCM works well at the multichannel network scale, where spatial flux distribution matters more than detailed channel flow structure. Furthermore, for single-channel scale cases, such as submerged
- smooth obstacles, FlowRCM is able to predict the regions of high and low velocities, and regions of water surface super-elevation and draw-down, although the exact shape of the regions or the values of the velocity and water surface elevation may be more qualitatively correct rather than quantitatively. While FlowRCM has been mainly applied in low-gradient environment where flow is typically sub-critical, the routing method
- <sup>20</sup> should work well for high-gradient and super-critical system, given the success of cellular routing schemes for erosional landscapes and braided rivers. In fact, the laboratory scale alluvial fan simulation in Part 1 is an example of how this scheme works for highgradient environments. The key parameters affected by switching between environments are the slope/inertia partitioning parameter  $\gamma$  in calculating routing probabilities and the 1-D profile equation for water surface elevation.

One characteristic of rule-based RCMs is the flexibility in making changes to one specific rule in the model, resulting in the opportunity to isolate processes, understand their effects and the behavior of the model, and potentially guide future model improvements. For example, FlowRCM does not resolve the water surface profile based on



2-D hydrodynamic equations. The water surface plays a role in distributing water fluxes through a feedback mechanism: the convergence of water flux causes water surface to rise up along the flow path, which introduces a positive surface gradient pointing away from the cells with high flux, and this surface gradient diverts flux sideways. This

<sup>5</sup> process is done through iterations and the delay in the responses between water surface and water flux causes an oscillation in the model outputs (example from test 4a in Fig. 14). At the same time, this iterative feedback mechanism allows the water flux to adjust beyond the conditions of immediate neighbors, thus reducing the "local effects". A similar iterative feedback mechanism can be found in the row-by-row depth-based
 <sup>10</sup> iteration method developed by Nicholas et al. (2010).

In Part 1, we presented both the hydrodynamic and morphodynamic components of the RCM. While our validation work presented here addresses the plausibility of the model's hydrodynamic results, it is interesting to investigate whether the ability of a flow routing scheme to correctly predict hydrodynamics controls its ability to produce plausible morphodynamic features. We can think, for example, about the process of bifurcation formation. In DeltaRCM a channel mouth goes through a series of stages (Fig. 15): (i) flow expands and sediment deposits with reduced flow velocity, which creates a wide lunate bar with noisy surface, (ii) the irregular topography of the bar forms "ridges" and "troughs" where troughs attract more water flux than ridges, (iii) the

- enhanced flow rate in troughs prevents sediment from settling while ridges continue to experience deposition, (iv) the process reaches equilibrium through the feedback mechanism between water surface elevation and water flux. The few paths established from the troughs outcompete the others. Interestingly, this process not only produces bifurcations, but also trifurcations and so on. Accordingly, DeltaRCM suggests that dis-
- tributary channel networks are not necessarily solely built by mouth-bar induced flow bifurcation (Edmonds and Slingerland, 2007). Another example of coupled hydrodynamic and morphodynamic performance is the sensitivity of cellular flow routing to topographic details, such as flow acceleration and change in flow orientation over short distances (Nicholas et al., 2012), which is caused by the local effects. By comparing



the results in test 4a using the synthetic WLD topography, the results from Delft3D look more "diffusive" than FlowRCM. The local effects, when combined with the use of parcels, may offer a richer flow pattern in response to small changes on the flood-plain. Although this observation requires further investigation, based on our results RC flow routing schemes seem to be less constrained by the complex flow boundaries

caused by wet-dry partitioning in the cells than higher-fidelity models based on partial differential equations.

While the main focus of this work is the validation of the reduced-complexity flow routing scheme in the delta formation model introduced in Part 1, the validation frame-<sup>10</sup> work we proposed can be applied to other RCMs with explicit flow routing schemes. In light of the rapid development of RCMs, we would like to make suggestions for the development of a comprehensive framework to validate RC flow routing schemes in the field of geomorphology, with an emphasis on the connection between hydrodynamic processes and morphodynamic processes. We identify the following key steps:

- 15 **1.** Identify key hydrodynamic processes that control the behavior of the modeled environment at the complexity level of interest.
  - 2. Design "benchmarking" test cases (based on field data and high-fidelity numerical simulations) that reveal the model's ability to reproduce these fundamental processes individually.
- 20 3. Perform an inter-comparison of models at different complexity levels (e.g. higherfidelity models).
  - 4. Identify individual or linked model rules responsible for physical and unphysical features in the model output.
  - 5. Link the performance of the routing scheme to the morphodynamic results, especially when sediment transport in the complete morphodynamic RCM is also rule-based, it is important to identify what features in the flow solver control the resolved morphology.



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## 6 Conclusions

In this work we have applied a series of numerical tests to validate the reducedcomplexity flow routing scheme, FlowRCM, which is introduced in Part 1 (Liang et al., 2014) as the hydrodynamic component of our RC delta formation model. We selected

- key hydrodynamic processes essential to channel processes in deltas and designed numerical tests as "benchmarking" cases for this specific environment. We compared the output from FlowRCM with the output from a higher-fidelity hydrodynamic model, Delft3D, which is based on rigorous CFD solutions. We also used theoretical solutions to demonstrate FlowRCM's ability to reproduce hydrodynamic details.
- <sup>10</sup> The results show that FlowRCM is able to reproduce most of the flow and water surface features of interest. Overall, it captures (1) the trend of water surface from upstream to downstream and from channels to floodplain, (2) flow partitioning corresponding to complex bed topography such as flow divergence and convergence around obstacles. The model shows the presence of "local effects", a common feature of cel-
- <sup>15</sup> lular routing schemes. We have also shown that the routing scheme is able to produce morphodynamic features such as mouth-bars, bifurcations and levee formation. The responsible process is an instability-feedback mechanism resulting from the coupling of the hydrodynamic component and the sediment transport rules.

This work suggests a validation framework for RCMs with explicit flow routing schemes. The key ideas include (1) designing test cases to evaluate the performance of the routing scheme in producing features related to the processes of interest; (2) identifying the effects of model rules and connecting them to model output individually; and (3) connecting the hydrodynamic to the morphodynamic performance to evaluate the flow routing scheme's ability to model morphodynamics accurately.

<sup>25</sup> Finally, we suggest that FlowRCM is appropriate for modeling environments with multi-channel networks where morphodynamic features can be produced from the estimation of channel-to-channel and channel-to-island/floodplain flow partitioning. More detailed prediction of in-channel flow patterns such as spatial distribution of high/low



velocity and surface deformation could also be achieved but it is not intended for smallscale engineering purposes.

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**Table 1.** Discharge asymmetry and upstream surface elevation results from FlowRCM and Delft3D for all single bifurcation runs.

Run #	Discharge Asymmetry (%)			Upstream Surface Elevation (m)		
	FlowRCM	Delft3D	difference	FlowRCM	Delft3D	difference
A1	0.16%	0.00%	+0.16%	0.3226	0.2067	+0.1159
A2	20.82 %	24.04 %	-3.23%	0.3160	0.2048	+0.1112
A3	41.04 %	47.69 %	-6.65 %	0.3156	0.2016	+0.1140
B1	0.16%	0.00%	+0.16%	0.3226	0.2067	+0.1159
B2	21.59 %	21.17 %	+0.42%	0.3230	0.2068	+0.1162
B3	40.76 %	42.78%	-2.02%	0.3301	0.2075	+0.1226
C1	0.21%	0.01 %	+0.19%	0.1472	0.1091	+0.0381
C2	28.22%	27.84%	+0.37 %	0.1417	0.1057	+0.0360
C3	51.49%	52.66 %	-1.17%	0.1286	0.0963	+0.0323



**Figure 1.** Basic setup of the model. The calculation domain is represented by a lattice of square cells (shown as a cartoon on the left). Primary quantities associated with each cell include flow depth, water surface elevation, bed elevation and flow unit discharge vector.





**Figure 2.** The setup of the straight channel test. The channel has a rectangular cross-section. The bed has a constant slope and a constant friction coefficient. A constant discharge is fed into the upstream inlet. The downstream outlet has a fixed water surface elevation as boundary condition. Three backwater profiles are shown in the bottom cartoon where downstream water surface elevation is above, equal to, or below that of normal flow.





**Figure 3.** Setup of the bump test (flow around a mouth bar). A smooth Gaussian-shape bump is placed in a straight channel where we observe two scenarios of flow interacting with the bump topography: (i) acceleration over the bump or, (ii) deceleration over the bump and diversion around the bump. The lower plot is taken from Edmonds and Slingerland (2007), where they show the transition between the two scenarios as channel mouth bar grows in height.





**Figure 4.** Channel geometries for the single bifurcation test. Group A (A1, A2 and A3) and group B (B1, B2 and B3) have smaller domain and input discharge. Within group A we vary the ratio of depth between the two downstream branches while keeping width constant. Within group B we vary the ratio of width between the two downstream branches while keeping the depth constant. Within group C (C1, C2 and C3) we vary width and depth at the same proportion while keeping the summation of cross-sectional area constant.







Interactive Discussion



**Figure 6.** Results from the straight channel test. Cross-stream averaged water surface profile calculated by FlowRCM is compared to the numerical solution of backwater equation. (a) Downstream water surface elevation is fixed at higher than that of normal flow (M1 curve). (b) Downstream water surface elevation is fixed at that of normal flow. (c) Downstream water surface elevation is fixed at that of normal flow. (M2 curve).











**Figure 7.** Water velocity magnitude (normalized by the upstream velocity magnitude) and water surface elevation contour plots (bump height at 20, 60 and 90 % flow depth). Flow direction is from top to bottom. Notice the deformation of water surface and the development of low velocity region in front of and behind the bump.





**Figure 8.** Both FlowRCM and Delft3D predict a rising then falling normalized flow velocity (measured at the top of the bump) as normalized bump height goes to 1. FlowRCM also captures the turning point where rising changes to falling (~ 60 % flow depth). Flow velocity is normalized by the upstream velocity magnitude, and bump height is normalized by water depth.





**Figure 9.** The discharge asymmetry and the cross-sectional areas asymmetry of the two bifurcation branches compare well between FlowRCM and Delft3D simulations. Overall the asymmetry of discharge is proportional to the asymmetry of cross-sectional area.





**Figure 10.** Velocity and water surface contour plots from Run C3. In dashed square region is the qualitative difference between FlowRCM and Delft3D results: upstream of the front tip of the island, while Delft3D exhibits a low velocity zone with a high water surface elevation, FlowRCM exhibits a high velocity and a low water surface elevation.





**Figure 11.** Hydrodynamic test calculating flow patterns over the synthetic bathymetry of Wax Lake Delta (WLD) in Louisiana. **(a)** Water surface profiles from the two models have similar distribution but FlowRCM predicts a significantly higher gradient. **(b)** Velocity contour maps from model results; FlowRCM and Delft3D give similar flow distributions, and predict "hot zones" where water velocity is significantly higher in channels at the same locations.





**Figure 12. (a)** red dashed square marks one of the regions where FlowRCM display strong local effects **(b)** detailed view from both models' results demonstrate the "local effects" created by FlowRCM, which are not present in the Delft3D simulation.





**Figure 13.** Flow test results using DeltaRCM generated delta topography. The water surface elevation and unit discharge from the outputs of the RCM model are compared to the results from running Delft3D hydrodynamic module with the same topography and input conditions. The results show that: (1) both models give similar discharge distribution throughout the topography; (2) both models give similar water surface profile: same magnitude, although RCM has a more consistent surface profile and more pronounced gradient across the channel into the floodplains.





**Figure 14.** The dynamic balance between water surface gradient and flux distribution. On the left the dashed square shows the region of enlarged areas. On the right it shows the oscillations of flow velocity between iterations in the enlarged areas.

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Cross-sectional view at channel mouth.



Some troughs become established channels and the ridges on the side become levees.

**Figure 15.** Illustration of the mechanics of bifurcation formation in the DeltaRCM. (i) flow expands and sediment deposits with reduced flow velocity, which creates a wide lunate bar with noisy surface; (ii) the irregular topography of the bar forms "ridges" and "troughs" where troughs attract more water flux than ridges; (iii) the enhanced flow rate in troughs prevents sediment from settling while ridges continue to experience deposition; (iv) the process reaches equilibrium by the feedback mechanism between water surface elevation and water flux. The few paths established from the troughs outcompete the others.

Stage: troughs and ridges

Stage: channels and levees

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