Effect of sediment transport boundary conditions on the numerical modeling of bed morphodynamics

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ABSTRACT

Experimental sediment transport studies in laboratory flumes can use two sediment-supply methods: an imposed feed at the upstream end or recirculation of sediment from the downstream end to the upstream end. These methods generally produce similar equilibrium bed morphology, but temporal evolution can differ. The adjustment of natural rivers to sediment supply usually includes both modes. Nevertheless, computer models of river morphodynamics typically use a sediment-feed boundary condition, and can therefore produce inaccurate bed morphology. The effect of sediment transport boundary conditions on bed-form dynamics was analyzed through numerical experiments using the two-dimensional, depth-averaged sediment transport model Telemac2D-Sisyphe of the open-source TELEMAC-MASCARET system. Two different boundary conditions were imposed at the inlet (a constant sediment feed and sediment recirculated from the outlet) for two bed-form scales (dunes and bars). Sediment transport boundary conditions greatly influenced dune development. The sediment-recirculating condition produced a more dynamic bed morphology with dunes of higher amplitude. The resulting zones of higher shear stress had a direct impact on the hydrodynamics and patterns of sediment transport. In the case of the bar bed morphology, the simulated bars had similar mean length and height for both sediment boundary conditions. However, the sediment-recirculating case produced a more

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dynamic bed, where the dominant bar length varied over time. Finally, the simulated bed morphology with bars, agreed much better with that observed when using a calibrated sediment transport equation to match sediment transport rates instead of the standard empirical sediment transport equations available in literature.

INTRODUCTION

The impact of sediment transport boundary condition for mobile-bed flumes, upstream feed or sediment-recirculation, on sediment transport rates and bed morphology has been studied to clarify their suitability relative to the conducted sediment transport experiment (Parker and Wilcock 1993; Parker 2003). Parker and Wilcock (1993) showed that the sediment-feed case should be used for analyzing channel response to an imposed sediment transport rate, whereas sediment recirculation is more suitable when analyzing the sediment transport response to a certain imposed hydraulic condition. Further, Parker and Wilcock (1993) demonstrated that in the case of uniform sediment, both boundary conditions yield the same equilibrium bed morphology.

For experiments conducted in sediment-recirculating flumes, Lisle et al. (1997) found random rises and falls in sediment transport rate. Abad and Garcia (2009b) observed variations of one order of magnitude above and below the mean sediment transport rate in a flume with meanders of high-amplitude. Abad and Garcia (2009b) explained that the nature of such variations is a consequence of the constantly changing local hydrodynamics caused by progression of bed forms. The recirculation of sediment induces fluctuations in sediment discharge at the flume inlet that could produce more variable and dynamic bed forms compared to the case of constant sediment feed at the inlet. This presents important implications not only for the hydrodynamics because of change in roughness caused by bed forms (Engelund and Fredsoe 1982; van Rijn 1984; Shimizu et al. 2009), but also for the bed morphology itself (Best 2005).

With the increasing emphasis on numerical modeling of river hydrodynamics and bed evolution, the type of sediment transport boundary condition used (sediment-feed or sediment-recirculation) requires careful consideration. For example, Shimizu et al. (2009) employed a vertically (width averaged) two-dimensional model to study the development of dunes as a response to a hydrograph, and they used a periodic boundary condition for flow and sediment that resembles the case of sediment-recirculation. For the case of bar development, numerical experiments were carried out by Nelson and Smith (1989) using a sediment-recirculation approach and Defina (2003) using a sediment-feed approach based on sediment transport equilibrium. It is important to note that Lanzoni (2000) in his laboratory experiments on free bars observed the attainment of a stable condition where free bars continued to develop in a sustained way along the flume. This is difficult to reproduce numerically, since small fluctuations in flow and bed elevation that promote bar development are not simulated. Hence, Defina (2003) imposed an initial bed-elevation disturbance at the flume inlet to enhance bar development.

This paper presents numerical experiments carried out with the two-dimensional (2D), depth-averaged model Telemac2D-Sisyphe, of the open-source TELEMAC-MASCARET system version 6.2 (Hervouet 2000b; Hervouet 2007), to examine the effect of upstream sediment-transport boundary conditions on simulated bed-form development. Hereafter, the sediment-feed scenario is named Constant Sediment Boundary Condition (CSBC), while the sediment-recirculation scenario is named Recirculating-Sediment Boundary Condition (RSBC). The simulated test cases are published flume experiments of dune development in a meandering channel and free-bar development in a straight channel. Since a 2D model cannot accurately simulate the complex three-dimensional flow over dunes (Frias and Abad 2013), the purpose of the dune experiments was to determine the differences in simulated bed morphology of each boundary-condition scenario. In the case of bars, a 2D model is suitable (e.g., Defina 2003; Crosato et al. 2012), and the simulated bar geometry was therefore also compared to that observed. A point to emphasize about 2D hydrodynamic and morphodynamic models is their increasing application for riverine analyses in recent years (Legleiter et al. 2011). For example, Asahi et al. (2013) utilized a 2D model for studying the patterns of erosion and accretion in meandering channels. Chen and Duan (2008) modeled the migration of the West Jordan River, Utah, finding good agreement between simulated cross sections and those measured. Sloff and Mosselman (2012) analyzed the hydrodynamics and morphologic behavior at a bifurcation utilizing 2D and 3D models. Although the use of 3D models is also increasing, these models are mainly used for research purposes and have limited practical application. The effects of three-dimensional flow phenomena, such as secondary flows, on bed morphology can be considered with parameterized corrections (e.g., Engelund 1974).

METHODS

Experimental data

Dune bed-form

Abad and Garcia (2009b) conducted experiments to study the hydrodynamics and bed morphology of upstream and downstream oriented meander bends in a sediment-recirculating meandering flume with a planform represented by a Kinoshita curve (Parker et al. 1983). The channel had three 10 m-long bends with a width of 0.6 m (see Figure 1). The experiment selected for numerical modeling had upstream-skewed bends (that is, flow is from left to right in Figure 1). The discharge $Q = 0.025$ m^3/s and the average flow depth $H = 0.15$ m. The bed material was well-sorted quartz sand with a median particle size $D_{50} = 0.832$ mm and a geometric standard deviation $\sigma_g = 1.23$ mm. The measured particle density $\rho_s = 2,570$ kg/m^3 and the measured bed porosity $\lambda_p = 0.4$. Sediment was recirculated by pumping the sediment collected at the downstream trap to a sand distribution channel (SDC) at the upstream end of the flume (Figure 1). Sediment transport rates were measured by directing the flow coming from the SDC into a sediment container with a sieve (a mesh of 100 microns was used) that allowed water to pass through while retaining the sediment particles.

The experiment started from a flat bed, and a dynamic equilibrium of the longitudinal slope of the free surface and bed was reached after approximately 100 hours (Abad and Garcia 2009b). The measured average bedload $q_b = 1.05 \times 10^{-6}$ m^2/s. Dune-like bed forms developed during the experiments, which did not change the average longitudinal bed slope, but did change the transverse bed slope at a cross section. The dune dynamics showed processes of migration and amalgamation typical of dune development (Coleman and Melville 1994). The migration of dunes not only changed the local bed morphology but also the flow structure (Abad et al. 2013). The measured sediment transport rate varied one order of magnitude above and below the average value. Dunes migrated at an average celerity of 0.26 m/h, with an average height of 0.065 m and an average wave length of 1.04 m, see Table 1.

Bar bed-form

Lanzoni (2000) performed a set of 11 experiments on bar formation in a sediment-recirculating flume with a length of 55 m, a width of 1.5 m, and a depth of 1 m. Bed material was composed of well-sorted quartz sand with a geometric mean diameter $d_g = 0.48$ mm, $\sigma_g = 1.3$ mm, and $\rho_s = 2650$ kg/m^3. The sediment was recirculated by pumping the sediment collected at the downstream trap to a storage tank installed at the upstream end of the flume. The increase in weight of this tank was continuously recorded to determine sediment transport rate. At a preset weight the storage tank automatically opened and the sediment was dropped into the flume via a diffuser.

Experiment P1505 was selected for the numerical modeling study, which had a flow discharge $Q = 0.03$ m^3/s and an average depth $H = 0.044$ m. The initial bed was almost flat, and the experiment was stopped when equilibrium conditions were reached after 28 hours. At that time, bed slope was equal to water surface slope, and sediment discharge and bar geometry and celerity obtained nearly constant values. The average volumetric sediment discharge, including pores, was $Q_s = 94.5$ L/h, which is equivalent to a unit discharge $q_s = 7.0 \times 10^{-6}$ m^2/s without pores. The mean bar wavelength (L_b), height (H_b), and celerity (c_b) were 10.0 m, 0.07 m, and 2.8 m/h, respectively.

Numerical model

The numerical experiments were carried out using the computer models Telemac2D and Sisyphe, which couple the equations for two-dimensional, depth-averaged free surface flow with sediment transport and Exner equations for the computation of bed evolution. Telemac2D and Sisyphe are modules of the TELEMAC-MASCARET integrated suite of solvers for use in the field of free-surface flows (Hervouet 2000b; Hervouet 2007).

Telemac2D has been widely used. Hicks et al. (2005) analyzed the impacts of a historical flood in the central Appalachians, where they found that the fluvial impacts were consistent with the patterns of shear stress computed with Telemac2D. Hervouet (2000a) modeled the flood produced by the Malpasset Dam break accident. Horritt et al. (2007) performed a sensitivity analysis of Telemac2D and compared the results to those produced by a finite volume model. They concluded that Telemac2D exhibited less sensitivity to Manning roughness coefficient, but more sensitivity to the mesh resolution compared to the finite volume model. Further, when simulating the flow in meandering channels, Horritt (2000) found that mesh configuration (e.g., well-shaped triangles without small internal angles) was more important than the resolution of the mesh. Wang et al. (2014) showed that Telemac2D and Sisyphe can adequately simulate bar dynamics in large amplitude meanders.

Hydrodynamic model

Telemac2D solves the depth-averaged St. Venant equations of free surface flow. Equations (1), (2) and (3) describe the conservation of mass and momentum in x- and y-direction, respectively:

$$\frac{\partial h}{\partial t} + \vec{U} \cdot \nabla h + h \nabla \cdot \vec{U} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + \vec{U} \cdot \nabla u = F_x - g\frac{\partial z}{\partial x} + \frac{1}{h}\nabla(h\nu_t \nabla u) \tag{2}$$

$$\frac{\partial v}{\partial t} + \vec{U} \cdot \nabla v = F_y - g\frac{\partial z}{\partial y} + \frac{1}{h}\nabla(h\nu_t \nabla v) \tag{3}$$

where $\vec{U}$ is the vector of depth-averaged velocities u and v in x- and y-direction, h is the water depth, ν_t is the effective diffusion (sum of turbulent and molecular diffusivities), and F_x

and F_y account for the external forces such as the bed friction, drag caused by atmospheric phenomena, and Coriolis force. Here, bed friction was the only force considered, which is computed as

$$F_x = \frac{1}{2h} C_f u \sqrt{u^2 + v^2} \text{ and } F_y = \frac{1}{2h} C_f v \sqrt{u^2 + v^2} \tag{4}$$

where C_f is the dimensionless friction coefficient.

Telemac2D solves the governing equations (1) to (3) on an unstructured mesh and uses both finite volume and finite element methods (Hervouet 2007; EDF R&D 2010). In this study the finite element method was utilized.

Bed morphology model

Sisyphe is the sediment transport and bed morphology module of the TELEMAC-MASCARET system (Villaret and Tassi 2014). Sediment transport rates are computed by a set of empirical sediment transport capacity equations, and the evolution of the bed is computed using the Exner equation:

$$\frac{\partial z}{\partial t} = -\frac{1}{1-\lambda} \nabla \cdot \vec{q} \tag{5}$$

where z is bed elevation, λ is porosity, and $\vec{q}$ is the vector of unit sediment discharges in x- and y-directions.

Three key aspects must be considered for computing the magnitude and direction of bed load: the effect of the local bed slope, the bed-shear stress partitioning into components affected by skin friction and drag from bed forms, and secondary flow effects. Sisyphe includes methods for evaluating all three aspects. The deviation of the bed load direction from the flow direction depends on the secondary flow and the bed slope (Talmon et al. 1995):

$$\tan \alpha = \tan \delta - T \frac{\partial z}{\partial n} \tag{6}$$

where α is the angle between sediment transport and flow directions, $\tan\delta$ is the deviation of the bottom shear stress direction from the flow direction caused by the secondary flow, n is the direction normal to the flow, and T is a parameter that depends on the Shields number θ.

The used secondary-flow correction is (Engelund 1974):

$$\tan\delta = A\frac{h}{R} \tag{7}$$

where R is the radius of curvature of the flow, which is computed as a function of the average velocity and the transverse slope of the water surface (Villaret and Tassi 2014). The coefficient A has a default value of 7, but was calibrated as $A = 12$ in the simulation of the dune bedform study. It should be noted that this correction is only necessary for depth-averaged models (Abad et al. 2008) and is only used here to modify the sediment transport. Corrections for the effect of secondary flows on simulated 2D primary flow (e.g., Finnie et al. 1999) were not considered.

The parameter T in the bed-slope correction term is given by Talmon et al. (1995) as:

$$T = \frac{1}{\beta_2\sqrt{\theta}} \tag{8}$$

where β_2 is an empirical coefficient with a default value of 0.85 but was calibrated in the numerical experiments as $\beta_2 = 1.6$ for both dune and bar experiments.

The effect of the bed slope on sediment transport rate is accounted for by modifying the critical Shields parameter as (Soulsby 1997):

$$\frac{\theta_{\beta c}}{\theta_c} = \frac{\cos\psi\sin\beta + \sqrt{\cos^2\beta\tan^2\phi_i - \sin^2\psi\sin^2\beta}}{\tan\phi_i} \tag{9}$$

where $\theta_{\beta c}$ is the corrected critical Shields number for a sloping bed, θ_c is the critical Shields number for a flat, horizontal bed, ϕ_i is the angle of repose of the sediment, β is the bed slope, and ψ is the angle between the flow direction and the bed slope direction.

The total bed shear stress is caused by skin friction and form drag. The former is used to calculate the bedload transport rate and is expressed here as $\tau' = \mu\tau_0$, with $\tau_0 = 0.5\rho C_f(u^2 + v^2)$ is the total bed shear stress and the fraction μ is:

$$\mu = \frac{C_f'}{C_f} \tag{10}$$

where C_f is the friction coefficient representing the combined form drag and skin friction, and C_f' is the friction coefficient representing only skin friction, which is computed by assuming a flat bed as:

$$C_f' = 2\left(\frac{\kappa}{\log(12h/k_s')}\right)^2 \tag{11}$$

where κ is the von Kármán coefficient, the roughness height $k_s' = \alpha D_{50}$, and the coefficient α is used as a calibration parameter. The calibration of α for both bed morphologies, dunes and bars, was performed by trial and error until the observed sediment transport rate was reproduced. For dune experiments $\alpha = 37$ and for bars $\alpha = 3.6$.

The utilized version of Sisyphe (version 6.2) does not include a sediment-recirculation boundary condition. The source code of Sisyphe was therefore modified. Similarly to laboratory experiments in flumes, the simulated transverse distribution of unit sediment transport at the the model outlet was uniformly redistributed at the model inlet.

NUMERICAL EXPERIMENTS

Validation of the hydrodynamic model

Because sediment transport and bed morphology are strongly influenced by flow hydraulics, it is important to verify that the hydraulics are accurately simulated. The flow over bars in a straight flume (Lanzoni 2000) was mainly affected by the bed forms themselves. However, the flow in the meandering flume experiments (Abad and Garcia 2009a; Abad and Garcia 2009b) was strongly influenced by the planform of the flume, which exerts a stronger forcing on the mean flow. In that sense, it was very important to perform the comparison of the 2D depth-averaged model to validate its results against the measurements of Abad and Garcia (2009b) experiment.

Flow validation was performed for the flat, fixed bed experiment Q25H15U (Abad and Garcia 2009a), which had a discharge $Q = 25$ L/s, a reach-averaged water depth $h = 0.15$ m, and a longitudinal water slope of 0.0004. The reason for choosing the hydrodynamics of the flat bed case presented in Abad and Garcia (2009a) for validation, instead of the case with bed morphology is the availability of data. The flow in the flat bed case is steady and velocities could therefore be measured across entire sections, whereas flow over a mobile bed is unsteady due to the migration of dunes and only single point velocity measurements are available in a given section. Figure 2 presents the comparison of the simulated and measured depth-averaged longitudinal component of velocities between cross sections CS-10 and CS-20 (see Figure 1 for their locations). Velocities are normalized by the reach averaged velocity $U = 0.28$ m/s. Profiles are plotted in the direction normal to the channel centerline. The transverse profiles and velocity magnitudes computed by Telemac2D agree well with those measured. Note that Lien et al. (1999) also found that two-dimensional models without a secondary flow correction to the hydraulics can accurately predict the depth-averaged flow in sharp meander bends. Therefore, it is assumed that Telemac2D will also accurately simulate the flow for the mobile bed scenario presented in the next section. It must be kept in mind that the secondary flow correction to sediment transport is utilized..

Dune bed forms

The computational mesh comprised 39,555 triangular elements with an average area of 4.8 cm^2 and an average edge length of 3.3 cm. For the 60 cm wide flume there were on average 18 cells across its width. Time step was set to 0.02 s. An important aspect of modeling bed morphology is proper calibration of the sediment transport rate since a numerical model should minimally reproduce the same magnitude of sediment transport rate to reproduce the evolution of observed bed forms. For example, van Rijn (1984) showed that bed form geometry and celerity are directly related to sediment transport rate. The

sediment transport formulas implemented in Sisyphe could not accurately reproduce the measured sediment transport. It was found that the sediment transport rate calculated by the Wong and Parker (2006) sediment transport equation agreed best with those measured in this specific experiment, which was then coded into Sisyphe. Further improvement was obtained by adjusting the variable μ (Eq. 10) through calibration of the coefficient α in the roughness height of the bed material k'_s; the calibrated value was $\alpha = 37$ (RSBC scenario).

Secondary flow effects on bed morphology were simulated by setting $A = 12$ (Equation 7), and transverse bed slope effects were simulated by setting $\beta_2 = 1.6$. The values of A and β_2 were calibrated by trial and error until the transverse bed slope in the bends was similar to that observed in Abad and Garcia (2009b).

The numerical modeling started from a flat bed with a streamwise slope that equaled the observed slope of 0.0017 (Abad and Garcia 2009b). The simulation duration was 260 hours. The first 200 hours of the simulation were used to establish a quasi-steady equilibrium of sediment transport and bed morphology. Hence, the below analysis of the numerical modeling results uses data from simulation time 200 to 260 hours.

The simulated bed morphology for the RSBC scenario averaged over 60 hours is shown in Figure 3 for the central bend located between cross sections CS-10 and CS-20. The left plot in Figure 4 shows a typical instantaneous configuration of the bed. The CSBC scenario was modeled by imposing the average bedload measured in the experiment at the inlet, $q_s = 1.06 \times 10^{-6}$ m^2/s for two cases. In the first case, CSBC1, the values of the parameters A, β_2 and α were the same as those in the RSBC scenario. Since CSBC1 did not reproduce the correct amount of sediment transport at the outlet, the parameter α was calibrated in the second case, CSBC2, to reproduce the same magnitude as the reference experiments (Abad and Garcia 2009b). The value is set to $\alpha = 55$. The simulated bed morphology for the CSBC1 and CSBC2 scenarios are shown in Figures 3 (average) and 4 (instantaneous). Note, the average fraction of skin friction to total friction (μ) is 0.58 for RSBC and CSBC1, computed with Equations (10) and (11), whereas it is 0.71 for CSBC2.

Bar bed forms

The mesh dimensions of the initial computer model of the Lanzoni (2000) free-bar experiments matched the experimental flume dimensions (length of 55 m and width of 1.5 m). The mesh comprised 6,941 triangular elements with an average area of 12.7 cm^2 and average side length of 5.4 cm. The time step was set to 0.1 s. The Meyer-Peter and Müller (1948) formula was used to compute the bedload discharge, since it is the one that gives the closest magnitude to sediment transport rate measured in Lanzoni 2000 experiments; the grain roughness height, k', was used as a calibration parameter to replicate the exact measured bedload ($q_b = 7.0 \times 10^{-6}$ m^2/s); the calibrated value was $\alpha = 3.6$. Similar to Defina (2003), a small bump on the bed at the left margin of the inlet was introduced at start-up to initiate the development of bars. However, unlike the Lanzoni (2000) experiments, the simulated bar development and dynamics could not be sustained; after a certain duration, all the simulated bars migrated out of the computational domain. Though, the sediment-recirculation boundary condition introduces a perturbation in the upstream bed elevation, it is not enough to sustain bar development.

Since the main interest is to analyze the effect of RSBC and CSBC, two modeling scenarios were examined: a) the presence of a permanent perturbation for the development of bars, which is achieved by adding a bend upstream of the straight channel (labeled BPC for bend-perturbation channel, see Figure 5); and b) an extended channel with a length of 117.5 m similar to Defina (2003), which is labeled LC (long channel) where the initial perturbation is again a bump on the bed at the inlet. Figures 5 and 6 show the simulated evolution of bed morphology for the BPC and LC cases, respectively. Both results correspond to the RSBC scenario. Bars were continuously produced in both RSBC scenarios and BPC-CSBC scenario, but not for the LC-CSBC scenario.

ANALYSIS OF THE NUMERICAL EXPERIMENTS

Dune bed morphology

Figure 3 shows that the simulated time-averaged bed configuration is slightly different for the RSBC and CSBC scenarios. However, for the case of instantaneous bed forms (Figure 4) this difference is even bigger, which means that sediment transport calibration plays a major role for instantaneous bed roughness. For the RSBC case, the mean bottom elevation of the pool downstream of the apex near the outer bank is lower than -0.09 m, and the elevation of the bed forms on the point bar near the inner bank exceeds 0.17 m. The CSBC1 and CSBC2 cases produce a more uniform bed, the average elevations of the pool and bed-form troughs drop below -0.09 m only in some spots, and the dunes have a more regular shape as can be observed downstream of the apex. Figure 7 shows a more detailed comparison of the bed forms simulated by the RSBC, CSBC1 and CSBC2 scenarios. The temporal evolution of the simulated bed profiles between cross sections CS-10 and CS-20 shows that the dunes in scenario RSBC have greater amplitude than the ones from CSBC1 and CSBC2 scenarios.

A Fourier analysis was performed on the simulated longitudinal bed profiles shown in Figure 7. The profiles where detrended by the spatially mean bed elevation to remove the point bars and only retain the dunes. The resulting spectra are shown in Figure 8. The plotted bands correspond to the envelope of the spectra for dune wave lengths, where the vertical limits represent the maximum and minimum spectral values determined during a period of 60 hours. The width and height of the plotted bands are markedly different near the flume sidewalls. This indicates not only a greater range in dune wave lengths but also a greater range in dominance of the different wave lengths, hence greater bed morphodynamics for the RSBC scenario as compared to both CSBC scenarios.

The dominant wave lengths (L_d) of the simulated bed forms were obtained from the Fourier analysis, and are listed in Table 1. The amplitude of the bed forms cannot be determined from the Fourier analysis. Therefore, the height of the dunes was computed by averaging the height of bed forms in the detrended streamwise bed profiles. The average dune height (H_d) for each scenario is also reported in Table 1. It should be noted that a 2D computer model cannot accurately simulate dune geometry, because it cannot account for important three-dimensional flow effects (Frias and Abad 2013). However, this is outside the scope of the presented research, which compares the impact of sediment transport boundary conditions.

The RSBC scenario simulates dunes with an average amplitude that is 66% larger than that simulated by the CSBC1 and CSBC2 scenarios. This should have a direct impact on the local hydrodynamics and sediment transport rates. Hence, the simulated bed shear stress and sediment transport discharge were averaged over the flume width between sections CS-5 and CS-25 every 10 minutes for the last 60 hours of the simulation. The mean and standard deviation of the resulting time series were then computed for each section. Figures 9A and 9B plot the bed shear stress and sediment discharge values one standard deviation above and below the mean for both RSBC and CSBC scenarios. The RSBC scenario produces both greater and a wider range of bed shear stresses (Figure 9A). These results are similar to those presented by Abad et al. (2013), who performed three-dimensional numerical modeling using the same experimental data but for the case with and without bedforms. This directly impacts the sediment transport patterns along the channel; Figure 9B shows the range in sediment transport rate along the flume between cross section CS-5 to CS-25 resulting from dune migration and the corresponding shear stress variations. The mean and standard deviation of the sediment transport rate are summarized in Table 2 for cross sections CS-05, CS-15 and CS-25 (located at the apex of each meander bend). The standard deviation of the sediment transport rate for the RSBC is on average more than twice as large at a meander bend apex than that for CSBC1, and almost twice as large than that for CSBC2. The pattern is the same at the outlet. Note, since the mean sediment transport rate was calibrated for the RSBC and CSBC2 scenarios in the first 200 hours of the model simulation, the average sediment transport at the outlet can differ in the subsequent 60-hours analysis period because of the continuously changing bed morphology. For RSBC there is an increase of 35% in mean sediment transport rate, whereas there is little change in mean sediment transport rate for

CSBC2. However, for the uncalibrated CSBC1 scenario, the average unit sediment transport rate at the outlet is 31% smaller than that observed in the first 200 hours of the simulation, and is 14% smaller in the next 60 hours. Also note, the sediment transport is more variable for the constant sediment boundary condition scenario with calibrated sediment transport rate (CSBC2) than the same scenario without calibration (CSBC1). The standard deviation of sediment transport rates for CSBC2 is on average 30% larger than that for CSBC1.

Table 2 and Figure 9 show that the simulated bed morphology for the RSBC scenario is generally more dynamic. Figure 10 compares the time-average spatial distribution of bed shear stress in the middle meander bend for each scenario. The RSBC scenario produces larger regions of higher and lower bed shear stresses compared to the CSBC scenarios, particularly in the region downstream of the bend apex. Note, even though the unit sediment discharge is larger for CSBC2 than for CSBC1, due to larger values of μ, the shear stresses are higher for the CSBC1 scenario. An explanation of such behavior in the shear stress may be given by the different nature of bed morphology developed for CSBC2 scenario. Table 1 shows that dunes in CSBC2 have a larger wavelength but similar amplitude than CSBC1, as a consequence dune crests with higher shear stress are less frequent in CSBC2 scenario. The different dune dynamics between CSBC1 and CSBC2 is also shown in Figure 8. This difference might be important for simulating planform shapes of high curvature channels.

Bar bed morphology

Table 3 compares the simulated bar geometry of Lanzoni (2000)'s P1505 experiment for the LC and BPC scenarios and for each boundary-condition type. The length, height, and celerity of the bars were obtained from Fourier analysis (Figure 11). The simulated mean bar length for the four modeling scenarios is in general about 20% smaller than that observed, whereas the simulated bar height is about 30% to 50% smaller than that measured by Lanzoni (2000).

Figure 11 shows the simulated bed elevation along the left sidewall of the flume at three points in time for each modeling scenario. For the LC channel there is not a significant difference between CSBC and RSBC scenarios for the first 40 hours of simulation (Figures 11A and 11B). However, after 40 hours the RSBC scenario produces a state of continuous bar development, whereas the CSBC scenario produces a flat bed. For the case of the BPC channel, the CSBC scenario shows a more uniform temporal and spatial development of bars (Figure 11B) compared to the RSBC scenario (Figure 11C). A Fourier analysis of the simulated bed profile along the left bank was carried out over the downstream 35 m of the channel for the two BPC scenarios. The Fourier transforms of the bed profiles are shown in Figure 12. The dominant wave length of the bars at different simulation times is very consistent for the CSBC scenario (about 8.5 m, see also Table 3), but varies between 6.5 and 8.5 m for the RSBC scenario.

DISCUSSION

Inlet boundary conditions comprising small periodic fluctuations are critical for some hydrodynamics problems. For example, in the modeling of turbulent flows, the turbulence characteristics within a computational domain can be strongly linked to the inlet boundary conditions, which requires an upstream condition representing turbulence structures (de Villers 2006). For Large Eddy Simulation (LES) the turbulence structures from a plane inside the domain are typically mapped to the inlet. Similarly, the modeling of sediment transport problems needs to address the propagation of periodic features such as bed forms. A periodic or fluctuating condition at the inlet could lead to a different evolution of bed forms compared to a constant sediment-feed condition. Since the bed evolution depends directly on the sediment-flux divergence and hydrodynamics and sediment transport are strongly linked, the effect of the inlet boundary condition should propagate through the entire domain.

The presented numerical experiments support this statement, because differences in the simulated evolution of dunes and bars are observed between CSBC and RSBC scenarios. The type of sediment transport boundary condition has a greater effect on the development of dunes than bars, in the sense that the amplitude and length are more affected for the former bed forms. Though, this needs to be verified with three-dimensional modeling. The use of RSBC leads to the development of dunes of higher amplitude, which were about twice as large as those in the CSBC scenario. As a consequence, the shear-stress patterns differ. Especially, RSBC produces larger regions of both higher and smaller shear stresses (Figure 10).

For the case of the bar bed morphology, an important difference between RSBC and CSBC is that the former leads to a condition of continuous bar development in the LC scenario, similar to that observed in the experiments performed by Lanzoni (2000). Table 3 shows that the average geometrical characteristics of the simulated bars for the BPC modeling scenarios are similar but smaller than those measured by Lanzoni (2000). For the BPC channel both RSBC and CSBC scenarios simulate a sustained production of bars over time. However, the RSBC produces increased bed-form dynamics with a wider range of bar wave lengths as is shown by the Fourier transform of the longitudinal bed profile (Figure 12).

CONCLUSIONS

Careful selection of boundary conditions in sediment transport computer models is essential because of the advective nature of the problem (Federici and Seminara 2003). This is even more important when modeling the development of bed forms in computational domains of finite length. The effect of constant sediment-feed and sediment-recirculation boundary conditions was analyzed for two bed-form scales, dunes and bars, using the 2D, depth-averaged model Telemac2D-Sisyphe (version 6.2) of the TELEMAC-MASCARET System.

To more accurately model bed morphodynamics the simulated mean sediment transport rate needs to agree with that observed. A calibrated sediment transport equation in the modeling of the dune dynamics experiments of Abad and Garcia (2009b) produced sediment transport and shear stress patterns with greater variability and larger bed forms than the initial approach for the modeling, whithout a calibrated equation.

The sediment transport boundary condition influenced both the simulated dune and bar bed-morphology. In the case of dunes, the sediment-recirculation boundary condition produced a wider range of dune lengths and larger dune heights. This results in a stronger interaction between hydrodynamics, sediment transport and bed morphology for the sediment-recirculation boundary condition as zones of higher and lower shear stresses are present, which yields a greater variability in sediment flux.

Telemac2D-Sisyphe was unable to sustain a continuous development of bars as observed in the experiments of Lanzoni (2000) with a 55 m length channel, even when the RSBC is utilized. However, with a longer channel (LC case) similar to Defina (2003), the RSBC produced a condition where bars were constantly re-generated over time. A permanent perturbation in the form of a 180-degree bend at the upstream end of the channel (BPC case) produced a constant development of free bars for both sediment transport boundary conditions. This allowed a more detailed analysis of the development of bars for constant-feed and sediment-recirculation boundary conditions. The type of sediment transport boundary condition minimally affected bar geometry. However, the temporal evolution of the bars was more dynamic as the bar wave lengths are more variable for the sediment-recirculation boundary condition.

The presented findings have implications for the modeling of river morphodynamics. In general, a constant sediment transport rate is imposed at the inlet, which may result in an unrealistic bed morphology. The sediment-recirculation boundary condition has shown to produce bed forms that agree better with those observed and that are more dynamic. Additionally the modeling of CSBC1 and CSBC2 scenarios for dune bed forms shows the impact of the calibration of the parameters for sediment transport on the evolution of the bed.

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