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Analysis of pool-riffle dynamics through numerical morphological modelling

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ABSTRACT: An issue that has puzzled geomorphologists for a long time is the ubiquity and persistence of pool-riffle sequences in rivers over a wide range of slope and substrate conditions. In particular, the mechanisms responsible for the self-maintenance of pools and riffles have been the subject of intense research and controversy. Most of the investigation has focused on inferring the observed morphological dynamics based on some characteristics of both the spatial and temporal variability of the flow, often overlooking intermediate sediment transport processes that are responsible for the link between flow and morphology. The main reason of this omission is the inherent difficulty in measuring and predicting transport variables (e.g. fractional transport, bed grain size distribution) over a range of time and spatial scales, even under controlled laboratory conditions. This paper analyses some important aspects of pool-riffle dynamics through continuous simulations of a coupled unsteady 1D flow-morphology- bed sorting model. The model is used to simulate the evolution of a reach with pools and riffles on the Bear Creek, Arkansas, for a one-year period. Based on the detailed model prediction regarding the time and spatial distribution of fractional sediment transport (bedload by size class), bed composition and topography, some important mechanisms controlling pool-riffle maintenance that so far have been omitted in the literature are unveiled and used to propose a more complete explanation for this phenomenon.

Keywords: Pool-riffle, Morphological model, Velocity reversal

1 INTRODUCTION

One of the main complexities of pool-riffle dynamics is that different spatial distribution of erosion and aggradation occur under different flow conditions. Research on the mechanisms responsible for the self-maintenance of pools and riffles has observed that during low and medium discharges aggradation occurs in pools while riffles are eroded. During high discharge episodes this situation is inverted and pool erosion takes place while riffles aggrade (e.g. Lisle 1979; Leopold and Wolman, 1960). The velocity reversal hypothesis (Keller, 1971, after Seddon, 1900 and Gilbert, 1914) emerged as an explanation for this behaviour. This hypothesis states that at low flow the velocity is smaller in the pool than in the adjacent riffles; and with increasing discharge the velocity in pools increases faster, eventually exceeding riffle velocity.

The reversal hypothesis has been investigated in several studies based on the analysis of field (e.g. Keller, 1971; Lisle 1979; Sear 1996; Bhowmik and Demissie, 1982; Thompson and Wohl, 2009;) and laboratory (e.g. Thompson et al. 1999) data, as well as through hydrodynamic numerical simulations (Cao et al. 2003; Harrison and Keller, 2007; Keller and Florsheim, 1993; Carling and Wood, 1994; Booker et al., 2001; Wilkinson et al. 2004; Richards, 1978). Although some results have shown the occurrence of a reversal in a number of flow variables (MacWilliams et. al. 2006; Cao et al. 2003; Lisle, 1979), other have reported no reversal (e.g. Carling, 1991; Richards, 1978) or that reversal was found only in some of the pool-riffle analysed or under some conditions (Carling and Wood, 1994; Wilkinson et al., 2004; Booker et al 2001; Sear 1996). However, most of these researchers agree that at least a convergence of one or some flow variables occur with increasing discharges (e.g. Carling, 1991; Carling and Wood, 1994; Keller, 1971; Richards, 1978; Rhoads et al., 2008, Rodríguez et al., 2004).

In this paper a numerical 1D flow-morphology and bed-sorting model is applied to a 1.1Km long reach with marked pool-riffle sequences. The model is systematically used to illustrate some important mechanisms governing pool-riffle morphodynamics.

2 POOL-RIFFLE SELF-MAINTENANCE

From the perspective of very basic hydraulics concepts (e.g. 1D flow mass conservation equation and quasi-steady simplification) higher velocities in pools will occur only if the flow area in the riffle is greater than that in the adjacent pool. In subcritical flows, water levels are expected to decrease in the riffle due to the higher bottom elevation. Therefore, higher mean velocities in the pool can only be possible in those situations where the shape of the pool cross-section is more contracted than that of the riffle. Several researchers have raised similar concerns (Caamaño et al. 2008; Cao et. al. 2003; Carling, 1991; Carling and Wood, 1994; Bhowmik and Demissie, 1982; Wilkinson et al., 2004).

Another argument challenging the reversal hypothesis is that if the highest shear stresses are exerted in the pools, sediment found in the bed surface of pools should be coarser than in riffles, which is contrary to experience (Bhowmik and Demissie, 1982; USGS, 2003; Hirsch and Abrahams, 1981; Keller, 1971; Lisle, 1979; Richards 1976; Sear, 1996).

The limitations of a reversal hypothesis based on averaged flow variables have driven many researchers (e.g MacWilliams et al, 2006; Thompson et al., 1999; Harrison and Keller, 2007; Thompson and Wohl, 2009) to seek an explanation for the observed behaviour in two and three dimensional flow features. One of the soundest hypotheses found in the literature is based on the convergence of flow in the centre of the channel due to some kind of lateral contraction (MacWilliams et. al., 2006). According to this hypothesis, local velocities are considerably stronger in pools than in riffles during high discharges due to the presence of the constriction. Also, this effect is "convected" downstream in the form of a jet so that it is not restricted to the constriction itself. This is a meaningful argument for explaining some pool-riffle maintenance, but it requires the presence of some sort of flow contraction, and does not explain those cases where pool-riffle are found in reaches with relatively uniform width. Clifford (1993) argues that "even where a clear relationship exists between obstructions and pool-bar topography, most pools in a riffle-pool sequence do not have obstructions with which they can immediately be associated". Booker et al. (2001) observed that near-bed velocities trajectories do not converge into pools, and sediment is routed away from the deepest part of them. Only in one out of four pools the same author has observed flow concentration in the centre of the pool. Conversely, Buffington et al. (2002) have observed that flow obstructions were the most significant mechanisms responsible for pool formation in forest rivers.

3 THE ROLE OF SEDIMENT TRANSPORT

Most of the difficulties for providing reliable predictions of pool-riffle evolution reside on the significant number of variables and physical phenomena involved. Although important progresses have been made in understanding some complex properties of flows in pool-riffle sequences, little attention has been devoted to sediment transport itself. Conclusions on the maintenance of these morphological features have been based virtually solely on flow patterns, neglecting complex sediment transport phenomena, which are the ultimate drivers of morphology. In particular, fractional transport, longitudinal grain sorting, bed level fluctuations and their feedback on flow, and the history of past flows are expected to play a significant role in pool-riffle morphodynamics. If, for instance, a sequence of medium flow episodes is able to produce considerable erosion of the finer fractions in the riffle, pools may have a significant storage of fine material which may be easily entrained while the armoured riffle may be virtually immobile. The deposition of fines in pools by successive medium episodes also reduces its flow area, so that for a given discharge velocities in pools may be significantly different depending on the history of previous episodes. Finally, the hydraulic characteristics of a given pool is highly dependent on the control exerted by the downstream riffle (Richards, 1978; Carling, 1991; Pasternack et al., 2008), and for higher discharges riffle flow may be also controlled by a downstream riffle. As the riffle crests can experience significant fluctuations during floods, the idealized hydraulic characteristics based on fixed bed is at least questionable.

One of the main reasons for this gap between flow and morphology is the difficulty in obtaining synchronous detailed information on variables such as fractional sediment transport rates and bed grainsize distributions over time either in field or in laboratory. In face of these inconveniences, numerical modelling of morphology emerges as an interesting alternative to understand and predict pool-riffle evolution, as it allows the inclusion of different physical mechanisms acting in different time and spatial scales and provides considerably detailed results.

4 MODEL FORMULATION

4.1 *Hydraulic model*

The hydraulic model solves the Saint Venant one-dimensional unsteady flow equations (Liggett & Cunge, 1975):

$$\frac{\partial y}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\frac{Q}{A}\right) + \frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{2A^2}\right) + g\frac{\partial y}{\partial x} + gS_f = 0 \tag{2}$$

where t is the time; x the streamwise coordinate; y the water surface elevation; g the gravitational acceleration; Q the flow discharge; A the flow area; α the non-uniform velocity distribution coefficient; S_f the energy slope. Equations 1 and 2 are solved simultaneously by using a generalized form of the Preissmann four-point implicit finite difference scheme.

4.2 *Sediment transport model*

Sediment transport rates are estimated for individual size fractions using the Wilcock & Crowe (2003) equation. The equation provides the rates of sediment transport by size fractions, incorporating a hiding function to take into account differences of mobility for each grainsize. It also includes a function for the effect of the sand content on the critical shear stress of mean size of bed surface. More details of the model can be found in Wilcock & Crowe (2003).

In one-dimensional models the use of cross-sectional average shear stress may give rise to significant underestimations of sediment transport rate due to the non-linearity of bedload relations. In order to improve the estimation of total sediment transport rate, in this work the cross section is subdivided into vertical strips and the transport formula is applied individually. The cross section transport rate of grainsize i is the sum of transport rate in each strip. Shear stress in each strip is estimated using hydrodynamic information as

$$\tau_m = \gamma R_{hm} S_f \tag{3}$$

where R_{hm} is the hydraulic radio of the individual vertical strip m.

4.3 *Morphological model*

Bed level changes are solved in two steps. First, the one-dimensional sediment continuity equation (Exner equation)

$$\frac{\partial Q_s}{\partial x} + (1-\lambda)B\frac{\partial z}{\partial t} = 0 \tag{4}$$

is solved providing the cross-section averaged values of erosion (or sedimentation) ΔZ. In (4) Q_s is the bedload transport and λ the porosity of the bed material. The second step consists in distributing ΔZ over the cross section. This is done by weighting local ΔZ values as a function of the transport rate in each point on the bed.

4.4 *Grain sorting model*

Substrate grainsize distribution changes are calculated based on the mass conservation of a thin layer of thickness L_a on the bed surface (active layer):

$$(1-\lambda)\left[f_i\frac{\partial z}{\partial t} + \frac{\partial}{\partial t}(F_i L_a)\right] = -\frac{1}{B}\frac{\partial}{\partial x}(Qs_i) \tag{5}$$

where F_i is the fraction of sediment size i in the active layer. This equation has the same form as that used by Hirano (1971), Ribberink (1987), Parker & Sutherland (1990) and Parker (1991). f_i is defined differently depending on whether erosion or deposition occurs. If erosion takes place, the active layer is displaced downwards incorporating the material of the layer immediately below and f_i takes the value of the fraction of sediment size i in the layer below. In the case of aggradation, the control volume of the active layer loses particles as it is displaced upwards so that f_i is equal to the fraction of sediment size i in the active layer. The vertical substrate profile is divided into layers that store a particular grainsize distribution. Several layers are necessary to record the history of successive erosion/sedimentation episodes.

5 MODEL APPLICATION

In this paper the model is applied to a reach of Bear Creek, a tributary of the Buffalo River in Arkansas, USA. Field data for this site was acquired as part of a study on the habitat dynamics in the Lower Bear Creek (USGS, 2003; Rabeni and Jacobson, 1993). The selected reach (Crane Bottom) is 1.1Km long and its downstream end is situated approximately 1Km from the confluence with the Buffalo River. Except for the upstream bend, most of the reach is considerably straight with cross sections of relatively uniform shape, which makes the results of a 1D model more reliable and also ensures that meandering is not the dominant process in the maintenance of the pool-riffle sequence.

Flow data used in this study is presented in Figure 1. The first months during the course of the study (June-December 2001) were relatively dry, with the largest daily mean flow of 10.6m^3/s. For the period between December 2001 and February 2002 two major floods occurred, with discharges of 310 and 460m^3/s. These floods were estimated as approximately 1~2 and 2~4-year recurrence interval, respectively (USGS, 2003). Between February 2002 and June 2002 four flood episodes with recurrence interval of around 1 year occurred.

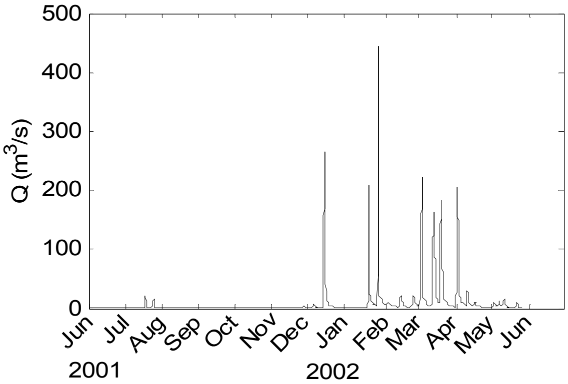

Figure 1. One-year hydrograph in Bear Creek used in the simulation.

Reach-average sediment transport capacity has been used as the upstream boundary condition in Exner equation (sediment supply). Firstly, several simulations have been performed with different flow discharges, and a relationship between flow discharge and fractional sediment transport has been established. Secondly a time series of fractional sediment supply as a function of flow discharge has been used as the boundary condition based on this relation. The choice of reach-averaged transport capacity as the boundary condition is based on the assumption that the reach is under equilibrium conditions. This is considered a good approximation, specially taking into account that alterations driven by changes in sediment supply are associated with longer time scales, in contrast to the few flow pulses used in this simulation. Figure 2 shows the initial bed longitudinal profile of the reach, along with the measured water surface. By observing the water surface profiles in these figures, one can identify three distinct pool-riffle units. The first unit is between sections 0 and 350, and includes the upstream bend. The second and third units are located between sections 350-700 and 700-1000, respectively. These three units will be referred to as PR1, PR2 and PR3.

6 RESULTS

The performance of the model to reproduce bed dynamics in the Bear Creek has been tested in Almeida and Rodríguez (2010, submitted), where results have shown a relatively good agreement between modelled and measured topography at different times during the course of the analysed period. One of the model characteristics of particular interest for the study of pool-riffle dynamics is the ability to capture different bed surface alterations (erosion or deposition) in pools and riffles as a function of discharge and other variables, which is in accordance with field observations.

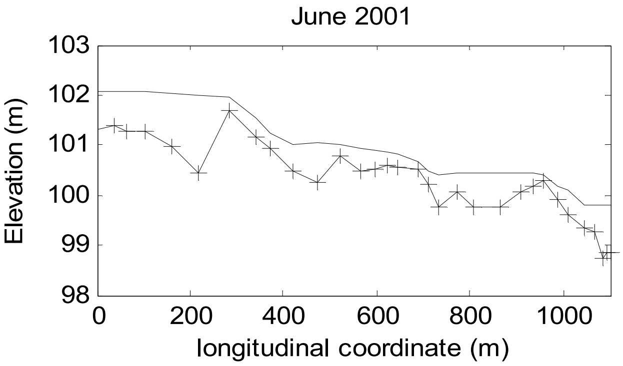

Figure 2. Initial bed and water surface profiles.

6.1 *Sediment transport and velocity reversal*

At this point it is interesting to approach the velocity reversal hypothesis and to investigate its importance in determining sediment transport reversal, which is the ultimate driver for morphological dynamics. Transport reversal is defined here similarly to velocity reversal as the situation when transport in the pool is higher than in the downstream riffle. The relationship between velocity and transport reversal has always been assumed as evident in previous studies, as transport relations may be easily written as a function of velocity. On the contrary, the role played by longitudinal sorting in determining sediment transport reversal has never been analysed.

Figures 3.a to 3.c show the relation between velocity reversal, represented by V_p/V_r, and sediment transport reversal, Qs_p/Qs_r for the three pool-riffle units. Subscripts p and r indicate respectively pool and riffle sections and the sections used in this comparison are at sections 218/283, 473/683 and 809/957. The choice of riffle sections was based on its role as a control for upstream water elevation, while the lowest section upstream of the riffle was chosen to represent the contiguous pool.

Figures 3.a to 3.c may be divided into four quadrants, with centre coordinates (1,1). If velocity reversal can be used as a surrogate for transport reversal, data would be concentrated only in quadrants 1 and 3. That is, when pool velocity is greater than riffle velocity $V_p/V_r>1$, sediment transport in the pool must be greater than that in the riffle ($Qs_p/Qs_r>1$) and, conversely when $V_p/V_r<1$, Qs_p/Qs_r should be also less than unity. The situation depicted in Figure 3 however shows a considerable amount of data in quadrants 2 and 4 (especially in Figures 3.b and 3.c). Quadrant 2 corresponds to a situation where sediment transport is higher in the pool even with higher velocity in the riffle. This is intimately related with differences in sediment size distributions in pools and riffles. If a certain sequence of low/medium flows is able to relocate fine materials from riffles to pools, the erodibility of pools may be considerably increased, enabling transport reversal before a velocity reversal takes place.

The great majority of points in quadrant 2 of Figures 3.a to 3.c correspond to the rising limb of medium/large floods and to the full range of the low discharge episodes in July 2001. Transport reversal in these cases is explained by differences in sediment size distribution in pools and riffles.

Figure 4 is used here to illustrate a situation where transport reversal occurred in PR2 without the need of a reversal in velocity. The figure shows the bed grainsize distribution and the corresponding fractional sediment transport before, during and after the peak discharge of the first flood episode in March 2002.

The effect of longitudinal sorting on transport reversal is evident by comparing the bed grainsize distribution with fractional transport rates before and after the peak. During the very first stages of the flood, the higher fraction of fines in the pool is responsible for a significantly higher transport in this zone ($Qs_p/Qs_r=45$ and $V_p/V_r<0.86$). This remarkable difference is the result of the higher availability of fines in the pool (which are more easily transported) and the increased mobility of the coarser fractions due to the higher percent of sand in the mixture (Wilcock and Crowe, 2003). During the rising limb of the hydrograph this difference in the transport rate of fines produces an equalization of finer fractions and similar bedloads in the pool and in the riffle at the peak discharge ($Qs_p/Qs_r=1.32$ and $V_p/V_r<1.16$). 20 hours after the peak discharge, when the sand fraction in the pool and in the riffle are of the same order of magnitude, sediment transport is considerably higher in the riffle due to higher velocities ($Qs_p/Qs_r=0.10$ and $V_p/V_r<0.85$). Comparing the bedload before and after the peak, it is interesting to remark that an approximately equal velocity reversal index produces a considerably different sediment transport in the pool-riffle unit as a function of the size distribution of the bed.

These findings highlight the importance of fractional transport and longitudinal grain sorting on the onset and magnitude of transport reversal. Although the degree of velocity reversal is a key variable for pool-riffle morphological dynamics, it should not be regarded as a surrogate of transport reversal. The latter depends on the complex combined effect of different velocities and grainsize distributions in pools and riffles and on the non-linear relations governing fractional transport.

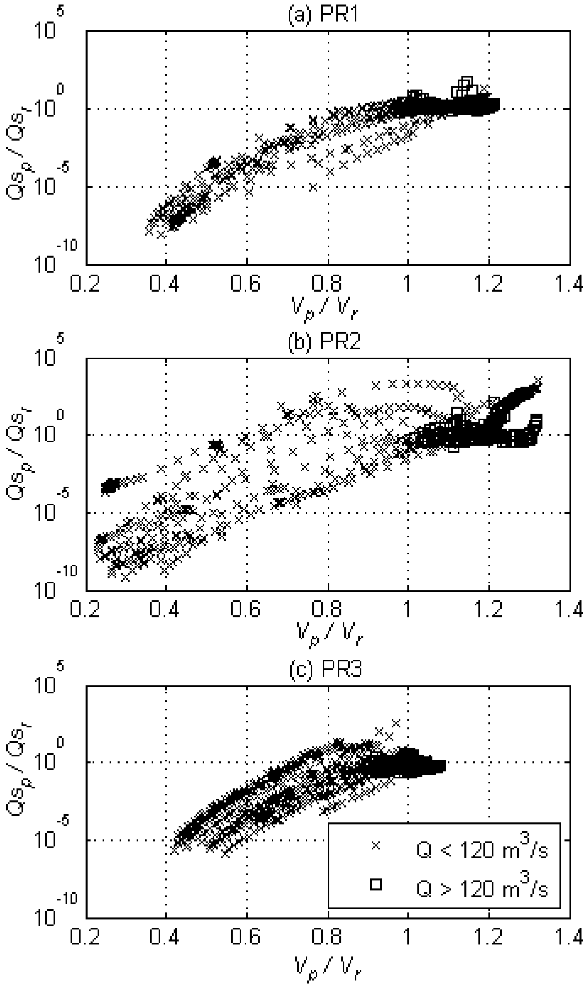

Figure 3. Velocity reversal versus sediment transport reversal for three pool-riffle units. a)PR1, b) PR2, c)PR3.

6.2 *Downstream control and pool-riffle units interdependence*

Data in Figure 3 has been divided in two different groups as a function of flow discharge. The division has been carried out to highlight the difficulty in establishing a threshold value for the onset of velocity reversal. The discharge $Q=120m^3/s$ has been selected in an attempt to estimate a critical value of discharge associated with reversal conditions. In Figures 3.a and 3.b it is easily recognizable that most of the points for $Q>120m^3/s$ correspond to velocity reversal indexes higher than unity, while most $Q<120m^3/s$ points correspond to $V_p/V_r<1$. The critical value is however far from clear. In Figure 3.c for instance there is a considerable amount of data for $Q>120m^3/s$ and $V_p/V_r <1$, and in Figures 3.a to 3.c a significant number of points with $Q<120m^3/s$ and $V_p/V_r >1$.

The above remarks shed light on two important characteristics. Firstly, the estimation of a single critical discharge for the onset of velocity reversal in different pool-riffle units is at least questionable. Reversal conditions are highly dependent on differences in cross section shapes in pools and riffles; and so far no evidence of a ubiquitous shape proportion pattern supporting the idea of a unique critical flow for different pool-riffle units has been demonstrated. Secondly, for a given pool-riffle unit, velocity reversal may take place under different discharges. This observation draws attention to the importance of downstream control on pool-riffle water levels. In the case of Bear Creek, water surface elevations during floods may be considerably influenced by backwater effects associated with high water levels in the Buffalo River. When the downstream water elevation is sufficiently high then the riffle may be drowned-out, dramatically reducing the differences between pool and riffle water levels. If the downstream-controlled water surface determines an inversion of flow areas, then velocity reversal occurs in an almost discharge-independent fashion.

Out of the range of influence of tributaries, water surface downstream of a given pool-riffle unit is mainly controlled by the elevation of the downstream riffle, which works analogously to engineering weirs controlling the water surface elevation upstream (e.g Richards, 1978; Carling, 1991; Pasternack et al, 2008). As a result, critical discharge for velocity reversal will be significantly dependent on downstream riffle crest elevation.

A series of simulations has been carried out to illustrate the influence of downstream riffle elevation on the velocity reversal index. In these simulations steady flow conditions and fixed bed were used to separate the influence of flow unsteadiness and bed mobility. Backwater effects due to the confluence were also eliminated by using a normal depth downstream boundary condition. The influence of riffle crest elevation on the reversal index of the upstream unit has been analysed by increasing the height of the bed in the downstream riffle in PR3 (section at x=957m). This elevation is expected to control water levels downstream the riffle in PR2, and therefore controls its drown-out conditions. Figure 5 presents the relation between discharge and the velocity reversal index in PR2 for the initial bed profile along with three bed profiles obtained by increasing the downstream riffle elevation (20, 40 and 60cm higher than the initial ele-

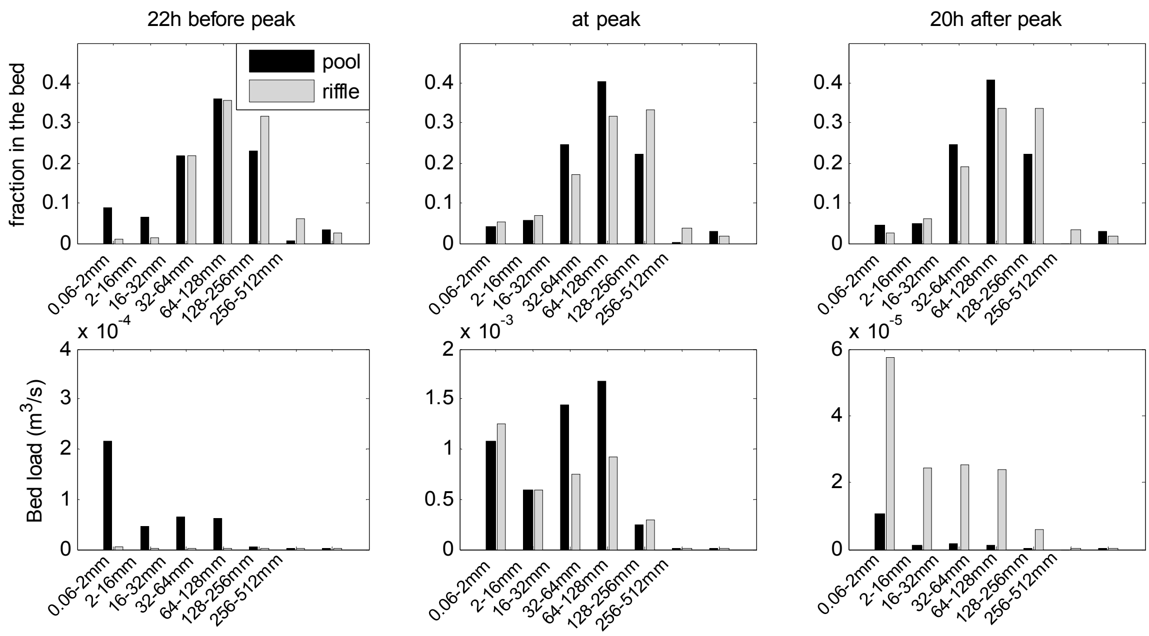

Figure 4. Bed grainsize distribution and fractional sediment transport during three different stages of the first flood in March 2002. Left: 22h before the peak discharge ($Q=69.0m^3/s$); centre: during the peak ($Q=222.6m^3/s$); right 20h after peak ($Q=68.54m^3/s$). PR2.

vation). It is important to highlight that the increments used are not unrealistic. Scour chains installed during the course of the USGS project (USGS, 2003) have indicated, for instance, bed fluctuations higher than 50cm in 6 out of 18 sections surveyed from September 2001 and June 2002.

The dependence illustrated in Figure 5 shows an important mechanism that takes place during floods: changes in riffle elevation due to erosion or deposition affects the dynamics of upstream pool-riffle units. In particular, downstream riffle deposition enhances the reversal probability in the upstream unit.

Apart from the effect over the upstream unit, riffle crest elevation is also responsible for a second mechanism, which controls the reversal conditions in its own unit.

The drown-out condition in any given riffle, which somehow dictates whether erosion or deposition will occur, is a function of the difference between riffle crest and downstream water elevation. As a result, riffle deposition reduces the probability of drowning-out and consequently the magnitude of the reversal. Figure 6 is similar to Figure 5 but in this case the elevations were increased at cross-section 687 (i.e. riffle of PR2).

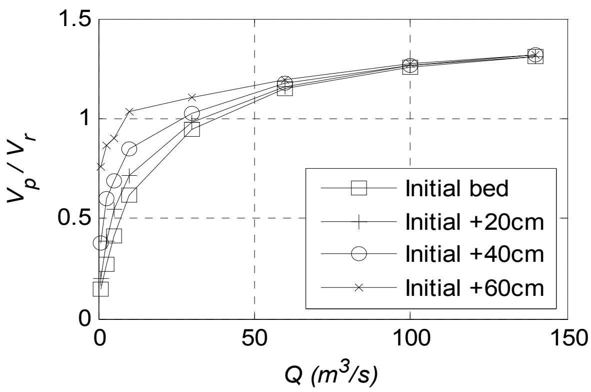

Figure 5. Velocity reversal index in PR2 as a function of flow discharge. Curves were obtained using the initial bed shape and increasing the elevation of the downstream riffle (at coordinate x=957m) by 20, 40 and 60cm.

The above observations highlight two important mechanisms governing the self-maintenance of pool-riffle sequence. Firstly, the aggradation of a downstream riffle increases the probability and magnitude of flow reversal in the contiguous (upstream) pool-riffle sequence. The expected result is the increment in the ability of the upstream riffle to aggrade and the pool to erode. Conversely, the erosion of a downstream riffle reduces flow reversal ability in the upstream pool-riffle sequence, which as a result becomes more prone to riffle erosion. This mechanism demonstrates the interdependence among different pool-riffle units in a given sequence. Localized alterations on the bed are thus expected to propagate their effects towards neighbouring units, precluding the formation of isolated extreme peaks. Secondly, the aggradation of a given riffle reduces the probability of flow reversal in the same unit (Figure 6), thus increasing the riffle erodibility. On the contrary, an eroded riffle becomes more prone to deposition. This mechanism is an essential self-control that prevents unbounded riffle deposition or erosion.

7 CONCLUSIONS

In this paper a physically-based numerical model integrating unsteady hydraulics, fractional sediment transport, morphological changes and grain sorting to predict pool-riffle morphodynamics has been applied to a pool-riffle sequence. One feature of particular interest for the analysis of pool-riffle sequences is the ability of the model to capture pool erosion and riffle deposition under certain conditions. This situation, which has been widely acknowledged as the main mechanism responsible for pool-riffle maintenance, is shown to be significantly dependent on the interaction of different variables. Results have demonstrated that longitudinal grain sorting plays a significant role on pool-riffle morphodynamics. In particular, results have shown that sediment transport reversal, which is ultimately responsible for pool-riffle self-maintenance, may occur under flow discharges considerably smaller than those associated with velocity reversal. The occurrence of transport reversal without a reversal in the velocity is a consequence of different grainsize distribution in pools and riffles. This finding indicates that maintenance mechanisms operates more frequently than once has been deduced based on the velocity reversal hypothesis.

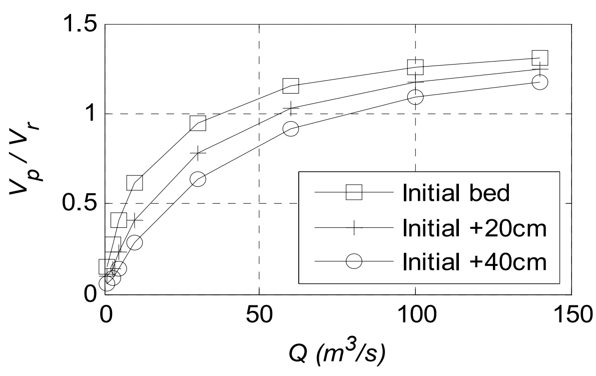

Figure 6. Velocity reversal index in PR2 as a function of flow discharge. Curves were obtained using the initial bed shape and increasing the elevation of the riffle at x=687m by 20 and 40cm.

The feedbacks of bed alterations on the flow characteristics and its consequences for the maintenance of pool-riffle sequences have been analysed. Two key mechanisms responsible for pool-riffle maintenance have been unveiled. Firstly, the aggradation of a downstream riffle enhances flow reversal probability in the upstream pool-riffle sequence by backwater, which induces upstream riffle deposition and ultimately prevents the formation of flattened bed. Secondly, as deposition occurs in a given riffle, the probability flow reversal in the same pool-riffle unit is reduced (opposite of enhanced), which prevents unbounded riffle deposition.

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