Advances in Water Resources 92 (2016) 10–22

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Assessment of the performance of numerical modeling in reproducing a replenishment of sediments in a water-worked channel

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A R T I C L E   I N F O

Article history:
Received 20 October 2015
Revised 11 March 2016
Accepted 23 March 2016
Available online 1 April 2016

Keywords:
2D Shallow water
Sediment replenishment
Bed-load transport
Dam impact
Bed-shear stress
Sediment management

A B S T R A C T

The artificial replenishment of sediment is used as a method to re-establish sediment continuity downstream of a dam. However, the impact of this technique on the hydraulics conditions, and resulting bed morphology, is yet to be understood. Several numerical tools have been developed during last years for modeling sediment transport and morphology evolution which can be used for this application. These models range from 1D to 3D approaches: the first being over simplistic for the simulation of such a complex geometry; the latter requires often a prohibitive computational effort. However, 2D models are computationally efficient and in these cases may already provide sufficiently accurate predictions of the morphology evolution caused by the sediment replenishment in a river. Here, the 2D shallow water equations in combination with the Exner equation are solved by means of a weak-coupled strategy. The classical friction approach considered for reproducing the bed channel roughness has been modified to take into account the morphological effect of replenishment which provokes a channel bed fining. Computational outcomes are compared with four sets of experimental data obtained from several replenishment configurations studied in the laboratory. The experiments differ in terms of placement volume and configuration. A set of analysis parameters is proposed for the experimental-numerical comparison, with particular attention to the spreading, covered surface and travel distance of placed replenishment grains. The numerical tool is reliable in reproducing the overall tendency shown by the experimental data. The effect of fining roughness is better reproduced with the approach herein proposed. However, it is also highlighted that the sediment clusters found in the experiment are not well numerically reproduced in the regions of the channel with a limited number of sediment grains.

1. Introduction

Dams interrupt the longitudinal sediment continuum of the river by trapping and storing sediment and water in the upstream reservoir (Brandt, 2000; Grant et al., 2005; Petts and Gurnell, 2005). Due to the lack in sediment supply, many negative changes occur along the downstream river from the morphological and ecological point of view. The main morphological changes are related to tendency to riverbed incision, generation of an armored layer and coarsening of the bed, together with bank instability and changes in channel width. Correspondingly, these changes also can negatively impact the ecosystem along the river, inducing a loss in the aquatic and riparian habitats with consequences on the water quality (Kantoush et al., 2010; Kondolf, 1997; Merz et al., 2006; Power et al., 1996). The above-mentioned outcomes limit the possibilities for fish spawning and survival.

In the last decades, the replenishment of sediment (also called gravel augmentation) technique has been applied in order to supply sediments lacking in the downstream reaches. The artificial addition of sediments into the rivers has been used since the 1980's with the main purpose to restore a sediment continuity along the impacted reach (Balland, 2004). More recently, it was stated in Ock et al. (2013); Venditti et al. (2010a) that the added material for replenishment purposes should be smaller than the existing bed material in order to favor the fine sediment availability for the spawning habitats and to enhance bed elevation variations. Correspondingly, field experiments carried out in the United States, Japan and Europe, as well as laboratory investigations, have improved the understanding of the complex geomorphological processes occurring in rivers subjected to the replenishment of sediment (Gaeuman, 2012; Zeh and Donni, 1994). Nowadays, the replenishment of sediment is more often applied in rivers for geomorphic purposes, using a specific grain size, to maintain or even increase the morphologic variability, including bed forms in a channel (Gaeuman, 2008; 2012; Wheaton et al., 2004). The efficiency of the application of

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http://dx.doi.org/10.1016/j.advwatres.2016.03.010

the replenishment may be evaluated in terms of areas occupied by the placed material or in terms of the duration of the morphological changes, depending on the main purpose of the specific project (Parker et al., 2003; Sklar et al., 2009; Wheaton et al., 2010). During the last years, several laboratory experiments were performed to assess the general erosion process of replenishment deposits (Kantoush et al., 2010) and the influence of added sediment supply on river bed morphology (Ikeda, 1983; Nelson et al., 2015; Venditti et al., 2010a; 2012). In particular, the erosion process of sediment deposits is presented by the laboratory results from (Kantoush et al., 2010). Here, the erosion mechanism is described as a combination of lateral erosion on the sediment deposit toe by hydraulic forces, and the subsequent mass failure by geotechnical failure, due to the over steepening of the banks. Field observations downstream of the Murou dam confirm these laboratory findings (Kantoush et al., 2010). After collapsing, the eroded mass of the replenishment is transported further downstream. Translation and dispersion are the two main transport types occurring for sediment augmentation (Cui et al., 2003; Sklar et al., 2009). Generally, when aiming to increase the morphology diversity, a successful replenishment of sediments would be: first, transported mainly in a translation fashion until it reaches the sediment depleted zone of the river; then, it would disperse.

In addition to the field and the laboratory experiments, numerical morphodynamic models have been developed as a decision making tool about the replenishment technique. Gaeuman (2014) remarked that their numerical tool was not reliable in predicting the magnitudes in bed elevation changes and failed to reproduce the riffle-pool-pattern observed in field experiments with sediment replenishment. In (Gomez and Church, 1989) the inability of estimating the bed load transport in gravel bed rivers by any of sediment transport formulas was stated. Hence, the gap of knowledge about the existing link between sediment supply and channel bed morphology has still to be fulfilled (Lisle et al., 1997; Venditti et al., 2012). More detailed studies are required on the influencing factors affecting the fate of gravel augmentation projects, since the conceptional design of many of the restoration projects are still designed based only on past experiences (Kantoush et al., 2010; Kondolf, 1997; Sklar et al., 2009). Above all, the role played by the discharge, the necessary amount of sediments and the mechanism of sediment propagation through the channel are of interest to better understand (Kantoush et al., 2010; Venditti et al., 2012). Since in-situ monitoring campaigns are difficult to carry out and considering that the laboratory experiments cannot fulfill all the not-yet investigated domain, the implementation of numerical tools arises as a helpful approach for better understanding the morphological consequences due to a sediment replenishment.

Depending on the number of equations to be solved the morphodynamic models range from 1D to 3D. Traditionally, 1D models have been considered due to their low computational cost and data requirement. However, under the presence of complex topography, the use of 2D/3D hydrodynamic models is required. The negative points of the 3D models are: (i) the high number of closure equations they require and (ii) the high computational cost. Conversely, the 2D models are computationally-efficient since the number of equations and closure equations is limited and in addition, they provide accurate bidimensional predictions for the water and solid fluxes at the cost of a fine topographic representation. In this work the 2D depth-averaged mathematical model is considered. The morphodynamic evolution of the replenishment material is computed by means of the Exner equation. The spatial and temporal evolution of the hydrodynamic and morphodynamic models must be solved through a synchronous treatment, Aricò and Tucciarelli (2008), since there is a strong interaction between the flow and the replenishment material. The main drawback of the synchronous procedure is the high number of algebraic operations required for solving the whole set of equations in the same time step. In this study the weakly-coupled approach between the two models proposed in Juez et al. (2014) is considered, since there is a gain in the computational cost without compromising the level of accuracy. Regarding the numerical scheme, computations are based on an explicit Finite Volume strategy described in Juez et al. (2014), which was proven to be self-stable and accurate. Hence, this numerical tool will be used for studying the hydro-morphodynamic behavior of the replenishment process when dealing with different configurations.

The remainder of this paper is structured as follows: first, the methodology used to obtain the experimental data is described. Second, the mathematical model and numerical scheme is briefly outlined. Third, the results obtained in this study are presented and discussed. Finally, the major conclusions of the work are summarized.

2. Experimental methodology

In the experimental study, a flume was used to evaluate the fate of four different sediment replenishment configurations under a single constant discharge regime. The laboratory experiments were performed at the Laboratory of Hydraulic Constructions (LCH) at École Polytechnique Fédérale de Lausanne (EPFL), in Switzerland. The tests were performed in a 15 m long channel with a bed width of 0.4 m. The typical features of an alpine gravel stream were reproduced in terms of slope, grain size distribution and Froude number Parker and Toro-Escobar (2002). The cross-sectional section bank slope was 2:3 (height:length) (see Fig. 1). Longitudinally the flume presented a slope of 1.5%. The model was scaled using Froude similarity consistent with open-channel hydraulic modeling as mentioned by (Heller, 2011). The Froude number for mountain streams range normally from 0.3 to 1 (Cui et al., 2003) and it was 0.65 in these experiments.

The water entered from an upper stilling basin throughout the channel reaching the outlet basin downstream. The performed discharge was controlled by a pump system. The discharge is indirectly determined by the imposed replenishment submergence condition. A single discharge regime is considered in this work, equal to 19 l/s. The value corresponds to an optimum condition determined in former tests, (Bösch et al., 2015). The replenishment height is kept constant and corresponds to a completely submerged condition of the volume (volume height = water depth). The length of the replenishment volumes, L, is equal to 0.74 m. Furthermore, the set submergence condition of the replenishment exceeds the rate of shear stress for the replenishment material, but it should be not enough for mobilizing the bed material. The existing bed sediments were fixed to the bed using a concrete mixture to ensure that they would not be mobilized in the experiments, thereby emulating an armored, immobile bed (Venditti et al., 2010b).

Furthermore, the grain size distributions of both the channel bed and the replenishment mixture were chosen based on Shields criteria. In Fig. 2, the grain size distributions for the channel bed and for the replenishment material are displayed. The bed grain size distribution, used for creating the fixed bed and the banks, is representative of a typical alpine river. The replenishment volumes are composed of a finer grain distribution with dimensions varying from 3 to 8 mm. The ecological needs for spawning grounds, were considered in this grain choice (Ock et al., 2013; Venditti et al., 2010a). Each test last three hours. In a preliminary analysis on the evolution of the morphological bed forms demonstrated that, with this flow condition, a certain morphological equilibrium is reached in two hours, (Battisacco et al., 2015).

The influence of different amounts of replenishment together with four different geometrical configurations were investigated.