Environmental Modelling & Software 88 (2017) 10–21

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

A two-dimensional hydro-morphological model for river hydraulics and morphology with vegetation

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ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form
24 October 2016
Accepted 8 November 2016

Keywords:
Vegetation effects
Non-equilibrium sediment transport model
River hydraulics
Morphological changes
Shallow water equations

ABSTRACT

This work develops a two-dimensional hydro-morphological model which can be used to simulate river hydraulics and morphology with various vegetation covers. The model system consists of five modules, including a hydrodynamic model, a sediment transport model, a vegetation model, a bank failure model and a bed deformation model. The secondary flow effects are incorporated through additional dispersion terms. The core components of the model system solve the full shallow water equations; this is coupled with a non-equilibrium sediment transport model. The new integrated model system is validated against a number of laboratory-scale test cases and then applied to a natural river. The satisfactory simulation results confirm the model's capability in reproducing both stream hydraulics and channel morphological changes with vegetation. Several hypothetical simulations indicate that the model can be used not only to predict flooding and morphological evolution with vegetation, but also to assess river restoration involving vegetation.

1. Introduction

Vegetation plays multiple roles in real-world river streams. For example, riparian vegetation can protect against bank erosion, and in-stream vegetation may significantly influence flow propagation, sediment movement and river morphology (Darby, 1999; Hickin, 1984; Hupp and Osterkamp, 1996; Keller and Swanson, 1979). Vegetation has been widely used for improving stream corridor habitat and other ecological functions in many river restoration programmes. Understanding the multiple effects of vegetation is highly important in river management.

In the recent decades, the effects of vegetation on river flows have been extensively investigated through laboratory experiments (Armanini et al., 2010; Bennett et al., 2008; Gorrick and Rodríguez, 2012; Jordanova and James, 2003) and modelling (e.g (Anderson et al., 2006; Crosato and Saleh, 2011; Gran and Paola, 2001; Jang and Shimizu, 2007; Li and Millar, 2011; Tal and Paola, 2007, 2010; Tsujimoto, 1999; Wu et al., 2005b)). These studies have clearly emphasised that vegetation affects flow hydraulics in various ways, and thereby plays a crucial role in river morphology and ecological diversity. However, the majority of the existing studies have been focused on the effects of vegetation on pure flow characteristics, with some considering the long-term flow-vegetation-sediment interaction in braided rivers. Research into the direct fluvial response to vegetation during flooding remains rare.

On the other hand, numerical models for hydro-geomorphological processes have been extensively developed (Guan et al., 2013, 2015b; Liang, 2010). When considering the importance of vegetation, hydro-morphological modelling should take into account the vegetation effects, particularly under conditions where vegetation may play a key role. Flow-sediment-vegetation interaction is a highly complex process where the three components may dynamically interact with each other. Few models have been reported to represent the whole physical process. The current study, therefore, presents a hydro-morphodynamic model with the inclusion of vegetation dynamics to fill this knowledge gap.

In reality, vegetation may or may not be fully submerged by river flows. For example, soft grass and plants are generally submerged during flooding seasons, while rigid vegetation, e.g. trees is usually emergent. In hydraulic and sediment transport modelling, the effects of vegetation is conventionally taken into account through increased resistant force and the Manning's equation has been the most widely-used approach to represent flow resistance (Green,

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http://dx.doi.org/10.1016/j.envsoft.2016.11.008
1364-8152/

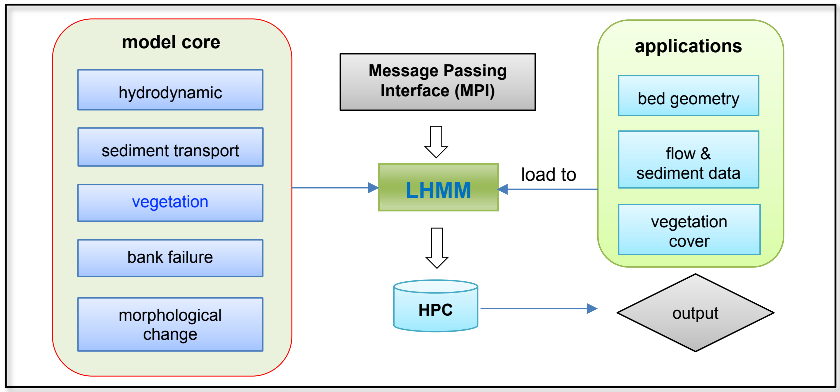

Fig. 1. Model framework of LHMM.

2005; Guan et al., 2013, 2015b; Liang, 2010; Sellin et al., 2003; Wu et al., 1999). The Manning's coefficient is usually estimated according to specific channel conditions and its accurate estimation requires abundant experience. However, this traditional way of representing flow resistance is not appropriate for cases when rigid plants are present, e.g. flow through emergent vegetation. In such flow scenarios, resistance is primarily exerted by the stem's drag throughout the flow depth rather than by shear stress at the bed (James et al., 2004). A more appropriate approach is to split channel resistance into several components and then estimate each one separately (Cowan, 1956; Morin et al., 2000). Recently, some approaches have been successively proposed to estimate the flow resistance for modelling flows over or through a vegetated channel (Baptist et al., 2007; Vionnet et al., 2004). This study adopts the estimation method of separating the total resistance into vegetation resistance and bed resistance. The vegetation resistance is then treated as a *drag force* exerted by vegetation. This vegetation resistance usually dominates flow resistance for the vegetated flows (Temple, 1986; Wu et al., 1999) because the presence of emergent vegetation (such as trees), to a certain extent, narrows the channel width, thereby altering flow properties.

This study aims to develop a depth-averaged 2D numerical model for river hydraulics and morphology with vegetation effects, and to better understand the effects of vegetation on changing river morphology through intensive numerical experiments. The numerical model is built upon a layer-based 2D hydro-morphodynamic model (LHMM) (Guan et al., 2014, 2015b) which has been validated by a variety of flood events. A vegetation module is developed and incorporated in the model system to simulate vegetation effects. The model is validated against several laboratory experiments before a real-world application is considered.

2. Numerical model (LHMM)

2.1. Model framework

Shallow water based numerical models have been widely used for river flow modelling (Costabile and Macchione, 2015; Guan et al., 2013; Hou et al., 2015; Vacondio et al., 2014). The layer-based hydro-morphodynamic model (LHMM) that has been presented in previous work (Guan et al., 2014, 2015b, 2015a) also solves the fully coupled shallow water equations (SWEs) and the sediment transport formulation. Herein, a new vegetation model component is developed and included in LHMM to consider the vegetation effects. The model system considers the mass and momentum exchange of non-cohesive sediment between bed and flow, and updates the hydraulic and sediment quantities per grid cell, per time step. Fig. 1 shows the entire LHMM model framework, which includes four modules:

- ***Hydrodynamic module***: The depth-averaged 2D shallow water equations are solved to predict rapidly varying unsteady flows, taking into account the feedback from sediment and vegetation.
- ***Sediment transport module***: A non-uniform sediment transport model is developed to describe the transport of sediment particles.
- ***Vegetation module***: The external force exerted by vegetation on flow and sediment is parameterised.
- ***Bank failure module***: Is a model component to simulate lateral bank erosion or failure.
- ***Bed deformation module***: The bed elevation is updated after localised erosion and deposition of sediment.

2.2. Hydrodynamic module

The hydrodynamic module solves the depth-averaged 2D shallow water equations, including the effects of sediment and vegetation on flow dynamics. In a vector form, the governing equations can be expressed by

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}=\frac{\partial \tilde{\mathbf{E}}}{\partial x}+\frac{\partial \tilde{\mathbf{F}}}{\partial y}+\mathbf{S_o}+\mathbf{S_f}+\mathbf{S_v}+\mathbf{S_{fb}} \quad (1)$$

where

where $\mathbf{U}$ is the vector of conserved variables; $\mathbf{E}$ and $\mathbf{F}$ are the flux vectors of the flow in the x and y directions respectively, $\tilde{\mathbf{E}}$and $\tilde{\mathbf{F}}$ contain the turbulent and dispersion terms in the x and y directions, $\mathbf{S_o}$ and $\mathbf{S_f}$ are the vectors containing the bed slope terms and the frictional slope terms, $\mathbf{S_v}$ contains vegetation terms, and $\mathbf{S_{fb}}$ is the vector of flow-bed interaction terms. In these vector terms, h = flow depth, z_b = bed elevation, η = water surface elevation, u and v = the depth-averaged flow velocity components in the two Cartesian directions, T_{xx}, T_{xy}, T_{yx} and T_{yy} are the depth-averaged turbulent stresses, D_{xx}, D_{xy}, D_{yx} and D_{yy} are the dispersion terms due to the effect of secondary flow, p = sediment porosity, c = total volumetric sediment concentration, τ_{vx} and τ_{vy} are the vegetation shear stresses in the x and y directions; ρ_s and ρ_w denote the densities of sediment and water respectively, $\Delta\rho = \rho_s$ - ρ_w, ρ = density of flow-sediment mixture, α = sediment-to-flow velocity ratio determined by