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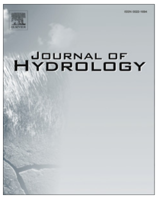

Simulating unsteady flow and sediment transport in vegetated channel network

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SUMMARY

This paper presents a one-dimensional model for simulating flood routing and sediment transport over mobile alluvium in a vegetated channel network. The modified St. Venant equations together with the governing equations for suspended sediment and bed load transport were solved simultaneously to obtain flow properties and sediment transport rate. The Godunov-type finite volume method is employed to discretize the governing equations. Then, the Exner equation was solved for bed elevation change. Since sediment transport is non-equilibrium when bed is degrading or aggrading, a recovery coefficient for suspended sediment and an adaptation length for bed load transport were used to quantify the differences between equilibrium and non-equilibrium sediment transport rate. The influence of vegetation on floodplain and main channel was accounted for by adjusting resistance terms in the momentum equations for flow field. A procedure to separate the grain resistance from the total resistance was proposed and implemented to calculate sediment transport rate. The model was tested by a flume experiment case and an unprecedented flood event occurred in the Santa Cruz River, Tucson, Arizona, in July 2006. Simulated results of flow discharge and bed elevation changes showed satisfactory agreements with the measurements. The impacts of vegetation density on sediment transport and significance of non-equilibrium sediment transport model were discussed.

1. Introduction

Vegetation in natural rivers increases flow resistance and bank stability, improves water quality, and promotes habitat diversity, but reduces flood conveyance. The presence of vegetation changes both flow field and sediment transport processes. Although the impact of vegetation on flow and sediment transport has been studied for decades (Cowan, 1956; Duan et al., 2006; Fisher, 1992; Luhar and Nepf, 2013; Nepf, 2012; Tsujimoto, 1999), the simulation of flow and sediment transport in vegetated alluvial channels is still challenging because of the complex interactions among flow, vegetation, and mobile bed sediment.

Many empirical relations have been proposed to quantify the resistance of vegetated flow over a rigid bed through adjusting Manning's, Darcy's, or Chezy's coefficients. Early researchers (Chow, 1959; Cowan, 1956; Kouwen, 1969) found that the Manning's coefficient varies with vegetation type, density, and distribution. Relationships between Manning's coefficient and vegetation properties are formulated for limited vegetation types and experimental conditions. Klopstra (2002) established an analytical model to calculate the Chezy's coefficient for submerged vegetation as a function of vegetation height and density, stem diameter, drag coefficient, and the characteristic length of large scale turbulence. Kouwen and Unny (1973) found the drag force of flexible vegetation is smaller than that for rigid upright vegetation because of a change in vegetation morphology. Similar research results can be found in other literatures (Carollo et al., 2005; Darby, 1999b; Duan et al., 2006; James et al., 2004; Katul et al., 2002; Kim et al., 2012; Neary et al., 2012; Stephan and Gutknecht, 2002). To simulate vegetated open channel flow using numerical models, some researchers (Baptist, 2005) modified source terms in the momentum equations by incorporating an equation for calculating the roughness; other researchers (Stone and Shen, 2002; Wu and Marsooli, 2012) added vegetation drag forces to the momentum equations as additional source terms. Both methods accounted for the influence of vegetation by modifying source terms in the momentum equations.

A few laboratory and field experiments were conducted to study the effects of vegetation on sediment transport and channel morphodynamic changes. Prosser's (1995) experiments showed upland erosion and channel initiation can be prevented by strong soil cohesion from a dense root mat. López and García (1998) derived an empirical equation from field data to estimate suspended sediment transport, and their results showed the

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Nomenclature

A	flow area
A_b	mobile bed area
B	width of cross section
C	concentration of suspended load
C_t	volumetric concentration of total load sediment
C_a	the actual suspended sediment concentration at the interface
C_{a^*}	sediment concentration at the interface at equilibrium
C_D	drag coefficient
C_R	representative Chezy coefficient
d	stem diameter
d_f	infiltration rate
d_{50}	median grain diameter
D, E	deposition and entrainment rate at the interface between bed load and suspended load
D_f	total infiltrated depth
f_w	wall-related Darcy-Weisbach friction factor
f_{ws}	smooth-sidewall friction factor
f_{wr}	rough-sidewall friction factor
F_w, F_b, F_D and F_t	wall shear stress, bed shear stress, vegetation drag force and total resistance force
$\boldsymbol{F}$	intercell numerical flux at the cell face
g	gravitational acceleration
h	averaged flow depth in a cross section
h_v	vegetation height
h_s	flow depth over vegetation layer (upper layer)
h_s	$h–h_v$
H_f	capillary pressure head at the wetting front
k_{sw}	the equivalent wall-roughness height
K_s	saturated hydraulic conductivity
L	non-equilibrium adaptation length
M_d	soil moisture deficit
n	Manning's roughness
O_i and C_i	are the ith observed and calculated data for Nash-scliffeut efficiency calculation
p_m	the porosity of bed load sediment
P_w, P_b, P_v and P_t	wall-related, bed-related, vegetation-related and total wetted perimeters, respectively
Q	flow discharge
Q_b	actual bed load transport rate
Q_{b^*}	bed load transport capacity under equilibrium state

R	hydraulic radius
Re	Reynolds number
R_w, R_b, R_v and R_t	wall-related, bed-related, vegetation-related and total wetted perimeters, respectively
s	energy slope
$\boldsymbol{S}$	source terms
SG	sediment specific gravity
T	time
$\bar{u}$	mean velocity
u'_*	grain shear velocity
u_v	average pore velocity
x	longitudinal coordinate
z	elevation
z_b	bed elevation
z_s	water surface elevation

Subscript

i	node number

Superscript

n	time level

Greek

θ_e	effective porosity
θ_i	soil initial moisture content
w_s	settling velocity of sediment particles
α	the non-equilibrium suspended load recovery coefficient
a	the reference bed level
R_0	the Rouse number
κ	von Karman constant, assumed as 0.41
$\boldsymbol{\Phi}$	vector of unknown variables
Δt	time step
Δx	distance between two cross sections
ρ	density of water-sediment mixture
ρ_w, ρ_s	the density of water and sediment, respectively
ρ_b	density of mobile bed layer
λ	vegetation density
υ	kinematic viscosity of fluid
τ'_{b^*}	the effective dimensionless surface shea

suspended sediment transport capacities in vegetated waterways are smaller than that in non-vegetated channels. Zong and Nepf (2011) found that for a patch of vegetation located at a channel side, sediment deposition was the highest near the streamwise patch edge and decreased into the patch. Only a few numerical models (Wu and Shields, 2005) were capable of simulating both flow and sediment transport in vegetated channels. Wu and Shields (2005) developed a two-dimensional depth-averaged model to simulate flow and sediment in channels with riparian vegetation. However, their model can only be used in small scale curved channels.

Most sediment transport formulae are developed for predicting equilibrium sediment transport rate in steady uniform flow, which assumes sediment transport rate is equal to the transport capacity. However, when channel bed is degrading or aggrading, sediment transport rate can be greater or less than the transport capacity, called non-equilibrium transport (Zhang et al., 2013). To simulate the process that sediment transport rate gradually develops into the transport capacity, the adaptation length (Duc and Rodi, 2008; El kadi Abderrezzak and Paquier, 2009; Wu and Wang, 2007; Zhang et al., 2013) is often used to calibrate bed load transport, and the recovering coefficient is used for suspended sediment transport. The adaptation length is defined as the distance required for the bed load transport rate to reach equilibrium at a given flow condition. And the suspended load recovering coefficient is defined as the ratio of near-bed suspended sediment concentration to the depth-averaged concentration at equilibrium state (Zhang et al., 2013). The non-equilibrium sediment transport algorithm is adopted here to simulate sediment transport in vegetated channel network.

Although 2D and 3D models have been developed to simulate flow and sediment transport in vegetated channels (Wu, 2005), 1D channel network model is the most cost-effective for engineering practices when simulating fluvial processes of a long river reach for a long time. This paper presents a one-dimensional model for simulating unsteady flow and sediment transport in a vegetated channel network. The model accounts for the effect of vegetation on flow resistance and sediment transport by using the modified roughness coefficient and shear velocity. A laboratory experimental case and an unsteady flow event occurred in the