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Research Paper

Application and evaluation of the HEC-RAS – riparian vegetation simulation module to the Sacramento River

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ABSTRACT

Life cycles of riparian vegetation are substantially impacted by river flow regime, groundwater and morphodynamics. The polygon-based riparian vegetation simulation module (RVSM) was developed and integrated into HEC-RAS one-dimensional flow model to predict spatially-explicit seed germination, seedling establishment, plant growth and mortality in response to fluvial processes. The HEC-RAS – RVSM system was applied to the Sacramento River reach to evaluate its capability in modeling temporal and spatial changes of riparian vegetation and the interactions between flow and riparian vegetation dynamics. River hydraulics, groundwater level and five vegetation types of the study reach were simulated for the eight-year (1999–2007) period. Model results demonstrate that the HEC-RAS – RVSM system reproduced the coverage increase of cottonwood, riparian shrub, invasive species and grass as well as the coverage decrease in mixed forest over the eight-year. The RVSM was able to capture sites for cottonwood establishment observed on certain point bars. The modeled variations of cottonwood coverage in response to dynamic flow regime facilitated determining and managing environmental flow for riparian vegetation restoration. The height of capillary fringe and root growth rate were two key parameters influencing riparian vegetation distribution.

1. Introduction

Riparian zones are long strips of vegetation adjacent to streams, rivers, lakes, reservoirs, and other inland aquatic systems (Fischer and Fischenich, 2000). Riparian zones range in width from a few to hundreds of meters. Riparian vegetation is diverse in species and varies from aquatic graminiod-sedge wet meadows to extensive forests. Life cycles of the riparian vegetation species are directly and indirectly affected by flow regime (Tabacchi et al., 1998). The flow regime is the main driver of channel morphology through its influence on sediment transport and channel structure. Flood and drought disturbances, and the erosion and deposition of sediments all have major impacts on shaping the composition, structure and abundance of riparian vegetation (Merritt et al., 2010). Riparian vegetation species have evolved specific traits to survive and reproduce in response to these disturbances (Naiman et al., 2010). For instance, seed release of the pioneer riparian trees like cottonwood and black willow often coincides with peak runoff or flood recession (Stella et al., 2006). Some riparian plants depend on flow dynamics to enable long distance seed dispersal (Johansson et al., 1996). In addition, groundwater level and soil moisture of floodplains influenced by river flow are also determinant environmental factors for seed germination and seedling establishment particularly in the riparian zones of arid and semiarid basins (Stromberg, 2001; Stromberg et al., 1996). Unfortunately, alterations of flow regime worldwide due to dam operation and river regulation have highly modified and degraded the riparian vegetation community. Some of the negative effects of altered flow regimes on riparian vegetation may be alleviated through ecosystem management and restoration.

Vegetation in riparian zones plays a significant role in controlling channel morphology, maintaining a favorable habitat for aquatic organisms and improving river water quality (Tabacchi et al., 1998; Perucca et al., 2007). Riparian vegetation increases the bank resistance against erosion directly by root binding, and indirectly by enhancing local deposition of organic material and fine sediment, which increases the soil cohesion (Tal et al., 2004). By trapping organic matter and sediment as well as assimilating excessive nutrients, riparian vegetation has a strong ability to mitigate nutrients and contaminants contents of adjacent rivers

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(Dosskey et al., 2010). Thus, vegetated riparian buffer zones established between agricultural fields and receiving waters have been widely used for water quality improvement (Comerford et al., 1992). Moreover, as a result of widespread loss and degradation of global riparian habitat, riparian vegetation rehabilitation has become an important component for many river restoration programs (Goodwin et al., 1997; Merritt et al., 2010; Rood et al., 2005; Stromberg, 2001).

To support the riparian ecosystem management and restoration, there is a critical need for developing a physically based quantitative tool to predict riparian vegetation's response to fluvial processes, and to evaluate alternative operations and management plans. Most of existing riparian vegetation models, such as Ecological Dynamics Simulation Model (EDYS) and Riparian Ecosystem Management Model (REMM) have not linked their vegetation simulation with river hydraulics and sediment transport (Coldren et al., 2011; Lowrance et al., 2000). The complex interactions between flow dynamics and riparian vegetation cannot be quantified with these models. The U.S. Bureau of Reclamation (USBR) has added a riparian vegetation simulation component into its SRH-1D model called SRH-1DV for modeling the interactions of flow and riparian vegetation. The SRH-1D is USBR's one-dimensional (1-D) hydraulics and sediment transport model. The SRH-1DV model has been applied to the Sacramento River, Rio Grande River and San Joaquin River in support of water management decision making, environmental planning, and ecosystem restoration analysis (Fotherby et al., 2012; Greimann, 2016).

In this study, the riparian vegetation simulation component within the SRH-1DV model was improved and further developed as a polygon-based riparian vegetation simulation module (RVSM). The RVSM simulates life cycles of vegetation species within the riparian zone using polygons instead of cross-section points used in SRH-1DV. Advantages of the polygon-based riparian vegetation model are (1) to better represent the spatial distribution of real world riparian vegetation; (2) to fit for coupling with both 1-D and two-dimensional (2-D) flow models; (3) to directly overlay model results with a vegetation map for performing spatial analysis. The RVSM has been integrated into the HEC-RAS (Hydrologic Engineering Center-River Analysis System) 1-D flow model. HEC-RAS is used to simulate riverine hydraulics and performs mobile bed sediment transport. Both capabilities are critically important when simulating the effects of vegetation on hydraulic roughness and the life cycles of various vegetation species. The HEC-RAS model was chosen also because it has been continuously developed and supported by U.S. Army Corps of Engineers (USACE) and widely used in the U.S. and world. Most large river systems as well as many smaller rivers and streams in the U.S. have already been modeled with HEC-RAS. Aim of this study was to apply the HEC-RAS – RVSM system to a reach of Sacramento River in modeling spatial and temporal changes of riparian vegetation over eight-year period and to evaluate its capability for predicting interactions between flow and riparian vegetation dynamics.

2. HEC-RAS – riparian vegetation simulation module

This section briefly describes the integrated HEC-RAS – RVSM system.

2.1. HEC-RAS model

HEC-RAS is a public domain river hydraulic model. It contains five components (Brunner, 2016): (1) 1-D steady flow water surface profile computations, (2) 1-D unsteady flow simulation, (3) 2-D unsteady flow simulation, (4) movable boundary sediment transport computations, and (5) water quality analysis through plug-in water quality modules. The latest version of HEC-RAS model can be freely downloaded from the website: http://www.hec.usace.army.mil.

Currently the RVSM was integrated into the 1-D unsteady flow engine in HEC-RAS. The HEC-RAS model computes water surface elevation, discharge, average velocity, energy slope of each cross section. The mass and momentum equations that govern the 1-D unsteady flow are described by:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \tag{1a}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{1b}$$

where Q is inflow; A is cross-sectional flow area; x is distance along channel; t is time; q_l is lateral inflow per unit length of channel; V is velocity; z is water surface elevation; S_f is friction slope; g is acceleration of gravity.

Eqs. (1a) and (1b) are commonly referred as the Saint-Venant equations. The unsteady flow engine solves these equations using implicit finite difference approximations and Preissman's second-order scheme (Brunner, 2016). The required input data include channel network connectivity, cross-section geometry, reach lengths, energy loss coefficients etc. Boundary conditions are necessary to define discharge and water depth at the system end-points, i.e., upstream and downstream. Lateral inflows and a variety of hydraulic structures can be prescribed within the model domain.

2.2. Groundwater module

Groundwater model is necessary to provide groundwater table and capillary fringe information required in RVSM. A simplified groundwater module is developed to compute the groundwater levels of cross sections within the model domain and coupled with RVSM. The groundwater levels are estimated based on river water surface elevation, soil hydraulic conductivity, and groundwater boundary conditions. The 1-D groundwater governing equation is given by

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial y}\left(h_c \frac{\partial h}{\partial y}\right) \tag{2}$$

where h is groundwater level; h_c is saturated hydraulic conductivity; y is the length along cross section.

Finite difference scheme is used to solve the governing equation. It is assumed that the groundwater flow along the cross section is 1-D. The left and right boundary conditions for each cross section are defined as $\partial h/\partial y = 0$. Wherever the water surface intersects the river cross section, their groundwater levels are set to the water surface elevation as internal boundaries.

2.3. Riparian vegetation simulation module

2.3.1. Vegetation classification and representation

Vegetation species on the riparian zone are classified into certain types. Vegetation types simulated in the model can be a species, an alliance of species, or a land use designation. Multiple species that have similar life cycles may be also simulated as one type, for example, several grass species are often grouped into one type – herbs. In general, a special vegetation type, called "no grow", is defined to represent the agricultural, industrial and urban land on floodplains. This vegetation type just occupies the space and prevents the colonization of other vegetation types. Its life cycle is not simulated.

For each vegetation type, plant organs such as root, stem and leaves are quantified using following indicators: plant height, canopy height, canopy width, stem diameter, number of stems and