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Effects of LiDAR-derived, spatially distributed vegetation roughness on two-dimensional hydraulics in a gravel-cobble river at flows of 0.2 to 20 times bankfull

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ABSTRACT

The spatially distributed effects of riparian vegetation on fluvial hydrodynamics during low flows to large floods are poorly documented. Drawing on a LiDAR-derived, meter-scale resolution raster of vegetation canopy height as well as an existing algorithm to spatially distribute stage-dependent channel roughness, this study developed a meter-scale two-dimensional hydrodynamic model of ~28.3 km of a gravel/cobble-bed river corridor for flows ranging from 0.2 to 20 times bankfull discharge, with and without spatially distributed vegetation roughness. Results were analyzed to gain insight into stage-dependent and scale-dependent effects of vegetation on velocities, depths, and flow patterns. At the floodplain filling flow of 597.49 m^3/s, adding spatially distributed vegetation roughness parameters caused 8.0 and 7.4% increases in wetted area and mean depth, respectively, while mean velocity decreased 17.5%. Vegetation has a strong channelization effect on the flow, increasing the difference between mid-channel and bank velocities. It also diverted flow away from densely vegetated areas. On the floodplain, vegetation stands caused high velocity preferential flow paths that were otherwise unaccounted for in the unvegetated model runs. For the river as a whole, as discharge increases, overall roughness increases as well, contrary to popular conception.

1. Introduction

Two-dimensional (2D) hydrodynamic models are emerging as a standard for predicting flood conditions. The preference arises from their ability to more accurately predict complex out-of-bank flow patterns (Bates et al., 1992; Anderson and Bates, 1994; Bates and Anderson, 1996; Bates et al., 1997), overbank depositional patterns (Nicholas and Walling, 1997, 1998; Hardy et al., 2000), and stage-dependent thalweg position relative to one-dimensional (1D) models. These models solve the 2D (depth-averaged) Navier–Stokes equations to predict depth, velocity, and inundation extent for site- and reach-scale floods (Bates et al., 1992; Anderson and Bates, 1994). Finite element models reduce the number of nodes and allow for variable element sizes to resolve details of complex topography or bed roughness (Hardy et al., 1999). Conventionally, hydraulic roughness coefficients are generalized as a constant for all nodes in each delineated cover class (Pasternack, 2011; Straatsma and Huthoff, 2011). The overall goal of this study was to implement a distributed roughness parameterization scheme and then investigate its effects on river hydraulics at three spatial scales ranging from 10^{-1} to 10^3 channel widths and for a wide range of flows (0.2 to 20 times bankfull discharge).

1.1. Motivation

Floodplain roughness parameterization is a major concern in 2D modeling. Vegetation has a dynamic effect on flow by causing momentum loss or drag that is dependent on vegetation structure. Flow resistance of different plant species has been explored using flume studies (Kouwen and Li, 1980; Kouwen, 1988; Kouwen and Fathi-Moghadam, 2000) and in situ analyses (Straatsma, 2009; Sukhodolov and Sukhodolova, 2010). However, obtained equations require detailed, species-specific inputs about vegetation structure unobtainable for large models. Many 2D models do not spatially distribute roughness or use sufficient detail to accurately predict flood hydrodynamics (Marks and Bates, 2000). Roughness values lumped by cover classes are typically empirically estimated or calibrated within an uncertain, acceptable range until results match observations (Bates and Anderson, 1996; Bates et al., 1997). However, this methodology lacks a physical basis. The accuracy value of 2D over 1D modeling stems from its spatially explicit representation of boundary conditions (Brown and Pasternack, 2009; Pasternack and Senter, 2011) and ability to capture

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2D flow patterns, both of which should be sensitive to roughness distribution.

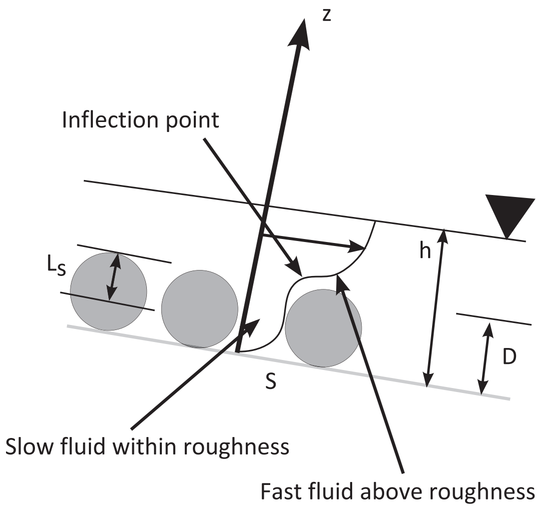
1.2. Distributed roughness concepts

Airborne Light Detection and Ranging (LiDAR) can map vegetation presence and canopy height with ~4–8 observations per 1 m^2, enabling accurate averaging to resolve 1-m^2 features over large areas (Menenti and Ritchie, 1994; Cobby et al., 2001). Data from LiDAR has yielded spatially distributed roughness maps for 2D modeling (Cobby et al., 2003; Mason et al., 2003; Antonarakis, 2008) by borrowing relationships between vegetation height and hydraulic roughness from flume studies (Kouwen, 1988; Kouwen and Fathi-Moghadam, 2000). Multispectral remote sensing and LiDAR data can be used in tree-segmentation algorithms to classify vegetation based on more detailed parameters such as species, vegetation density, leaf area index, biomass, and basal area (e.g., Antonarakis et al., 2008; Straatsma and Baptist, 2008; Watershed Sciences, 2010). Then a force balance can be applied to determine a roughness coefficient at each node.

A roughness parameterization method using LiDAR data was developed that diverges from traditional approaches. Using equations from atmospheric mixing-layer theory above vegetation canopies (Raupach et al., 1996), Katul et al. (2002) hypothesized that the vertical velocity profile (including the region with roughness elements) above a riverbed follows a hyperbolic tangent distribution with an inflection at the top of the roughness element (Fig. 1). By integrating this velocity profile, an equation was derived for hydraulic roughness as a function of vegetation height and water depth. Casas et al. (2010) used Katul et al.'s (2002) results to demonstrate that spatially distributed, stage-dependent roughness values consistent with accepted literature values could be obtained for 2D models from LiDAR-derived canopy heights and estimated water depths for an ~500-m^2 floodplain area. Most importantly, this scheme is easily scalable to vastly larger areas at 1-m resolution, as demonstrated herein. This enables new scientific research on the role of vegetation on river hydraulics.

1.3. Objectives

This study sought to statistically describe and qualitatively explain scale-dependent effects of spatially distributed bank and floodplain vegetation by applying Katul et al. (2002) methodology to a multimillion node, 2D, finite-volume model that solves the depth-averaged Reynolds equations within an ~1–3-m nodal mesh grid for a 28.3-km river corridor over roughly three orders of magnitude of flow. Specifically, the two objectives of this research were to (i) compare modeled inundation extents, depths, and velocities using stage-dependent, spatially distributed roughness for floodplain vegetation with a constant nodal roughness model excluding vegetation for flows ranging from 0.2 to 20 times bankfull discharge at segment (10^3–10^4 channel widths (W)), reach (10^2–10^3 W), and morphological unit (1–10 W) spatial scales; and (ii) analyze the sensitivity of scale-dependent hydraulic features to the use of spatially distributed roughness values versus a constant roughness scheme. The study presented herein demonstrates that incorporating spatially distributed vegetated roughness has a significant effect on hydrodynamic models by channelizing the thalweg velocities, generating a complex pattern of velocity minima and maxima on the floodplain, and creating backwater depths that increase the wetted area for a given discharge.



Modified after Casas et al. (2010)

Fig. 1. Schematic of the mixing layer in shallow streams.

2. Study area

The Yuba River is a tributary of the Feather River in north-central California, USA, that drains 3480 km^2 of the western Sierra Nevada range (Fig. 2). Historic hydraulic mining yielded massive alluvial storage in the valley. Englebright Dam, completed in 1940, traps nearly all sediment, promoting a downstream geomorphic recovery that continues today (Carley et al., 2012). The 37.1-km river segment between Englebright Dam and the Feather River confluence is defined as the lower Yuba River (LYR) (Fig. 2), a single-thread channel (~20 emergent bars/islands at bankfull) with low sinuosity, high width-to-depth ratio, mean bed slope of 0.185%, mean bed surface sediment size of 97 mm (i.e., small cobble), and slight to no entrenchment. The river corridor is confined in a steep-walled bedrock canyon for the upper 3.1 km, then transitions first into a wider confined valley with some meandering through Timbuctoo Bend, then into a wide, alluvial valley downstream to the mouth. Sediment berms train the active river corridor to isolate it from the ~4000 ha Yuba Goldfields. Daguerre Point Dam (DPD) is an 8-m-high irrigation diversion dam 17.8 km upstream of the Feather that creates a slope break and partial sediment barrier. Existing literature with more information about the hydrogeomorphology of the LYR include Pasternack (2008), Moir and Pasternack (2008, 2010), James et al. (2009), Sawyer et al. (2010), White et al. (2010), and Wyrick and Pasternack (2012).

This study investigated 28.3 km of the LYR in the wide, alluvial valley (starting at 39°13′13″ N, 121°20′7″ W). In addition to assessing segment-averaged effects, the river was segregated into five geomorphic reaches (Fig. 2) and 31 morphological units (MUs) (i.e., subwidth-scale landforms). Seven MUs (i.e., chute, floodplain, lateral bar, point bar, pool, riffle, and run) were used in this study to exemplify the effects of spatially distributed roughness at the MU scale. Full landform descriptions and analyses at segment, reach, and MU scales is available in Wyrick and Pasternack (2012).

Because of insufficient surficial sand and mud in the LYR as well as frequent and aggressive overbank floods, woody vegetation covers 22% of the entire ~37.5 km of LYR floodplain (i.e., inundation area for 597.49 m^3/s), with reach coverages in the study domain varying from 16.7% for Marysville to 29.8% for DPD. The Marysville reach has the tallest woody vegetation (average height of 8.6 m) compared to 5.6 m for the DPD reach. Much woody vegetation aligns in patches along current or historic banks. Dense vegetation stands in swales, side channels, and backwaters also exist. The riparian forest is dominated by Fremont cottonwood (*Populus fremontij*), white alder (*Alnus rhombifolia*), and willow (primarily *Salix lasiandra*, *S. hindsiana*, *S. goodingii var. racemosa*, and *S. laevigata*). Herbaceous vegetation is a mix of native and exotic species including rushes (*Junells* spp.), sedges (*Carex* spp.), bull thistle (*Circium vulgare*), mullein (*Verbascum Thapsus*), cocklebur (*Xanthium strunarium var. canadense*), and several exotic grasses (*Bromus* spp., *Avena* spp.) (Beak Consultants, Inc., 1989).