Application of remote sensing techniques to characterize riparian vegetation for modeling hydraulic roughness

Smriti Chaulagain, University of New Mexico, Albuquerque, NM, schaulagain@unm.edu
Mark Stone, University of New Mexico, Albuquerque, NM, stone@unm.edu
Danial Dombroski, United States Bureau of Reclamation, Denver, CO, ddombroski@usbr.gov

Abstract

The objectives of this study were to investigate the resistance equations for the computation of vegetation-induced roughness in a two-dimensional (2D) hydrodynamic model and to evaluate two vegetation roughness approaches compared to the standard user-assigned roughness approach. To calculate the spatially distributed vegetation-induced roughness based on vegetation parameters, an existing 2D model coupled with two roughness algorithms was used. Vegetation parameters such as vegetation height, density, and leaf area index were determined using light detection and ranging data for the San Joaquin River in California, USA. Water surface elevations modeled using vegetation-induced roughness approaches produced an acceptable overall performance. The results demonstrate the spatial variability of roughness based on discharge and vegetation species in the floodplain. The method investigated in this study is beneficial for describing the hydraulic conditions due to spatially variable vegetation. In addition, this study improved the understanding of vegetation-induced roughness and its influence on hydraulic parameters such as water depth and velocity.

Introduction

Riparian vegetation, vegetation between the terrestrial and aquatic vegetation, is rich in ecosystem services that is beneficial for both the river system and human communities vicinity of the river. Besides ecosystem services, riparian vegetation has a major impact on the hydrodynamics of river and floodplain systems in terms of flow resistance (roughness) (Chow, 1959). The ability to estimate the flow resistance caused by vegetation and the consequences for hydrodynamic processes have long been a vexing problem for engineers since the mid-20th century (Ree & Palmer, 1949). The complex structure of vegetation has varying effects on hydraulics based on the submergence conditions. Thus, the traditional approach of defining constant roughness for land cover can produce erroneous results in estimating hydraulic characteristics.

Extensive studies have been done to determine the effects of vegetation on roughness considering vegetation structures/characteristics such as height, density, leaf area index (LAI), flexibility, etc. (Baptist et al., 2007; Maghadam & Kouwen, 1997; Järvelä, 2004). Several studies have proposed a relationship to estimate hydraulic roughness based on vegetation characteristics. For example, Järvelä (2004) determined the hydraulic roughness considering vegetation height and LAI as vegetation density. Baptist et al. (2007) determined the relationship between vegetation-induced roughness due to vegetation height (submerged or unsubmerged) and stem density (that induces vegetation drag).

The complex structure of vegetation makes the application and evaluation of existing resistance equation challenging. Very few studies have implemented the resistance equations in the presence of vegetation. Determination of vegetation characteristics from field data collection is time-consuming, labor-intensive, and not feasible for the larger study area. Thus, the remote sensing approach provides benefits over field measurement for a larger area.

The objectives of this study were to investigate the resistance equations for the computation of vegetation-induced roughness in a two-dimensional (2D) hydrodynamic model and to evaluate two vegetation roughness approaches compared to the standard user-assigned roughness approach. The equations developed by Baptist et al. (2007) (*Baptist, hereafter*) and Järvelä (2004) (*Järvelä, hereafter*) were used in this study to determine the roughness due to vegetation. Remote sensing data (Light detection and ranging (LiDAR)) was used for the determination of vegetation parameters.

Methodology

Study area

This study was conducted over a 20 km reach of the San Joaquin River, located between Highway 99 Bridge to Gravelly Ford, west of Fresno, California, USA. For this reach, the average bankfull discharge is about 31 m^3/s. The dominant vegetation species along the study reach include Cottonwood, herbaceous, mixed riparian forest, willow, oak forest, riparian scrub, wetland, willow scrub, exotic tree, and arundo.

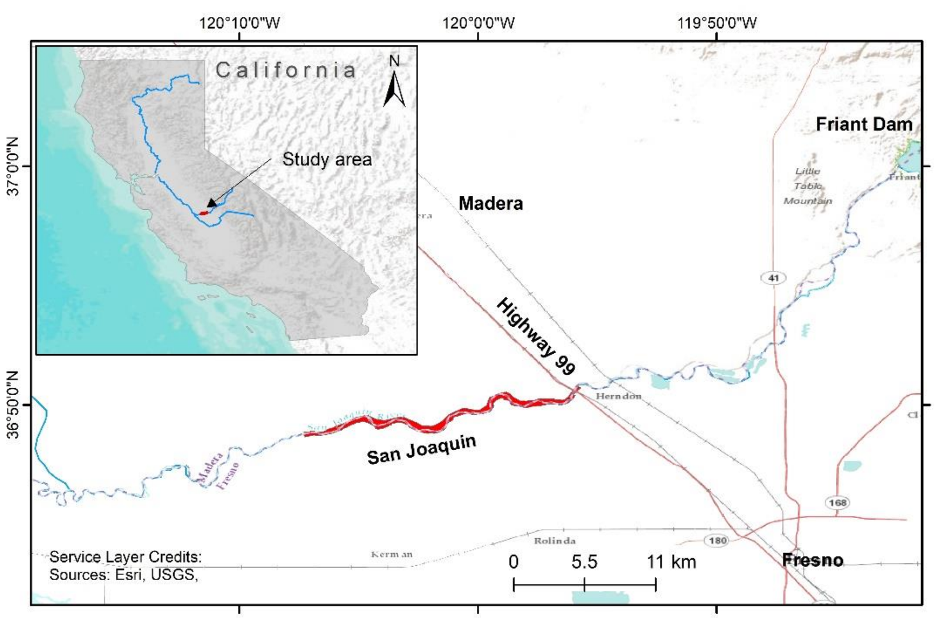

Figure 1: Location map with the study area highlighted by red

Vegetation parameters

Vegetation parameters such as vegetation height, density, and LAI are required for the two approaches to determine vegetation-induced roughness. LiDAR data collected in the year 2015 was used for computing the vegetation height, density, and LAI. Vegetation height was determined based on the Canopy Height Model. LAI was determined using the modified Beer-Lambert equation (Richardson et al., 2009). The approach followed by Straatsma & Baptist (2008) was used to determine vegetation density. The vegetation parameters determined from LiDAR were verified based on the field data collections.

Hydrodynamic model and model set-ups

In this study, two two-dimensional hydrodynamic models were used. The sediment and River Hydraulics (SRH-2D) model, developed by the United States Bureau of Reclamation (BOR), was used for this research. This model is designed to simulate flow hydraulics in open channel river systems by solving the two-dimensional, depth-averaged, St. Venant equations (Lai, 2010). SRH-2D is based on user-assigned roughness. The source code of the SRH-2D model was modified using two roughness approaches Baptist et al. (2007) and Järvelä (2004) to calculate hydraulic roughness from vegetation parameters within the model (*SRH-2DV* hereafter).

For user-assigned roughness approach, SRH-2D model simulation for the study reach was developed. The original model of the study reach was developed and calibrated by BOR. The 2D mesh was generated using third-party software Surface-water Modeling System (SMS) graphical user interface developed by Aquaveo LLC, Provo, UT. The mesh resolution was 9.5 m average spacing (Reclamation, 2012). Floodplain topography was represented by LiDAR data collected in 2008. River bathymetry was represented by SONAR data collected from 2009-2011 (Reclamation, 2012).

The model was simulated for steady-state conditions for two flows (113 and 212 m^3/s). These two flows were selected because the field water surface elevations (WSEs) for these two flows were available for calibration. SRH-2D model was calibrated for these two flows by adjusting the manning's roughness without consideration of vegetation.

SRH2DV model was applied to determine the depth and velocity-dependent roughness that varies spatially depending on the vertical distribution and spatial variation of vegetation characteristics (Chaulagain et al., 2022). This model utilizes the same mesh and boundary conditions except for the assignment of manning's roughness that was used in the SRH-2D model. Vegetation parameters are prepared to provide input for the SRH-2DV model. Manning's roughness values were calculated iteratively based on the user-assigned vegetation parameters within the model. The details of the methods are described in Chaulagain et al. (2022).

Results and discussion

Model evaluation

The model was evaluated by calculating Root Mean Square Errors (RMSE) between the measured WSEs and the WSEs from the models. RMSE calculated between the measured, and different models are represented in Table 1. While comparing RMSE, the user-assigned approach has a lower RMSE which is expected because the model was calibrated to match the measured WSE. However, the Baptist approach has a lower RMSE than the Järvelä approach, representing better performance.

Table 1. Root mean square between the models and the measure WSEs

Discharges (m^3/s)	113	212
	RMSE (meter)	
User-assigned roughness	0.16	0.13
Järvelä approach	0.37	0.48
Baptist approach	0.17	0.41

Hydraulic roughness

Hydraulic roughness due to vegetation varies based on vegetation parameters, which vary spatially. Figure 2 represents the roughness values based on different modeling approaches for a section of the study reach. This figure shows that the roughness values are different even for the same vegetation types and discharges based on the spatial location. The roughness due to vegetation has a wider range of values than user-assigned roughness. The variation of roughness impacts the hydraulic parameters such as velocity and water depth. Figure 3 represents the differences in velocity between the user-assigned and vegetation-induced roughness approaches. Positive values mean the vegetation-induced roughness overpredicted the velocity compared to user-assigned roughness. The difference in velocity is higher on the floodplain and varies in different natures, even for the same vegetation species. This signifies that roughness values vary spatially based on vegetation species influencing the velocity distribution.

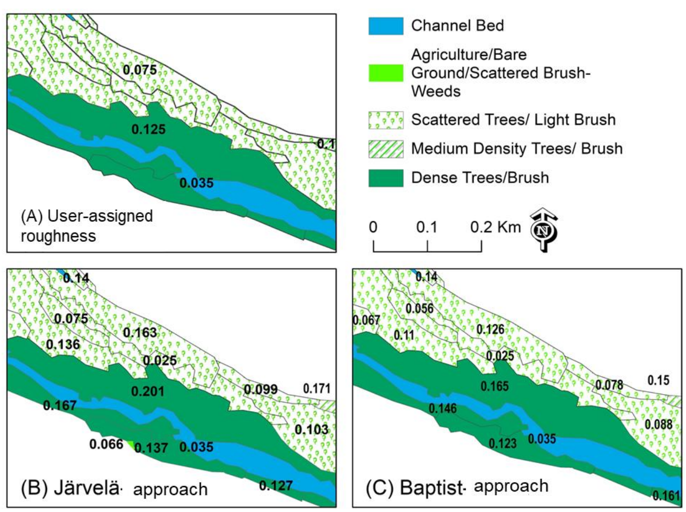

Figure 2. Roughness based on different modeling approaches for 212 m^3/s

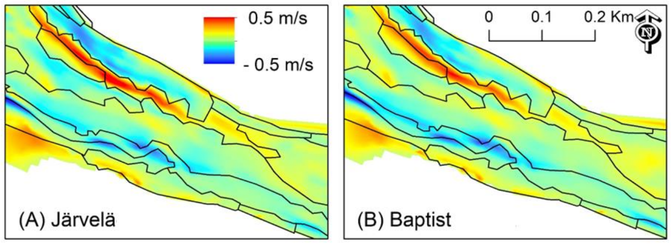

Figure 3. Velocity differences between user-assigned roughness and vegetation roughness approach for 212 m^3/s. [Positive values indicate the roughness model overpredicted velocities relative to the user-assigned and vice versa]

Conclusion

The objectives of this study were accomplished by implementing two 2D hydrodynamic models. Vegetation parameters that are used in the SRH-2DV model were determined from LiDAR data. The RMSE of WSEs between simulated and observed shows the acceptable model performance. The approach and methodology used in this study are easily applicable in other study areas. The spatial variability of roughness based on vegetation species directs towards the necessity of defining hydraulic roughness for site-specific projects such as habitat restoration and sediment transport processes.

Disclosure

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