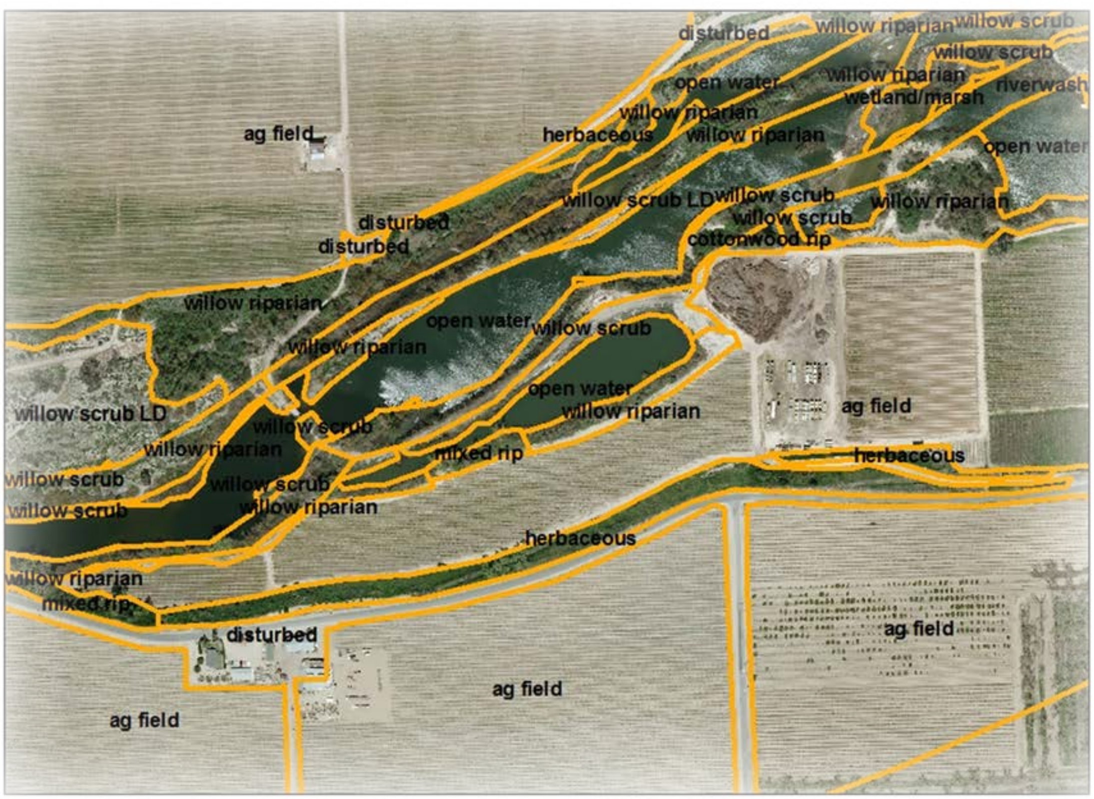
RECLAMATION
Managing Water in the West

Remote Sensing of Vegetation Characteristics for Estimation of Partitioned Roughness in Hydraulic and Sediment Transport Modeling Applications

Research and Development Office
Science and Technology Program
(Final Report) ST-2017-6034-01



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

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Mission Statements

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14. ABSTRACT A quantitative two-dimensional model (Dombroski D. E., 2014) has been developed at the Technical Service Center for simulating the effect of vegetation characteristics on river and floodplain hydraulics through spatially distributed roughness. The model is based upon the SRH-2D package (Lai, 2010), which contains a two-dimensional flow and mobile bed sediment transport model. The work documented herein addresses two primary challenges associated with the vegetation-hydraulic solver by (a) implementing algorithms to estimate roughness based on remotely-sensed vegetation characteristics and (b) introducing a partitioned roughness that separates grain roughness used to compute sediment transport capacity from the total hydraulic roughness. The developments represent important improvements to the model that increase the usability and accuracy in simulating vegetation effects on hydraulics and sediment transport.

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Executive Summary

Predicting the effects of riparian vegetation on hydraulics and sediment transport within managed riverine systems is a growing challenge due to the increasing priority of maintaining ecosystem function while sustaining water conveyance. Quantitative predictive tools are needed to aid the science, economics, and policy of establishing environmental flows by addressing questions regarding the physical interaction of flow, vegetation, and sediment in rivers and floodplains.

A quantitative two-dimensional model (Dombroski D. E., 2014) has been developed at the Technical Service Center for simulating the effect of vegetation characteristics on river and floodplain hydraulics through spatially distributed roughness. The model is based upon the SRH-2D package (Lai, 2010), which contains a two-dimensional flow and mobile bed sediment transport model. The vegetation-hydraulic solver uses measured vegetation parameters and calculated hydraulic variables to estimate a spatially-distributed, dynamic roughness coefficient that is coupled to the simulated hydrodynamics through the bed shear stress. Two primary challenges associated with the new capability were identified: (1) Direct measurement of vegetation characteristics becomes unfeasible for large riparian corridors, and (2) increasing roughness to account for hydraulic resistance may cause gross over-predictions of sediment transport capacity.

The work documented herein addresses two primary challenges associated with the vegetation-hydraulic solver by (a) implementing algorithms to estimate roughness based on remotely-sensed vegetation characteristics and (b) introducing a partitioned roughness that separates grain roughness used to compute sediment transport capacity from the total hydraulic roughness. The developments represent important improvements to the model that increase the usability and accuracy in simulating vegetation effects on hydraulics and sediment transport.

Further testing, validation, and refinement of the model will continue as it is applied at the project level with support from the San Joaquin River Restoration Program and Platte River Recovery Implementation Program offices.

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Theoretical Background

Predicting the effects of riparian vegetation on hydraulics and sediment transport within managed riverine systems is a growing challenge due to the increasing priority of maintaining ecosystem function while sustaining water conveyance. Quantitative predictive tools are needed to aid the science, economics, and policy of establishing environmental flows by addressing questions regarding the physical interaction of flow, vegetation, and sediment in rivers and floodplains. These tools are especially critical for regions of the Western U.S. like Central California, in which multi-benefit water projects (e.g., projects that enhance flood safety, wildlife habitat, and public recreation) are legally mandated components of regional and State-wide planning and funding efforts. These multi-benefit projects can be critically dependent on accurate estimates and modeling of vegetation effects on hydraulic conveyance, due to concerns over increases in roughness resulting from vegetation establishment and growth.

The new SRH-2D package features the addition of a hydraulic roughness module for computing dynamic, spatially-distributed Manning's *n* values based on vegetation characteristics (Dombroski D. , 2014). The computed Manning's *n* roughness values (4) incorporate resistance due to form drag of flow through the vegetation. The vegetation module receives spatially-distributed input data via a user-generated ArcGIS shapefile that is automatically mapped to the computational grid of the hydraulic solver at runtime. The computational time step for the hydraulic solver is generally limited by numerical instability, whereas the computational time step for the vegetation module is limited by ecologically-relevant scales, and can generally be significantly larger. A larger vegetation time step offers the benefit of decreased computational overhead.

The vegetated flow formulas of Baptist et al. (2007) and Järvelä (2004) for calculating roughness were implemented in the model during initial phase of development; the algorithms depend on parameters that are correlated to measured vegetation characteristics. Two primary challenges associated with the new capability were identified:

1. Direct measurement of vegetation characteristics becomes unfeasible for large riparian corridors
2. Increased roughness to account for hydraulic resistance may cause gross over-predictions of sediment transport capacity

The work documented herein addresses two primary challenges associated with the vegetation-hydraulic solver by (a) implementing algorithms to estimate roughness based on remotely-sensed vegetation characteristics and (b) introducing a partitioned roughness that separates grain roughness used to compute sediment transport capacity from the total hydraulic roughness. The developments represent important improvements to the model that increase the usability and accuracy in simulating vegetation effects on hydraulics and sediment transport.

SRH-2D Model Overview

A quantitative two-dimensional model (Dombroski D. E., 2014) is in active development at the Bureau of Reclamation Technical Service Center for simulating the effect of riparian vegetation on hydraulics and sediment transport in the river and floodplain environment. The model is based upon the SRH-2D package (Lai, 2010), which contains a two-dimensional flow and mobile bed sediment transport model. Hydraulic variables are computed by solving the depth-averaged dynamic wave (St. Venant) equations using a finite volume numerical method:

$$\frac{\partial h}{\partial t} + \frac{\partial hU}{\partial x} + \frac{\partial hV}{\partial y} = e \tag{1}$$

$$\frac{\partial hU}{\partial t} + \frac{\partial hUU}{\partial x} + \frac{\partial hVU}{\partial y} = \frac{\partial hT_{xx}}{\partial x} + \frac{\partial hT_{xy}}{\partial y} - gh\frac{\partial z}{\partial x} - \frac{\tau_{bx}}{\rho} + D_{xx} + D_{xy} \tag{2}$$

$$\frac{\partial hV}{\partial t} + \frac{\partial hUV}{\partial x} + \frac{\partial hVV}{\partial y} = \frac{\partial hT_{xy}}{\partial x} + \frac{\partial hT_{yy}}{\partial y} - gh\frac{\partial z}{\partial y} - \frac{\tau_{by}}{\rho} + D_{yx} + D_{yy} \tag{3}$$

In the above, t is time, x and y are horizontal Cartesian coordinates, h is water depth, U and V are depth-averaged velocity components in x and y directions, respectively, e is excess rainfall rate, g is gravitational acceleration, T_{xx}, T_{xy}, T_{yy} are depth-averaged turbulent stresses, D_{xx}, D_{xy}, D_{yx}, D_{yy} are dispersion terms due to depth averaging, $z = z_b + h$ is water surface elevation, z_b is bed elevation, ρ is water density, and τ_{bx}, τ_{by} are the bed shear stresses (friction). Bed shear stresses are calculated by the SRH-2D hydraulic solver using the Manning's roughness equation as follows:

$$\begin{pmatrix}\tau_{bx}\\ \tau_{by}\end{pmatrix} = \rho C_f \begin{pmatrix}U_x\\ U_y\end{pmatrix}\sqrt{U_x^2 + U_y^2}; \quad C_f = \frac{gn^2}{h^{1/3}} \tag{4}$$

where n is the Manning's roughness coefficient. The user-specified Manning's n is generally spatially-distributed yet independent of the computed hydraulic variables, and is the primary "tuning" parameter used during model calibration. The turbulent stresses are computed through an enhanced viscosity (Boussinesq assumption):

$$T_{xx} = 2(\nu + \nu_t)\frac{\partial U}{\partial x} - \frac{2}{3}k \tag{5}$$

$$T_{xy} = (\nu + \nu_t)\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) \tag{6}$$

$$T_{yy} = 2(\nu + \nu_t)\frac{\partial V}{\partial y} - \frac{2}{3}k \tag{7}$$

where ν is kinematic viscosity of water, ν_t is the turbulent eddy viscosity, and k is the turbulent kinetic energy. One of two turbulence closure schemes is used to model the eddy viscosity: $\nu_t = C_t U_* h$ (parabolic model) or $\nu_t = C_\mu k^2/\varepsilon$ (k-ε model), where C_t and C_μ are constants, U_* is the bed frictional velocity, and ε is turbulent energy dissipation. Solution requires solving additional conservation equations for k and ε.

Sediment transport computations are performed within SRH-2D by solving a total load (combined bed and suspended load) conservation equation that attributes sediment concentration rate of change to the sum of the divergence of the sediment flux and the inequality between equilibrium and local transport rates (Greimann, Lai, & Huang, 2008):

$$\frac{\partial hC_k}{\partial t} + \frac{\partial \cos \propto_k \beta_k V_t hC_k}{\partial x} + \frac{\partial \sin \propto_k \beta_k V_t hC_k}{\partial y} = \frac{\partial}{\partial x}\left(hf_k D_{sx}\frac{\partial C_k}{\partial x}\right) + \frac{\partial}{\partial y}\left(hf_k D_{sy}\frac{\partial C_k}{\partial y}\right) + S_{e,k} \tag{8}$$

Equation (8) is valid for each sediment size class k, where C_k is depth-averaged sediment concentration, α_k is the direction angle of sediment transport, V_t is depth-averaged resultant flow velocity, D_{sx}, D_{sy} are sediment dispersion coefficients, f_k is the transport mode parameter ($0 \le f_k \le 1$), β_k is the sediment-to-flow velocity ratio, and $S_{e,k}$ is a source term accounting for sediment erosion and deposition:

$$S_{e,k} = \frac{1}{L_{t,k}}\left(q_{t,k}^{*} - \beta_k V_t hC_k\right) \tag{9}$$

In the above, $L_{t,k}$ is the adaptation length scale and $q_{t,k}^{*}$ is the equilibrium capacity sediment transport rate for size class k. The form of Equation (9) represents total load; pure bed load or suspended load formulas can be recovered by adjusting f_k and $S_{e,k}$ (Lai & Gaeuman, 2013) (Greimann, Lai, & Huang, 2008):

$$S_{e,k} = \zeta_k \omega_{s,k}\left(C_{s,k}^{*} - C_{s,k}\right), f_k = 1 \text{ for suspended load}$$

$$S_{e,k} = \frac{1}{L_{b,k}}\left(q_{b,k}^{*} - q_{b,k}\right), f_k = 0 \text{ for bed load}$$

A sediment transport capacity equation is needed to calculate $q_{t,k}^{*}$ in Equation (9); SRH-2D offers the user options to select from equations by Engelund-Hanson (1972), Meter-Peter and Muller (Modified; 1948), Parker (1990), Wilcock and Crowe (2003), Wu et al. (2000), and Yang (1973, 1979, 1984).

Vegetation and Sediment Transport

The presence of vegetation within open channel flows generally increases inundation which can be accounted for in numerical modeling exercises by increasing the substrate roughness values as a function of the plant patch characteristics. The SRH-2D module simulates the effect of vegetation in this manner, dynamically adjusting Manning's n according to equivalent roughness formulations (Dombroski D. , 2014). However, the presence of vegetation also effects the vertical distribution of velocities and near-bed stresses, which cannot generally be simulated through modification of the roughness alone. Flow within the vegetation zone is generally slow moving relative to that outside of the vegetation, which alters the near-bed shear stresses. For submerged vegetation, faster moving flow is partitioned above with high shear and turbulence levels at the interface (Simon, Bennett, & Neary, 2004) (Le Bouteiller & Venditti, 2015).

Sediment transport is driven in large part by the near-bed shear stress and resistance to scour, both of which may be highly dependent on the vegetative conditions. Simon et al. (2004) summarize potentially stabilizing (hydrologic: canopy interception and transpiration; mechanical: root reinforcement) and destabilizing (hydrologic: increased infiltration rate and capacity; mechanical: surcharge) effects of riparian vegetation on bank stability. Although systematically increasing the Manning's *n* for presence of vegetation at the patch scale may correctly model the effect on water surface elevation, the associated increase in bed shear stresses (4) may incorrectly model the effect on sediment by overestimating transport capacity. This is especially true for the likely scenario in which the vegetation induces lower velocities and smaller shear stresses in the submerged partition of the water column, mechanistically trapping sediment.

Nepf and Ghisalberti (2008) review advances in understanding flow and transport phenomena in channels with submerged vegetation. They describe a dominant shear layer at the top of the canopy controlling the vertical mass and momentum exchange. Near the bed, transport is determined by characteristics of the vegetation stems that control the scales of turbulent motion. In non-vegetated flow, bed shear stresses are highly correlated to the vertical velocity distribution; however, in vegetated flow the bed shear stresses are determined largely by the characteristics of the vegetation (Huai, Zeng, & Yang, 2009). Although the bulk drag resistance of flow through vegetation has been shown to reduce bed shear stress (Lopez & Garcia, 1997) (Thompson, Wilson, & Hansen, 2004), turbulence enhancement around stems can increase sediment entrainment locally for some spacing and geometry configurations (Nepf H. M., 1999) (Nezu & Onitsuka, 2001), complicating the analysis. Building on prior work investigating flow characteristics in vegetated open-channel flows (Wilson, Stoesser, Bates, & Pinzen, 2011) (Ghisalberti & Nepf, 2006), Chen et al. (2011) studied the effects of vegetation spacing and configuration on the flow structure within submerged flexible vegetation at specific locations. Huai et al. (2009) proposed a three-layer model for predicting the vertical velocity distribution of flow through submerged rigid vegetation. However, without explicit consideration of the stresses induced by the presence of vegetation in the flow, such models are not entirely useful in predicting sediment transport effects (Larsen, 2008). An explicit treatment of the effect of vegetation characteristics on drag resistance and bed shear stresses is needed in order to predict mass transport trends that are directly coupled.

Larsen (2008) coupled a one-dimensional hydraulic and sediment transport model, advancing an algebraic turbulence closure scheme based on vegetation characteristics. Le Bouteiller and Venditti (2015) demonstrated, with laboratory measurements of sediment transport through artificial eelgrass, that bed shear stress partitioning is necessary to account for the effects of sediment trapping. Bed shear stress partitioning attributes additive components of shear stress due to grain τ_g (skin friction), plants τ_v (form drag), and bed morphology τ_f (form drag).

$$\tau_b = \tau_g + \tau_v + \tau_f \tag{10}$$

The form drag associated with the presence of the vegetation generally reduces the skin friction component of bed shear stress relative to the total stress ($\alpha = \tau_g / \tau_b$), reducing the sediment transport capacity. Therefore, the skin friction τ_g component of shear stress is used in evaluating transport capacity formulas. Bed morphology adjustments (e.g., changes in bed slope) may follow in order to restore capacity (Le Bouteiller & Venditti, 2015). Le Bouteiller & Venditti (2015) present various algorithms and criteria for evaluating the skin friction. They conclude that inverting bed load formulas to obtain the skin friction is an advisable approach when measured transport data is available and that the Einstein and Banks (1950) method should be used otherwise.

Roughness Partitioning

Vegetation resists flow due to drag on discrete elements and nonlinear interactions between multiple elements (Nepf H. M., 2012). Although flow resistance in natural systems is often characterized through the estimation of a dimensionless (e.g., Darcy friction factor f) or dimensional (e.g., Chezy coefficient C and Manning's n) bulk roughness parameter that is used to model the effect on hydraulics, this approach is insufficient when coupling sediment transport predictions because the forces determining transport capacity are not appropriately accounted for. Ongoing work within the Sedimentation and River Hydraulics Group at Reclamation's TSC is aimed at enhancing the SRH-2D model capabilities in predicting sediment transport in vegetated conditions by mechanistically partitioning the spatially-distributed roughness n, analogous to the concept of shear stress partitioning described above. The total roughness n is partitioned into a grain roughness n_g and a vegetation roughness n_v, the former associated with predicting sediment transport capacity:

$$n = n_g + n_v \tag{11}$$

The vegetation roughness n_v is formulated in terms of the form drag and is a function of the vegetation characteristics. In fluid mechanics, the drag force F_{Di} acting on an element i subject to flow of velocity u is computed according to $F_{Di} = 0.5\rho C_{Di} A_i u^2$, where ρ is water density, C_{Di} is drag coefficient, and A_i is frontal area of the object. A bulk drag force F_D is generally computed by averaging the drag force contribution over all elements i and assuming that C_{Di}, A_i, and u are independent variables such that $F_D = 0.5\rho C_D A U^2$, where C_D, A, and U are spatially-averaged values. The contribution of stress due to form drag of flow through the vegetation is $\tau_v = mF_D$, where m is the number of elements (i.e., plants) per unit ground area. Aberle & Jarvela (2013) and (Zahidi, Yusuf, & Cope, 2014) summarize approaches to parameterizing vegetative roughness equations formulated in terms of drag resistance for a variety of vegetation types.

Formulations based on the work of Jarvela (2004) and Baptist (2007) were initially implemented in the SRH-2D module for predicting spatially-distributed, dynamic roughness due to vegetation (Dombroski D. , 2014). Additional formulations are readily implemented within the modeling framework assuming that any necessary parameters and field data are available. Results from the model have generally demonstrated ability to predict effects of vegetation on hydraulic conditions; partitioning of the roughness (11) has now been implemented within the SRH-2D solver in order to more appropriately calculate the stresses that are used to evaluate sediment transport capacity. Additional improvement in the estimation of sediment transport could be gained by developing alternative formulations of transport capacity in which the effect of bed shear stress has been decoupled from the effect of flow turbulence.

Remote Sensing of Vegetation Characteristics

Aerial mapping using scanning laser and imaging techniques is a powerful tool that is commonly used in large scale river restoration, monitoring, and management projects. Light detection and ranging (LiDAR) technology is typically used to measure the height of surfaces and objects in the landscape below an aircraft, while simultaneous imagery provides a reference basemap for photogrammetry applications. The geo-referenced photography and digital elevation model (DEM) produced are necessary for incorporating accurate geometry into a computational mesh or cross-sections for two-dimensional and one-dimensional hydraulic models, respectively. The collection of aerial LiDAR data and digital imagery is typically built into the scope of large scale river restoration, monitoring, and management projects that involve hydraulic modeling as part of the analysis.

Aerial LiDAR and digital imagery are also used to remotely sense vegetation biophysical characteristics. Multi-return LiDAR data can be used to determine vegetation structure and height based on the waveform of the reflected signal (Lefsky, Cohen, Parker, & Harding, 2002). Canopy properties, such as leaf area index (LAI) can be estimated from LiDAR data through regression with ground-based estimates (Riaño, Valladares, Condés, & Chuvieco, 2004). Digital imagery, either airborne or satellite-based, is used to augment LiDAR data in characterizing vegetation by taking advantage of differential reflectance between spectral bands. Biophysical characteristics of interest are often regressed with calculated vegetation indices, such as the normalized difference (NDVI) (Elvidge & Chen, 1995). The NDVI indicates relative density of green leaves based on comparative reflectance from the visible and near-infrared spectral bands. Reflectance in the shortwave infrared band has been used to enhance discrimination between phenologic types based on leaf water content (Ceccato, Flasse, Tarantola, Jacquemoud, & Grégoire, 2001). Vegetation classification can also be improved by examining peaks in the panchromatic band due to differential shadowing that are not distinguishable in the visible and near-infrared spectra (Bryant, Moran, & McElroy, 2001). Joffre and Lacaze May (1993) used panchromatic images to measure tree density using a threshold-based filtering approach. The TREEVAW tool (Kini & Popescu, 2004) is an integrated Lidar processing software application developed for extracting forest inventory parameters at a per-tree granularity from a Lidar-derived Canopy Height Model (CHM).

Application of LiDAR data to parameterize roughness formulations in two-dimensional hydraulic models has been investigated previously. Mason et al. (2003) applied formulations developed by Kouwen & Li (1980) and Kouwen & Fathi-Moghadam (2000) to calculate friction factors for vegetation classified as short and tall, respectively. Although the formulations depend on estimates of plant flexural rigidity, the authors rely on correlations to vegetation height and make assumptions regarding cross-species applicability in order to limit the input vegetation attribute to height, which is obtained from the LiDAR data. The authors point out that while errors are inherently introduced, the approach represents an improvement over assuming a static, spatially-uniform roughness coefficient. Antonarakis et al. (2008) utilized allometric relations to estimate vegetation roughness at the trunk level by relating unmeasurable characteristics (e.g., trunk diameter) to those that can be estimated from LiDAR (e.g., height, canopy dimensions, and location). The allometric relations, such as that used to determine trunk area, are determined from regression with field measurements. The observed and calculated vegetation characteristics were used to parameterize a drag-based resistance equation applicable to rigid woody stems. Abu-Aly et al. (2014), using the approach of Casas et al. (2010), estimated roughness from mixing layer theory and LiDAR-derived vegetation height. The theory is valid for shallow flow with sufficiently tall woody vegetation. The authors investigated the effects of spatially-distributed roughness on simulated hydraulics using SRH-2D; however, because the algorithm was not implemented within the solver, a manual iteration was required to achieve converged solution.

The initial phase of development of the coupled module for calculating dynamic, spatially-distributed vegetative roughness has been documented (Dombroski D. E., 2014). Following the work of Mason et al. (2003), the hydraulic solver now incorporates the formulations developed by Kouwen & Li (1980) and Kouwen & Fathi-Moghadam (2000) to calculate friction factors from LiDAR derived vegetation height. Initial results show promise; ongoing work supported by restoration project offices will incorporate additional methodology for calculating spatially-distributed, dynamic roughness from LiDAR-derived vegetation characteristics.

Methods

The vegetation routines are contained within a module that interfaces with the SRH-2D hydraulic solver through a simple function call at each time step. By keeping the vegetation module distinct, coupling to the hydraulic solver is confined to several lines of code, and overhead associated with versioning and maintenance is kept to a minimum.

Roughness Partitioning

Roughness partitioning requires tracking of a grain roughness n_g and a vegetative form roughness n_v. In principal, additional roughness contributions due to other sources of hydraulic resistance could also be independently tracked. The vegetation module computes the vegetative roughness n_v. Because the SRH-2D hydraulic solver was initially designed to store a total roughness n, a new grain roughness n_g was introduced. If the vegetation module is called, both total roughness n and the calculated vegetative roughness n_v are returned to the hydraulic solver. The hydraulic solver uses the total roughness n to parameterize the bed shear stress formula (4); if the mobile bed sediment module is being called, the grain roughness $n_g = n - n_v$ is used to calculate sediment transport capacity (for shear-based capacity equations). The total roughness n is then recovered after sediment computations are complete.

Within the vegetation module, some basic error checking has been employed regarding the physical reasonableness of the computed roughness n_v at each wetted cell within the mesh.

Invalid Input Parameters

- If parameters input to the chosen algorithm are invalid (e.g., water depth is too high relative to vegetation height), the vegetative roughness n_v is assigned the value of the grain roughness n_g, such that the total roughness n takes on a value of twice the grain roughness.

Invalid Output Parameters

- If the calculated vegetative roughness n_v is higher than a physically reasonable value (e.g., $n_v > 0.2$), the vegetative roughness n_v is assigned the maximum value.
- If the calculated vegetative roughness n_v is less than zero, the vegetative roughness n_v is assigned a value of zero, such that the total roughness n takes on a value of the grain roughness.

It is important to note that the roughness partitioning is only expected to have an effect on the sediment transport computations if the selected capacity equation is a function of the roughness-based bed shear stress.

Vegetation Characteristics

Following the methodology of Mason et al. (2003), the capability of calculating dynamic, spatially-distributed roughness from remotely-sensed data was introduced. Vegetation height information was extracted from LiDAR data and assigned to the attribute table of the ArcGIS shapefile which provides spatial distribution and computational parameters to the module (Dombroski D. , 2014). A series of steps are involved in realizing usable vegetation information from LiDAR point cloud data, and a Python scripting tool was developed to facilitate the process:

- Each of the LiDAR returns classified as “ground”, “low veg”, “med veg”, and “high veg” are converted to a raster
- The ground elevation raster is subtracted from each of the vegetation elevation rasters to obtain vegetation height
- The vegetation height rasters are combined into a single vegetation height raster, keeping only the maximum height value in each cell
- Mean vegetation height is computed based on the spatially delineated polygons within the ArcGIS input shapefile.
- The table of mean vegetation heights for each polygon are joined to the input shapefile attribute table

The result from the above steps is a shapefile that contains spatially-delineated vegetation information on a polygon basis where each polygon has attributed to it a mean maximum vegetation height derived from LiDAR point cloud data. The spatial resolution of the vegetation information can be controlled by altering the number and extent of the polygons within the shapefile. The process of deriving vegetation characteristics from LiDAR data is extendable and may have applications beyond the roughness calculation algorithms of Kouwen & Li (1980) and Kouwen & Fathi-Moghadam (2000).

Case Study: San Joaquin River

The San Joaquin River Restoration Project was established in late 2006 to implement the Stipulation of Settlement (Settlement) in *Natural Resources Defense Council, et al., v. Kirk Rodgers, et al*. The effort aims to restore flows to the San Joaquin River and restore a self-sustaining Chinook salmon fishery while avoiding adverse water supply impacts. The project area extends from the confluence with the Merced River up to Friant Dam; the SJRRP office has requested the Technical Service Center to design restoration features in Reach 2B of the San Joaquin River upstream of Mendota Dam. Restoration activities are expected to include construction of a bypass channel around Mendota Dam, side-channel habitat for salmonids above the dam, and comprehensive revegetation of the surrounding areas.

The San Joaquin River Restoration Project office continues to invest in the development of the SRH-2D vegetation module because of the utility provided in evaluating restoration design alternatives. The roughness partitioning algorithm and calculation of vegetative roughness from remotely-sensed data is actively tested by applying the SRH-2D model in simulating vegetation and sediment transport effects within a short section of the San Joaquin River, in collaboration with the San Joaquin River Restoration Project design of Reach 2B. The implementation of the restoration project in this section of the river will include riparian planting and construction of new side-channel habitat for Spring and Fall run Chinook salmon. Evaluation of design alternatives requires quantitative assessment of dynamic hydraulic, vegetative, and sediment conditions, all of which will be affected by restoration actions (Greimann B. P., 2015; Greimann, O'Meara, & Kallio, 2016; Greimann, O'Meara, & Kallio, 2016). Design alternatives are implemented into the model by incorporating the constructed bathymetry and estimating the vegetation and sediment characteristics of the as-built condition (Figure 1 and Figure 2).

The San Joaquin River Restoration Program (SJRRP) contracted with Fugro EarthData in August, 2014 to provide high resolution aerial LiDAR and digital imagery data for 332 mi^2 of river corridor; the product was delivered in 2016. The SJRRP provided the aerial data to the benefit of the proposed work at no additional cost.

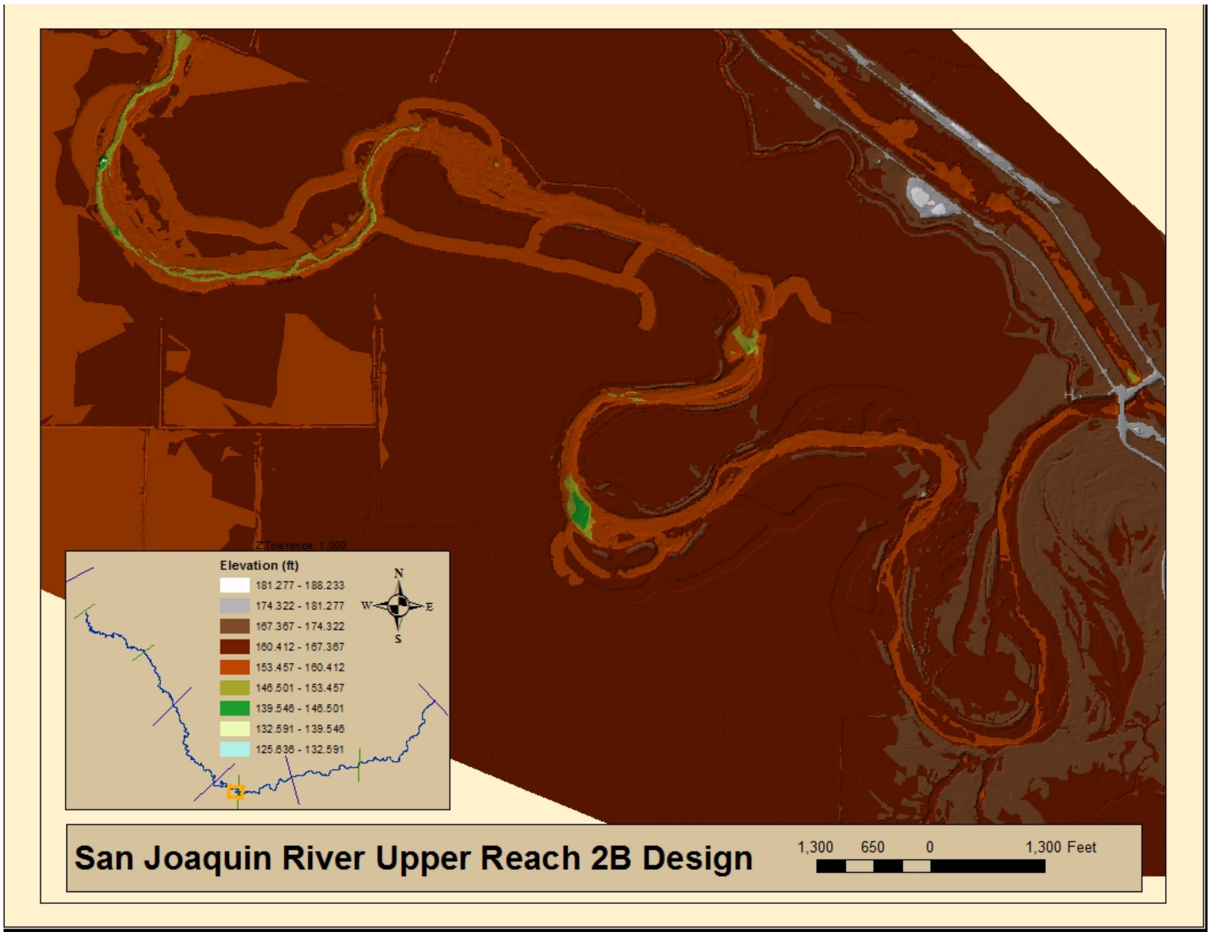

Figure 1. Design bathymetry of San Joaquin River Restoration Project Reach 2B, showing main channel and constructed side channel habitat in the upper section of the reach. The restoration design alternatives provide opportunities to apply the hydraulic, vegetation, and sediment model.

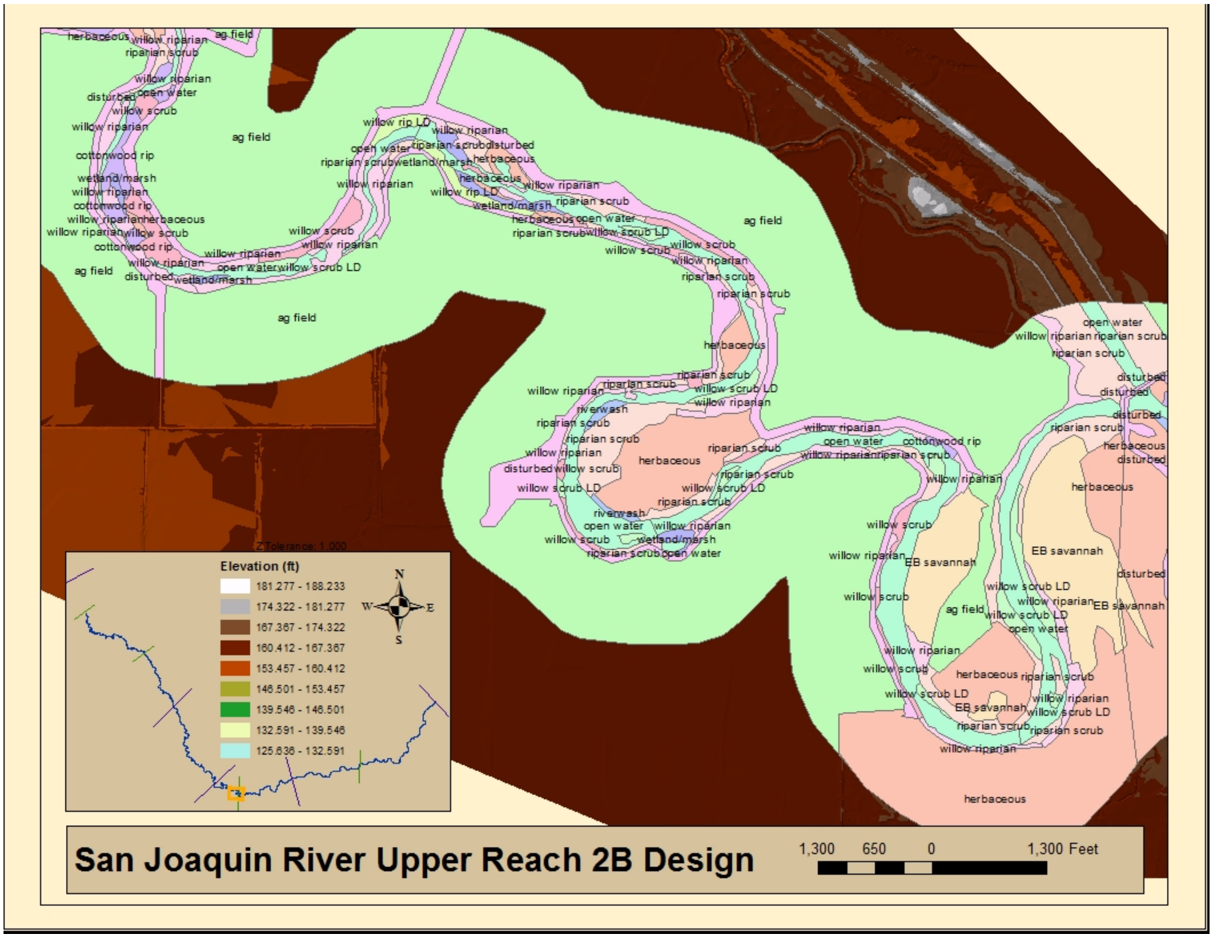

Figure 2. Example vegetation mapping of San Joaquin River Restoration Project Reach 2B, showing delineated polygons that spatially classify vegetation types. The vegetation mapping is an input to the model which defines the spatial distribution of vegetation characteristics needed to parameterize the roughness algorithms.

Field Data

A field study was conducted to test the usefulness of LiDAR data in estimating vegetation characteristics; the on-site measurements were made using standard hand-held forestry tools. In order to compare LiDAR data to actual on-the-ground vegetation measurements, data pertaining to four vegetation parameters used to estimate roughness in the model were collected: leaf area index (LAI), height, stem diameter, and stem density. Data was collected within 50-m^2 belt transects (50 m transect, 1 m wide with the exception of Transect 10, which had a plot 25m x 2m). Belt transects were located using a random start point but oriented so that the transect fit into the vegetation type polygon being sampled. Details of the methodology and results are provided in Appendix A. Methods are a modification of protocol employed by Gillihan (2013).

Recommendations for Next Steps

A theoretical framework for estimating dynamic, spatially-distributed roughness due to vegetative resistance has been coupled to the SRH-2D hydraulic solver. Additionally, total roughness is partitioned into the vegetative component and the grain component in order to improve physical representation of sediment transport processes. Initial testing has proved promising. Although thorough comparisons of model performance with measured conditions have not yet been performed, the work presented is focused on the development of new analytical frameworks within an existing tool, the results of which will be beneficial in investigating physical processes related to the interactions of vegetation with hydraulics and sediment transport.

The work is in a continuing status with the support of the San Joaquin River Restoration Project office and the Platte River Rehabilitation Implementation Program office; both organizations are investing in the development of tools that will facilitate greater understanding of physical processes underpinning restoration actions and ability to objectively evaluate restoration alternatives. Specific development objectives include the implementation of additional established algorithms for computing distributed roughness from LiDAR-derived vegetation characteristics (Antonarakis, Richards, Brasington, Bithell, & Muller, 2008; Abu-Aly, et al., 2014) and exploration of the importance of trunk spacing and vegetation density on roughness estimates.

Related model development, testing, and validation is being conducted through a collaboration with the Nepf Environmental Fluid Mechanics Laboratory at MIT (Dombroski, Greimann, & Nepf, 2016), a research group that examines physical mechanisms effecting transport dynamics within vegetated flows (Nepf & Ghisalberti, 2008). Sediment transport under complex flow conditions has been studied in the laboratory setting in order to develop better understanding of the interactions and important parameters governing transport rates and distributions. Active areas of research include how vegetation characteristics within a flow determine the trapping and redistribution of sediment (Nepf H. M., 2012; Nepf H. , 2012). Controlled experiments have been conducted in outdoor (e.g., Rominger, Lightbody, & Nepf, 2010) and indoor (e.g., Yang, Kerger, & Nepf, 2015) laboratories in order to measure flow and vegetation characteristics with the intent of developing relationships to physical mechanisms governing sediment transport. The ongoing research builds upon prior work at Reclamation's TSC by incorporating detailed measurements from within controlled flow environments to improve ability to numerically model complex sedimentation processes such as created through interaction with riparian vegetation. Current and newly developed formulations for computing sediment transport will be tested through physical experimentation. The final model will allow more realistic simulation of sediment transport, erosion, and deposition for use in river restoration design.

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Appendix A – San Joaquin River Riparian Vegetation Field Study

Introduction

The San Joaquin River Restoration Program (SJRRP) is a comprehensive long-term effort to restore flows to the San Joaquin River from Friant Dam to the confluence of the Merced River and restore a self-sustaining Chinook salmon fishery in the river while reducing or avoiding adverse water supply impacts from restoration flows. In association with restoration efforts, Bureau of Reclamation engineers are utilizing the Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) model to predict river flow hydraulics. A newly developed capability of the SRH-2D model estimates spatially-distributed dynamic roughness due to vegetation. This study was conducted to test the usefulness of LiDAR and photography in estimating vegetation characteristics for parameterizing the model. Vegetation characteristics were measured in the field and regression relationships developed between ground-based and remotely-sensed data; the ultimate goal is to demonstrate that the relationships between hydraulic roughness and vegetation characteristics can be parameterized using remotely-sensed data.

Methods

In order to compare LiDAR data to actual on-the-ground vegetation measurements, data pertaining to four vegetation parameters used to estimate roughness in the model were collected: leaf area index (LAI), height, stem diameter, and stem density. Data was collected within 50-m^2 belt transects (50 m transect, 1 m wide with the exception of Transect 10, which had a plot 25m x 2m). Belt transects were located using a random start point but oriented so that the transect fit into the vegetation type polygon being sampled. Methods used to measure the four vegetation variables are described below. Methods are a modification of protocol employed by Gillihan (2013).

LAI - LAI was measured using the AccuPAR LP-80. The AccuPAR works by taking both above and below canopy measurements of direct sun radiation. The machine estimates LAI from the fraction of light entering the canopy using a predictive mathematical model. Measurements were taken at breast height along the transect at 5 m intervals. The instrument averages these readings to generate one LAI value. For sparse vegetation that is composed of herbaceous species and/or low shrubs, measurements will be taken near knee height.

Height – The height of all woody plants that fall within the plot will be quantified using a meter measuring rod. For shrubby species with more than 1 stem per plant, an average of 3 to 5 stems will be calculated and recorded as one value. For trees that were taller than the meter rod, a hypsometer was used to calculate height.

Stem Diameter - Vegetation stem diameter was estimated using precision calipers for small branches and a DBH tape for bigger stems. All branches that fell at breast height and within the plot boundaries were counted. Stems were tallied by species and by size class in 5 cm intervals.

Stem Density - Stem density was measured by counting the total number of tallies recorded for every diameter bin at each site.

Results

Vegetation data was collected within 12 belt transects located in Reaches 1A, 2B and 4B2 from March 8 through 10, 2016 (Figure A 1). Data is provided in the associated Excel spreadsheet and ArcGIS files. In the original study plan, plots were located within a variety of vegetation types to provide a range of information. In the field, accessibility issues and inaccuracies in vegetation maps limited the range of vegetation types that could be included. The vegetation types of transects sampled are shown in Table A 1. Vegetation types are those used in vegetation mapping along the San Joaquin in 2012 (Reclamation 2014) and described by Sawyer et al (2009) as alliances or semi-natural stands.

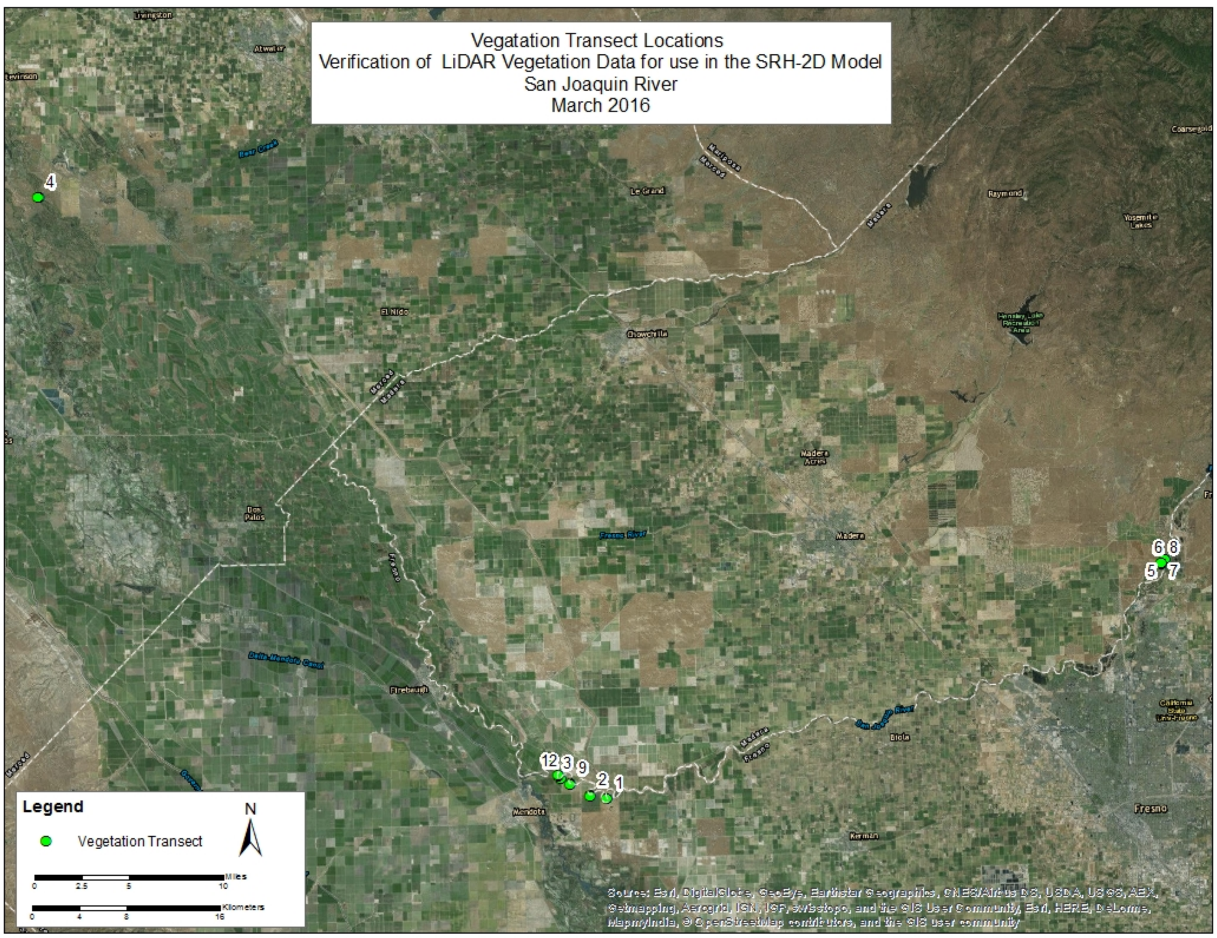

Figure A 1. Vegetation sampling plots within Reaches 1A, 2B, and 4B2 along the San Joaquin River.

Table A 1. Dominant vegetation types of sampled transects as identified in 2012 vegetation mapping.

Transect	Reach	Vegetation Type
1	2B	*Lupinus albifrons*
2	2B	*Salix gooddingii*
3	2B	*Salix gooddingii*
4	4B2	*Salix gooddingii*
5	1A	*Salix gooddingii*
6	1A	*Populus fremontii*
7	1A	*Populus fremontii*
8	1A	*Populus fremontii*
9	2B	*Populus fremontii*
10	2B	*Salix exigua*
11	2B	*Populus fremontii*
12	2B	Naturalized annual and perennial grassland

While conducting field sampling, some observations were made regarding methods used to collect vegetation data and potential issues in applying the data in the model. These observations may be helpful in data interpretation:

- Because density was measured at breast height, vegetation near ground level was not captured and sometimes made up a large proportion of the understory; the lower vegetation would probably be an important component in estimating "roughness" for the SRH-2D model. Another issue with measuring at breast height was that in some cases, stems that were measured were actually branches attached to tree limbs and were not rooted in the ground.
- Using an average for the height value does not account for an understory and overstory layer and could distort the actual height of the stand.
- The subshrub Himalayan blackberry *(Rubus armeniacus*) was not included in measurements however California wildrose (*Rosa californica*) was included due to the assumption that California wildrose is classified as a shrub. Post-inspection revealed that both species fall within the same category and either both should have been included or both omitted, which may have caused inconsistencies in understory data.

For access to complete data collected in the field study, contact the project principal investigator:

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