Modeling Riparian Vegetation and Effects on Hydraulics and Sediment Transport in Support of River Restoration and Management

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Abstract

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. A modeling suite has been developed by the Bureau of Reclamation for simulating vegetation lifecycle and the effects on hydraulics and sediment transport in the riparian environment. The models are based upon the SRH-2D package (Lai, 2010), which contains a two-dimensional flow and mobile bed sediment transport model. The capabilities of the modeling suite are comprised of two distinct components:

- A vegetation-hydraulic solver that 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.
- A cumulative stress lifecycle algorithm that predicts the establishment, growth, and removal of riparian vegetation based on measured parameters and calculated hydraulic variables.

The components of the riparian vegetation modeling suite have been developed and enhanced through a series of individually funded projects, the utility of which have been demonstrated at the project level. Here we provide a background of development for the modeling framework, a review of literature on the topic, and the theory upon which the algorithms are developed. We provide conceptual guidance on how the modeling tools may be effectively applied and review common questions associated with challenges in managing water and riparian corridors in the West. References to application of the modeling suite are provided, drawn from Bureau of Reclamation case studies. The model components are in active development; testing, validation, and refinement of the riparian vegetation modeling suite is needed to improve the usability, workflow, and accuracy of the simulations. The model development has leveraged in-kind support through mutually-beneficial collaborations with other agencies and institutions, including the U.S. Army Corps of Engineers, Massachusetts Institute of Technology, and University of New Mexico.

Introduction

Motivation

The Bureau of Reclamation's mission to manage, develop, and protect water and related resources in an environmentally and economically sound manner is more challenging than ever due to increasing and often competing demands. Science and technology has provided a key role in the advancement of tools to address these challenges in a comprehensive and efficient manner. It is therefore vitally important that Reclamation stay on the cutting edge of available technologies and remain poised to integrate technological innovations into daily operations. Development of riparian modeling tools are motivated by a need to quantitatively address questions such as the following:

- *Conveyance:* How will re-vegetation actions within restoration projects affect flood risks?
- *Sediment:* How do varying riparian vegetation characteristics associated with restoration actions influence sediment transport dynamics within the system?
- *Habitat:* How will restoration actions impact quality, quantity, and distribution of habitat?
- *Management:* How do reservoir operations affect vegetation recruitment and survival in the downstream riparian corridor?

These questions are particularly relevant to regions of the Western U.S. where multi-benefit water projects (e.g., projects that enhance flood safety, irrigation, 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 modeling of riparian vegetation and the effects on hydraulic conveyance and sediment transport.

Background

Vegetation resists flow due to drag forces on discrete elements and nonlinear interactions between multiple elements (Nepf H. M., 2012). 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) roughness parameter that is used to model the hydraulics. Roughness parameters derive from a combination of empiricism and hydrodynamic theory and are generally interrelated deterministically. The roughness of a vegetated channel is a function of both the characteristics of the vegetation (e.g., size, density, flexibility, leaf area) and the flow itself (due to streamlining effects). Chow (1959) produced a list of bracketed roughness values corresponding to various vegetated flow types. Thompson & Roberson (1976) presented an analytical method for predicting roughness due to a flow through vegetation modeled as rigid or flexible cylinders. The method depends on estimation of a drag coefficient, stem spacing and diameter, and flexural rigidity. Kouwen & Li (1980) developed an iterative approach for calculating roughness as a function of vegetation rigidity, and estimated plant deflection in response to forcing exerted by the flow. The Kouwen & Li (1980) approach is generally applicable to grasses, and the authors provided a table with stiffness values for a large variety of grass types. Kouwen & Fathi-Moghadam (2000) describe methodology to estimate resistance due to coniferous trees in open-channel flow by modifying a previously existing model (Fathi-Moghadam & Kouwen, 1997) in order to account for variations in the flexibility between species. The authors obtained species-specific parameters for the equations by conducting intricate laboratory and field experiments to measure drag force on model trees. Darby (1999) presents a simplified cross-section based model for predicting roughness associated with sediment or vegetation. The approach applies one of six different empirically calibrated flow resistance equations at each computational node. An equation similar to the Kouwen & Li (1980) approach is used for flexible vegetation, while an equation similar to the Thompson & Roberson (1976) approach is used for nonflexible vegetation. A procedure for estimating roughness due to flow through stiff or flexible woody vegetation is described by Jarvela (2004). The method, limited to emergent vegetation, incorporates leaf area index (LAI) to account for the effect of leaf distribution on drag resistance. The author also presents (Jarvela, 2005) an analysis of flow structure over submerged flexible vegetation with a focus on velocity profiles and turbulence characteristics. Baptist et al. (2007) derive a Chezy-type formulation for calculating resistance due to submerged or emergent vegetation. The representative resistance coefficient includes contributions from the bed roughness, form drag from flow through the vegetation, and shear due the velocity profile above the vegetation. Hession and Curran (2013) provide a literature review of trends and research in the topic of vegetation-induced roughness in fluvial systems; the authors discuss the spatio-temporal complexity of processes related to vegetation-flow-sediment interactions. Abu-Aly et al. (2014) present the results of two-dimensional hydraulic modeling using roughness derived from LiDAR. The authors demonstrate the effects of spatially-distributed roughness on hydraulics at the local and reach scale, and underscore the importance of systematically defining roughness at the resolution of the computational grid. The challenge of capturing the complexity of effects due to flow through a broad range of vegetation types is reflected by the diversity of predictive tools developed during more than five decades of research.

The local hydraulics within a river system in part determines the establishment, growth, and removal of riparian vegetation. Complicating the interplay between ecology and hydraulics are processes related to hydrology and climate, substrate and groundwater, and species-species interactions. The timescales of ecohydraulic processes range from short (e.g., seed dispersal, scour) to long (e.g., establishment and seasonal growth). The desire to better manage riparian vegetation has led to a body of research aimed at modeling ecohydraulic processes. Mahoney & Rood (1998) describe an integrative conceptual model that defines the hydrologic and environmental conditions required for successful Cottonwood recruitment. The authors make quantitative recommendations regarding water table and pore water recedence rates. A review of Cottonwood ecophysiology is given by Rood et al. (2003), in which physiological and morphological changes are documented due to dewatering processes within river channels. A river seeding concept (Meier, 2008) argues the importance of seed dispersal as a function of flood stage and drawdown rate, challenging aspects of the work of Mahooney & Rood (1998). Merritt & Wohl (2002) discuss vegetation recruitment and hydrochory dependencies on hydraulics, hydrology, and dispersal phenology, and suggest physical parameters relevant to a model framework. Groves et al. (2009) developed a stochastic seed dispersal model using an analytical expression with inputs dependent on local kinematics. The aforementioned studies have contributed to a better mechanistic understanding of specific ecohydraulic processes.

While many studies have advanced the understanding of focused processes related to vegetation-flow interactions, comparatively few have attempted a comprehensive modeling effort. Lytle & Merritt (2004) describe an approach to model how cycles of flood and drought affect long-term Cottonwood forest population dynamics. The stochastic matrix model predicts succession by adjusting probabilities according to environmental conditions. Hooke et al. (2005) developed a rule-based model for morphology, vegetation, and sediment changes in ephemeral streams. Perona et al. (2009) provide a review of vegetation and flow modeling using deterministic and stochastic approaches with varying levels of simplification, and include a discussion of dynamics at relevant scales of interest. A comprehensive modeling effort by Shafroth et al. (2010) links flow events, geomorphic processes, and biotic responses. The authors used existing modeling tools (HEC-RAS, MDSWMS, MODFLOW, HEC-EFM) to simulate the effects of experimental controlled dam releases, including river morphology changes, incipient motion and scour thresholds, and stochastic vegetation response. Despite a broad base of prior work concerning vegetation-flow interactions, the need remains for a generally applicable modeling framework that can be used in a predictive sense at the operation level.

Described herein is a deterministic computational tool for modeling spatially-distributed flow and vegetation interactions. The riparian modeling suite is based upon the SRH-2D package (Lai, 2010), which contains a two-dimensional flow and mobile bed sediment transport model. The capabilities of the modeling suite are comprised of two distinct components:

- A vegetation-hydraulic solver that 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.
- A cumulative stress lifecycle algorithm that predicts the establishment, growth, and removal of riparian vegetation based on measured parameters and calculated hydraulic variables.

The components of the riparian vegetation modeling suite have been developed and enhanced through a series of individually funded projects. The initial vegetation lifecycle model was developed with support from the Platte River Recovery Implementation Program (Murphy, Fotherby, Randle, & Simons, 2006) and was later ported to a two-dimensional framework (Dombroski D. E., 2014). Fotherby (2013) produced a compendium of species-specific vegetation parameters of common use in the lifecycle model. Dombroski (2014) developed a separate module for simulating the effect of vegetation on river and floodplain hydraulics through spatially-distributed roughness; the algorithms were refined through a collaboration with the U.S. Army Corps of Engineers (Wang, Zhang, Greimann, & Huang, 2018). Further work extended the application of the dynamic roughness simulation module to better predict suppression of sediment transport capacity in vegetated flow conditions (Dombroski D. E., 2017; Dombroski D. E., 2016). Funded by the Reclamation Research Office in collaboration with University of New Mexico, the project also demonstrated the utility of using remotely-sensed LiDAR data to inform the model with vegetation characteristics over great spatial extent (Chaulagain, et al., 2022). In a collaboration with the Massachusetts Institute of Technology, laboratory flume measurements and a theoretical turbulence model were used to conceptually demonstrate how model accuracy could be improved in predicting hydraulics and sediment transport by directly accounting for the effects of vegetation stem-generated turbulence (Dombroski D. E., 2019). Ongoing work in collaboration with the Reclamation Albuquerque Area Office seeks to implement better scour algorithms in the vegetation lifecycle module for improved prediction of seed removal and effect on germination and establishment. Also under development is a user manual that will be publicly available along with the modeling suite.

While the riparian vegetation modeling capabilities at Reclamation have been in continual development over a period of approximately two decades, the utility and effectiveness of model components have also been demonstrated through numerous case studies and project application: Platte River Recovery Implementation Program (Murphy, Fotherby, Randle, & Simons, 2006), San Joaquin River Restoration Project (Dombroski D. E., 2017; Chaulagain, et al., 2022; Dombroski D. E., 2014), Trinity River Restoration Program (Dombroski D. E., 2016), Rio Grande Bosque Del Apache Realignment Project (Dombroski & Holste, 2023). The application of the riparian vegetation model and dissemination of results has led to increasing frequency of request for the adoption of the modeling capabilities in a variety of projects within Reclamation and beyond.

Model Description

SRH-2D Solver

The SRH-2D flow solver (Lai, 2010) is used as the computational base for the coupled flow and vegetation model. Solutions can be computed over an unstructured hybrid mesh (Lai, 1997; 2000), and the solver includes a seamless wetting-drying algorithm that is applied at each time step. With appropriate boundary conditions, constant or varying discharge flows may be simulated. The solver can compute subcritical and supercritical flow conditions without special treatment. Hydraulic variables are computed by solving the depth-averaged dynamic wave 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} and 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 (Lai Y. G., 2020) 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, Vt is depth-averaged resultant flow velocity, D_{sx}, D_{sy} are sediment dispersion coefficients, f_k is the transport mode parameter ($0 \leq f_k \leq 1$), 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 sediment transport rate for size class k. The form of Equation (8) for pure bed load or suspended load transport 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 Lifecycle Module

The vegetation lifecycle module predicts spatially-distributed seed dispersal, establishment, growth, and removal in response to dynamic hydraulic conditions. The algorithms are based largely on the one-dimensional vegetation and hydraulics simulation tool (SRH-1DV) discussed in Huang (2016) and Fotherby (2013); here, the methodology has been ported to the two-dimensional framework of SRH-2D. The spatial extent of vegetation communities are delineated by polygons in an ArcGIS shapefile; the probabilistic distribution of vegetation types within these communities and the parameters that govern establishment, growth, and mortality are provided in an accompanying text file. Any number of vegetation types can be simulated provided one or more differentiating characteristics for each type can be quantified through the input parameters. The vegetation lifecycle evolves temporally with the solution to the hydraulic variables; a hydrograph and rating curve specify the dynamic input and output boundary conditions (Lai Y. G., 2010) for the hydraulic solver. An initial establishment of vegetation can be specified for each polygon in the shapefile. 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.

In the lifecycle model, plants establish at grid cells based on seed dispersal and suitability criteria. During the germination window for each vegetation type, seeds are dispersed to every cell in the computational grid. Density ranging from 0 to 1 can be specified for each modeled species within a vegetation community in the input shapefile, and is treated as a probability of occurrence at computational grid cells. Vegetation at each cell is allowed to grow based on age-specific rates given as input. The model tracks root depth & width, canopy width, and plant height at each cell. Root depth is limited by ground water elevation, which is assumed to be equal to the water elevation of the nearest wetted cell. Processes in the model that may kill vegetation include age, scour, desiccation, and inundation. Species competition is not treated explicitly; however, dynamic conditions may favor the growth of one species over another. The effect of desiccation and inundation are a function of the age of the vegetation and cumulative duration of drying or wetting. The velocity-based scour threshold for each vegetation type is dependent on the age of the vegetation, where increasing time since establishment is generally associated with higher resistance to removal.

Vegetation characteristics are an important model input including the spatial distribution, species type, age, and density. A database of germination, growth, and stressor sensitivity parameters for a variety of common Western riparian species is available for parameterizing the model and is based on prior vegetation field studies and modeling work (Fotherby L. , 2013). In the model, vegetation communities within any region are fractionally composed of individual species. To develop a distribution of established (current conditions) vegetation communities, the practitioner is advised to utilize prior mapping studies if available (e.g., according to the Hink and Ohmart classification system as presented in Siegle and Ahlers (2017)). The pre-project classification can then be modified to account for project design or re-management considerations, including vegetation clearing and planting.

Typically, the goal when applying the model is not to make absolute or definitive predictions, but to develop hypotheses that inform monitoring and adaptive management. Relationships between hydrology, hydraulics, groundwater, and vegetation are complex, and the modeling provides useful insights by parameterizing variables and linking important physical processes.

Typical modeling workflow may include exploring sensitivity to a variety of physical and biological factors:

- Initial condition (e.g., vegetated vs. non-vegetated)
- Hydrologic regime (e.g., wet vs. dry seasonal flows)
- Invasive plant species
- Germination windowing
- Resistance to stressors (e.g., draught, inundation, etc.)
- Environmental flow management (e.g., dam releases)
- Channel modifications
- Floodplain management

For example, a vegetation lifecycle model may be initialized with different conditions: a vegetated initial condition (developed from steps above) and a completely non-vegetated initial condition. The purpose of two initial conditions may be to analyze sensitivity of germination to the presence of existing vegetation. A non-vegetated initial condition implies that existing vegetation at the beginning of a model run does not affect the potential for new germination. This provides insight about where new vegetation would be likely to grow if the landscape were completely barren. A vegetated initial condition, accounting for project implementation as described above, can help evaluate if new vegetation would be able to outcompete existing vegetation.

Another study may explore riparian species response to varying seasonal hydrographs (e.g., "wet" vs. "dry" vs. "average" water year types). Species-specific parameterizations govern the germination, establishment, and removal as a function of historically observed water year type hydrographs. Germination success or failure, and subsequent distribution of seedlings, is generally a much more complex process than would be indicated by volume of water under each hydrograph alone. Resulting spatial distribution can show strong dependence on hydrograph type; e.g., dry years with low spring runoffs tend to show germination concentrated near the channel margins.

A vegetation modeling case study may alternatively be designed to evaluate riparian response processes to designed channel realignment conditions. The scope of river restoration projects often includes channel and floodplain modifications in order to achieve ecological rehabilitation goals; modeling the effects on the riparian landscape provides a systematic way of evaluating design alternatives and testing hypotheses that inform monitoring and adaptive management.

In any scenario, seed distribution is assumed to cover the full model domain; the actual germination is governed by species-specific parameters that control behavioral rules within the model's lifecycle algorithms. Germination is limited by the following factors:

- Germination temporal window
- Seed elevation relative to water surface
- Time ground has been dry
- Co-location of pre-existing species

Conceptually, the rule-based limitations on germination are designed to prevent the model from predicting establishment in space or time that is biologically or physically unrealistic.

The primary utility of the vegetation lifecycle module is in gauging the differential effects of variation in operation, as opposed to predicting absolute end conditions. The underlying assumption is that capturing dominant physical processes that may be directly affected by operational changes is sufficient for quantitatively predicting the effect of variation in hydraulic conditions on riparian vegetation. Although the model could not possibly consider all the biotic and abiotic factors effecting germination, establishment, and removal, concluding remarks from prior studies include the following observations:

- Germination and establishment of vegetation in the riparian landscape shows a complex dependency on the dynamics of the hydrologic season convolved with the natural germination timescale.
- Susceptibility of newly-germinated vegetation to natural stressors is not only a function of the species-specific biological attributes, but also the spatio-temporal conditions of the riparian landscape and hydraulic conditions under which the vegetation is establishing.
- An existing riparian landscape may have a very different response to new hydrologic events and natural stressors than a barren landscape initially devoid of vegetation; likewise, landscape modification can impart significant change to the riparian communities due to the natural coupling of physical and biological processes.

The comparison of establishment patterns as a function of differential initial conditions (vegetated vs bare) illustrates the susceptibility of newly germinated seedlings to natural stressors. Depending on project objectives, the results of the modeling effort and comparisons drawn may motivate the need for active revegetation actions to be incorporated within river restoration and channel grading projects. Active planting may provide greater control over evolution of the riparian landscape post-construction, whereas the project outcome may otherwise be in part left to chance due to variability in water availability and distribution. Conversely, results from such a comparison may demonstrate that a passive approach to vegetation establishment is warranted, mitigating the costs associated with active clearing and revegetation. Ultimately, the efficacy of a strategy to support riparian vegetation is likely application dependent and a function of the species composition, hydrologic regime, and inherent stressors within the system.

Vegetative Roughness Module

The vegetative roughness module features an integrated set of tools for computing dynamic, spatially-distributed Manning's *n* values based on vegetation characteristics (Chaulagain, et al., 2022; Dombroski D. E., 2014). Vegetation roughness can generally be predicted numerically based on measured or projected biological conditions of the species present and utilized to predict hydraulic conditions, including distributions of depth and velocity. 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. Each polygon is assigned a method of computation and corresponding vegetation parameters. 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.

Four published formulations for computing roughness from vegetation characteristics are currently implemented within the vegetative roughness module and are described below. The module provides alternative capability to assign a user-specified static vegetative roughness. For polygons covering areas in which vegetation-based roughness is not applicable (e.g., in-channel, urban areas, etc.), a default roughness value can be specified. 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. Additional formulations are readily implemented within the modeling framework assuming that any necessary parameters and field data are available.

Jarvela (2004) Formulation: The Jarvela (2004) algorithm uses hydraulic and consideration of the mechanical properties of woody plants to determine resistance. In general, the procedure is dependent on field measurements of vegetation characteristics. There may be allometric or other regression relationships in the literature that can be used to estimate leaf area index (LAI) from other more easily-measurable quantities. In the Jarvela (2004) approach, the friction factor *f* is calculated as

$$f = 4C_{dX}\mathrm{LAI}\left(\frac{U}{U_X}\right)^X \frac{h}{H} \tag{10}$$

where C_{dX} is a species-specific drag coefficient, LAI is the leaf-area-index, X is a species-specific exponent, U is the flow velocity, and U_x is a reference velocity. The ratio of h (water depth) over H (plant height) is a scaling factor to account for partial submergence ($h<H$). The parameters C_{dX}, LAI, X, U_x, and H are measured in the field and are defined spatially in the ArcGIS input shapefile. The variable flow velocity and water depth are obtained from the coupled hydraulic solver, where U is calculated as the resultant of the horizontal velocity components at each grid cell. Thus the friction factor is a function of spatial variation in the plant parameters and spatial and temporal variation in the hydraulic variables. In practice, the Manning's n is used by the hydraulic solver and is computed from the friction factor as

$$n = \frac{R^{1/6}}{\sqrt{8g/f}} \tag{11}$$

where R is the hydraulic radius and g is the acceleration of gravity.

Baptist (2007) Formulation: The Baptist et al. (2007) algorithm is based on a Chezy-style formulation for estimating roughness over a wide range of water depths and vegetation properties, including both emergent and submerged conditions. Roughness can be calculated using the Baptist (2007) approach according to

$$C_r = \sqrt{\frac{1}{(1/C_b^2) + (C_d mDH/2g)}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{H}\right) \tag{12}$$

where C_b is the Chezy bed coefficient, C_d is the drag coefficient, m is plant density, D is stem diameter, H is plant height, κ = 0.41 is the von Karman constant, and h is the flow depth. Thus the composite resistance coefficient C_r includes the effects of bed resistance, form drag of flow through the vegetation, and the boundary layer formed above the vegetation. For emergent vegetation, the logarithmic term in (12) is dropped since the resistance is only a function of the bed roughness and vegetative drag. For dense vegetation, the contribution of the bed roughness term may be considered insignificant compared to the contribution of the vegetative drag term. The parameters C_b, C_d, m, D, and H are measured in the field and defined spatially in the ArcGIS input shapefile. The resistance in (12) is converted to Manning's n as

$$n = \frac{1}{C_r}R^{1/6} \tag{13}$$

The water depth h and hydraulic radius R are treated equivalently as either (A) the water depth at each grid cell or (B) the average water depth over the wetted cells within each polygon defined by the shapefile.

Kouwen & Li (1980) Formulation: The Kouwen & Li (1980) algorithm is applicable to short floodplain vegetation (up to 1 m high) that are treated as flexible. The drag force exerted on the water flow by the vegetation depends on its flexural rigidity and stem density. The friction factor f is computed using the resistance relation

$$\frac{1}{\sqrt{f}} = a + b \log\left(\frac{y_n}{k}\right) \tag{14}$$

where y_n is water depth and k is the deflected vegetation height, estimated by

$$k = 0.14h \left[\frac{\left(\frac{MEI}{\tau}\right)^{0.25}}{h}\right]^{1.59} \tag{15}$$

The undeflected vegetation height h is measured in the field, $\tau = \rho {v_*}^2$ is the local boundary shear stress calculated from water density ρ and friction velocity v_*, and MEI is the product of stem density M, stem modulus of elasticity E, and stem area second moment of inertia I. The individual components M, E, and I are challenging to quantify; however, the product MEI is correlated to vegetation height and can be estimated as follows (Mason, Cobby, Horritt, & Bates, 2003):

$$MEI = \begin{cases} 319h^{3.3} & \text{(growing grass)} \\ 25.4h^{2.26} & \text{(dormant grass)} \end{cases} \tag{16}$$

In (14), a and b are fitted parameters that are dependent on the ratio $v_*/v_{*\mathrm{crit}}$, where the critical shear velocity $v_{*\mathrm{crit}}$ is estimated according to (Table 1)

$$v_{*\mathrm{crit}} = \min(0.028 + 6.33MEI, 0.23MEI^{0.106})$$

Table 1. Values of a and b, table adapted from (Mason, Cobby, Horritt, & Bates, 2003)

Classification	Criteria	*a*	*b*
Erect	$v_*/v_{*\mathrm{crit}} \le 1.0$	0.15	1.85
Prone	$1.0 < v_*/v_{*\mathrm{crit}} \le 1.5$	0.20	2.70
Prone	$1.5 < v_*/v_{*\mathrm{crit}} \le 2.5$	0.28	3.08
Prone	$2.5 < v_*/v_{*\mathrm{crit}}$	0.29	3.50

Kouwen & Fathi-Moghadam (2000) Formulation: The Kouwen & Fathi-Moghadam (2000) algorithm is applicable to medium-to-tall coniferous trees that are treated as flexible. The authors observed a linear relationship between drag and flow velocity (due to streamlining of foliage) in contrast to the expected squared relationship observed for rigid vegetation. The authors found additional effects related to the variation of foliage with height and account for this by including a linear dependency. Following the method of Mason et al. (2003), the algorithm is applied to species other than coniferous trees with the assumption that the estimated roughness will be more accurate than other methods that do not consider flexibility of vegetation. The friction factor is calculated according to

$$f = 4.06\left[\frac{V}{\sqrt{\frac{\xi E}{\rho}}}\right]^{-0.46}\frac{y_n}{h} \tag{17}$$

where V is flow velocity, E is the tree modulus of elasticity, and ξ is a streamlining parameter. Recommended values of ξE are given by Kouwen & Fathi-Moghadam (2000) and reproduced in Table 2.

Table 2. Estimated vegetation indices, adapted from Kouwen & Fathi-Moghadam (2000)

Species	ξE (N/m^2)
Cedar	2.07
Spruce	3.36
White pine	2.99
Austrian pine	4.54

Static Vegetation: The static vegetation option is not actually a roughness computation method but instead simply applies a user-specified roughness value to the cells in that polygon at each timestep. No consideration is given for temporal context or variation in vegetative or hydraulic conditions. The total roughness (n) then becomes the static vegetative roughness value (n_v) plus the roughness value specified in the SIF file (n_o). Roughness partitioning is discussed below.

For hydraulics-only computations within SRH-2D, using a static vegetation roughness value essentially provides an alternative way to specify roughness distribution from the conventional method of defining material zones within the .2dm file. In this way, roughness could be specified according to a shapefile delineation.

For mobile-bed simulations within SRH-2D, using a static vegetation roughness value provides a simple way to engage the roughness partitioning algorithm to modify sediment transport capacity calculations, since the n_v vegetative resistance component and n_o grain roughness component are tracked and applied independently. See section on vegetation and sediment transport for more details.

Static No Vegetation: The static no vegetation option is not actually a roughness estimation method but instead simply assigns a value of $n_v = 0$ to the cells in that polygon at each timestep. Thus the total roughness (n) defaults to the bed roughness value (n_o) value. This mode of operation is useful for areas where no vegetation is present and therefore the total roughness is well-represented by a single grain roughness value.

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. E., 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).

$$\tau_b = \tau_g + \tau_v + \tau_f \tag{18}$$

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.

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. The SRH-2D model capabilities in predicting sediment transport in vegetated conditions are enhanced 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:

$$n = n_g + n_v \tag{19}$$

The vegetation roughness n_v is formulated in terms of the vegetative resistance and is a function of the vegetation characteristics as described above in the section Vegetative Roughness Module.

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. Although not yet implemented within the SRH-2D vegetation modeling suite, a preliminary study (Dombroski D. E., 2019) demonstrated the potential improvement in sediment transport calculations by implementing a transport formulation that is based on prediction of turbulent kinetic energy in vegetated conditions.

Case Studies

For details on application of the vegetation modeling suite to specific case studies along with analyses and results, the reader is deferred to the following works: Platte River Recovery Implementation Program (Murphy, Fotherby, Randle, & Simons, 2006), San Joaquin River Restoration Project (Dombroski D. E., 2017; Chaulagain, et al., 2022; Dombroski D. E., 2014), Trinity River Restoration Program (Dombroski D. E., 2016), Rio Grande Bosque Del Apache Realignment Project (Dombroski & Holste, 2023).

Conclusions and Future Development

Study results demonstrate that the vegetation model for computing hydraulic roughness is generally successful in reproducing the effect of riparian vegetation on water surface elevation as compared to that of measurements and manually calibrated simulations. Distributions of calculated roughness values due to vegetation are generally consistent with values compiled in the literature (Hession & Curran, 2013). The leaf area index is generally a convenient physically-based metric for quantifying vegetal density and area (Jalonen, Jarvela, & Aberle, 2013), and can be estimated by in situ observation or remote sensing. Water depth and velocity distribution are directly computed by the hydraulic solver and therefore easily incorporated into formulations for computing roughness. Given the spatially-detailed information that a two-dimensional hydraulic model can provide, it would be desirable to map input vegetation parameters at similar scale and resolution (Abu-Aly, Pasternack, Wyrick, Barker, Massa, & Johnson, 2014), which would necessitate the use of remote sensing technologies (Dombroski D. E., 2017; Chaulagain, et al., 2022). The distributions of calculated roughness values produced by the model and the effect of varying input parameters indicate that predicting the effects of vegetation on hydraulics is dependent on quantifying complicated species-specific coupling between the vegetation characteristics and local hydraulics. Further exploration of input parameter values and species dependency, a topic of active research (Aberle & Jarvela, 2013), would be useful in gauging applicability and evaluating performance of the algorithms. Despite the uncertainties and challenges involved, the vegetation module for computing hydraulic roughness is a useful tool for predicting the effects of projected vegetation changes and for use as a design tool in restoring riparian vegetation.

The vegetation lifecycle module is capable of simulating the distribution of seedling establishment, plant growth, and vegetation removal in response to dynamic hydraulic conditions. Results from the model indicate that the predictions are qualitatively reasonable, however further testing would be required in order to verify accuracy for specific applications. It is likely that further development of algorithms for modeling physical processes would be required on a case-by-case basis in order to increase the applicability of the module to a wide variety of natural systems. For example, significant assumptions regarding species competition, seed dispersal, and ground water may not be satisfactory in some cases. However, the primary utility of the vegetation lifecycle module is in gauging the differential effects of variation in operation, as opposed to predicting absolute end conditions. For this reason, it is likely that capturing dominant physical processes that may be directly affected by operational changes is sufficient for quantitatively predicting the effect of variation in hydraulic conditions on riparian vegetation.

Continuing development efforts will be focused on integration of the independent hydraulic roughness and lifecycle modules into a coupled framework with feedback interactions. The algorithms within each of the modules are highly empirical and require specific parameters. The primary challenge associated with the task of module integration is in developing relationships between conceptually similar (yet quantitatively distinct) parameters and variables. This is not only a challenge from a coding perspective, but also from a biological perspective. For example, leaf area index (used to predict hydraulic roughness) and vegetation canopy size (tracked in the vegetation lifecycle module) are clearly interrelated; however, further work will be required in order to deterministically relate one to the other within the constraints of the model framework. Some physical processes, such as vegetation density, will need to be more directly modeled in the lifecycle algorithms in order to be applicable within the hydraulic roughness calculations.

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