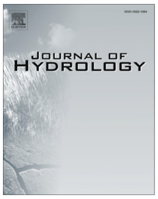
Journal of Hydrology 505 (2013) 364–376

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Review Papers

Vegetative impacts on hydraulics and sediment processes across the fluvial system

Joanna Crowe Curran [a,*], W. Cully Hession [b]

[a] Civil and Environmental Engineering, University of Virginia, PO Box 400742, Thornton Hall B228, Charlottesville, VA 22904, United States
[b] Center for Watershed Studies, Biological Systems Engineering, 200 Seitz Hall, Mail Code 0303 Virginia Tech, Blacksburg, VA 24061, United States

ARTICLE INFO

Article history:
Received 22 February 2012
Received in revised form 17 July 2013
Accepted 10 October 2013
Available online 16 October 2013
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of M. Todd Walter, Associate Editor

Keywords:
Vegetation
Fluvial system
Ecogeomorphology
Flow
Sediment

SUMMARY

Vegetation creates a complicated system of feedbacks and linkages across the fluvial system that is realized through river planform shape. Interactions occur among flow hydraulics, sediment deposition and erosion, and plant morphology, density, and biomechanics. Interest in the interactions and feedback loops between vegetation and the fluvial system has grown extensively in the past few years. This interest is partially driven by the popularity of stream restoration activities worldwide that include re-vegetation of stream banks and formation of an ecosystem that is intended to encourage the growth of aquatic macrophytes. We present a review of the research into the interactions and dependencies between vegetation and the fluvial system to identify hydraulic and sediment dynamics that are consistent around vegetation located in the channel, on channel banks, and over the floodplain. We illustrate process commonalities operating across spatial locations within the fluvial system and highlight some of the current research opportunities and challenges to encourage research collaborations between those working in areas of the fluvial system traditionally viewed as disparate.

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[*] Corresponding author. Tel.: +1 434 924 6224.
E-mail addresses: curran@virginia.edu (J.C. Curran), chession@vt.edu (W.C. Hession).

0022-1694/$ - see front matter
http://dx.doi.org/10.1016/j.jhydrol.2013.10.013

1. Introduction

Research into the linkages and interdependencies between vegetation and fluvial geomorphology attracts a great deal of interest due in part to the growing recognition of the role vegetation can play in ecological engineering and the potential for application in river and stream restoration projects (e.g. Bennett and Simon, 2004; Hession et al., 2010; N.R.C., 2002, 2007). Vegetated channel areas can alter fluvial morphology through feedback with hydraulics and sediment mechanics over planform, reach and local scales. Evidence for the increased complexity in the flow paths through vegetated reaches comes from field estimates of the dispersion coefficient, which provides a measure of fluid mixing. The coefficient was 70–100% higher in a vegetated river reach when compared to an unvegetated reach (Perucca et al., 2009). Vegetation has been traditionally either managed or removed to reduce roughness and flooding nuisance (Bal and Meire, 2009; Darby and Thorne, 1995; Jarvela, 2004). However, a recent general trend worldwide is to encourage the growth of channel area vegetation. Control of in-channel vegetation growth, its influence on stream flows, and the restoration of riparian or streamside forests to aid in bank stabilization are major foci of many stream restoration activities worldwide (Bernhardt et al., 2005; N.R.C., 1992; U.S. E.P.A., 1999). The Federal Conservation Reserve Enhancement Program (N.R.C., 2002) and a recently-launched initiative of the Conservation Reserve Program have set a goal to reforest 2025 km^2 of river floodplains across the US (Johnson, 2004). In addition to planned projects, natural reforestation is occurring where floodplains are reverting from crop and pasture (often abandoned) to woodland (Trimble, 2004). The impacts of activities such as riparian reforestation, the conversion from agricultural to forested floodplains, and manipulation of in-channel vegetation will have significant impacts on the morphology of streams, particularly in response to changes in roughness within a river corridor.

There is no standard, universal definition of where a stream ends and the actual streambank begins, much less a simple technique to delineate between the streambank and floodplain. Alluvial surface definitions and a block diagram showing their positions visually organizes the fluvial system for this paper (Fig. 1, Osterkamp and Hupp, 1984; Osterkamp and Hupp, 2010). Streambank vegetation is defined as those plants that are between the channel bank (AB) and shelf (AS), including the floodplain bank (FB). In-channel vegetation are those plants within the channel bed (CB) and on depositional bars in the channel (DB), rooted below the normal water surface and partially or fully submerged. Floodplains can be identified based on frequency of inundation (Moody et al., 1999), morphology (Leopold, 1994; Rosgen, 1996), or change in vegetation type (Richard et al., 2005), and are dynamic by nature (Hughes et al., 2008; Leopold et al., 1964). In this paper, we utilize Leopold's (1994) definition that the floodplain coincides with the elevation of bankfull stage and is "a level area near a river channel, constructed by the river in the present climate and overflowed during moderate flow events." Referring to Fig. 1, we extend our review only to the floodplain (FP) and do not include terraces (T) in our discussion. There are obvious uncertainties around these boundaries and they are referred to throughout the paper only to help organize the discussion.

The purpose of this paper is to identify commonalities in how vegetation in a fluvial system affects hydraulic and sediment transport processes over local and reach scales, which are then reflected in the channel form, and to identify areas for future research and collaboration. We focus on the interactions and dependencies between vegetation and the fluvial system to identify vegetative impacts that are consistent across areas traditionally viewed as disparate, namely within the channel area (CB, DB), on channel banks (AB, AS, FB), and on the floodplain (FP).

We seek to complement the existing literature reviews that detail the mean and turbulent flow fields over and through extended patches of aquatic vegetation (Nepf, 2012), the abiotic factors influencing plant species dynamics, aquatic habitat, and plant communities (Bornette and Puijalon, 2011), detailed dynamics operating in marshes (Andrea, 2011; Larsen and Harvey, 2011), and physical-biological feedbacks in ecogeomorphology (Darby, 2011; Reinhardt et al., 2010; Wheaton et al., 2011). Feedback between woody debris accumulations, sediment storage, and channel hydraulics at the reach scale has been documented for steep and low sloped channels (Abbe and Montgomery, 1996; Bennett et al., 2008), and recent research has quantified and correlated the distribution and transport of individual wood pieces and wood jams with channel planform morphology (Curran, 2010; Moulin et al., 2011). Thus, we do not include the influence of large woody debris in this paper choosing to focus instead on live and rooted vegetation.

There are a number of possible frameworks for organizing and presenting the research related to vegetative impact on a fluvial system. The primary functions of a river are the transport of flow and sediment, and we separate this discussion first into broad sections based on the fundamental hydraulic and sediment processes. Within these broad areas we divide the discussion into research focused on the channel planform, reach, and local scales. Each section ends with a summary focused on highlighting where similar processes are occurring at the different spatial scales. We chose not to organize sections based on physical location within

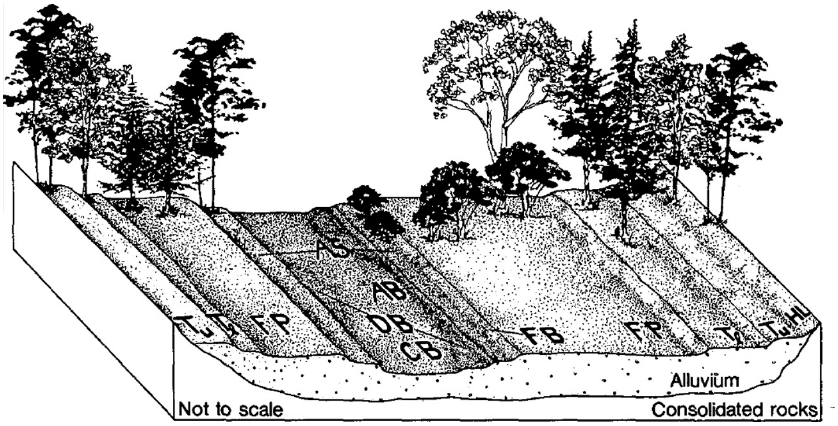

Fig. 1. Block diagram showing geomorphic features (Osterkamp and Hupp, 1984). Channel bank (AB), channel shelf (AS), floodplain bank (FB), channel bed (CB) and depositional bars in the channel (DB).

the fluvial system because our goal is to illustrate the similarity of process around vegetation across the system so that future research may be collaborative and apply findings from floodplain studies to channel bank studies, for example. There are overlaps in any organizational scheme, and it is the overlaps that we hope will become more common in the future. Modeling, which has the potential to extend across spatial scales, is included as a separate section. We close with a discussion of continuing research needs and directions.

2. Vegetative impacts on fluvial system hydraulics

The influence of vegetation over hydraulic processes within a fluvial system has often been evaluated through its contribution to roughness or overall flow resistance. Roughness is a critical characteristic influencing water-surface elevations and flow (Defra/EA, 2003), sediment transport (Cotton et al., 2006; Sand-Jensen, 1998), channel morphology (Hession et al., 2010; Millar, 2000; Tal and Paola, 2007), aquatic habitat (Downes et al., 1998; Muhar, 1996) and biodiversity (Beisel et al., 2000; Klaar et al., 2009; Sullivan et al., 2006). In general engineering practice flow resistance is most often parameterized by a Manning's n coefficient (1890) calculated using measurements of velocity, depth, and slope from gaging stations (Leopold et al., 1964; Limerinos, 1970). Although total roughness can be partitioned to determine the relative contributions due to surface material, vegetation type, spatial distribution of vegetation, and morphology (Arcement and Schneider, 1989; Cowen, 1956; Jordanova and James, 2003), these factors are often combined into a single parameter which also includes the impacts of vegetation density, flexibility, and morphology (Anderson et al., 2007; Diaz, 2005; Jarvela, 2002; Jin et al., 2001; Wilson, 2007; Wu et al., 1999). The use of a single parameter has led to a wide range in the estimated flow resistance where vegetation is present, with some estimates indicating as much as a 500% increase in the roughness parameter due to vegetation alone (Cowen, 1956).

Feedback between vegetation and channel hydraulics depends on numerous variables, including: type and physical characteristics of the vegetation (Antonarakis and Richards, 2010; Freeman et al., 2000); time of year or seasonal changes (Coon, 1998); vegetation succession (Geerling et al., 2007); density of vegetation (Wang and Wang, 2007); depth of flow (Anderson, 2006; Fischenich, 2000); geomorphic setting (Darby, 1999), and bank sediment characteristics (Darby et al., 2010; Parker et al., 2008). The acknowledged complexities of parameterizing how vegetation affects flow structure, flow resistance, and turbulent intensities has led to the recent development of additive approaches to quantify the separate vegetative influences creating roughness (Yang et al., 2007). In equation form, Yen (2002, eqn 32) defined a symbolic flow resistance parameter, f, as follows:

$$f = F(\mathrm{Re}, \mathrm{Fr}, S_w, S_o, K, L_v, J, D, M) \tag{1}$$

where Re is Reynolds number, Fr is Froude number, S_w is the water surface slope, S_o is the channel bed slope, K is relative roughness, L_v is a nondimensional vegetation parameter representing geometry, J represents plant flexibility, D is relative submergence of the vegetation, and M is the density of vegetation. Three of these parameters are a function of the species while two represent the interaction of the plants with the flow and four describe the channel hydraulics. This equation illustrates the large number of variables needed to describe how vegetation and hydraulics interact to define the channel form.

2.1. Planform scale

The significance of the interplay between vegetation and fluvial system hydraulics is observed through the influence of riparian and floodplain vegetation on channel planform morphology. Vegetation on channel floodplains and banks (FP, FB, AS, AB in Fig. 1) add stability to single-thread channels (Tal and Paola, 2007) and help maintain channel meanders (Braudrick et al., 2009). Upon re-vegetation of banks and floodplains, braided channels have been shown to narrow and return to a previous meandering state (Millar, 2000). Where floodplain and bank vegetation was removed from an ephemeral channel, the result was extensive bank erosion and channel widening during an extreme event. The eroded sediment deposited on the downstream channel bed and floodplain where vegetation had remained intact (Perignon et al., 2013). Field studies measuring high flows before and after removing rough vegetation from a bend show vegetation to be responsible for inducing a backwater effect that shifted the maximum velocity downstream and closer to the center of the channel while displacing higher velocity flow toward the outer bank (Thorne and Furbish, 1995). These results have led to speculation that natural variability in bank vegetation density and distribution may contribute to asymmetrical bend migration as hydraulics vary both around the bend and near vegetation.

2.2. Reach scale

The influence of vegetation morphology, flexibility, and density have been researched more fully at the reach scale as these experiments can often be carried out in laboratory flumes. Planting across a flume width simulates interaction between vegetation and flow hydraulics acting either within a channel or on a channel floodplain (DB, CB, FP in Fig. 1). Spatial density and rigidity of the plants (J, M in Eq. (1)) exert a significant influence over friction factor, as does the presence or absence of leaves on willows (Lv). In an experiment where sedges and willows were planted in a flume and the effects of plant flexibility and spatial distribution over the reach-averaged friction factor measured, a heightened impact on reach scale hydraulics was quantified when growth occurred in discrete patches (Jarvela, 2002; Wilson, 2007). When the density of willow plantings was doubled, the friction factor also doubled, and when leaves were present on the willows, changing the species specific morphology, the friction factor tripled.

Field studies have confirmed the influence of spatial patterns of vegetation on flow resistance and expanded the research to include a temporal component. During spring and summer, when vegetation was abundant in a channel, flow resistance and depth were increased (Gurnell et al., 2006, 2010). Changes in vegetative roughness impacted seasonal overbank flooding as flows were elevated when in-channel plants were fully grown (Asaeda et al., 2010). As vegetation density and spatial coverage across the channel increased during the summer months, distinct meso-habitats formed where the local flow rate was reduced and sediment accumulated (Champion and Tanner, 2000; Wharton et al., 2006). During the subsequent die-back during fall and winter, flow depth lowered. The feedback between seasonal vegetation growth and channel morphology is further complicated by the changing mechanical properties of aquatic vegetation change over a life cycle (J in Eq. (1)). As plants grew and aged, the mechanical properties were altered such that plants became more flexible (Shucksmith et al., 2011b). Thus, for the same flow rate the older plants bent further during lab experiments, becoming more streamlined with the flow.

Much of the research over the reach scale has been to inform selection of a single relative roughness (K in Eq. (1)) or Manning's n value for use in hydraulic engineering, planning channel construction, and flood modeling (Anderson and Rutherfurd, 2006; Fathi-Moghadam et al., 2011). However, frequent disturbance by flooding develops diverse vegetation communities on floodplains and channel banks (Gregory, 1992; Osterkamp and Hupp, 2010). This diversity has led to spatially heterogeneous roughness, complicating attempts to estimate a single roughness value for the vegetated reach (Forzieri et al., 2010; Freeman et al., 2000; Geerling et al., 2007; Girard et al., 2010). Several researchers have applied airborne laser scanning altimetry or airborne LIght Detection And Ranging (LiDAR, Coby et al., 2002; Forzieri et al., 2010; Perignon et al., 2013), as well as Terrestrial Laser Scanning (TLS, Antonarakis and Richards, 2010) to define an average area roughness height, but these tools remain cost prohibitive for broad application.

2.3. Local scale

The interaction between vegetation and hydraulics acting at a local patch or stem scale has been measured through changes in velocity profiles, turbulent mixing patterns, and Reynolds stresses around vegetation (Fig. 2). Much of this research has been conducted in laboratory flumes, where experimental conditions can be somewhat controlled and the complex flow dynamics around individual and patches of vegetation can be measured. The plants used in flume experiments range from simulated plant stems using cylindrical objects like wooden dowels (Bennett et al., 2002) to natural grasses and willows (Jarvela, 2002). Simulated vegetation remains popular in flume experiments because it has the advantage of control over spatial density and does not require a natural substrate (Bennett et al., 2002).

Flume experiments using hot wire anemometers (Sand-Jensen and Pedersen, 1999), electric current meters (Green, 2005), Acoustic Doppler Velocimeters (ADV, Jarvela, 2005), Particle Image Velocimetry (PIV, Nepf et al., 1997; Nepf, 1999; Serra et al., 2004; Shucksmith et al., 2011a) and Planar Laser Induced Fluorescence (PLIF) have measured velocities in detail in vegetated channels. Visualization and quantification of flow hydraulics immediately around plants has become a burgeoning area of research with the growth of the application of PIV and PLIF in flume studies. In PIV high speed photography is used to capture laser illuminated tracer particles in the flow. Image analysis allows the user to measure the direction and speed of individual seed particles, which enables calculation of turbulent flow properties. The reader is referred to works by Hart (1998), Fox and Belcher (2009), and Hurther et al. (2009) for a complete description of the principles and application of PIV. During PLIF studies, a dye is mixed into the flow that absorbs laser light at a single frequency and emits fluorescent light at a different frequency and with brightness proportional to its concentration. Images record the path of the dye as it passes through the laser illuminated area, capturing the mixing and diffusion processes. A full description of PLIF is provided by Reidenbach et al. (2010).

Local scale experiments seek to identify coherent flow structures generated around vegetation that may be responsible for the larger changes manifested over channel reach or planform morphologies. Visualization studies have shown the extent of change in the velocity profile to be a function of vegetation density, type, channel flow (Jarvela, 2002; Nepf and Ghisalberti, 2008; Petryk, 1969), and location either within a vegetated area or at the interface between the vegetation and the open flow.

2.3.1. Hydraulics within vegetation

Vegetated areas are considered dense or sparsely planted according to the frontal area of plants for a given bed area and where this value is over ~10% the vegetation is considered dense (Nepf, 2012). The measured turbulent flow velocity profile within a channel with a densely vegetated patch shows reduced flow rates and turbulence below the vegetation canopy (Fig. 2, Souliotis and Prinos, 2008). Where flow had a low Reynolds Number, mixing processes were dominated by diffusion. At higher Reynolds Number flows ($\sim 10^3$) the inertial-viscous flow regime was dominated by wake effects generated around individual stems, and diffusion coefficients were increased. Significant shear stresses developed only in the near bed region, indicating the turbulent exchange of fluid and momentum was limited to this area (Liu et al., 2008; Nepf and Vivoni, 2000). Reynolds stress profiles measured within patches of artificial plants have shown regions of turbulent energy movement were localized and energy transfer to the mean flow occurred on a limited basis within the vegetated area (Siniscalchi et al., 2012). A horseshoe vortex formed around the base of each dowel due to the velocity gradient between the slower flow in line behind the dowel and the higher velocity flow on either side of the dowel. This vortex moved high-velocity flows into the region at the dowel base, creating a localized area of increased turbulence and a counterclockwise mixing pattern. Flow velocities and turbulence lessened immediately above this area, marking the transition to near bed flow as an inflection point in the velocity profile. Fluid exchange within the vegetation occurred primarily through longitudinal advection driven by turbulent wakes generated by these

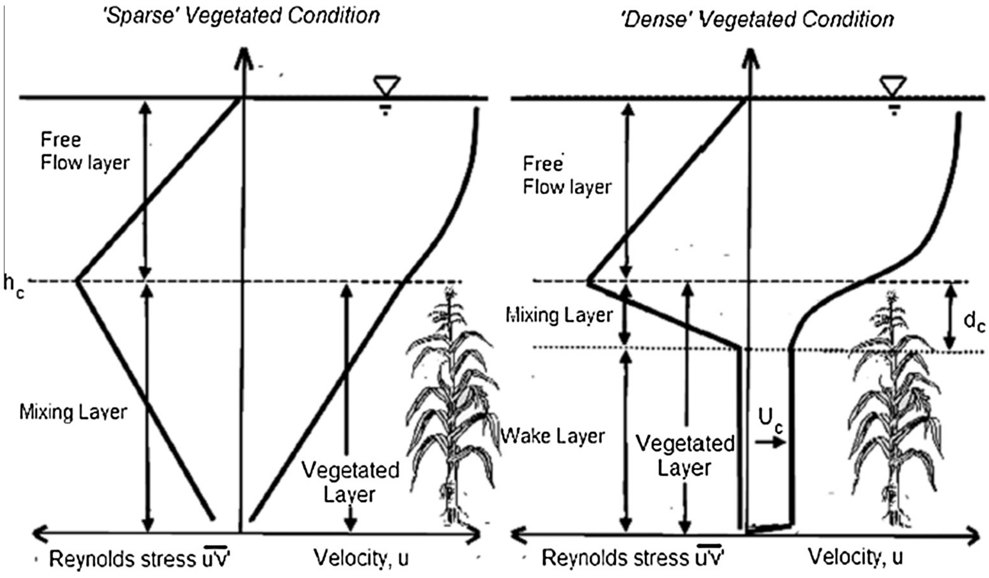

Fig. 2. Conceptual model of velocity flow profile through sparsely and densely planted submerged vegetation (from Shucksmith et al., 2011a).

horseshoe vortices that formed around plant stems (Nepf and Vivoni, 2000).

2.3.2. Hydraulics at the vegetated interface

Flow adjacent to vegetation is characterized as free-flowing but influenced by the characteristics of the submerged plants. An example of interface flow hydraulics comes from the transition between channel area and floodplain (Fig. 3), and many of the observed hydraulic patterns are similar where open channel flow interfaces with vegetation. Significant lateral flow hydraulics and vortices form at the interface between vegetated and non-vegetated channel areas (Fig. 3), regardless of whether the interface is across submerged vegetation in the channel (CD, DB in Fig. 1), around vegetation on the floodplain (FP in Fig. 1) and riparian area (Shiono and Knight, 1991), or within a partially vegetated channel (AB, AS, FB in Eq. (1), Shiono and Knight, 1991; Tsujimoto, 1999). A full description of this flow requires incorporating parameters for plant deflection, density, and morphology into the logarithmic profile equation, and various forms of the logarithmic profile equation have been developed (Baptist, 2003; Champion and Tanner, 2000; Chen et al., 2011; Green, 2005; Jarvela, 2005; Nepf and Ghisalberti, 2008; Stephan and Gutknecht, 2002). Laboratory experiments were used to visualize two-dimensional flows and quantify the increase in the complexity of Reynolds stresses at the vegetated interface, and results have been used to expand modeling efforts to include secondary flow patterns (White and Nepf, 2008; Zong and Nepf, 2010). Mixing across the interface was limited where simulated vegetation was dense and the velocity profile above the submerged vegetation was logarithmic (Kouwen et al., 1969). Coherent vortices developed into a shear layer and enabled turbulent momentum exchange across the interface (refer to Figs. 2 and 3). Ejections of slow moving fluid parcels from the vegetated area and into the adjacent flow enhanced mixing, and a measured increase in Turbulent Kinetic Energy (TKE) illustrated an increase in the energy per unit mass within the turbulent eddies in this layer (Siniscalchi et al., 2012; Wang et al., 2009). Research using real plants has focused on how changes to species morphology affects flow profiles. Vegetation type exerted a measurable influence over the amount of TKE generated at the transition, and the longer bladed species increased turbulence magnitudes and retarded flows (McBride et al., 2007; McBride et al., 2008; Yang et al., 2007). The general velocity profile across the vegetation transition has been fit to a hyperbolic tangent, reproducing the sharp decline in flow velocity with distance into the vegetated region. An inflection point is formed in the turbulent flow profile at the transition between the vegetated and non-vegetated flow areas, characterized by a sharp spike in Reynolds stresses similar to that measured near the base of a plant stem (Fig. 2). A slip velocity has been defined at the transition to connect the flow velocity profile across the channel depth and account for momentum exchange across the vegetated interface (White and Nepf, 2008).

The extent to which the vortices and mixing fluid extends into the vegetated area depends on plant density (Sand-Jensen and Pedersen, 1999; Souliotis and Prinos, 2008). Flows measured through a patch with low plant density were spatially variable, and Reynolds stresses were similar to those in areas without vegetation (Hopkinson and Wynn, 2009; Lacy and Wyllie-Echeverria, 2011). Both the logarithmic velocity profile and the mixing layer were able to extend to the bed (Shucksmith et al., 2010). In contrast, vortices formed along a dense vegetative interface had a limited penetration distance into the vegetation which led to a reduction in shear dispersion, and hence longitudinal mixing, and a greater importance of diffusivity in mass transfer (Fig. 2, Shucksmith et al., 2011a). For both sparse and dense patches, lateral flow velocities were reduced not only within the vegetated region but also over a distance upstream of the plants. Flows began

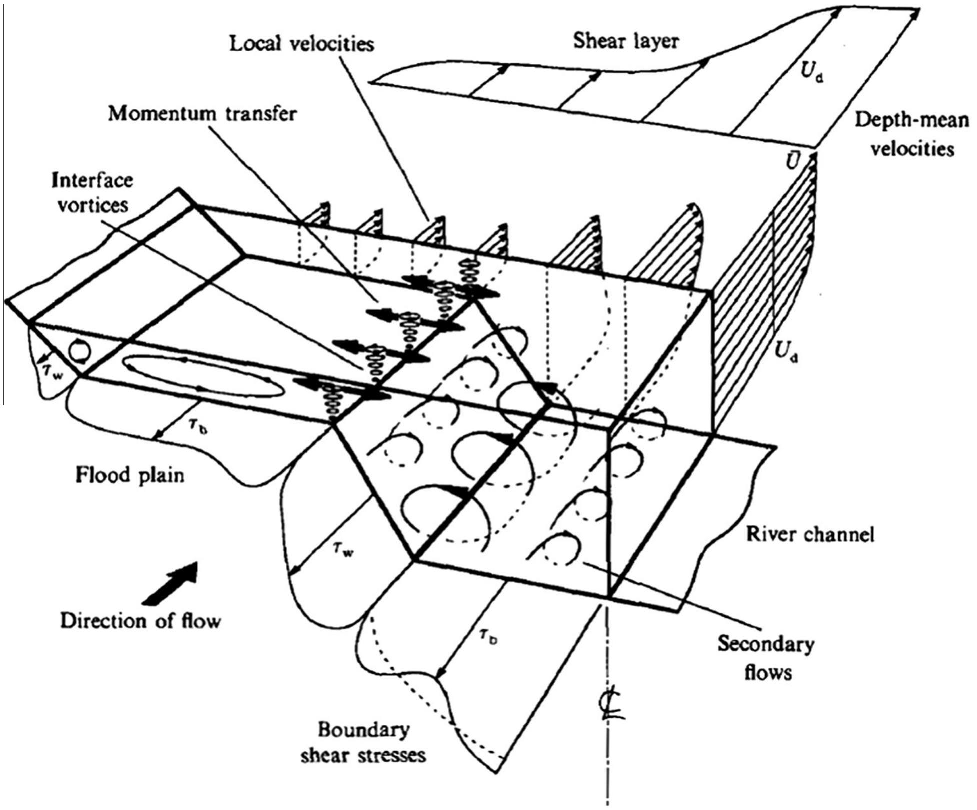

Fig. 3. Hydraulic parameters associated with overbank flow in a channel (from Shiono and Knight, 1991).

to slow at a distance upstream equal to the effective width of the vegetated region, and once within the vegetation, flow velocity decreased rapidly. Plant density influenced the magnitude of this effect, as velocity reduction occurred closer to sparse patches and decreased less within sparse patches (Zong and Nepf, 2010).

Plant biomechanics, previously discussed for the effect on planform morphology, have complicated attempts to define a single velocity profile for flows in a vegetated area. Plant flexibility (Ghisalberti and Nepf, 2005) and age (Shucksmith et al., 2011b) affected the extent to which vortices extended into vegetation. Highly flexible plants were able to pronate during high flows, reducing the overall drag force on the plant, the drag coefficient, and the ability of flow vortices to penetrate into the vegetation patch (Armanini et al., 2005). The drag coefficient became dependent on Reynolds number and thus also on plant biometrics and density. Flume studies have established a correlation between drag coefficient and the percent flow area filled with plant stems, illustrating the importance of plant density to the contribution of vegetation to roughness (Green, 2006, Helmio, 2002, 2004). A number of calibrated roughness coefficients have been developed for use in modeling velocity profiles through specific types of vegetation but these remain species specific and empirical (Fathi-Moghadam et al., 2011; James et al., 2004; Jordanova and James, 2003; Kouwen, 1988; Petryk and Bosmajian, 1975; Righetti and Armanini, 2002; Shucksmith et al., 2011b).

2.4. Hydraulics summary

These experiments and field observations show that the feedback between hydraulics and vegetation helps maintain channel morphology by creating a spatially and temporally variable flow pattern and flow resistance. Details of the hydraulic processes active around vegetation are manifested by the channel form. Although the hydrodynamic effect of a vegetated patch or corridor has often been parameterized through a single friction factor or drag coefficient acting over the length of vegetated channel, recent research has explored the interaction between plant features and flows responsible for generating the flow resistance. Vegetative drag in river reaches and over river corridors can change on a seasonal time scale, depending on the particular morphology, density, and life cycle of the plant species. These field observations have led to experiments measuring or re-creating plant specific properties to quantify how changes in species specific characteristics alter hydraulic patterns and mixing. The similarity in results between the flume experiments with simulated vegetation, flume experiments with real vegetation, and field studies illustrates common processes occurring at the vegetation interface, regardless of location within a channel, at the channel bank, or on the floodplain. Vegetative roughness related to plant biomechanics and density affect flow velocity profiles and turbulent mixing processes similarly across the fluvial system which is observed by change in reach and planform morphology.

3. Vegetative impacts on fluvial system sediments

Sediment feedbacks within vegetated areas of the fluvial system have not been as well-studied to date as hydraulics, despite recognition of the importance of sediment feedback processes. Riparian or floodplain forests are considered efficient traps for sediments and other pollutants, but few studies have quantified storage or the associated impact on channel form and processes (Noe and Hupp, 2009). Vegetation can create transient storage for channel sediment, and can also increase erosion outside of vegetated areas (Champion and Tanner, 2000; Jones et al., 2011). Sediment transport and river morphology are known to be impacted by streambank vegetation (Afzalimehr and Dey, 2009; Li and Millar, 2010; Wang et al., 2009), and much research related to streambank vegetation and sediment has been focused on either streambank retreat and stability (e.g. Lawler, 2008; Pollen-Bankhead and Simon, 2010; Wynn and Mostaghimi, 2006a) or the contribution of sediment loads from eroding banks at the watershed level (Lawler, 2008).

3.1. Planform scale

A feedback develops between vegetation and sediment across channel bank and floodplain areas (AS, AB, FB, FP in Fig. 1). Field observations have shown that thick vegetative growth in near-bank areas can act as a very effective sediment trap (Gurnell et al., 2006), and floodplains are well known locations of sediment storage (Phillips, 1989; Steiger et al., 2003). The sediment trapping ability of the vegetation allows for more growth and in turn, further deposition. In the absence of external influences, an excavated floodplain has been shown to undergo plant succession and sediment deposition until softwood forest establishment (Geerling et al., 2007). A recent field study connected the sediment eroded from a channel bed and banks to that deposited on a vegetated floodplain. Sediment deposition was spatially uneven with larger accumulations where plants reached 60–70% density and also more variable within species with widely spaced stems (Perignon et al., 2013). Nutrient deposition and storage on floodplains has been shown to occur concurrent with sedimentation, making the ability to increase sediment storage of increasing interest as part of effort to reduce nutrient loading to waterways (Osterkamp et al., 2012). Estimates of sediment storage and retention rates rely on site specific measurements which may then be scaled to provide relative nutrient retention rates over a watershed (Noe and Hupp, 2009). Given the importance of sediment retention to reduce nutrient transport, there is a need for a large number of site specific measurements of sediment retention to build a database from which the broader trends connecting sediment retention rates to geographic area.

3.2. Reach scale

Attempts to connect riparian vegetation to channel width within a reach have produced apparently contradictory results. Several studies have shown that North American temperate streams with secondary growth riparian forests are wider than those with riparian grasses (Hession et al., 2003; McBride et al., 2010; Zimmerman et al., 1967). Other studies suggest that grassland streams are generally wider than forested channels (Bledsoe et al., 2011; Gregory and Gurnell, 1988; Hey and Thorne, 1986; Rosgen, 1996). This contradiction was hypothesized to be the result of a scale-dependency, such that streams with watersheds greater than 10–100 km^2 would be narrower when thick woody vegetation was present while in smaller watersheds the opposite would occur (Anderson et al., 2004). However, three-dimensional Computational Fluid Dynamics (CFD) modeling has not been able to reproduce the observed scale-dependent feedback (Bledsoe et al., 2011). Other researchers have focused on a mechanistic explanation for differences in channel widths between forested and non-forested reaches in which grasses continually trapping sediments would constrict channels in non-forested meadows over time (Davies-Colley, 1997; Hession et al., 2003; Trimble, 2004). In support of this hypothesis, rates of sediment deposition and lateral migration were shown to be higher in non-forested reaches than in adjacent forested reaches of the same channel (Allmendinger et al., 2005). Flume experiments have demonstrated an increase in near-bank turbulence during overbank flows in forested streams indicating a sequence of stream incision, widening, and recovery as the riparian vegetation transitions from grasses to forest (McBride et al., 2007; McBride et al., 2008; McBride et al., 2010).

Seasonal vegetative growth and species specific parameters affect not only channel hydraulics as already discussed but also sediment transport and deposition rates. The influence of seasonal vegetation growth on fine-sediment deposition is manifested through the effect of changing physical plant properties, as demonstrated by field studies measuring over channel reaches (Asaeda et al., 2010; Champion and Tanner, 2000). When plants first emerged in the channel area in spring (CD, DB in Fig. 1), deposition rates around the plants were high, but as the plants grew to full size in the summer, the sediment accumulated in the vegetated patch eroded. This occurred despite a significant reduction in flow velocity through the plants. Sediments accumulated again during the shoot collapse phase when flow resistance in the channel increased and did not erode until the plants had fully decomposed. This cycle was observed to repeat showing that the range in plant morphologies exerted a greater influence over sediment transport, deposition, and erosion rates in the reach than did the flow rate (Asaeda et al., 2010). Species specific mechanics (J in Eq. (1)) also affected sediment deposition volumes. The longer and more flexible plants bent forward onto the channel bed, which reduced sediment deposition in those areas. Where sediment deposited on the bed before the plant protonated it was protected from erosion by the plant stems (Abt et al., 1994).

Sediment transport rates are often predicted using an excess shear stress equation, whereby the shear stress in excess of that required to mobilize a sediment bed contributes to the overall transport rate. A number of sediment transport formulae are based on this hypothesis, applying modifying coefficients to fit the equation to specific bed characteristics (e.g. Meyer-Peter and Mueller, 1948; Wilcock and Crowe, 2003; Wong and Parker, 2006). Excess shear stress transport equations have been adjusted for the presence of in-channel emergent vegetation using the results of flume experiments where uniform sediment was fed into a field of rigid, fixed rods arranged in a pre-determined spatial pattern and density until an equilibrium transport rate was reached (Jordanova and James, 2003). Rod density and flow depth were shown to affect transport rates but attempts to apply excess shear stress transport equations were mixed as the complex effects of vegetation on flow hydraulics and sediment transport rate were condensed into a single roughness parameter.

3.3. Local scale

Hydraulic variable control over sediment deposition rates, sizes, and volumes at the localized scale within a vegetated patch has been hypothesized from field observations in salt marshes (Mudd et al., 2010), tidal flats (Bouma et al., 2007), and small streams channels (Sand-Jensen and Madsen, 1992). Flow velocities have a direct control over the amount of suspended sediment that entered and deposited within a patch of marsh vegetation. Low density emergent vegetation patches experienced a net loss of fine sediment and organic matter within the patch (van Katwijk et al., 2010) while suspended sediment transported through the patch and deposited in the steady wake area behind the patch (Chen et al., 2012; Follett and Nepf, 2012; Zong and Nepf, 2012). The loss of sediment from within a low density plant patch area indicated the elevated levels of turbulence within the vegetation resulted in sediment erosion. The horseshoe vortex known to form around the plant stems (and discussed in the previous section) created an increase in bed shear stresses, localized bed erosion, and induced localized scour (Liu et al., 2008; Nepf, 1999; Nepf and Vivoni, 2000). A similar situation was observed around the patch as a whole where the change in flow hydraulics was manifested through a spatially variable sediment texture, as the finer grain sizes and organic matter preferentially accumulated within the patch area and coarser sediments dominated between patches (Kleeberg et al., 2010; Sand-Jensen and Madsen, 1992). The selective trapping of fine sediment by vegetative patches can lead to an alteration in the grain size distribution of surface sediments over time. Many aquatic plants prefer a gravel substrate, and the continued trapping and storage of fine sediments can alter the bed composition over time and eventually lead to species succession (Heppell et al., 2009; Regina, 1992; Sand-Jensen, 1998).

Spatial plant distributions, already shown to impact the local and reach scale hydraulics, have a similar effect on local scale sediment deposition patterns across the fluvial system. Depositional patterns within and around vegetated patches, whether in the channel, on the banks, or on the floodplain, are a function of the stem density within the patch, the total projected frontal surface area of the plants, and the ability to dampen turbulent flows (Bos et al., 2007; Gacia et al., 1999; Mudd et al., 2010; Sharpe and James, 2006). Both within channels and on floodplains, large grain sizes preferentially deposit near vegetation edges while finer sediments transport further into vegetation before depositing. Dowel density had a similar effect on deposition volumes, with larger sediment volumes near the patch edge when stem density was high. Around patch edges, where flow was diverted away from the vegetation, erosion occurred due to locally accelerated flows (Bouma et al., 2007; Rominger et al., 2010).

3.4. Summary

Research at the reach scale and planform scale has focused on linking channel width and morphology to sediment transport and storage processes around vegetation. Contradictory research results and difficulties creating representative process-based models at the reach and corridor scales indicates an incomplete understanding of the feedback between riparian vegetation and channel form and illustrates the need for further studies from a range of geomorphic settings. Existing studies come from a limited range of physiographic regions, which may have contributed to the disparate interpretations of vegetation effects on the channel planform.

4. Modeling

Modeling presents a potential means for linking vegetative influences and feedbacks across spatial systems. Because of the advances possible through modeling, we include a brief review. Although most models are currently applied at a single spatial scale, insights gained from models can be applied broadly, allowing researchers to work across spatial scales.

4.1. Planform scale

At the planform scale, many models of channel morphology have been expanded to include bank and floodplain vegetation (e.g. Crosato and Saleh, 2011; Kwan, 2009; Mosselman, 1998). For example, Li and Millar (2011) modified an existing two-dimensional morphodynamic model of a gravel-bed river to include floodplain vegetation in order to predict changes in bedload transport and channel morphology that may occur upon vegetating a floodplain. This model was able to reproduce a reduction in near-bank and floodplain velocities around vegetation, stabilized bank sediments, and showed the influence of vegetation on bedload transport and channel morphology. The University of British Columbia Regime Model (UBCRM) applies the regime theory that an equilibrium river channel adjusts over time to a width and bed slope that allows for maximum sediment transport efficiency (Millar and Eaton, 2011). UBCRM is a numerical model which predicts changes in channel planform morphology in response to alteration of riparian vegetation as well as the response of vegetated banks to changes in channel flows (Eaton, 2003). Both models can be applied to analyze long-term historic changes in a river system or as a planning tool when designing restoration projects within a river corridor. Current application of river corridor models during restoration planning remains the exception rather than the rule, but these models are encouraging more quantitative planning and understanding of how and when riverbank plantings can enhance bank stability.

4.2. Reach scale

A primary influence of bank vegetation at the reach scale is bank stabilization which in turn acts to reduce streambank retreat rates (Gregory and Gurnell, 1988; Pizzuto et al., 2010). Streambank vegetation alters soil moisture and bank temperature (Wynn and Mostaghimi, 2006a), provides mechanical reinforcement of the bank through the root structure (Simon et al., 2004; Wynn and Mostaghimi, 2006b), absorbs momentum from the flow, and lowers Reynolds stresses (Dehsorkhi et al., 2011). As a consequence, streambank vegetation is nearly always included in stream restoration designs (Jennings et al., 1999; Shields et al., 1995). It is necessary to parameterize the roughness of a vegetated channel bank in modeling, and this has been approached by balancing the gravitational forces driving flow through a vegetated channel against the drag forces acting on vegetation within the channel and the surface friction acting on the bed and banks. Vegetation is characterized by λAL, where λ is the vegetal area coefficient defined by the area fraction per unit length of channel and dependent on vegetation type, density, and configuration which correspond to variables Lv, J, K, and M in Eq. (1); A is area; and L is channel reach length (Petryk and Bosmajian, 1975; Wu et al., 1999). When the type of vegetation is specified, λAL is converted to a Manning's n value that can be applied over the reach and used in river restoration modeling. This work represents a step toward increased representation of vegetation-specific variables in the modeling of reach-scale roughness.

A popular model for predicting river bank stability is the Bank Stability and Toe Erosion Model (BSTEM), which predicts the factor of safety for a river bank under different limit equilibrium scenarios (Simon et al., 2000; Simon and Collison, 2002). BSTEM quantifies the separate hydrologic and mechanical contributions to overall bank stability by plant roots and canopy cover (Pollen-Bankhead and Simon, 2009; Simon and Collison, 2002), and has been applied to predict bank stability over a range of flow scenarios in a number of different geographic settings (Simon et al., 2011). The limited spatial scale of model application makes BSTEM well suited to application in the stream restoration industry during the planning of riparian restoration over localized river reaches. Longer spatial and temporal scales of bank mechanics and channel evolution have been successfully modeled through the 1D Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) model which simulates the effects of channel hydraulics and sediment transport processes on channel morphology (Langendoen et al., 2001). CONCEPTS incorporates interaction between the flow, streambank mechanics, and bank vegetation, and has successfully reproduced streambank erosion around channel bends (Langendoen et al., 2009; Langendoen, 2011).

4.3. Local scale

Two basic types of turbulent flow models had evolved by 2005 and continue to be popular for modeling turbulent flows around plant stems and through vegetated patches. One considers the flow profile as a single layer and vegetation is modeled by modifying the κ–ε turbulence model. The other is distinct to submerged vegetation and flow is separated into layers: flow within the vegetated area, flow above the canopy, and often also a third layer for flow in the mixing zone at the canopy's edge (Defina and Bixio, 2005; Nepf, 2012; Shucksmith et al., 2011a). Both types of models have reproduced the experimentally measured velocity profile shape, shear stress, and eddy viscosity within the vegetation, but neither reproduced the velocity profile in the region immediately adjacent to the bed. When compared to measured values, quantitative turbulent values predicted for the vegetated region of a floodplain had only 10% agreement when using a two-layer model, and the agreement was worse with a κ–ε model. The vegetated interface has been difficult to reproduce numerically regardless of location in the fluvial system as a consequence of the drag generated by velocity gradients, eddies formed around vegetation during inundation flows, and the resultant momentum losses (Fischenich, 2000; Kadlec, 1990; Thornton et al., 2000). When the results of dye studies through a vegetated flume were compared to predictions obtained using a multilayer model of flow through submerged vegetation, it was shown that the most difficult part of the system to model and also the source of most model error were processes occurring at the vegetative interface, particularly the size of the mixing layer which is dependent on channel flow and vegetative properties, as already discussed (Shucksmith et al., 2011b). The shear layer and associated vortex shedding created by the velocity differential at the interface (Shiono and Knight, 1991; Wormleaton, 1998) has been modeled as an imaginary vertical wall by several researchers (Naot et al., 1996; Pasche and Rouve, 1985). Detailed numerical models have also been developed to model flows over floodplains, but like the other models discussed, parameterization of vegetation induced drag remains difficult (Fathi-Moghadam et al., 2011). In a test of turbulent closure schemes for which the detailed turbulent hydraulics around vegetation were modeled using Reynolds Averaged Navier–Stokes (RANS) equations (Souliotis and Prinos, 2008), the turbulent transport parameters defining the mixing area around the vegetation interface were identified as in need of validation.

RANS models have been limited in their application to model the details of turbulent flows around and within vegetation due to the large amount of computing power required. Large Eddy Simulation (LES) modeling was recently shown to be a computationally efficient alternative to RANS models (Kim and Stoesser, 2011). Using LES modeling, the stem spacing at which vortices shed from individual plant stems begins to interact and effect the overall vegetative influence on the flow through the a patch was found to be 2.5 times the stem diameter (Kim and Stoesser, 2011; Stoesser et al., 2010).

Recognizing turbulent flow as a hydraulic condition common to fluvial ecology, in channel hydraulics, and the response of vegetation to channel flows, Nikora (2010) proposed the use of the Double Averaging Method (DAM) as a means of linking these disciplines. DAM is a procedure for spatial and temporal averaging of the continuity, momentum, advection–diffusion, and energy equations and provides a means of quantifying the turbulent flow through a vegetated reach at a scale larger than that of the individual plant stem or blade (Nikora et al., 2007a,b). The individual equations retain the details of flow through the different regions of the fluvial system. For example, within a patch of submerged vegetation, the momentum equation incorporates terms for the turbulent and dispersive forces, as well as the hydrostatic pressure gradient. When applying the DAM, spatial averaging removes element-scale heterogeneity and allows the user to apply the scale of interest (Nikora, 2010). Modeling using LES, RANS, DAM, and other numerical schemes will continue to improve in the future, providing further insights to the feedback between turbulent hydraulics, sediment, and vegetation acting within a patch and eventually across the fluvial system.

4.4. Summary

These models are promising advances toward reproducing the complexities across the fluvial system and show the potential for empirical and numerical modeling to reproduce the observed hydraulic and sediment processes around vegetation. At all scales, the complexities introduced by species specific variables such as flexibility, morphology, and life cycle have presented challenges to accurate replication of measured results over a wide range of vegetation. Modeling efforts have included a number of methods for incorporating species specific variables, and as further information is gained from field and laboratory experiments about the role of these variables in defining channel hydraulics and sediment movement, the ability of models to replicate the feedback between vegetation and channel processes will advance.

Current modeling efforts are generally focused at a single spatial scale. local, reach, and planform scales. As process similarities are identified across different areas of the fluvial system, modeling has the opportunity to further an understanding of how the interaction of plants, hydraulics, and channel sediments at the local and reach scales influences channel planform morphology.

5. Summary and future research needs

This review has highlighted the trends and recent research advances in the complexities caused by vegetation in and near channels. As described in Tsujimoto (1999), vegetated channels are an inter-connected system of feedbacks acting between the flow, sediment transport, geomorphology, and vegetation. Research has begun to show how the impacts of vegetation on hydraulics and sediment transport processes across the fluvial system are reflected in the channel form. Advances will be made both through individual research and from the gathering and exchanges of ideas between those working at the various research scales and methods. Cause and effect relationships are rarely clear, necessitating the need for multiple research methods across disciplines to begin to understand the effects and impact of vegetation across complex fluvial systems. However, research has traditionally followed two basic approaches. One approach focuses on a single aspect of the vegetated channel system, working to explain processes occurring at a specific part of the fluvial system. The second approach studies over a large spatial scale, working to establish the general feedbacks operating broadly. Both approaches are necessary but progress will occur when recognizing the similarities across spatial scales and working jointly to develop a full understanding of how vegetation influences a channel system.

We have tried to highlight where sediment and hydraulic processes act similarly around vegetation within the channel, across the streambank, and on the floodplain. Flow profile characterization studies have formed a consensus on the general shape of the velocity profile through vegetation. Profiles are uniform within submerged plants, pass through an inflection point at the flow interface, and transition to logarithmic in the open channel. While this profile description applies in general, accurate representation of the detailed mixing processes and turbulence generated along the interface between vegetated and non-vegetated areas remains a source of error in models and a location where future work is needed. Mixing processes are complicated by plant biomechanics, which can change with plant species, density, and age to affect local hydraulics, channel stresses, and the transport or storage of channel sediments. These complications highlight a need for future research documenting plant biomechanics across the fluvial system and linking differences in specific plant properties to the formation and strength of the hydraulic mixing layer at the interface of vegetation and open flow and the accumulation or erosion of sediment within and around a plant patch. Understanding the degree to which these processes depend on species specific factors will improve estimates of how the feedback between vegetation, hydraulics, and sediment processes can affect channel form over the life cycle of the plants. This will require further research on the local scale accomplished in both flumes and field situations.

Frictional resistance due to vegetation has been parameterized generally, but complications have prevented accurate representation of vegetative roughness over a large spatial and temporal scale. The influence of plant density, seasonality, and flexibility on local flow hydraulics has a direct link to reach scale estimates of roughness factors, making species specific information a necessary part of any predictive modeling efforts. Vegetation specific variables can be incorporated into the calculation of a roughness parameter, but much more research is needed to expand the base of knowledge over a broad range of vegetative morphologies and fully establish the functional relationships. Field and flume investigations are needed to build these databases, while numerical modeling advances continues to incorporate processes acting on local and reach scales, building towards full morphodynamics models of fluvial systems. Further modeling will become predictive as a general understanding of the feedback processes is gained from field and laboratory research.

Floodplains are re-vegetating at a high rate in the US, illustrating a need for more research to develop and improved methods for predicting the impact of altered hydraulics and sediment storage and transport dynamics sediment on surrounding communities (Bernhardt et al., 2005; Hassett et al., 2005; Hession et al., 2008). River restoration projects rely on accurate modeling of the flow resistance generated around vegetation. A process based understanding of how flow and sediment move through a vegetated river corridor is necessary for developing large scale interventions that will be successful in designing successful river restoration projects and reducing nutrient and sediment transport rates from fluvial systems.

Acknowledgements

We are grateful to Gordon Grant, the anonymous reviewers, and the associate editor for their comments which have helped to improve the manuscript.

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