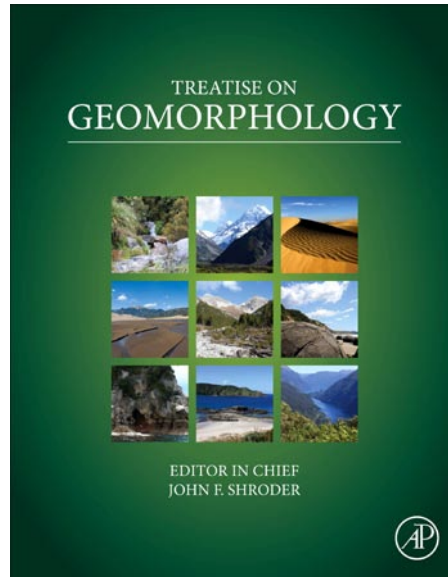


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## 12.6 The Impacts of Vegetation on Roughness in Fluvial Systems

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### Glossary

**Effective plant height** The mean plant height after flexible plants have been deflected by the flow.

**Einstein transport equation** A stochastic equation of sediment transport derived from probabilities of sediment movement in a channel. The equation predicts the total sediment load.

**Fronds** The large, divided leaf of the plant that extended from the plant stem.

**Horseshoe vortex** A vortex characterized by a horseshoe morphology. The vortex consists of a core vortex and two vortices trailing in the stream wise direction at a 45 angle to the bed.

**$\kappa - \epsilon$  turbulence model** A two equation turbulence model that accounts for both the turbulent kinetic energy and the turbulent dissipation in the flow. The turbulent dissipation measures the scale of the turbulence in the flow.

**Kelvin-Helmholtz instability** Instability between two fluid masses as a result of velocity shear between the fluids.

**Laser doppler velocimetry (LDV)** An optical technique to measure the local velocity field in a fluid. Application of LDV involves shining a laser light sheet in a flow that has been seeded with micron-size particles and

measuring the Doppler shift of laser light scattered by the particles.

**Log law equation** The equation describing the logarithmic form of the velocity profile. The exact form of the equation is dependent on the characteristics of the flow.

**Meyer-Peter and Mueller transport equation** A widely used sediment transport equation that predicts the rate of sediment transport through a channel as a function of the amount of shear stress acting on the channel boundaries that is in excess of the minimum shear stress required to initiate sediment movement.

**Particle image velocimetry (PIV)** A tool used to quantify the velocity field in a fluid. Application of PIV involves pulsing a laser light sheet in a flow that has been seeded with micron-size particles. The light sheet is recorded by video camera or photographed and the displacement of seeded particles between sequential images is measured to determine the movement of the particles with the flow. With a known time between sequential images, the velocity of the particles can be calculated.

**Reynolds stress** The mean forces per unit area imposed on fluid flow by fluctuations in turbulent velocities. The Reynolds stresses are expressed mathematically by a tensor.

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**Shear velocity** The shear stress created by the flow expressed in terms of velocity. It is found by taking the square root of the shear stress divided by density.

**Turbulent kinetic energy (TKE)** Measure of the energy in the flow, specifically the energy associated with the turbulent eddies in a flow. TKE is expressed per unit mass. It

is the sum of the root mean squares of the fluctuating components of the three-dimensional flow. Units are of velocity squared [ $L^2T^{-2}$ ].

**Von Karman vortex street** A series of alternating vortices in the streamwise direction that dissipate with distance downstream.

## Abstract

Interest in the interactions and feedback loops between vegetation and geomorphology has grown largely in recent years. This interest is partially driven by the popularity of stream restoration activities worldwide. Plants create a complicated system of feedbacks and linkages between channel flow and morphology, sediment deposition and erosion, and plant morphology, density, and spatial extent. Here, we focus on what we feel is the first step in understanding the complex processes involved – how vegetation impacts roughness in fluvial systems. We frame our discussion through the location of vegetation in relation to open channels and the flows they encounter: in-channel emergent; in-channel submerged; streambank; and floodplain. For each section, we begin with a focused discussion of how vegetation influences roughness at the reach scale, then concentrate specifically on hydraulics and turbulence, and conclude with a discussion on how the vegetation and associated roughness influence sediment dynamics. The chapter ends with a discussion on the complexities related to vegetation and fluvial processes, and some of the research opportunities and challenges.

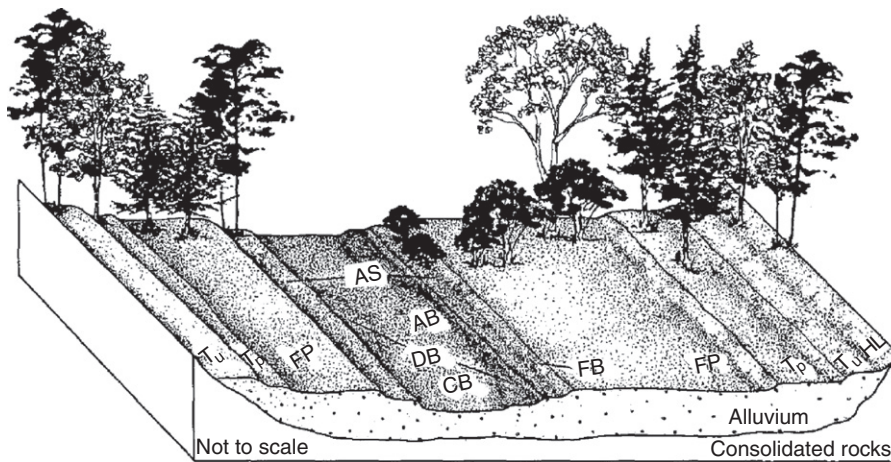
### 12.6.1 Introduction

Research in linkages between vegetation and geomorphology continues to grow (e.g., N.R.C., 2002, 2007; Bennett and Simon, 2004; Hession et al., 2010). For example, interest in river and stream restoration has increased dramatically over the last two decades. Conservative estimates place river restoration costs for the continental US in excess of \$14 billion since 1990 with more than \$400 million spent on restoration projects in the Chesapeake Bay Watershed alone (Bernhardt et al., 2005; Hassett et al., 2005). Restoration of riparian or streamside forests is a major focus of many stream restoration activities throughout the US (N.R.C., 1992; U.S.E.P.A., 1999; Bernhardt et al., 2005). In fact, the Chesapeake Bay Program exceeded a goal of establishing at least 16 090 km (10 000 mi) of riparian forest buffers by the year 2010, and have expanded their goal to reforesting 70% of all streams and shorelines in the basin (Chesapeake Bay Executive Council, 2003). Additional riparian forest programs include the Federal Conservation Reserve Enhancement Program (CREP; N.R.C., 2002) and a recently launched initiative of the Conservation Reserve Program to reforest 2025 km<sup>2</sup> of river floodplains in the US (Johnson, 2004). In addition to these government-sponsored reforestation efforts, large areas of bottomland are naturally reverting from crop and pasture (commonly abandoned) to woodland (Trimble, 2004). These reforestation efforts are not limited to the US, but are a worldwide trend (Gippel, 1999; Anderson, 2006). The impacts of activities such as riparian reforestation and conversion from agricultural to forest uplands will have a significant impact on fluvial geomorphology, with a major effect coming from the changes to how roughness is characterized across a landscape. Here, we focus on how vegetation influences roughness in fluvial systems.

Roughness in fluvial systems is a critical characteristic influencing water-surface elevations and flow (Defra/EA,

2003), sediment transport (Sand-Jensen, 1998; Cotton et al., 2006) and channel morphology (Tal and Paola, 2007; Hession et al., 2010), and aquatic habitat (Muhar, 1996; Downes et al., 1998) and biodiversity (Beisel et al., 2000; Sullivan et al., 2006; Klaar et al., 2009). In general, the roughness of streams/ivers and their floodplains can be partitioned into components, mainly the roughness due to surface material, vegetation, and morphology irregularity (Cowen, 1956; Arcement and Schneider, 1989; Defra/EA, 2003). This chapter is focused on the impact of vegetation on roughness in fluvial systems. We have divided our discussion into broad category distinctions: (1) in-stream emergent vegetation; (2) in-stream submerged vegetation; (3) streambank vegetation; and (4) floodplain vegetation. The discussion in each category includes field studies, flume studies, and modeling activities. Each section begins with a discussion of reach-scale effects, changes to local channel hydraulics, and closes by reviewing implications for sediment transport and deposition.

There is no standard, universal definition of where a stream ends and the actual streambank begins, much less a simple technique to define the end of the streambank and beginning of floodplain. Floodplains can be identified based on frequency of inundation (Moody et al., 1999), morphology (Leopold, 1994; Rosgen, 1996), or change in vegetation type (Osterkamp and Hupp, 1984; Richard et al., 2005), and are dynamic by nature (Leopold et al., 1964; Hughes et al., 2008). In this chapter, we utilize Leopold's (1994) definition of the floodplain as "a level area near a river channel, constructed by the river in the present climate and overflowed during moderate flow events" and that it coincides with the elevation of bankfull stage. Osterkamp and Hupp (1984, 2010) provided definitions of alluvial surfaces and a block diagram showing their positions (Figure 1) that visually organizes our sections.



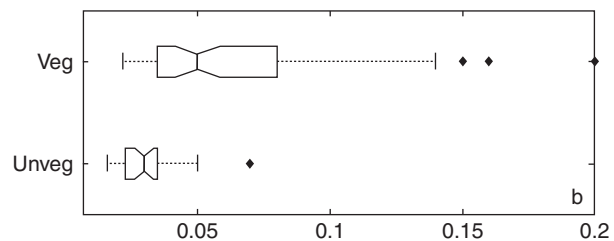
**Figure 1** Block diagram showing geomorphic features. Reproduced from Osterkamp, W.R., Hupp, C.R., 1984. Geomorphic and vegetative characteristics along three northern Virginia streams. GSA Bulletin 95, 1093–1101, with permission from GSA.

The most widely used methods for describing roughness in streams are based on the semi-empirical formulas of Chezy and Manning (1890). Most commonly used in general engineering practice is the Manning equation

$$V = \frac{R^{2/3} S^{1/2}}{n}$$

where  $V$  is the mean flow velocity ( $\text{m s}^{-1}$ ),  $R$  the hydraulic radius (m),  $S$  the friction slope (m/m), and  $n$  the Manning's roughness coefficient. Values of  $n$  (or flow resistance) can be calculated using measurements of velocity, depth, and slope (Leopold et al., 1964; Limerinos, 1970). Calculations are commonly performed at gauging stations to provide estimates of  $n$  over various flow conditions (Barnes, 1967; Hicks and Mason, 1998), but this process provides a roughness value that lumps together the effects of all types of roughness (Leopold et al., 1964; Defra/EA, 2003) and can have high levels of uncertainty (Kim et al., 2010). Despite these drawbacks, this method has been used to estimate the incremental increase in  $n$  value due to the presence of vegetation by calculating the  $n$  values for sites with a range of bank vegetation (Coon, 1995, 1998).

The influence of vegetation on overall stream roughness has traditionally been incorporated into the Manning's roughness. To provide a general sense of the range of roughness values attributed to vegetation, we summarized some Manning's  $n$  values or incremental factors from previous publications. For instance, Cowen's (1956) procedure increases Manning's  $n$  by 0.005–0.10 for vegetation influences on flow. Given that basic  $n_0$  (for a straight, uniform, and smooth channel in natural materials) ranges from 0.020 to 0.028, this represents as much as a 500% increase in roughness due to vegetation alone. Chow (1959) recommended that flow resistance values for stream channels with and without vegetation are summarized in Figure 2 (Anderson, 2006). As with Cowen's (1956) values, roughness values change drastically in the presence of vegetation.



**Figure 2** Boxplot showing the range of flow resistance values recommended for stream channels with (veg) and without vegetation (unveg) as compiled from Chow (1959). Reproduced from Anderson, B.G., 2006. Quantifying the interaction between riparian vegetation and flooding: from cross-section to catchment scale. Dissertation in support of doctoral degree. School of Anthropology, Geography and Environmental Studies, University of Melbourne, 529 pp, with permission from Geography and Environmental Studies.

### 12.6.2 In-Stream Emergent Vegetation

Emergent vegetation refers to plants rooted below the normal water surface whose stems extend above this surface. The stems of these plants alter the velocity profile, channel stresses, and sediment transport rates. This section explores recent research concerning the effects of emergent vegetation by reviewing the methods used to measure flow resistance, reach-scale effects, changes to local channel hydraulics, and rates of sediment transport and deposition within areas of emergent vegetation.

The complex flow dynamics around emergent vegetation has led to a large amount of research being conducted in laboratory flumes, where experimental conditions can be somewhat controlled and hydraulics measured. The plants used in flume experiments range from simulated plant stems using cylindrical objects such as wooden dowels (Bennett et al., 2002) to natural grasses and willows (Jarvela, 2002). When using real plants, research has focused on how changes to plant morphology affects flow profiles. Simulated vegetation remains popular in flume experiments, as it has the advantage of control over spatial density (Bennett et al., 2002), and does

not require a natural substrate. Recent advances in instrumentation involve the application of laser technologies to hydraulic studies. The use of laser Doppler velocimetry, particle imaging, and the combination of dyes and laser-induced fluorescence with imaging all require clear water flow, making growing vegetation in a natural substrate difficult as fine sediment would be subject to entrainment.

### 12.6.2.1 Reach-Scale Impacts of Emergent Vegetation

Reach-scale hydraulics are altered where emergent vegetation growth occurs as discrete patches (Jarvela, 2002; Wilson, 2007). Sedges and willows were planted in a flume using a variety of arrangements to measure the effects of plant rigidity and spatial distribution on the reach-averaged friction factor. Results indicated a negative correlation between Reynolds number and friction factor, but did not completely explain measured changes in friction factor. The arrangement and density of the plants exerted a significant influence over friction factor, as did the presence or absence of leaves on willows. For example, where the density of willow plantings was doubled, the friction factor also doubled, and where leaves were present on the willows, the friction factor tripled.

The drag forces acting on emergent vegetation, together with surface friction acting on the bed and walls (or banks) of a flume (or river), balance the gravitational forces driving flow through a vegetated channel. Building on the work of Petryk and Bosmajian (1975), Wu et al. (1999) introduced a parameter,  $\lambda AL$ , to account for the influence of vegetation in their derivation of the drag coefficient, where  $\lambda$  is the vegetal area coefficient defined by the area fraction per unit length of channel and dependent on vegetation type, density, and configuration;  $A$  is the area; and  $L$  is the channel reach length. When the type of vegetation is specified, this parameter is converted to a Manning's  $n$ , making its application to reach-scale resistance estimates more generally accessible. The resulting roughness coefficient decreased with increased flow velocity, a consequence of a uniform flow velocity within emergent vegetation.

Field studies of emergent vegetation are limited and have focused on general patterns associated with plant growth. Gurnell et al. (2006, 2010) described the effects of seasonality and site characteristics on vegetation growth and flow patterns in the UK. By conducting field research, they were able to address both spatial and temporal variability of vegetation growth and the associated effects on channel flows. When vegetation was abundant in the spring and summer, flow resistance and depth increased. During the subsequent dieback during fall and winter, flow depth lowered. The authors speculated on a connection between seasonal overbank flooding and elevated flows due to plant growth. Effects of the seasonal growth and dieback of emergent vegetation were verified by a recent 3-year study of a river in Japan (Asaeda et al., 2010). As the vegetation in the channel grew during spring and summer, flow velocities slowed and water depth increased, similar to what was observed in the UK. When the plant shoots collapsed during dieback, overall channel roughness increased by almost 50% before the plants degraded.

### 12.6.2.2 Hydraulics and Turbulence

The stems of emergent vegetation have the potential to alter local and reach-scale hydraulics through their influence on bed roughness, Reynolds stresses, and flow profiles. Visualization and quantification of flow profiles is a burgeoning area of research with the growth of the use of Particle Image Velocimetry (PIV) in flume studies. As a brief description, micron-size particles are added to the flow and a laser is used to illuminate these particles. As the area is illuminated, a camera records images of the illuminated area at a minimum rate of 30 images per second. Because the images are taken quickly, individual seeding particles can be tracked over time. Image analysis allows the user to measure the direction and speed of individual flow 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.

At low Reynolds number flows, mixing processes are dominated by diffusion. Laser-enabled imaging was used in fluorescein dye studies of diffusive mixing processes through large areas of emergent simulated grasses to elucidate the effects of vegetation on diffusive mixing (Nepf et al., 1997; Nepf, 1999; Serra et al., 2004). Using imaging to trace the path of the dye over time, lateral diffusion and drag coefficients were calculated over a range of Reynolds numbers, relative depths, and percent channel area filled with plant stems. At low Reynolds number flow, the inertial-viscous flow regime was expected to be dominated by wake effects around individual stems. The diffusion coefficient did show a dependence on Reynolds number, with the largest diffusion coefficients at low Reynolds numbers. Dye measurements indicated that flow patterns depended on plant density; a finding confirmed by a measured correlation between drag coefficient and the percent channel area filled with plant stems. Drag coefficients were higher where plants were sparse because each stem exerted an individual influence on the flow. As the Reynolds number increased beyond 200, the flow regime shifted to the fully inertial regime, dominated by vortex shedding and turbulent flows. The drag coefficient became dependent on both Reynolds number and percent area of stems. These experimental results provided verification of a physically based model developed to describe the diffusive processes in emergent vegetation (Nepf et al., 1997). Similar experimental techniques were applied to a recent study of the mixing processes through natural vegetation, in this case, reeds (Shucksmith et al., 2010). This recent study also found a greater uniformity in velocity profiles and a concurrent reduction in shear dispersion, and hence longitudinal mixing, in emergent vegetation. The results verify those of earlier studies and extend their applicability to natural vegetation.

Nepf (1999) developed a physical model where turbulent kinetic energy was parametrized as the sum of bed shear and stem-generated wakes around simulated grasses. Diffusivity was modeled as a function of turbulent and mechanical diffusion, with mechanical diffusion dependent on the presence of vegetation. Building off experimental findings (Gambi et al., 1990), the model showed reduced velocity and turbulence intensities within the vegetated area. Thus, as plant

density increased, turbulence intensity increased, and mechanical diffusion contributed a greater proportion of the total diffusion. Total diffusivity was reduced in vegetated channels due to a decrease in the scale of the vortices created by the vegetation. Changes in flow velocity and turbulence production created a nonlinear response in the flow such that turbulent kinetic energy increased with increasing stem density until reaching a point above which the energy decreased as more stems were added.

Strong vortex formation occurs at the interface between vegetated and nonvegetated channel areas, regardless of whether the interface is between the channel and floodplain (Shiono and Knight, 1991) or within a partially vegetated channel (Tsujimoto, 1999). Vortices are an important means of energy dissipation, making the interface between vegetated and nonvegetated regions of interest for correctly estimating a reach-scale friction factor in a partially vegetated channel. Research into this topic has focused on quantifying the influence of spatial distribution of vegetated patches on channel hydraulics, which necessarily influences the total plant interface area in the channel (Helmio, 2002, 2004). Two basic types of models of the turbulent flow through vegetation had evolved by 2005. One considered the flow profile as a single layer and modeled vegetation by modifying the  $\kappa - \epsilon$  turbulence model. The other was distinct to submerged vegetation as it separated the flow into two separate layers: one for flow within the vegetated area and a second for flow above the canopy. Both types of models reproduced the general shape of the velocity profile, shear stress, and eddy viscosity within the vegetation as measured experimentally (Defina and Bixio, 2005), but neither reproduced the profile shape in the region immediately adjacent to the bed. When comparing quantitative turbulent values predicted and measured in the vegetated region, agreement was limited to 10% when using a two-layer model, and was worse with a  $\kappa - \epsilon$  model.

Laser Doppler velocimetry (LDV) systems measure turbulent flow characteristics, and the application of these systems to flows around emergent and submerged vegetation has advanced understanding of small-scale hydraulics. The turbulent exchange of fluid and momentum through simulated emergent grassy vegetation was measured using an LDV system (Nepf and Vivoni, 2000; Liu et al., 2008). Significant shear stresses were measured and turbulence intensity remained uniform with depth. A velocity gradient formed around each dowel between the slower flow in line behind the dowel and the higher velocity flow on either side of the dowel, creating a horseshoe vortex. A horseshoe vortex is identified by its characteristic morphology defined by a core vortex with two vortices trailing in the streamwise direction at a  $45^\circ$  angle to the bed. The horseshoe vortex brought high-velocity flows from the region near the dowel into the immediate region at the base, creating a localized area of increased turbulence and a counterclockwise mixing pattern. Directly above the spike in flow velocity and turbulence, the flow slowed and turbulence reduced, marking the area near the bed as an inflection point. Both turbulent and velocity profiles are uniform over depth above the inflection. Fluid exchange occurred primarily through longitudinal advection driven by turbulent wakes generated around plant stems (Nepf and Vivoni, 2000). In the flow regions between dowels, turbulent eddies shed from the

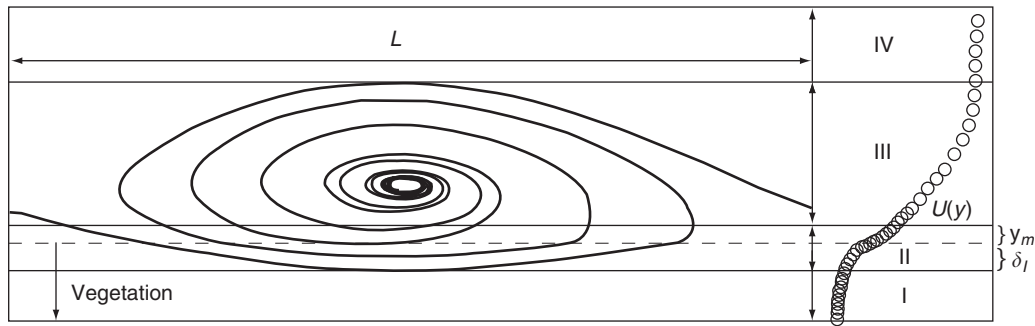
dowel area created a von Karman vortex street, a series of alternating vortices in the streamwise direction that dissipated with distance downstream. The combined results from Nepf and Vivoni (2000) and Liu et al. (2008) provided necessary details about flow hydraulics and a baseline of the wake-generated shear stress contribution needed to improve vegetated flow modeling.

Recent flume experiments investigated the lateral two-dimensional (2D) structure of flow at the interface of channel flow and emergent vegetation within a channel width (White and Nepf, 2008; Zong and Nepf, 2010). These experiments simulated vegetation using dowels so that the 2D flows could be visualized and current models expanded to include secondary flow patterns. Experimental results showed the presence of a second inflection point at the transition between the vegetated and nonvegetated channel areas, characterized by a similar sharp spike in Reynolds stresses to that measured near the bed of a vegetated region. The vegetated region affected flow velocities beyond the patch edge. As flow approached dense vegetation, it began to slow at a distance upstream equal to the effective width of the vegetated region. Once within the vegetation patch, flow velocity decreased rapidly. The same trend was measured for sparse vegetation patches, but velocity reduction occurred closer to the plants and decreased less within the patch (Zong and Nepf, 2010). Velocity and shear stress decreased gradually with lateral distance from the inflection point and into open channel flow. At the vegetation interface, a shear layer formed, characterized by coherent vortices that generated a regular pattern of momentum sweeps and ejections across the vegetation interface.

White and Nepf (2008) subsequently developed a 2D model describing the lateral flow profile in a partially vegetated channel. Flows were separated into four distinct zones (Figure 3). Zones I and IV were defined below and above the transition flows, respectively, and velocity scaled with a relationship between drag and gradient. Zone II marked the transition from channel flow to slow-moving flow within the vegetated area and was separated into an inner layer and a mixing layer. The inner layer width was dependent on drag forces generated by the vegetation and defined the mixing length into the vegetation field. The shape of the velocity profile in zone II fit a hyperbolic tangent, which reproduced the sharp decline in flow velocity with distance into the vegetation. Zone III represented the outer layer flow where hydraulics were independent of the forces acting on the lower flows. In this zone, the shear stresses were balanced by the pressure gradient, creating a gradual reduction in flow velocity with distance away from the vegetation. To connect the hydraulics across zones II and III, White and Nepf (2008) defined a slip velocity and momentum exchange at the inflection point. The model generated from this research represented an advance in the application of technology to the study of vegetated channels, and in the understanding and modeling of flows in channels with emergent vegetation.

### 12.6.2.3 Emergent Vegetation and Sediment Transport

Fine sediment deposition within emergent vegetation is not a well-studied process to date. This lack of research attention is



**Figure 3** Streamlines for a typical vortex structure in a frame moving with the vortex. Reproduced from White, B.L., Nepf, H.M., 2008. A vortex-based model of velocity and shear stress in a partially vegetated shallow channel. *Water Resources Research* 44, W10412, with permission from AGU.

more likely a reflection of the difficulties associated with the research and not a consequence of overlooking an important phenomenon. Recognition of the importance of sediment deposition within vegetation has proved to be much easier than quantification of rates and volumes. Field observations document thick vegetative growth in near-bank areas where vegetation acts as a very effective sediment trap (Gurnell et al., 2006). Sediment accumulation near banks may reduce the effective channel width over time, essentially altering the flow structure of the channel.

Theoretical models and flume experiments have attempted to predict and quantify sediment transport and deposition rates around and within plant areas. Agricultural concerns about sedimentation around row crops and stream buffers motivated many early flume experiments (e.g., Abt et al., 1994). Deposition rates onto removable plots of corn and grass were measured in a flume. The use of natural plants demonstrated the importance of plant flexibility and blade length on sediment deposition volume. The longer and more flexible plants bent forward onto the channel bed, which reduced sediment deposition in those areas. However, once sediment was deposited, it was protected from erosion by the plant stems (Abt et al., 1994). To parametrize the effects of vegetation, the Meyer-Peter and Mueller transport equation was adjusted for the presence of emergent vegetation using the results of flume experiments where uniform sediment was fed into a field of rigid, fixed rods arranged in a predetermined spatial pattern and density until an equilibrium transport rate was reached (Jordanova and James, 2003). The results were mixed as all the complexities of plant morphology and response to flow were condensed into a single parameter.

Depositional patterns within vegetated patches differ depending on the length and density of the simulated vegetation (dowels) and the size of the sediment in suspension (Sharpe and James, 2006). Large grain sizes deposited near patch edges, whereas finer sediments were transported further into patches before depositing. Dowel density had a similar effect on deposition volumes, with larger volumes depositing near the edge when stem density was high. The control exerted by hydraulic variables over sediment deposition rates and volumes was verified by observations in salt marshes (Mudd et al., 2010). Where velocities through marsh vegetation increased, the amount of suspended sediment that entered and deposited within vegetated patches increased.

The influence of seasonal phases of emergent grassy vegetation growth on fine-sediment deposition was recently measured in the field by Asaeda et al. (2010). When plants first emerged in spring, deposition rates were high, but as the plants grew to full size in the summer, the accumulated sediment 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. The sediment did not erode again until after the plants had fully decomposed. This cycle was observed to repeat over the 3 years of study observations showing that the range in plant morphologies exerted a greater influence over sediment deposition and erosion than did the flow rate (Asaeda et al., 2010). The results of these experiments confirmed the importance of vegetation parameters when considering how sediment transport and flow patterns are altered by emergent vegetation.

### 12.6.3 In-Stream Submerged Vegetation

Submerged vegetation grows in channels where the water depth is sufficient to form a velocity profile above the vegetation canopy. As a category, there has been much more research into the effects of submerged vegetation on channel form and processes than for emergent plants. Because the whole plant is submerged and not just the stem, the entire plant morphology alters the flow profile, turbulence, and sediment transport rates. The same methods and technologies are used to research submerged vegetation as were discussed in the previous section. Thus, this section explores the recent research concerning the effects of submerged vegetation by reviewing reach-scale effects, changes to local channel hydraulics, and sediment deposition rates and volumes.

#### 12.6.3.1 Reach-Scale Impacts of Submerged Vegetation

Submerged vegetation creates a drag force that reduces flow rates and, over the long term, alters channel shape. The loss of flow capacity due to submerged vegetation was widely recognized by the mid-twentieth century (e.g., Kouwen et al., 1969; Phelps, 1970), although field studies quantifying the effects of submerged vegetation were few due to the difficulties

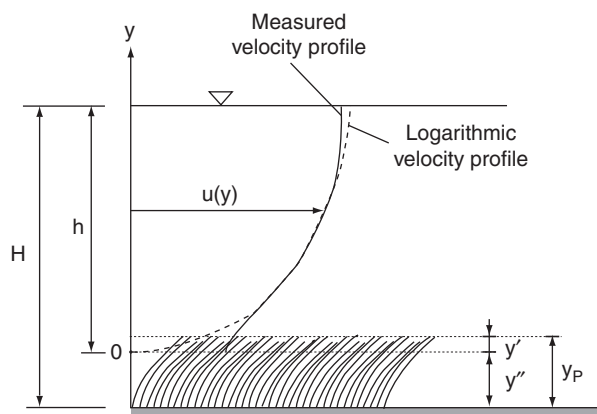
associated with making direct measurements. The influence of vegetation in establishing and altering channel morphologies over long reaches has also been recognized (Gurnell et al., 2010). In a study of rivers in the UK, macrophyte patches were shown to create distinctly different large-scale flow patterns depending on the density of the patch and the total amount of channel area covered by plants (Cotton et al., 2006). Where vegetation grew in individual stands, limited flow continued through the plants, whereas the majority passed through the narrow channels between plants. Flow velocities in the narrow channels were consistently higher due to flow constriction than within planted patches, where flow velocities were reduced by 48%. Where vegetated patches were thick and extensive across the channel, velocity reductions were general over the channel reach. Over time, the flow patterns in and around vegetation patches contributed to changes in channel bed topography and then general channel morphology.

The general velocity profile through a channel with submerged vegetation is characterized as consisting of two parts: a uniform low-flow profile within the vegetated area (Kouwen and Unny, 1973) and a logarithmic-shaped profile in the flow above the plant canopy (Figure 4). The universal log-law equation can be applied over the entire velocity profile, but modifications to the roughness height and zero plane displacement are required to account for flow over vegetation (Shi and Hughes, 2002). An added complexity of submerged vegetation is plant flexibility, the ability of submerged plants to bend and wave in the flow. An early and significant study on the change in flow profile in the presence of flexible, submerged vegetation parametrized the bending of the plants as a function of the elasticity of the plant and the channel flow (Kouwen et al., 1969). Combining these variables into a single parameter, the flexural rigidity of the vegetation ( $J$ ), Kouwen et al. defined  $J = EI$ , where  $E$  is the longitudinal modulus of elasticity of the plant and  $I$  the second increment of the plant cross-section. For low values of  $EI$ , the plant bends over completely and lies on the bed surface. For high rigidity values, plants remain erect. When this parameter is multiplied by the number of plants in a channel cross-section, it represents the total plant resistance to flow. The logarithmic velocity profile equation was adjusted to incorporate the new

parameter for roughness height and its application tested through a series of flume experiments using flexible plastic strips to simulate river grasses (Kouwen and Unny, 1973). Experimental results verified use of the modified velocity profile for erect and waving strips where plant roughness heights were similar. Prone vegetation reduced friction factors by a factor of 5 and did not produce a good fit to the modified profile. The results demonstrated a need to consider and further quantify vegetation flexibility and the feedback between flexibility and channel discharge when estimating the roughness height over vegetated channel beds.

Later research continued to focus on adjustments to the roughness factor (Petryk and Bosmajian, 1975; Kouwen and Li, 1980; Jarvela, 2002; Wilson, 2007). The body of literature for which vegetated roughness is parametrized through Manning's  $n$  is detailed by Green (2004), and a history of the early modifications to the log-law is given by Stephan and Gutknecht (2002). Jarvela's (2002) experiments were described in the emergent vegetation section but deserve another mention here as they also measured friction factors associated with different densities and arrangements of submerged grasses. The friction factor correlated to relative roughness and Reynolds number, decreasing with higher Reynolds numbers and increasing with relative roughness values. More recently, natural vegetation was studied to verify and extend the use of Kouwen's logarithmic profile method (Kouwen and Li, 1980; Carollo et al., 2002, 2005). Experimental results demonstrated a propensity for the equations of Kouwen to overestimate flow resistance and a need to calibrate to measured vegetation concentration and flexural rigidity. With these adjustments, the method applied well to natural submerged plants, either in patches or covering extensive amounts of channel area (Nikora et al., 2008).

The value assigned to the vegetation coefficient has a dominant influence over predicted channel roughness, and research has focused on adjusting this coefficient according to the amount of plant frontal area facing the flow (Green, 2004; Luhar et al., 2008). The derivation of a friction coefficient for vegetated regions by Wu et al. (1999) described for the case of emergent vegetation, also considered submerged vegetation when they incorporated information on plant stiffness and density into their coefficient,  $\lambda AL$ . Using an accurate value of the vegetation coefficient, the authors showed good agreement between predicted and experimental values of roughness. With the growing interest in vegetative resistance and number of adjustments to the friction factor, Baptist et al. (2006) compared the results of four methods to existing experimental data. The first was a theoretical derivation of the friction factor that divided the flow profile into segments and applied the effective water depth and velocity profile equations to calculate resistance separately in segments below and above the canopy. The second method was an analytical derivation of the velocity through the vegetated region using the conservation of momentum. The third employed numerical simulations using a 1D  $\kappa-\epsilon$  turbulence model. The fourth method, which employed a genetic programming technique, reproduced the experimental results with the greatest accuracy. The genetic programming method has not been employed extensively, as recent research has focused on developing process-based methods for calculating roughness, and the



**Figure 4** Vertical velocity profile above aquatic vegetation. Reproduced from Stephan, U., Gutknecht, D., 2002. Hydraulic resistance of submerged flexible vegetation. *Journal of Hydrology* 269, 27–43.



reader is referred to the work by Baptist et al. (2006) for a complete description of the technique.

The use of Acoustic Doppler Velocimeters (ADV) in flume experiments has enabled friction factor adjustments based on the measured turbulent flow field around flexible grasses (Stephan and Gutknecht, 2002). In flows without vegetation, turbulence intensity is reduced as relative submergence decreases because coherent flow structures, which create pressure fluctuation on the bed surface, were unable to form completely. In vegetated channels, this trend was not observed. Stephan and Gutknecht (2002) hypothesized that flexible vegetation responded to pressure fluctuations by bending. Pressure fluctuations formed and were dissipated by the waving of flexible plants. Thus, the flow profile over a bed of submerged vegetation with low relative roughness could be fit by a logarithmic profile modified for effective vegetation height. Defining effective plant height as the mean plant height after deflection by the flow, and reducing total flow depth by the effective plant height, caused the zero plane displacement to scale directly, and allowed for calculation of the shear velocity from the logarithmic profile. Building on this work, Jarvela (2005) measured the effective height and shear velocity over wheat. The experiments verified applicability of the shear velocity equation with depth adjusted for mean plant height to channels with submerged, flexible vegetation. The method provided a way to estimate shear velocity that did not require characterizing turbulence or calculating Reynolds stresses. This work extended the general applicability of the logarithmic velocity profile to the flow over submerged vegetation in general and made the calculation of the velocity profile generally accessible.

### 12.6.3.2 Hydraulics and Turbulence

Plant morphology, particularly the presence of leaves and the frond shape, has a demonstrated effect on the drag coefficient (Nepf, 1999; Baptist, 2003; Wilson et al., 2003). Aquatic plant growth has been shown to reduce bed shear stress by up to 80% (Baptist, 2003), and where the frontal area was dense, flow velocity into the vegetated reach reduced more quickly than for sparsely vegetated patches. Dense vegetation also reduced the longitudinal extent of momentum exchange across the plant interface. This effect was demonstrated by comparing the stems of plants to plants with fronds. Fronds increased the surface area of the plant region and created an additional drag element, which in turn increased the amount of turbulence in the flow (Wilson et al., 2003).

Reductions in flow velocity and turbulence intensity within a vegetated patch have been demonstrated over a range of flow velocities, vegetation densities, and locations within the vegetated area (Gambi et al., 1990). More recent detailed flow measurements across the full channel depth characterized the velocity profile by distinct flow regions within and above the vegetation, with a sharp spike in flow velocity and Reynolds stress at the transition (Nepf and Vivoni, 2000; Jarvela, 2005; Liu et al., 2008). The spike in Reynolds stresses just above the top of the canopy was independently verified using experiments where dowels simulated vegetation (Liu et al., 2008, 2010; Righetti, 2008), as were the similarities between this

layer and the inflection point just above the bed surface (described in the section on turbulence in emergent vegetation). The shear layer at the canopy was characterized as a second inflection point in the flow that moderated vertical momentum exchange across the canopy (Murphy et al., 2007). As flow moved upward through the canopy layer, it mixed with higher velocity flows above the canopy. The mixing created Kelvin–Helmholtz instability and a strong vorticity that pulled flow from above the canopy into the vegetated area and displaced slower moving flow upward in a clockwise pattern (Liu et al., 2008). As total turbulent kinetic energy increased, the inflection point shifted vertically upward and further from the canopy (Wilson et al., 2003). When flow in the shear transition layer was measured over three dimensions, vortex growth was shown to continue until balanced by drag dissipation around plant stems and fronds, and an equilibrium condition developed (Ghisalberti and Nepf, 2004). In fully developed flows at equilibrium over submerged vegetation, the ratio of turbulent production to dissipation attained a constant value.

The description of the inflection point is similar for flow processes operating at the lateral interface of submerged vegetation and clear channel flow (White and Nepf, 2008). A mixing layer characterized by formation of coherent vortices formed along the interface, creating velocity and turbulent flow profiles with similar spikes as were observed across the plant canopy. The similarities indicate that flow across a vegetation interface develops a similar layer of coherent vortices and peak in Reynolds stresses regardless of whether that transition is lateral or vertical. Mixing layers cannot be assumed for the interface of every submerged vegetation patch. They formed only where there was sufficient absorption of momentum by the plant frontal area of the canopy to trigger the Kelvin–Helmholtz instability (Nepf and Ghisalberti, 2008). Thus, only flows across densely vegetated interfaces were characterized by an inflection point.

Momentum exchange was limited by dense canopies where the frontal area of the plants consumed much of the turbulent energy, preventing it from penetrating into the canopy. Dye-tracing studies by Murphy et al. (2007) measured the limits of vortex-driven and diffusion exchange along dense plant canopies, simulated with wooden dowels. These results were used to develop a two-zone model of dispersion and diffusion across a submerged vegetation interface. Below the canopy, mixing was controlled by dispersion around individual plant stems and related to the density of the stems. Above the plant canopy, shear dispersion controlled mixing. Exchange across the canopy was by either vortices formed along the interface as part of a mixing layer characterized by Kelvin–Helmholtz instability, or diffusion processes operating within the canopy but near the interface. Recent dye-tracing experiments verified the increase in vertical shear and longitudinal mixing across natural canopies (Shucksmith et al., 2010).

Vortex-driven dispersion was dominant across sparsely vegetated regions where turbulent mixing penetrated into the vegetation, creating flow profiles with a large degree of uniformity (Righetti, 2008). The extent of momentum exchange across a canopy is a function of how far the Kelvin–Helmholtz vortices penetrate into the vegetated area, which is limited across dense canopies (Luhar et al., 2008). The distance over which momentum exchange occurs was defined by Nepf and

Vivoni (2000) as  $\delta_e$ . Beyond this length, turbulence is generated by individual plant stems. Significant wake zones around plant stems resulted in a dominance of relative plant submergence over mixing rates below the canopy (Shucksmith et al., 2010). Where vortex translation speed was large compared to rotation speed, and the submerged vegetation was flexible, the canopy developed a wave pattern with a frequency equal to the Kelvin–Helmholtz instability. The waving pattern enabled turbulent exchange closer to the bed, although not further below the canopy (Nepf and Ghisalberti, 2008).

Further review of the analytical methods used to calculate momentum and mass transport across submerged vegetation is presented in the work of Nepf and Ghisalberti (2008), where the turbulent flow characteristics around real vegetation planted in a flume were measured using PIV. An analytical treatment of the experimental results using the double-averaged Navier–Stokes (DANS) method is provided in Righetti (2008).

### 12.6.3.3 Submerged Vegetation and Sediment Transport

Quantification of sediment deposition rates within regions of submerged vegetation has suffered from the difficulties inherent in making measurements and the complications of flexible vegetation. Early approaches avoided the issue of direct measurements and derived analytical methods to estimate sediment deposition. One early contribution computed the deposition around submerged vegetation of different spatial density and arrangement (Li and Shen, 1973). This work built on the derivation of wake flow around a cylinder using linear supposition (Petryk, 1969) to extend the derivation to multiple cylinders in a variety of arrangements. The Shield's equation was combined with the drag model to estimate the sediment transport capacity of flow through the cylinders. Results showed a reduction in flow velocity and increase in sediment deposition when cylinder spacing was in a staggered as opposed to straight line arrangement (Li and Shen, 1973).

Interest in reducing the downstream transport of fine sediment in fluvial systems led to flume studies using simulated sediment (glass beads), cylinder arrays (Barfield et al., 1979; Tollner et al., 1982), and existing sediment transport models. The space between adjacent stems was modeled as a narrow channel, enabling the substitution of plant spacing for channel width. Transport rates in individual channels were predicted using the Einstein transport equation, and total transport was the sum of transport through all the individual channels. This approach led to an unrealistically uniform rate of sediment movement across the channel. Field observations showed that the distribution of vegetated patches created regions of high and low flow velocities, which created distinct areas of local sediment erosion and deposition (Gurnell et al., 2006). Deposition was predominantly within stands of extensive vegetation, and erosion occurred along flow paths between individual stands of sparsely vegetated areas. Monthly variations in depositional volumes indicated an active transport regime through the reach and the importance of changing plant morphology on sediment trapping efficiency (Cotton et al., 2006).

It was not until the 2000s that quantifying sediment deposition within aquatic plants became a significant research topic. The study by Baptist (2003), already described for its finding that submerged vegetation reduced bed shear stress by up to 80%, also measured sediment transport rates out of a vegetated area. During the experimental setup, a layer of uniform sand was placed within the vegetated area and changes in the bed profile during the experiment were measured using electronic conductivity bed profilers. As expected, without any sediment influx, the bed experienced net erosion. The unexpected result came from a comparison of shear stresses and associated transport rates for runs with and without vegetation. The same rate of transport could be achieved at a lower shear stress in a vegetated channel when compared to the nonvegetated state. Baptist hypothesized that higher turbulent flow fluctuations within the vegetation led to increased suspension rates of the fine sediment.

The volume of sediment deposition within a vegetated patch is necessarily a function of the extent to which flow can transport sediment into that patch. Therefore, models predicting deposition rates have been derived from analytical models of fluid exchange across a canopy (Luhar et al., 2008). Sediment deposition into a vegetated patch was simulated over a distance set by the diverging flow pattern created by shear vortices along the patch edge, regardless of whether the patch was densely or sparsely vegetated. Direct measurements of sedimentation rates were obtained from flume experiments recirculating water seeded with glass beads designed with settling velocity that promoted deposition (Zong and Nepf, 2010). Depositional patterns varied depending on the length of the vegetated path relative to the deposition length scale,  $x_e$ , defined by Zong and Nepf (2010) as the ratio of inertial force to settling velocity. Where the vegetation extent was less than  $x_e$ , sediment deposited uniformly throughout the vegetated area. Where vegetation extended beyond the length set by  $x_e$ , deposition was greater near the edge and declined with distance into the vegetated patch. A probabilistic model was developed from the experimental results to attempt to predict sediment deposition volumes in submerged vegetation. However, the measured extent of deposition was greater than that predicted by the model, indicating that increased turbulence intensities in the patch were not accounted for in the model.

### 12.6.4 Streambank Vegetation

We define streambank vegetation as those plants that are between the active-channel bank (AB) and shelf (AS), and we include the floodplain bank (FB) as shown in Figure 1. For our purposes, vegetation on depositional bars is classified as in-stream vegetation and discussed in previous sections. There are obvious uncertainties around these boundaries and they are utilized here only to help organize the discussion. Typically, the streambank is a sloping surface with or without vegetation connecting the active channel to the floodplain.

Streambank vegetation is generally acknowledged to have an influence on bank stability (Simon and Collison, 2002) and streambank retreat rates (Pizzuto et al., 2010). However, there is still much research needed to understand the complex

processes and feedbacks involved (Wynn and Mostaghimi, 2006a), especially as streambank vegetation is nearly always included in stream-restoration designs (Shields et al., 1995; Jennings et al., 1999). Interaction between vegetation growth on channel banks and sediment accretion on the banks is necessary to channel stability, and the rate of recovery of channel morphology in a post-channelization environment has been shown to be a function of the ability of vegetation to grow and stabilize the bank (Hupp and Simon, 1991). Streambank vegetation influences bank retreat rates by altering soil moisture and temperature in streambanks (Wynn and Mostaghimi, 2006a), through mechanical reinforcement due to root structure (Simon et al., 2004; Wynn and Mostaghimi, 2006b), and influencing the flow turbulence and boundary shear stress (Hopkinson and Wynn, 2009). Although much research has been done related to the roughness of in-stream vegetation and vegetation on the floodplain, less has been focused on the actual sloping streambanks (Hopkinson and Wynn, 2009).

#### 12.6.4.1 Reach-Scale Impacts of Streambank Vegetation

Most of the research related to streambank vegetation's influence on reach-scale roughness has been to inform the selection of roughness coefficients (e.g., Manning's  $n$ ) for use in hydraulic engineering for channel construction and flood modeling (Anderson et al., 2006); however, much more research is needed to fully establish the functional relationships (Yen, 2002). Yen (2002) provided an excellent review of studies and computational methods used to estimate the resistance coefficient attributed to vegetation in composite channels. He warned against "selecting the energy and momentum concept as the effective means for analysis" given the complex and variable interacting forces involved and increased energy loss due to wakes behind vegetation.

Many scientists and practitioners have utilized long-term records available from gaging stations to estimate or solve for Manning's  $n$  based on average velocity, depth, and slope (Leopold et al., 1964; Limerinos, 1970). Numerous studies have also provided tables with and without actual pictures of streams to help practitioners estimate roughness coefficients for natural streams with variable types of vegetation (Cowen, 1956; Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989; Hicks and Mason, 1998), but few have tried to parse out the roughness attributed specifically to streambank vegetation. Coon (1995, 1998) did set out to identify the impact of vegetated banks using 21 stream sites ranging in channel size and level of vegetation on their banks in New York, US, at or near United States Geological Survey (USGS) gauging stations. Using percentage of vegetated wetted perimeter as a variable and analyzing a range of flows at each site, he estimated the amount of roughness attributed to vegetation. For the most part, vegetation had little or no effect on roughness of streams wider than 33 m (100 ft); however, vegetated banks did increase Manning's roughness by 0.005–0.012 in narrower channels (Coon, 1995, 1998). Results depended on season and type, density, and percent submergence of vegetation, which is also supported by Fischnich (2000) and Anderson et al. (2006).

#### 12.6.4.2 Hydraulics and Turbulence

Several field efforts have been conducted to quantify roughness due to streambank vegetation based on fine-scale, at-a-site field measurements (Thorne and Furbish, 1995; Wang and Wang, 2007). Utilizing a coarsely vegetated bend in the Ocklawaha Creek in Florida, USA, they measured velocity and water-surface topography during high flows before and after removing the rough bank vegetation (Thorne and Furbish, 1995). Vegetation roughness on the curved streambank produced a backwater effect that inhibited flow directed toward the bank, shifting the highest velocity to near the center of the channel. After removing vegetation, higher velocity flow was displaced toward the outer bank. In addition, in the presence of roughness, the high-velocity core was shifted downstream, which they suggested contributed to asymmetrical bend migration (Thorne and Furbish, 1995). Wang and Wang (2007), using sections of the Chaodongweigang River in China with different densities of bank vegetation, measured velocities and water surfaces to determine the effects of density, stem diameter, and rigidity of reeds. The water-surface slope in the river reach with reeds was larger than without, and the cross-sectional elevation was concave with the higher elevations within the vegetation than in the middle of the channel. They concluded that the vegetation resulted in three velocity zones in rivers with streambank reeds: slack water zone in the vegetation, a transition zone, and the main flow zone (Wang and Wang, 2007).

Wang et al. (2009) followed up their field-based investigation with flume experiments using real vegetation (eel grass). In this study, they vegetated half the flume area and the results could realistically be applied to in-stream vegetation or streambank vegetation. Flow rate in the nonvegetation zone increased with increased vegetation density, and differences in streamwise velocities between the vegetated and nonvegetated zones generated high shear layers and a transverse vortex (Wang et al., 2009). These transverse vortices near the free surface increased with increased vegetation density and resulted in increased secondary currents and turbulence energy with increased Froude numbers. They cited the need for more research to investigate the interactions between the coherent vortices and the secondary currents in partially vegetated flows (Wang et al., 2009). Afzalimehr and Dey (2009) also performed flume studies, but focused on the effects of the interaction between bank vegetation and gravel beds on velocities and Reynolds stress distributions. Using the natural vegetation *Os* (similar to wheat), they found that vegetation on the banks caused the maximum velocity to be considerably different than the free-water-surface velocity, unlike flow over a gravel bed with no vegetation. The vegetation changed uniform flow to nonuniform flow due to nonlinear Reynolds stress distributions, and its shape varied with distance from the wall (Afzalimehr and Dey, 2009).

Much of the effort to understand the distribution of the Reynolds shear stresses was to obtain improved estimates of shear velocities for determining bed resistance (Afzalimehr and Dey, 2009). For uniform flow over a gravel bed (no vegetation), the Reynolds stress was linear, with maximum shear stress at the bed and minimum near the free surface. However, with vegetation on the banks (the flume walls in

this case) the Reynolds stress distribution was nonlinear or convex in shape with the apex at a higher location. A substantial deceleration near the vegetated walls created a strong lateral shear layer in the interfacial region (Afzalimehr and Dey, 2009). Hopkinson and Wynn (2009) conducted flume studies to evaluate the three-dimensional velocity structure, turbulence, and near-bank shear stresses across three vegetation treatments (tree, shrub, and grass) and a sloping streambank. Similar to Thorne and Furbish (1995), Wang and Wang (2007), and Wang et al. (2009), the free streamwise velocity was increased in the presence of bank vegetation and near-bank velocities were reduced for all three vegetation treatments. Hopkinson and Wynn (2009) did find differences in turbulence intensity and Reynolds stress distributions across the different vegetation treatments. Turbulent kinetic energy and Reynolds stresses near the streambank were increased for the upright shrub treatment, particularly at the toe, but grass folded to a prone position and protected the streambank by reducing shear stresses near the boundary (Hopkinson and Wynn, 2009). This finding supports a previous modeling study by Kean and Smith (2004) that found woody bank vegetation reduced perimeter-averaged boundary shear stress, as well as the boundary shear stress below the vegetation and velocity within the vegetation. Hopkinson and Wynn (2009) did find that at low tree densities, the turbulence intensity and Reynolds stress distributions were similar to those of the bare bank experiments. Similarly, Kean and Smith (2004) found reductions in near-bank flow and boundary shear stress due to both drag on vegetation and stress on the banks for sparse vegetation, but determined that drag on vegetation was the dominant effect in channels with dense vegetation.

Streambank vegetation type and density influence roughness (Coon, 1995, 1998), velocity distributions (Wang et al., 2009), and turbulence and shear stresses (Hopkinson and Wynn, 2009). In the discussion of floodplain vegetation, we see that the actual location of vegetation (streambank vs. floodplain) can also have a profound influence, particularly on the exact locations of turbulence intensity and shear stresses along the cross-sectional profile of the stream (McBride et al., 2007).

#### 12.6.4.3 Streambank Vegetation and Sediment Transport

Vegetation is used in stream restoration projects in an effort to stabilize banks and reduce streambank retreat (Bernhardt et al., 2005). Although it is generally accepted that vegetation that grows on the banks influences flow, sediment transport, and river morphology (Hupp and Simon, 1991; Afzalimehr and Dey, 2009; Wang et al., 2009; Li and Millar, 2010), most research related to streambank vegetation and sediment has been related to streambank retreat and bank stability (Wynn and Mostaghimi, 2006a; Lawler, 2008; Pollen-Bankhead and Simon, 2010) or the contribution of sediment loads from eroding banks at the watershed level (Lawler, 2008). Research focused specifically on how bank vegetation influences sediment transport has been limited. Those sections describing in-stream and floodplain vegetation influences on sediment transport pertain to streambank vegetation; therefore, the reader is referred to those sections for further information.

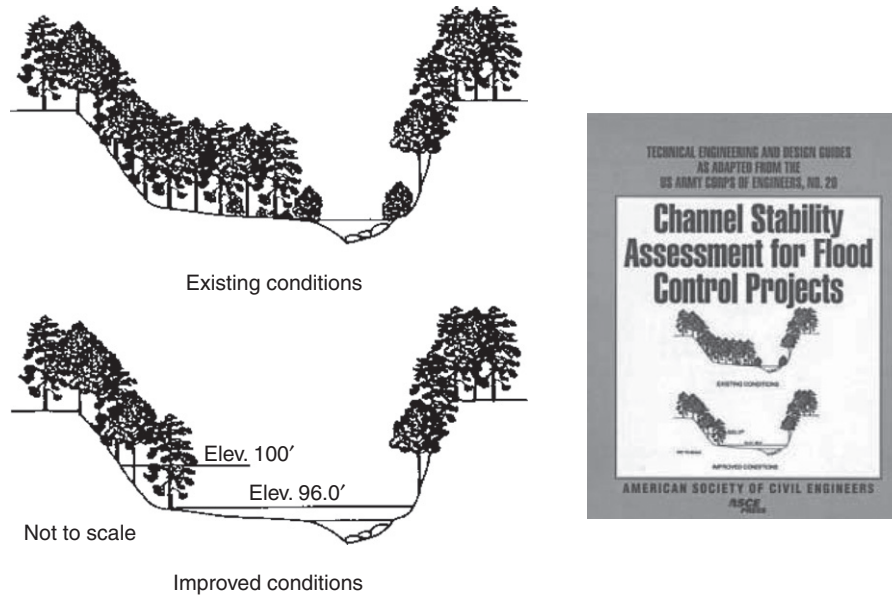
### 12.6.5 Floodplain Vegetation

As previously mentioned, we assume that the floodplain does not start until we reach a level area near a river channel (Leopold, 1994) and that this is typically equivalent to the bankfull stage (Rosgen, 1996). Referring to Figure 1, we include only the floodplain (FP) in this section as we have already discussed the FB as part of the streambank, and we will not extend to the terraces (T). This distinction is important because where the vegetation is located can drastically change how it influences flow, velocity, turbulence, and shear stresses and at what stage these influences become important.

Roughness due to vegetation on floodplains has long been of interest to engineers due to the role it plays in flooding and flood prediction (Lang et al., 2004). Floodplain vegetation was (and, in some cases, still is) considered a nuisance (Darby and Thorne, 1995; Jarvela, 2004) and was actively managed or removed to reduce roughness and, therefore, reduce flooding (see Figure 5, from the cover of U.S. Army Corps of Engineers, 1997). Although some floodplain vegetation is still managed or removed for flood reduction purposes (Leu et al., 2008), the general trend worldwide is to encourage more natural floodplain vegetation to improve streambank stability and ecological health (N.R.C., 2002). Re-vegetation of streambanks and floodplains is a widely practiced technique in river restoration activities worldwide (Gippel, 1999; Bernhardt et al., 2005; Anderson, 2006). Although there is concern that re-vegetation of river and stream corridors will increase flooding, the issue is complex, variable, and much uncertainty exists (Defra/EA, 2003; Anderson et al., 2006). Anderson et al. (2007) employed a newly developed model called roughness of vegetation in rivers (ROVER; Anderson et al., 2007) to model flood waves as they propagated down re-vegetated river reaches and found that the peak discharge was reduced, but the duration of the flood was increased.

#### 12.6.5.1 Reach-Scale Impacts of Floodplain Vegetation

Natural floodplains tend to have diverse vegetation communities due to frequent disturbance by flooding (Gregory, 1992; Hupp and Osterkamp, 1996; Osterkamp and Hupp, 2010). This diversity in vegetation has led to spatially heterogeneous roughness values (Freeman et al., 2000; Forzieri et al., 2010; Girard et al., 2010) over time (Geerling et al., 2007). Along the Amazon River in Brazil, Mertes et al. (1995) utilized remote sensing to evaluate the spatial heterogeneity of flood hydrology and vegetation; they found that vegetation community diversity was influenced by the manner in which the flood waters physically reach the floodplain (whether from local sources such as hillslopes or from exchange with the river). Several researchers have attempted to quantify this reach-scale variability in floodplain roughness using airborne laser scanning altimetry or airborne light detection and ranging (LIDAR; Coby et al., 2002; Forzieri et al., 2010), as well as terrestrial laser scanning (TLS; Antonarakis and Richards, 2010). However, there is some indication that such detailed quantification of complex roughness distributions does not significantly improve floodplain flow modeling over the more



**Figure 5** Cover of U.S. Army Corps of Engineers (1997) showing “improved” conditions as removing floodplain vegetation to reduce roughness and, therefore, flooding. Reproduced from U.S. Army Corps of Engineers, 1997. Channel stability assessment for flood control projects (Technical engineering and design guides as adapted from the U.S. Army Corps of Engineers, No. 20). American Society of Civil Engineers 978-0-7844-0201-6. ASCE Press, New York, NY, 108 pp, with permission from ASCE press.

traditional use of roughness values based on simple land use characteristics (Werner et al., 2005).

In general practice, roughness due to floodplain vegetation has been estimated using look-up tables or visual references (Cowen, 1956; Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989; Hicks and Mason, 1998), as described previously for streambank vegetation. Floodplain vegetation affects flow structure, flow resistance, and turbulent intensities (Yang et al., 2007). Resistance and flow structure depend on numerous variables, including: (1) type and physical characteristics of the vegetation (Freeman et al., 2000; Antonarakis and Richards, 2010); (2) time of year or seasonal changes (Coon, 1998); (3) vegetation succession (Geerling et al., 2007); (4) density of vegetation (Wang and Wang, 2007); (5) depth of flow (Fischenich, 2000; Anderson, 2006); and (6) geomorphic setting (Darby, 1999). In equation form, Yen (2002) defined a symbolic roughness parameter as follows:

$$f = F\left(Re, Fr, S_w, S_0, \frac{k_s}{R_c}, L_v, J, D, M\right)$$

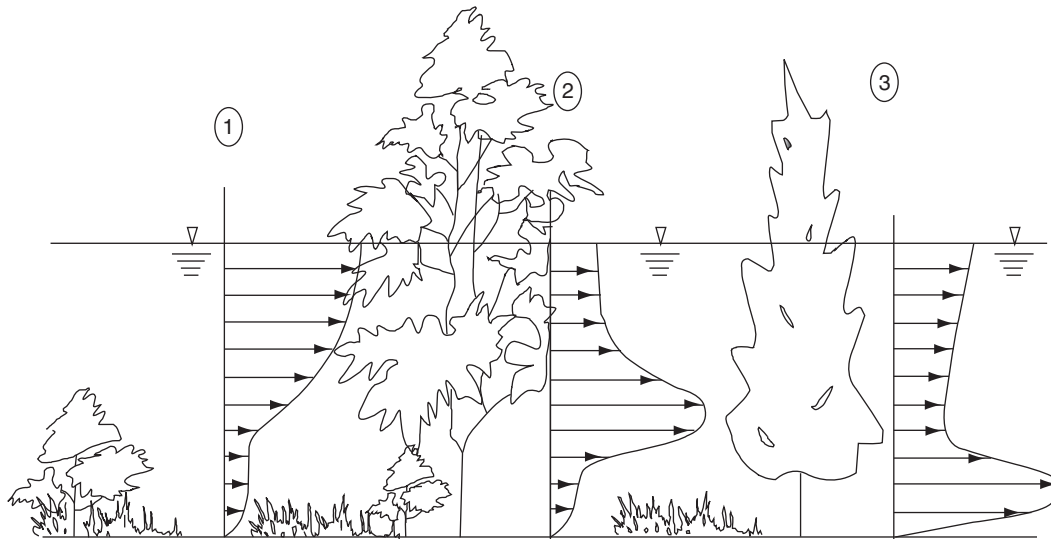
where  $f$  is the resistance,  $Re$  the Reynolds number,  $Fr$  the Froude number,  $S_w$  the water surface slope,  $S_0$  the channel bed slope,  $k_s$  the relative roughness,  $L_v$  a nondimensional vegetation parameter representing geometry,  $J$  represents flexibility,  $D$  the relative submergence of the vegetation, and  $M$  is the density of vegetation. Fischenich (2000) developed equations for estimating Manning's  $n$  for unsubmerged and submerged floodplain vegetation, noting that the velocity distributions (Figure 6) and, therefore, resistance varied greatly due to depth of flow and vegetation type. Perucca et al. (2009) estimated the dispersion coefficient for rivers with and without floodplain vegetation and concluded that the longitudinal

dispersion in vegetated rivers was as much as 70–100% larger than for rivers without vegetation.

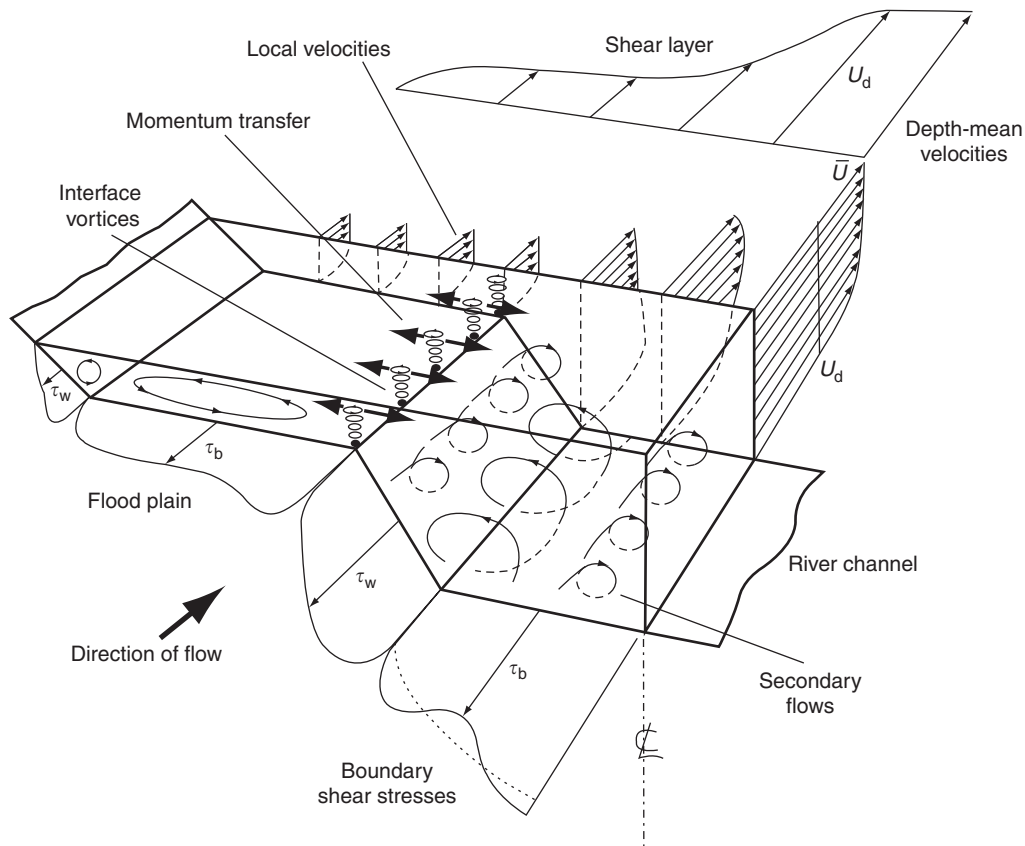
### 12.6.5.2 Hydraulics and Turbulence

Compound channels, even without floodplain vegetation, induce complex flow conditions (Figure 7; Shiono and Knight, 1991; Fischenich, 2000; Thornton et al., 2000; Harris et al., 2003). Where floodplain vegetation is present (Kadlec, 1990; Fischenich, 2000), drag is generated by velocity gradients and eddies are formed during inundation flows, resulting in momentum losses. These losses are typically not incorporated into the existing techniques used to predict roughness and resistance in natural rivers (Fischenich, 2000; Thornton et al., 2000). Harris et al. (2003) applied genetic programming to flume data and described how the complexity in flow is due to streamlines becoming circuitous as they bend and branch around surface-piercing vegetation elements (see Figure 3). During overbank flows, the resistance of the floodplain vegetation acts similarly to streambank vegetation and tends to reduce velocities in the floodplain and increase velocities in the main channel, which in turn influences turbulence intensities and shear stress distributions (Wang and Wang, 2007).

The velocity differential between the floodplain and the main channel can create a shear layer (Shiono and Knight, 1991; Wormleaton, 1998). This channel–floodplain interface has been modeled numerically as an imaginary vertical wall by several researchers (Pasche and Rouve, 1985; Naot et al., 1996). Intensive vortex shedding occurs at the channel–floodplain interface due to an intensive momentum exchange between two distinct regions of varying velocity (Pasche and Rouve, 1985).



**Figure 6** Velocity distribution for submerged and unsubmerged vegetation. Velocity distribution represents vegetation condition to the left. Reproduced from Fischenich, C., 2000. Resistance due to vegetation. ERDC TN-EMRRP-SR-07. U.S. Army Engineering Research and Development Center, Vicksburg, MS, with permission from U.S. Army.



**Figure 7** Hydraulic parameters associated with overbank flow in a two-stage channel. Reproduced from Shiono, K., Knight, D.W., 1991. Turbulent open-channel flows with variable depth across the channel. *Journal of Fluid Mechanics* 222, 617–646, with permission from Cambridge.

McBride et al. (2007) conducted a flume study of forested floodplain vegetation and found that, during overbank flows, there was a narrow band of high turbulence between the floodplain and main channel, and turbulent kinetic energy

(TKE) was 2 times greater than during overbank flows with grassy vegetation on the floodplain. The point of their study was to determine how and why channels started out as narrow grass-lined channels (Zimmerman et al., 1967), but eventually

widened during natural reforestation (McBride et al., 2008). They built on these results with field measurements of a prototype stream during five peak flows and found significantly greater TKE in the reforested reach than in the mature forest or grass-lined reaches. They used this information to develop a nonlinear conceptual model of incision, widening, and recovery of a stream during its transition from grass-lined channel to mature forest (McBride et al., 2008, 2010).

Yang et al. (2007) found that streamwise velocities have logarithmic distributions in nonvegetated floodplains, but that vegetated floodplains followed an S-shaped profile with three zones (which varied depending on whether woody or non-woody vegetation was simulated). The lateral velocity gradient increased with the addition of vegetation, with long grasses retarding flow the most. Floodplain vegetation increased apparent shear stress at the vertical interface between main channel and floodplain, and Reynolds stresses became very complex in the main channel side-slope zone, particularly at the floodplain-main channel boundary (Yang et al., 2007). Thornton et al. (2000) set out to quantify this apparent shear stress at the interface between the main channel and both a vegetated and nonvegetated floodplain as a function of fluctuations in channel velocities. They noted that most researchers focused on boundary shear force and gravitational force when estimating flow resistance, but that the apparent shear stress must be included to account for turbulence and momentum transfer (Thornton et al., 2000). Their experimental results showed that the apparent shear stress was greater at the interface than within the main channel or floodplain, and that as vegetation density increased, the apparent shear increased.

Darby (1999) modified a hydraulic model to evaluate flow resistance and flood potential for channels with nonuniform cross-sections, varying bed material, and riparian vegetation with and without flexibility. The resultant model accounted for lateral shear, but ignored secondary flows. Comparison of model results with field data suggested it could be a useful tool for design hydraulic analysis in stream restoration.

### 12.6.5.3 Floodplain Vegetation and Sediment Transport

Floodplains are well known to provide sediment storage in fluvial systems (Phillips, 1989; Steiger et al., 2003; Hupp et al., 2008, 2009). However, even though numerous publications (e.g., N.R.C., 2002) and government policies (Chesapeake Bay Executive Council, 2003) advocate riparian or floodplain forests as efficient traps for sediments and other pollutants, very few studies have quantified actual storage rates (Noe and Hupp, 2009). Geerling et al. (2007) studied plant succession, roughness, and aggradation of an excavated channel over 16 years as vegetation grew back on the floodplain. Softwood forest establishment increased sedimentation and an equal amount of sediment was excavated and re-deposited over the 16 years. The establishment of vegetation reduced overall mean flow velocity and had a positive effect on overall sedimentation, thereby creating more diverse flow velocity and sedimentation patterns (Geerling et al., 2007). This corresponds to the findings of Dunne et al. (1998), who conducted a sediment budget along reaches of the Amazon River and noted that the hydraulic roughness of floodplain (due to vegetation)

influenced the residence time of water on the floodplain, thereby increasing settling time. Noe and Hupp (2009) measured floodplain sediment and nutrient retention in the Coastal Plain floodplains of the Chesapeake Bay watershed, USA, and found that these floodplains stored large proportions of the river's annual loads of sediment and nutrients. They estimated median sediment retention rates of 119% for sediment, 59% for phosphorus, and 22% for nitrogen on floodplains of seven rivers over 1–6 years (Noe and Hupp, 2009). It is important to note that values above 100% were possible due to uncertainty in several of the estimation variables. Hupp et al. (2009) evaluated the effect of human alterations such as dam, stream channelization, and levee construction on floodplain geomorphic processes and concluded that "human alterations typically shift affected streams away from natural dynamic equilibrium" and alter the deposition/erosion processes.

Li and Millar (2010) modified an existing 2D morphodynamic model of a gravel-bed river to include floodplain vegetation in order to predict changes in bedload transport and channel morphology due to sediment deposition and erosion. They found that vegetation reduced near-bank and floodplain velocities and helped stabilize bank sediments, which in turn influenced bedload transport and channel morphology (Li and Millar, 2010). Woody floodplain vegetation often formed depositional sites during bedload transport events (McKenney et al., 1995).

McBride et al. (2008, 2010) studied the process of channel widening on small streams in Vermont, USA, during the process of riparian vegetation succession from grass-lined banks to forest through passive reforestation. They discussed the implications of their findings on the ever-popular stream restoration activities in the USA that typically include riparian reforestation (McBride et al., 2010). Allmendinger et al. (2005) found higher rates of deposition and lateral migration in reaches with non-forested floodplains versus those with forested floodplains. They suggested that differences in width between forested and nonforested reaches were related to a balance between rates of cut-bank erosion and rates of deposition on convex floodplains (Allmendinger et al., 2005). In discussing the sediment impacts of potential channel widening due to riparian reforestation, Hession et al. (2008) noted that much more research is needed to quantify sediment supply and storage dynamics, particularly given the incredible amount of re-vegetation taking place in the US (Bernhardt et al., 2005; Hassett et al., 2005).

### 12.6.6 Future Directions

This chapter has highlighted the trends and recent research advances in the complexities caused by vegetation in and near channels. Plants create a complicated system of feedbacks and linkages between channel flow and morphology, sediment deposition and erosion, plant morphology, density, and spatial extent. As research advances our knowledge in one direction, it opens more questions in another. Technological advances have also furthered understanding while reminding us of the many unknowns still needing investigation.

Studies that characterize flow profiles have formed a consensus on the shape of the velocity profile through vegetation. Where the flow is within a vegetated area, the velocity is

uniform following an inflection point near the bed, and velocities are much reduced when compared to open water flows. Profiles through submerged vegetation consist of a uniform profile within the plants that transitions to a logarithmic profile in the free channel flow by an inflection point just above a plant canopy (refer to [Figure 6](#)). This profile description holds in general but adjustments must be made for each specific channel as a result of feedbacks between the vegetation flexibility, density, and spatial extent in the channel. Similarly, frictional resistance due to vegetation can be parametrized on a general scale, but the complications due to plant flexibility and morphology make quantification on a local scale difficult. Given the number of variables interacting to create roughness over a channel and floodplain, [Gurnell et al. \(2010\)](#) speculated that a multivariate methodology needs to be developed. Recent research has also begun to investigate the interaction between sediment and vegetation, including sediment transport, erosion, and deposition in vegetated areas, but these interactions remain poorly quantified.

Research has followed two basic approaches. One approach focuses on a single aspect of the vegetated channel system, working to explain processes occurring at that spatial scale. For example, studies of fluid exchange across the vegetation interface. The second approach studies over a larger spatial scale, working to establish the feedbacks operating between vegetation and the channel system. For example, the feedbacks between processes at work along a vegetated channel bank and the evolution of channel width and morphology. Progress employing both methods is needed to develop a full understanding of how vegetation influences a channel system. Small scale research is necessary to produce a process-based understanding of the connections between flow hydraulics and sediment and plant mechanics. Larger scale research is needed to understand how the flow, vegetation, and sediment interact over a range of spatial and temporal scales.

As described in [Tsujimoto \(1999\)](#), vegetated channels are an inter-connected system of feedbacks between the flow, sediment transport, geomorphology, and vegetation. Advances will be made both through individual research and from the gathering and exchange of ideas between those working at the various research scales and methods. The 2009 Binghamton Geomorphology Symposium (BGS) serves as an example of the type of exchange needed to recur for progress to continue ([Hession et al., 2010](#)). The 2009 BGS was similar in theme to the 1995 BGS focused on biogeomorphology ([Hupp et al., 1995](#)) and represented a gathering of new researchers as well as veterans from the 1995 symposium. The 2009 symposium focused on the interactions, dependencies, and feedback loops at work in vegetated systems, and brought together a diverse group of researchers from a range of disciplines to advance the fundamental and applied thinking on vegetated fluvial systems. A common theme throughout the symposium was the difficulty of inferring processes in these inherently complex systems due to the feedbacks between vegetation and the landscape. Cause and effect relationships were rarely clear and the general feeling of the attendees was that we must use multiple research methods across disciplines to begin to understand these complex systems ([Hession et al., 2010](#)).

The lack of and need for collaborations across ecology and geomorphology led to the 2008 Meeting of Young Researchers

in Earth Science (MYRES III) focused on Dynamic Interactions of Life and its Landscape ([Reinhardt et al., 2010](#)). They identified two broad themes, one of which is relevant to our discussion here – the co-evolution of landforms and biological communities. This meeting and two manuscripts by the 2009 BGS keynote speakers ([Marston, 2010](#); [Osterkamp and Hupp, 2010](#)) are excellent source for identifying future directions for research. Reviewing these manuscripts provided some inspiration for future research needs and opportunities related to vegetation and roughness:

1. Use the ongoing river and stream restoration activities to our advantage. Conduct post-project monitoring over large spatial and temporal scales to help understand vegetation and geomorphology more fully. In the case of roughness, many of these restoration projects remove existing vegetation, reshape or re-engineer the stream morphology, and plant native vegetation. This vegetation will take years to mature, all the while changing its structure and density, which will influence roughness, hydraulics, and sediment transport and deposition.
2. Develop restoration plans through collaborations between engineers, ecologists, and geomorphologists. Also, where possible, develop the designs to test various hypotheses about how the stream morphology, flow hydraulics, and vegetation will respond. This could be done by developing restoration plans that vary longitudinally, or employing paired reach studies across similar watersheds.

The practical need for improved understanding of and prediction of the processes at work in vegetated systems comes from the use of a river as an ecological engineer. [Gurnell et al. \(2010\)](#) mentioned the need to consider river management schemes that include mowing of aquatic vegetation and channel dredging. By imposing a control over vegetation growth, management may be preventing the evolution of the channel form. It is possible that, if left to grow, the vegetation would form dense patches. These patches could trap large enough volumes of fine sediment to induce landform development around the plants and eventual island formation, which would alter the channel morphology away from that of a straight channel and toward a braided morphology ([Walter and Merritts, 2008](#)). However, it is not known what flow regimes would be required to induce some deposition but not choke the channel with sediment. This is analogous to the current use of vegetation in river restoration. Much is being done, both in terms of growing vegetation on the banks and removing it from the channel, without a clear understanding of how the channel responds to changes in one part of the feedback loop between vegetation, flow, sediment, and channel form.

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## Biographical Sketch



Dr. Cully Hession is an associate professor in the Center for Watershed Studies within the department of Biological Systems Engineering at Virginia Tech. He is a professional engineer in Virginia with over 25 years of experience in watershed hydrology/modeling and more than 15 years experience in stream morphology and aquatic ecosystem research, education, assessment, and design. Dr. Hession's main research involves cross-disciplinary efforts to understand the influence of watershed and riparian disturbance on channel structure, and linking physical channel conditions to aquatic ecosystem structure and function.



Joanna Crowe Curran is a fluvial geomorphologist and engineer. Her research focuses on the mechanics of sediment transport in open channel hydraulics, particularly on how changes in channel roughness and sediment supply effect the channel reach, whether these changes are due to dam removals or bed armoring. Her research has spans channels of both steep and low gradient, from step pool bedform formation processes to large woody debris transport in coastal areas.