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Flow characteristics in an alluvial channel covered partially with submerged vegetation

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ABSTRACT

The present study examines the flow characteristics in a stable alluvial channel partially covered with submerged *Oryza sativa* (rice) stems in a staggered pattern with downward seepage. Measurements were taken in transect across the flume at the vegetated region, interface or junction of vegetated and unvegetated region an unvegetated region to explore the difference in flow characteristics in these regions. The presence of vegetation reduces the velocity, Reynolds stress and turbulent intensities at the downstream vegetated region even with downward seepage which is an important finding for river restoration. An increase in the flow characteristics such as velocity, Reynolds stress and turbulent intensities are observed in the unvegetated region as the flow goes downstream which means that the reduction in the flow characteristics in the vegetated region is diverted towards the unvegetated region. Moment analysis shows that streamwise flux is occurring in the flow direction and vertical flux is occurring in downward direction and increases with increase in seepage percentage. Integral scales also exhibit that with downward seepage, the size of eddies increases. The maximum depth of erosion with downward seepage is more than for the case of no seepage and erosion increases as the flow goes downstream.

1. Introduction

Vegetation plays an important role in influencing the mean and turbulent flow field in a river channel (Nepf, 2012). It increases the flow resistance and hence it was considered as a nuisance in culverts and stream channels in earlier times (Kouwen and Unny, 1975). However, the modern river management highlights the importance of aquatic vegetation in increasing the ecological and aesthetic value for river ecological engineering and restoration (Nikora, 2010). Plant groups and species act as physical engineers of river ecosystems (sensu Jones et al., 1994), not only responding to their physical environment but also modifying it and thus controlling aquatic and riparian ecosystem structure and function as well as river morphodynamics. Recent investigations have been featuring the role of aquatic vegetation as improving water quality by removing nutrients from and releasing oxygen to the water column (Wilcock et al., 1999; Schulz et al., 2003; Zhu et al., 2016), promoting habitat diversity by creating a diversity of flow regimes (Kemp et al., 2000; Crowder and Diplas, 2002), stabilizing the river bed and channel morphologies (Braudrick et al., 2009; Wang et al., 2009; Li and Millar, 2010) and inducing sediment deposition and retention (Abt et al., 1994; Lopez and Garcia, 1998; Lee and Shih, 2004; Cotton et al., 2006; Gurnell et al., 2006). With this aspect, numerous research works have been found in the literature in studying the flow characteristics affected by the aquatic vegetation. de Lima et al. (2015) studied the flow patterns around two neighboring patches of emergent vegetation and observed that flow distribution is influenced by interaction between neighboring vegetation patches and suggest that this may create feedbacks that influence the evolution of vegetated landscapes. Folkard (2011) presented the analyses of results from laboratory flume experiments in which flow within gaps in canopies of flexible, submerged aquatic vegetation simulations is investigated. Okamoto and Nezu (2013) investigated the spatial evolution of coherent motions considering a finite length rigid vegetation patch and examined the transition from boundary-layer flow upstream of the patch to mixing-layer-type flow within the patch. Chen et al. (2011) analyzed the flow structures of fully submerged flexible plastic vegetation in different configurations (aligned, staggered, and columnar) with different streamwise and spanwise spacings and demonstrated that the vertical distributions of streamwise velocity of different vegetation configurations can be separated into the upper non-vegetated layer, middle vegetation layer, and lower sheath layer, and can be described by a three-layer model using various logarithmic equations. Pang et al. (2014)

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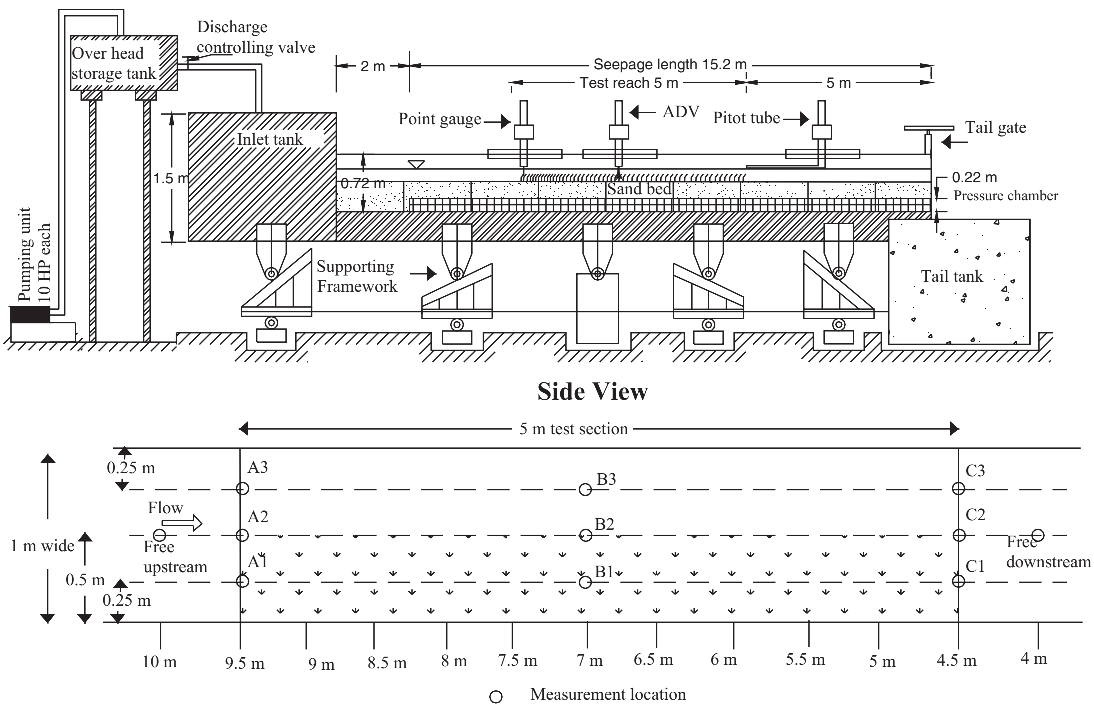

Fig. 1. Schematic diagram of the experimental flume set-up (a) Side view (b) test section showing measurement location (placing of vegetation not to scale).

investigated the turbulence structure and flow field of shallow water with a submerged eel grass patch and found that turbulent intensity increases from the water surface to the canopy, then decreases to the plant root. Vegetation produces drag and thus has a hydraulic impact on flow carrying capacity. The hydraulic resistance produced by vegetation depends on many factors, including the vegetation stem size, plant height, vegetation density and flow depth. Jarvela (2005) investigated experimentally the flow resistance above flexible vegetation in an open channel flume and confirmed that the logarithmic velocity profile for smooth open channel flow is altered in vegetated flow and the Darcy- Weisbach's friction factor can be related to the maximum shear stress which occurs approximately at the deflected plant height. Wilson (2007) investigated the variation of hydraulic roughness parameters with flow depth and found that the Manning roughness coefficient increases with decreasing flow depth. Nikora et al. (2008) studied the impacts of vegetation on hydraulic resistance and showed that the submergence depth ratio is the major parameter to determine hydraulic roughness. Drag coefficient is frequently used as a parameter for representing the flow resistance (Stone and Shen, 2002; Thompson et al., 2004; Armanini et al., 2005). Nepf (1999) developed a model to describe the drag, turbulence and diffusion for flow through emergent vegetation and covered the natural range of vegetation density and stem Reynolds numbers to extend the cylinder-based model for vegetative resistance by including the dependence of the drag coefficient, stem density and highlight the importance of mechanical diffusion in vegetated flows. Siniscalchi et al. (2012) investigated the effects of a finite-size vegetation patch on flow turbulence, variations in drag forces experienced by individual plants within the patch, and flow-drag interrelations. The bed condition in a natural channel also plays an important role in influencing the flow characteristics. Natural channels are composed of permeable boundaries in natural environments and the flow in natural channels is a complex interaction between surface and subsurface flows. Based on the difference in water level between the channel and the surrounding ground water, water seeps into (upward seepage) or out of the channel bed and channel banks (downward seepage). Tanji and Kielen (2002) estimated seepage losses of 20–50% of the total flow volume in unlined earthen canals. Kinzli et al. (2010) and Martin and Gates (2014) measured loss of water around 40% and 15% because of downward seepage. Besides seepage losses, it is known that the presence of downward seepage leads to an increase in bed shear stress and sediment transport which consequently changes the hydrodynamic characteristics of the channel (Rao and Sitaram, 1999; Dey et al., 2011; Rao et al., 2011; Cao and Chiew, 2014; Deshpande and Kumar, 2015; Patel et al., 2015). Alluvial channels can be designed on the basis of the incipient motion or threshold condition of the particles resting on the bed which can result in stable bed conditions where erosion and deposition of sediments is not appreciable. Application of downward seepage to such channels increases the mobility of bed particles because of increased bed shear stress (Dey and Nath, 2010; Rao et al., 2011). Thus downward seepage is one of the main factors which cannot be neglected while designing a channel. The study of the effect of seepage flows on the flow characteristics in a stable alluvial channel with the presence of vegetation is of great interest as this problem is related to the solution of important practical engineering problems. Devi and Kumar (2015) dealt with fully submerged artificial vegetation with downward seepage and shown that velocity measured at upstream vegetation section is always

Table 1
Uncertainty associated with ADV data.

	U	V	W	$\left(\overline{u'u'}\right)^{0.5}$	$\left(\overline{v'v'}\right)^{0.5}$	$\left(\overline{w'w'}\right)^{0.5}$
Standard deviation	4.34×10^{-3}	9.74×10^{-4}	4.24×10^{-4}	1.09×10^{-3}	9.04×10^{-4}	3.14×10^{-4}
Uncertainty%	0.30	0.07	0.03	0.06	0.07	0.03