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Original Research Paper

Study on the Pollutant Diffusion Regularity in Open Channel with Vegetation

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ABSTRACT

Instream vegetation not only affects the discharge capacity of the river but also plays an important role in the pollutants diffusion. So it is very important to study the pollutants diffusion in the open channels with vegetation. In order to experimentally investigate the effects of rigid vegetation on the characteristics of flow, the vegetation was modelled by a rigid cylindrical rod. The flow field is measured under the conditions of submerged rigid rod in a flume with single layer and double layer vegetation. Experiments were performed for various spacing of the rigid rods. The vegetation models were aligned with the approaching flow in a rectangular channel. Vertical distribution of pollutants was evaluated using image processing methods. The results indicate that the vegetation has a more stable effect on the spread of pollutants.

INTRODUCTION

Vegetation plays an important role in altering flow characteristics (such as velocity distribution, Reynolds, Manning coefficient) compared with non-vegetated conditions in rivers (Li 2014). Generally, the vertical velocity distribution is related directly to the bed shear stress for non-vegetation flow; while for vegetated flow, it's mainly decided by the vegetation drag, since the vegetation roughness is much larger than river bed roughness (Huai 2012). The influence mechanism of aquatic plants on flow is very complicated, which is not only dependent on the cross sectional shape of the river, water depth, discharge, but also on the species, bending rigidity, distribution, shape of vegetation and whether it is submerged (Wu 2011).

The mechanical effects of rivers with vegetation have been of primary interest for decades, because of their role in environmental fluid mechanics. A number of studies on the flow and turbulence characteristics through emergent vegetation are available (Fischer-Antz 2001, Leu 2008, Naot 1996). Flow phenomena become more complicated when the flow depth exceeds the height of vegetation. Laboratory studies on fully developed flows with submerged vegetation have demonstrated reduced velocities within the vegetation zone.

With respect to the role of water vegetation, the study of vegetation on the transport and diffusion of pollutants is relatively rare. Influence of plants on diffusion transport of pollutants is mainly in the following three aspects, (l) the physical blocking changes the motion path, (2) the uneven distribution of flow velocity causes convection, and (3) entrainment material on wake around plants. The influence study of vegetation on diffusion transport of pollutants helps to deepen the understanding of the turbulence problem itself and also it is important to have guiding role in water quality management and migration of contaminants.

Nepf et al. (1997a) established the diffusion model of a passive scalar in emergent vegetation conditions and they think that the macrophyte turbulence is mainly composed of the wake generated plant. This model can predict, the effect of wake on stable diffusion, better. But as it is difficult to determine the wake percentage as it has still limitations in practical application. In view of this, Nepf et al. (1997b) further studied the diffusion coefficient under different Reynolds number. Using the PIV flow visualization, a rigid diffusion trajectory of solid particles in submerged flow field is recorded. Fick diffusion analytical methods, the average method of the Euler equations and Lagrange methods are used for analysis and comparison. It is then found that the diffusion coefficient is close but not exactly the same, but there is no reasonable explanation on inconsistent trend yet. White and Nepf (2007) carried out two studies on diffusion mechanism of vegetation (wake vortex entrainment, uneven wake in the convection velocity field) through theoretical analysis and tracer substance experiment in a random arrangement of cylindrical group and its influencing factors. Poggi et al. (2006) studied the scalar transport using the vegetation flume experiment concluding that as long as appropriate turbulent energy dissipation rate is used, the standard Lagrangian dispersion model can

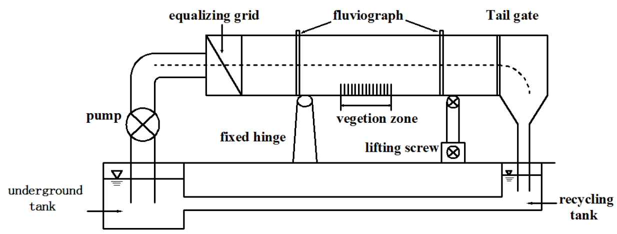

Fig. 1: The experimental re-circulating open-channel rectangle flume setup.

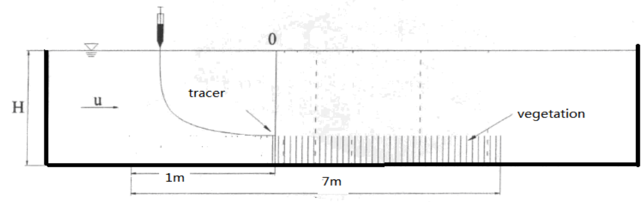

Fig. 2: The sketch of the experimental arrangement.

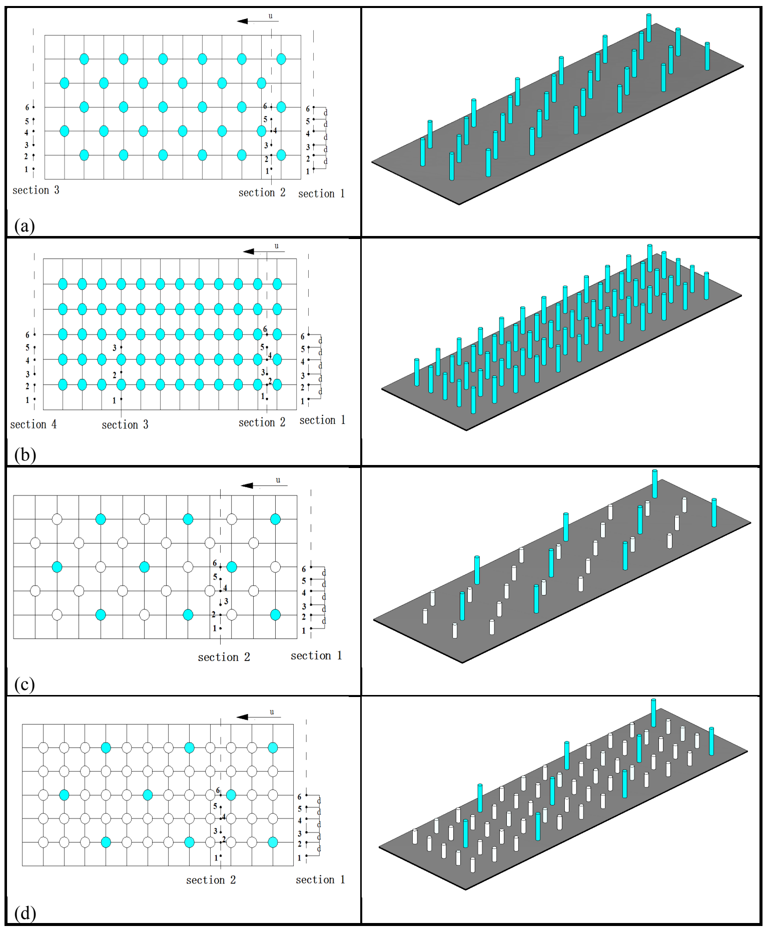

Fig. 3: Cylindrical rod configurations and measurement locations.

be used to simulate the scalar concentration. Ghisalberti et al. (2005) studied the transmission of substances under the submerged vegetation, and a two-zone model was proposed for longitudinal diffusion with submerged vegetation (Tanino 2008, 2009).

In this paper, a series of laboratory experiments were performed to investigate the connection between submerged vegetation and the key geomorphology around the vegetation. The submerged vegetation was modelled as bundled plastic fibres with a variation in vegetation density. The objective of this work is to describe the detailed characteristics of flow and pollutant distribution through a simulated array of rigid vegetation by examining its effects on the velocity and pollutant distribution, as well as, observing the influence of vegetation density and heights. Measurements of velocity and pollutant distribution are taken along the vertical at the locations with vegetation sections, to adequately represent the conditions everywhere within

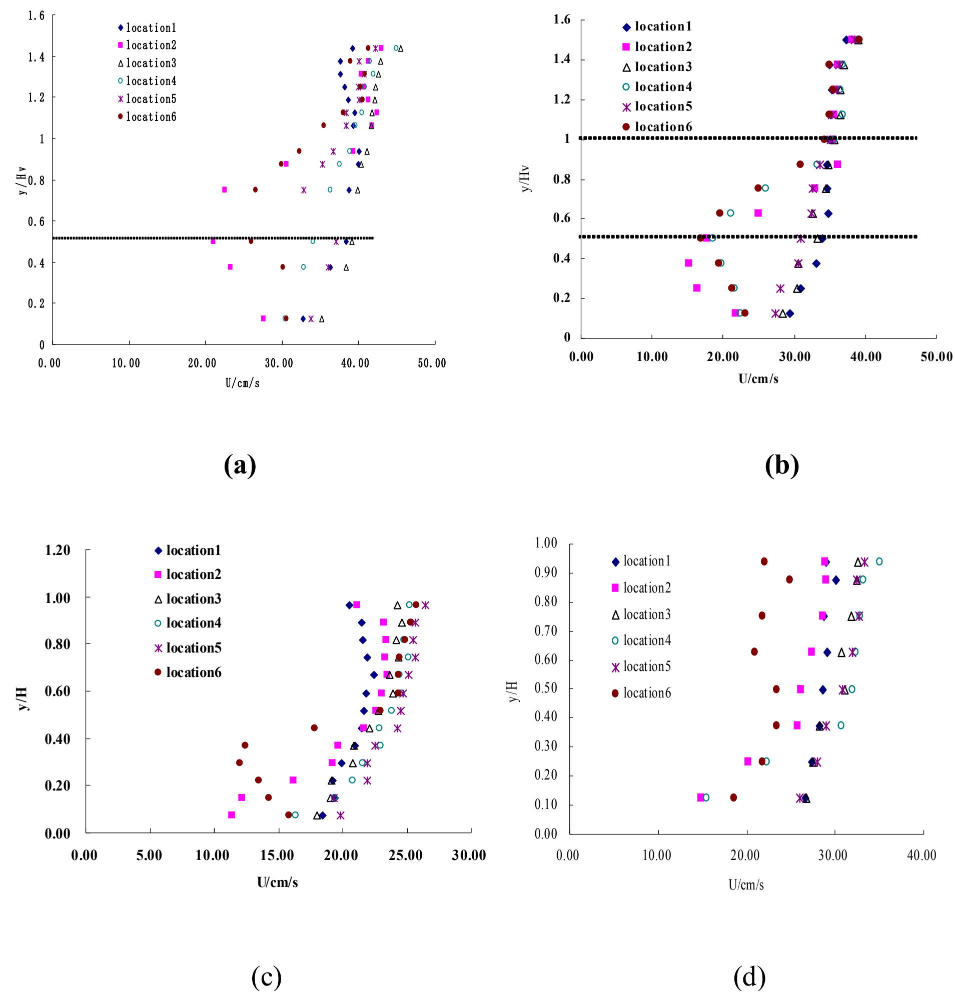

Fig. 4: Velocity profiles of vegetation (section 2) in the configuration a ,b, c, d.

the flow and to capture the flow response as it moves through the vegetation array. The experiments include single layer and double layer experiments of which the results are compared.

EXPERIMENTAL CONDITIONS

The experimental system (Fig. 1) is composed of two pumps to force-water through the system and maintaining recirculation, an inlet section with turning valves at the upstream end to control the flow discharge and generate fully developed turbulent flow, and an outlet section with a triangular adjustable weir at the downstream end to control the water level.

The flume was 7.0 m long, 0.5 m wide and 0.8 m high with glass-side walls and a concrete bottom, so that the interactions between the vegetation and flow could be observed clearly. The water levels were constant at the same flow rate. The vertical velocities of fully developed flow with rigid vegetation were measured.

Fig. 2 is the sketch of the experimental arrangement. Since measuring the tracer concentration is to uptake the tracer substance in the concentration tank side, the image brightness has reflected the concentration of the tracer substance, and therefore the experimental data reflect the average of the transverse cross-section.

The height of the rigid rod used in the arrangement (a) and (b) was 8 mm, and the height in the arrangement (c) and (d) was 4 mm and 8 mm arranged in staggered configuration (Fig. 3). These experiments focused on the effects of density and height of rigid rod on the flow velocity. Measurement location, shown in Fig. 3, was chosen as the downstream and upstream of rigid rod. Flow characteristics were measured at three sections, numbered sections 1 to 3 in Fig. 2. Sections 1 and 3, located outside of the vegetation area,

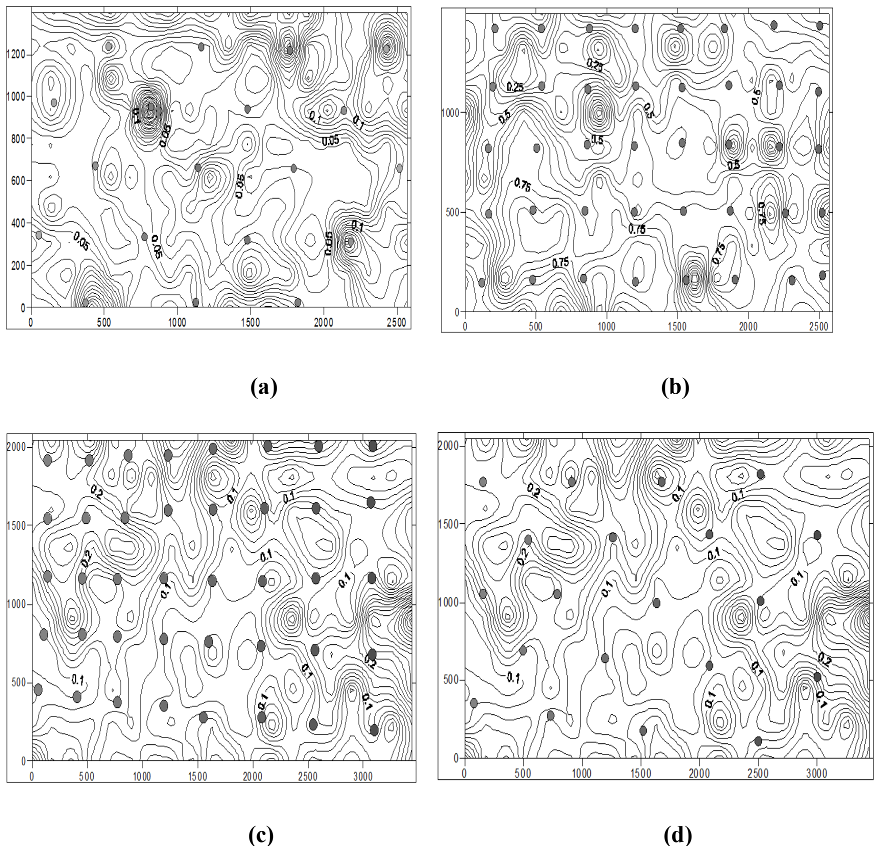

Fig. 5: Horizontal pollutant distribution under different cylindrical rod configurations.

were intended for studying the effect of rising and lowering of water level on flow characteristics. Section 2 was intended for investigating the influence of rigid cyclical rod on the flow characteristics. At each section, velocity was measured at six points starting from the bottom of the bed to the water surface. However, due to ADV limitations and flume channel structure, the ADV sensor suspended at 5 cm above the flume bed, still measures the flow characteristics at the nearest bed. The measurement was done at 0.5 cm increments from the bed towards the free water surface.

RESULTS AND DISCUSSION

Velocity profile: As seen from Fig. 4(a), in the vegetation region at the back of the rigid rod, the velocity is slower (location 2 and location 6) with the slowest velocities approximately at $y/H_v = 0.5$. This is similar to the velocity profile immediately behind a dowel for submerged vegetation flow shown at location 2 and location 6 in Fig. 4(a) and those of other researchers (Shimizu & Tsujimoto 1994, Lopez & Garcia 2001, Righetti & Armanini 2002).

As seen from Fig. 4(b) in the vegetation region, at the back of the rigid rod, the velocity is slower (location 2, location 4 and location 6) with the slowest velocities approximately at $y / H_v = 0.5$, and the shape of the velocity is 'S'. While in the upstream and the downstream, the velocity complies with the semi-logarithmic formula.

Velocity profiles with the short rigid rod submerged in double layer flows are shown in Fig. 4(c) and Fig. 4(d). The fastest velocities are in the lower free stream region (location 4) and the slowest velocities are in the region immediately downstream of the tall rigid rod (location 6). The velocities just beside the rigid rod (locations 1, 3, and 5) are approximately midway between the fastest and slowest velocities.

Horizontal distribution of pollutants: As seen from Fig. 5, due to the flow around the cylindrical rod, the concentration on both the sides of the rod is larger. It can be explained from the following aspects: One is the flow field and the other is pressure distribution.

1. Cylinder constraints the water flow, to make the flow velocity between the cylinders greater than the flow velocity in other location. Water flow will be hampered

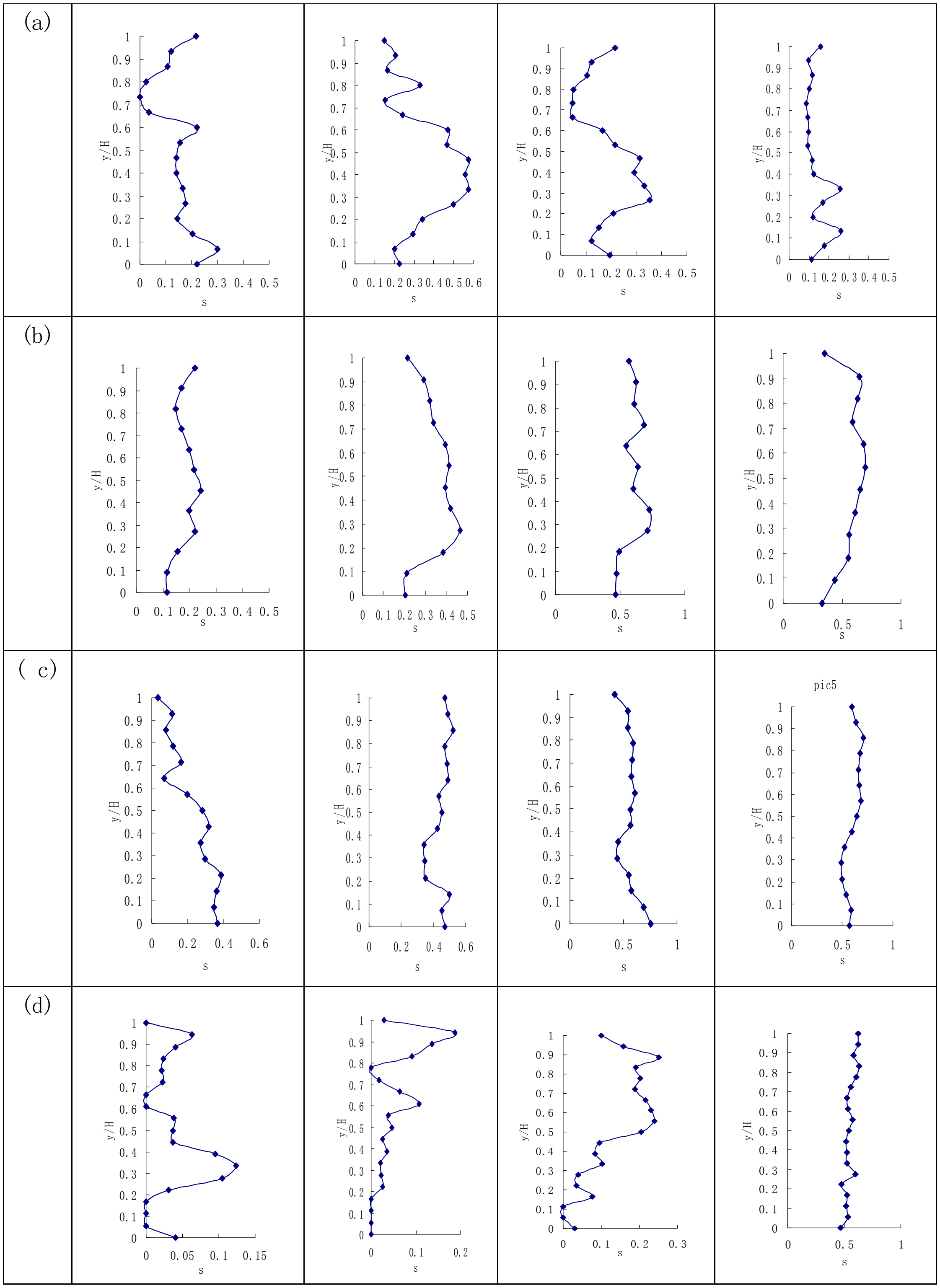

Fig. 6: Pollutant distribution under different cylindrical rod configurations.

in front of the cylinder; some water directly flows to the front cylinder due to which the velocity drops to a minimum before reaching the cylindrical rod. While some water flows around the rod, hence the flow velocity is the largest on the side of the cylinder, and then the fluid and cylinder are separated. The concentration of the pollutants is the largest.

2. Hydrostatic pressure of cylinder suffered from the water flow decreases along the cylinder to both sides and water back in turn. Dynamic water pressure value on both sides of the cylinder is greater than the cylinder while at the back surface is minimum, which is conformited with the surrounding cylinder velocity distribution.

Vertical pollutant distribution: It can be seen from Fig. 6 that the location of the maximum value of pollutant concentration under the influence of vegetation has a trend to move to the bottom. This is because, the existence of the vegetation can change the flow pattern, reduce the vegetation layer flow velocity and thus stranded the substances in the water.

The pollutants can quickly reach the state of vertical mixing within a short time, because the existence of vegetation can enhance the flow turbulence, increase the vertical diffusion of pollutants, so as to shorten the channels of vegetation vertical mixing of pollutants (Fig. 6). Hence, it can be inferred that vegetation can complete the initial dilution process faster under the action of pollutants within the channel, which can reduce the concentration of the pollutants in downstream, and effectively control the downstream water body pollution.

CONCLUSIONS

In this paper, flows and pollutants through double layer vegetation and single layer vegetation are simulated in flume. The flows in double layer vegetation are more complex than the single layer case. Some conclusions can be drawn as follows:

1. The existence of submerged plants increases the flow gradient, and the roughness of the bed surface become larger, which plays the role of spoiler. This becomes more obvious with the increasing plant density.
2. With the increasing of plant density, backwater phenomenon exists and is significant. But with the increase in water depth, this phenomenon is weakened. Therefore, in calculation of flow over the river containing plant, one must consider the impact of plant resistance.
3. Turbulence effects of water flow are enhanced under the action of submerged vegetation, increasing the vertical diffusion of pollutants, which can make the vertical concentration distribution of the pollutant even faster, shorten the vertical mixing of pollutants and speed up the initial dilution process of pollutants. This can effectively control the pollution to the downstream.

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