

## Chapter 19

# Nature of Bursting Events over a Rigid Bed with Emergent Vegetation



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**Abstract** The turbulent flow parameters and Reynolds stress analysis in flow over the smooth rigid bed with the emergent rigid vegetation in a straight channel have been investigated in this study. Higher-order turbulence parameters such as quadrant and octant analysis have been performed in the present study. Quadrant analysis shows that in the non-vegetation zone, sweep and ejection events have more dominant. In the vegetation zone, sweep and ejection have significant contributions as well as inward interaction event. Probability distribution shows that in the vegetation zone  $P_{(3,0)}$  and  $P_{(2,0)}$  have the least value, and in the vegetation zone,  $P_{(1,0)}$  has the maximum value. Occurrence of probability analysis will show the contribution of the different classes of events in the three-dimensional bursting phenomena. This paper investigated three-dimensional octant analysis used to clarify the function of bursting events in the particle entrainment process. The outcomes of this study provide an important and detailed view of turbulent flow structures in vegetation and non-vegetation zone in an open channel flow.

**Keywords** Rigid vegetation · Bursting event · Octant analysis · Probability distribution · Quadrant analysis

## 19.1 Introduction

Aquatic plants have a significant impact on nutrient transport, flow patterns, and turbulence in rivers and canals, as well as on aesthetics, ecological restoration, and flood management (Tsujiimoto 1999; Wang et al. 2021). In addition to create a habitat for aquatic life, vegetation also strengthens banks; reduces bank erosion, turbidity, and floods; and penetrates pollutants (Bennett et al. 2002; Gupta et al. 2023). One factor that alters the average and turbulent flow behavior of a channel is the presence of vegetation (Nepf 2012). The effect of vegetation on flow is

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influenced by both the characteristics of the channel and the vegetation. Many studies have been conducted in the past on numerical methods for experiments utilizing real or artificial vegetation in flumes (Järvelä 2002; Meijer and Van Velzen 1999; Righetti and Armanini 2002; Khan et al. 2022). In main channels, floodplains, and wetland water basins, vegetation like grasses, bushes, and mangroves often grows. They enhance shear stress at the channel bed and raise hydraulic resistance to water flow. As a result, the open channel's conveyance capacity of the channel will be reduced. Additionally, the potential for sediment containment and deposition will be enhanced. Vegetation in coastal and riverine areas is crucial for sediment movement as well as ecosystem regulation. Vegetation in rivers is crucial to the ecosystem's restoration. Whether they are ecological, morphological, hydrological, or water quality factors, restoration must take into account several functions (Brookes et al. 1996; Aamir et al. 2022).

In rivers and open channels, vegetation increases the hydraulic resistance to the flow, causing an increase in flow depth and a decrease in flow velocity. As a result, vegetation is crucial for riverbank stability and energy loss during feeding occasions. The features of turbulence and vegetation cover affect sediment transport. In some areas along the river, there is frequent vegetation at various heights. Depending on the flow conditions, some vegetation may be emergent or submerged. As a result of momentum transfer between various vegetation layers, this results in complex flow dynamics (Luhar et al. 2008; Pasha and Tanaka 2016; Pasha et al. 2018; Chembolu et al. 2019; Chatelain and Proust 2021; Sohrabi et al. 2022).

River flood risk and environmental management presently focus on how riparian vegetation affects biological and flow processes in channels. Prior research mainly examined and simulated vegetation that was uniform in height while submerged or emerging, which is contrary to the behavior of real river and floodplain systems. Conversely, there are several plant heights that simultaneously experience emergent and submerged environments. Consequently, an important scientific method for assessing the impact of vegetation in open channel flows would be properly studied on the hydrodynamics of vegetated flow in open channels under more realistic circumstances (Tsujimoto and Kitamura 1990; Nepf 1999; Carollo et al. 2002; Nezu and Sanjou 2008; Fathi-Moghadam et al. 2011).

Only few literatures focused on the comparison of higher-order turbulence and Reynolds stress with vegetation and non-vegetation condition for open channel flow. In this present study, the data has been taken from previous literature (Kumar and Sharma 2022) and is therefore devoted for analyzing the higher-order turbulent parameters and Reynolds stress in a straight open channel with the presence of emerged rigid vegetation and non-vegetation condition. In this paper, higher-order turbulence flow parameter such as based on velocity fluctuation quadrant analysis, the probability distribution for the four types of quadrant and octant probability analysis has been analyzed for vegetation ( $S_1$ ,  $S_2$ ) and non-vegetation zone ( $S_0$ ). The occurrence of probability for octant analysis has been investigated for vegetation and non-vegetation zone.

## 19.2 Experimental Setup and Methodology

The experiment was conducted in a 13 m long, 0.9 m wide, and 0.7 m deep recirculating straight rectangular channel. The channel sidewalls were made of glass, and the channel bed was constructed with concrete with a bed slope ( $S_0$ ) of 0.002. Steel is used for the channel sidewalls, and an overhead tank was positioned upstream of the test channel to transport the water, and it is useful to maintain the flow under stable head circumstances. In this study, water is extracted from a storage tank that stores water in an intake tank using centrifugal pumps. Fig. 19.1. shows the plan view of vegetation arrangement and experimental setup in the laboratory. In this experiment, 3D velocity data has been taken by SonTek 16 MHz acoustic Doppler velocimeter (ADV). For detailed information on experimental setup and procedure, refer literature by Kumar and Sharma (2022).

In this experiment, three sections ( $S_0, S_1, S_2$ ) have been taken for analysis.  $S_0$  is the non-vegetation zone, that is, 30 cm before the upstream vegetation. Both ( $S_1, S_2$ ) sections are in the vegetation zone, that is, 387 cm and 603 cm from the upstream vegetation, respectively.

## 19.3 Result and Discussion

### 19.3.1 Quadrant Analysis

Quadrant analysis is a very important parameter in analyzing fluid dynamics. The determination of quadrant analysis is based on the relative sign of velocity fluctuation. In this analysis, four quadrants will show the different bursting events. The bursting events are defined by four quadrants such as outward interactions ( $i = 1, u' > 0, w' > 0$ ), ejections ( $i = 2, u' < 0, w' > 0$ ), inward interactions ( $i = 3, u' < 0, w' < 0$ ), and sweeps ( $i = 4, u' > 0, w' < 0$ ). This analysis has been done at  $Z/Y \sim 0.1$  ( $Z =$  height from bed and  $Y =$  total depth of flow) at three different points in the channel. Fig. 19.1 shows the quadrant analysis at  $Z/Y \sim 0.1$ , where horizontal and vertical coordinates represent velocity fluctuation in the longitudinal and vertical direction, respectively. In the non-vegetation zone shown in Fig. 19.2a, the ejection

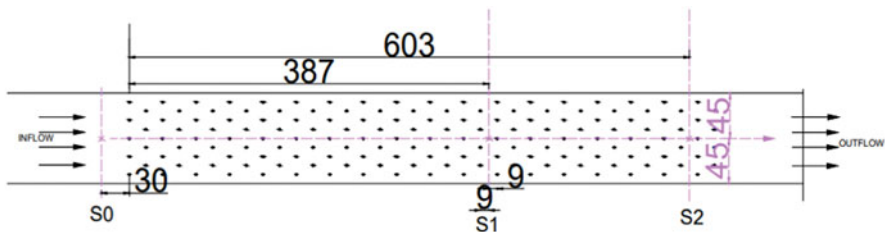
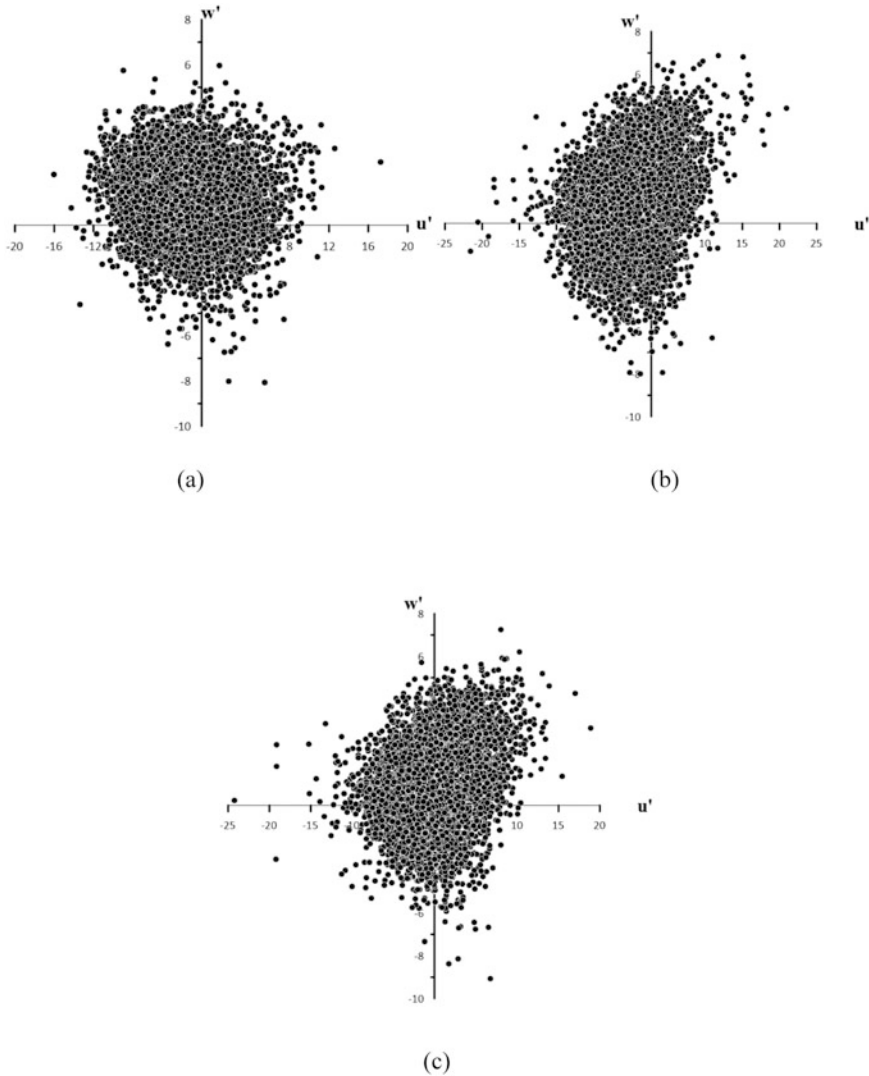


Fig. 19.1 Plan view and test section of experimental setup



**Fig. 19.2** Quadrant analysis at  $Z/Y \sim 0.1$  in flows subjected to (a) non-vegetation ( $S_0$ ) and (b, c) vegetation zone ( $S_1, S_2$ )

event is more dominant than other events. The least contribution is from the sweep and outward interaction. The contribution of ejection and inward interaction is 60–70%. The contribution of sweep and outward interaction is 20–30%.

Figure 19.2b shows the velocity fluctuation at the center of the vegetation zone. The ejection event is more dominant than other events. The least contribution is from the sweep event. The contribution of ejection is 70–80%. The contribution of inward and outward interaction is 30–20%. While flow is going through rigid vegetation

toward downstream, velocity fluctuation is less. The contribution of velocity fluctuation at the downstream vegetation end is shown in Fig. 19.2c. The sweep and ejection events are more dominant than other events. The least contribution is from the inward interaction event. The contribution of sweep and ejection is 50–70%. The contribution of inward and outward interaction is 40–30. Sweep and ejection event has more dominance in the non-vegetation zone ( $S_0$ ), while in the vegetation zone ( $S_1, S_2$ ), ejection and inward interaction have more contribution.

### 19.3.2 Probability Distribution

The probability  $P_{i,H}$  of the occurrence of the bursting events can be obtained from Eq. 19.1 (Sharma and Kumar 2017):

$$P_{i,H} = \frac{\int_{t=0}^{t=T} I_{i,H} dt}{\int_{t=0}^{t=T} [I_{1,H} + I_{2,H} + I_{3,H} + I_{4,H}] dt} \tag{19.1}$$

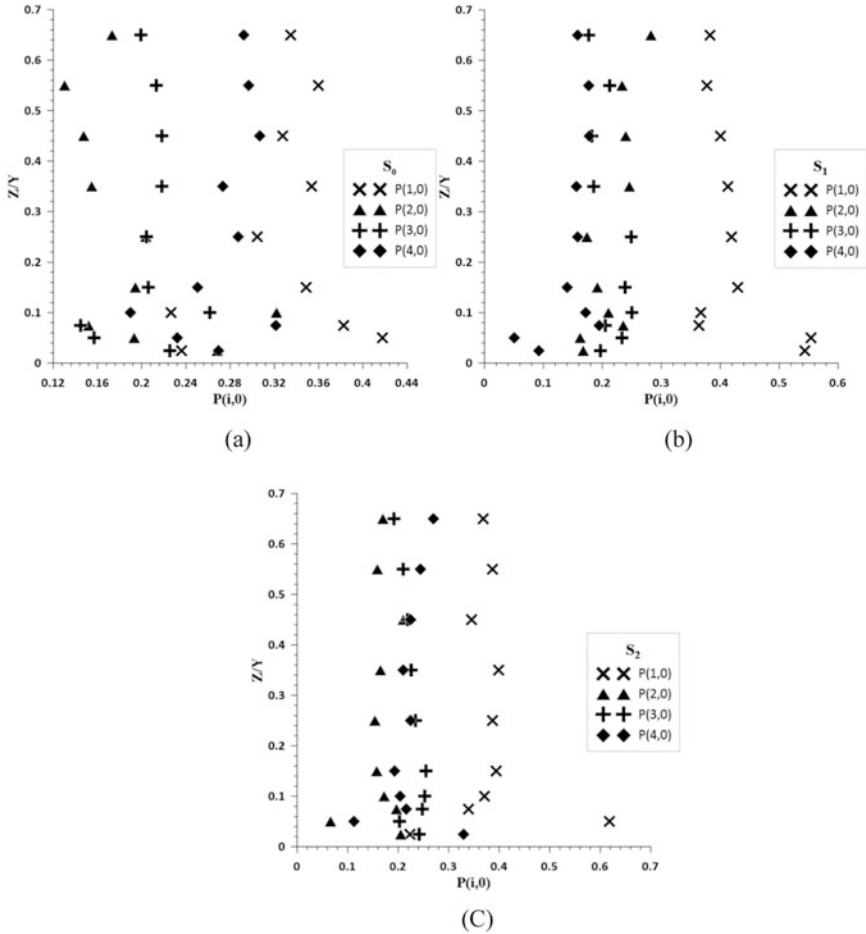
$$I_{i,H}[u'(t)w'(t)] = \begin{cases} 1, & \text{if } (u'w') \text{ is in quadrant } i \text{ and if} \\ |u'w'| = H(u'^2)^{0.5} (w'^2)^{0.5} & \\ 0, & \text{otherwise} \end{cases} \tag{19.2}$$

where  $I_{i,H}$  is an indicator function described by the Eq. 19.2 The vertical variations of  $P_{i,H}$  in flows subjected to non-vegetation zone, center of vegetation zone, and end of vegetation zone are plotted in Fig. 19.3.

In the non-vegetation zone,  $P_{(1,0)}$  and  $P_{(4,0)}$  are having higher probabilities as compared to the  $P_{(3,0)}$  and  $P_{(2,0)}$ . At the center of the vegetation ( $S_1$ ), the probability  $P_{(4,0)}$  has the least value as compared to other quadrant probabilities. At the end of the vegetation zone ( $S_2$ ),  $P_{(2,0)}$  has the least value of probability, and  $P_{(1,0)}$  has maximum probability.

### 19.3.3 Octant Analysis

The research by Keshavarzi and Gheisi (2006) also demonstrated that when there is fully three-dimensional flow in nature, two-dimensional analysis of bursting analysis cannot identify the entrainment process. They created a three-dimensional octant analysis technique to take into account for a secondary flow’s impact. The aforementioned method was utilized in this study to analyze experimentally recorded velocity data in order to evaluate the coherent turbulent flow structure around bridge pier.



**Fig. 19.3** Vertical profiles of  $P_{i,H}$  in flows subjected to (a) non-vegetation ( $S_0$ ) and (b, c) vegetation zone ( $S_1, S_2$ )

The classifications of bursting events were performed based on the sign of the velocity fluctuations in three dimensions that can be obtained from Eq. 19.3, and eight different events are described below:

$$u' = u_i - \bar{u}, v' = v_i - \bar{v}, w' = w_i - \bar{w} \tag{19.3}$$

1. Internal outward interaction or Class I-A ( $u' > 0, w' > 0, v' > 0$ );
2. Internal ejection or Class II-A ( $u' < 0, w' > 0, v' < 0$ );
3. Internal inward interaction or Class III-A ( $u' < 0, w' < 0, v' < 0$ );
4. Internal sweep or Class IV-A ( $u' > 0, w' < 0, v' > 0$ );
5. External outward interaction or Class I-B ( $u' > 0, w' > 0, v' < 0$ );

6. External ejection or Class II-B ( $u' < 0, w' > 0, v' > 0$ );
7. External inward interaction or Class III-B ( $u' < 0, w' < 0, v' > 0$ );
8. External sweep or Class IV-B ( $u' > 0, w' < 0, v' < 0$ );

Based on the three velocity fluctuations, the time fraction or occurrence probability of the eight orthogonal zones was calculated. To determine an event's likelihood of occurring given the sediment entrainment function, the time fraction of each event must be known. The following equation was presented by Keshavarzi and Gheisi (2006) to calculate the likelihood of occurrence for each event.

$$P_k = \frac{n_k}{N} \quad (19.4)$$

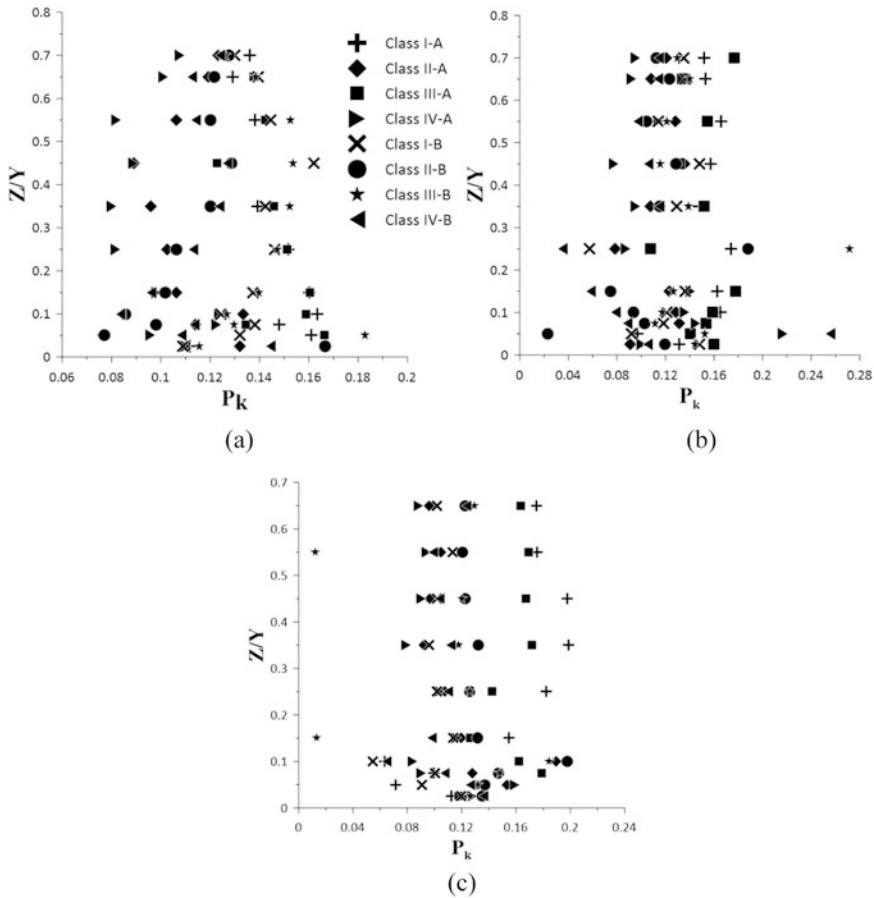
$$N = \sum_{k=1}^8 n_k \quad k = 1, 2, 3, 4, \dots, 8 \quad (19.5)$$

$P_k$  is the occurrence probability of each bursting event, which can be determined by Eqs. 19.4 and 19.5;  $n_k$  is the number of events in each class; and  $N$  is the total number of bursting events. Using the above equations, the occurrence probabilities for the eight different bursting events were computed for vegetation ( $S_1, S_2$ ) and non-vegetation zone ( $S_0$ ) shown in Fig. 19.4.

The occurrence of probability in octant analysis in eight classes shows the non-vegetation zone, in Fig. 19.4a at  $z/y \sim (0.3 \text{ to } 0.4)$ , and maximum probability of occurrence is for Class I-A and least value of probability of occurrence for Class IV-A. At the center of vegetation zone ( $S_1$ ), Class III-A and Class I-A have maximum probability, while at the bed surface  $Z/Y < 0.1$ , Class II-B and Class IV-B have minimum probability shown in Fig. 19.4b. Fig. 19.4c shows the occurrence of probability toward the downstream of the vegetation zone ( $S_2$ ) at the flow depth  $z/y > 0.1$  Class IV-A has minimum probability.

## 19.4 Discussion

A series of quasicyclic events that take place in the wall region of turbulent flows make up the bursting process. Approximately 70% of turbulence production happens during this procedure. The most significant process in wall-bounded turbulent shear flow is considered to be bursting. To have a more thorough understanding of the dynamics of the turbulent transport process, it is essential to understand bursting phenomenon. Reynolds shear stress transport can be observed in quadrant analysis. It has been observed that sweep and ejection have more contribution in the non-vegetation zone while in the vegetation zone ejection and inward have more contribution. Probability distribution will show the occurrence of the bursting events in the flow. Probability analysis has been done for hole region ( $H = 0$ ).  $P_{(1,0)}$  has maximum value in the vegetation and non-vegetation zone.  $P_{(2,0)}$  and  $P_{(4,0)}$  have



**Fig. 19.4** Vertical profiles of the occurrence of probability for different bursting events (a) Non-vegetation ( $S_0$ ) and (b, c) vegetation zone ( $S_1, S_2$ )

least value in the vegetation zone. Octant analysis shows the occurrence of probability for eight classes. Class I-A and Class III-A have maximum probability in the vegetation and non-vegetation zone. Class IV-B and Class II-B have minimum probability in the vegetation and non-vegetation zone.

### 19.5 Conclusion

An experimental investigation was conducted to examine changes in the turbulent flow characteristics caused by the application of vegetation and non-vegetation over a rigid bed with emergent rigid vegetation. In this paper, quadrant analysis shows the bursting event such as sweep and ejection has more contribution in the



non-vegetation zone. In the vegetation zone, sweep event reduces, and inward interactions have more contribution. Probability analysis shows the occurrence of bursting event. It shows  $P_{(2,0)}$  and  $P_{(4,0)}$  have more value in the vegetation zone as compared to the non-vegetation zone that shows the Reynolds shear stress transport by the sweep and ejection event. The probability occurrence of octant analysis shows the maximum value for Class I-A in the non-vegetation zone and at the center of the vegetation zone, while at the end of the vegetation zone, Class II-B has maximum probability. The minimum occurrence of probability for non-vegetation zone is Class IV-A, and the center of the vegetation has also similar effect, while at end of the vegetation zone, Class II-B and Class IV-B have least probability of occurrence at the bed surface.

## 19.6 Future Scope

In this study, analysis has been done for rigid bed with emergent rigid vegetation. In future research, detail analysis of turbulent flow characteristics can be done for flexible vegetation, and validation of the experimental results can be performed in Ansys Fluent and Flow3D.

## References

- Aamir M, Ahmad Z, Pandey M, Khan MA, Aldrees A, Mohamed A (2022) The effect of rough rigid apron on scour downstream of sluice gates. *Water* 14(14):2223. <https://doi.org/10.3390/w14142223>
- Bennett SJ, Pirim T, Barkdoll BD (2002) Using simulated emergent vegetation to alter stream flow direction within a straight experimental channel. *Geomorphology* 44(1–2):115–126
- Brookes A, Shields FD Jr, Brookes A, Shields FD Jr (1996) Perspectives on river channel restoration. In: *River Channel Restoration*. Wiley, Hoboken, NJ, pp 1–19
- Carollo FG, Ferro VITO, Termini D (2002) Flow velocity measurements in vegetated channels. *J Hydraul Eng* 128(7):664–673
- Chatelain M, Proust S (2021) Open-channel flow through emergent rigid vegetation: effects of bed roughness and shallowness on the flow structure and surface waves. *Phys Fluids*. <https://doi.org/10.1063/5.0063288>
- Chembolu V, Kakati R, Subashisa Dutta S (2019) A laboratory study of flow characteristics in natural heterogeneous vegetation patches under submerged conditions. *Adv Water Resour* 133: 103418
- Fathi-Moghadam M, Arman A, Emamgholizadeh S, Alikhani A (2011) Settling properties of cohesive sediments in lakes and reservoirs. *J Waterw Port Coast Ocean Eng* 137(4):204–209
- Gupta LK, Pandey M, Raj PA, Shukla AK (2023) Fine sediment intrusion and its consequences for river ecosystems: a review. *J Hazard Toxic Radioact Waste*. 27(1):04022036. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000729](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000729)
- Järvelä J (2002) Flow resistance of flexible and stiff vegetation: a flume study with natural plants. *J Hydrol* 269(1–2):44–54
- Keshavarzi AR, Gheisi AR (2006) Stochastic nature of three dimensional bursting events and sediment entrainment in vortex chamber. *Stoch Env Res Risk A* 21:75–87

- Khan MA, Sharma N, Pu JH, Pandey M, Azamathulla H (2022) Experimental observation of turbulent structure at region surrounding the mid-channel braid bar. *Marine Georesour Geotechnol* 40(4):448–461. <https://doi.org/10.1080/1064119X.2021.1906366>
- Kumar P, Sharma A (2022) Experimental investigation of 3D flow properties around emergent rigid vegetation. *Ecohydrology* 15(8):e2474
- Luhar M, Rominger J, Nepf HM (2008) Interaction between flow, transport and vegetation spatial structure. *Environ Fluid Mech* 8:423–439
- Meijer DG, Van Velzen EH (1999) Prototype-scale flume experiments on hydraulic roughness of submerged vegetation. In 28th International Conference, Int. Assoc. of Hydraul. Eng. and Res., Graz, Austria
- Nepf HM (1999) Drag, turbulence, and diffusion in flow through emergent vegetation. *Water Resour Res* 35(2):479–489
- Nepf HM (2012) Flow and transport in regions with aquatic vegetation. *Annu Rev Fluid Mech* 44:123–142
- Nezu I, Sanjou M (2008) Turbulence structure and coherent motion in vegetated canopy open-channel flows. *J Hydro Environ Res* 2(2):62–90
- Pasha GA, Tanaka N (2016) Effectiveness of finite length inland forest in trapping tsunami-borne wood debris. *J Earthq Tsunami* 10(4):1650008
- Pasha GA, Tanaka N, Yagisawa J, Achmad FN (2018) Tsunami mitigation by a combination of coastal vegetation and a backward-facing step. *Coast Eng J* 60:104–125
- Righetti M, Armanini A (2002) Flow resistance in open channel flows with sparsely distributed bushes. *J Hydrol* 269(1–2):55–64
- Sharma A, Kumar B (2017) Structure of turbulence over non-uniform sand bed channel with downward seepage. *Eur J Mech B/Fluids* 65:530–551
- Sohrabi S, Afzalimehr H, Singh VP (2022) Estimation of drag coefficient of emergent and submerged vegetation patches with various densities and arrangements in open channel flow. *ISH J Hydraul Eng*. <https://doi.org/10.1080/09715010.2022.2066482>
- Tsujimoto T (1999) Fluvial processes in streams with vegetation. *J Hydraul Res* 37(6):789–803
- Tsujimoto T, Kitamura T (1990) Velocity profile of flow in vegetated-bed channels. *KHL Progressive Report*. 1:43e55
- Wang J, Liu X, Min F, Dai J, Jiang X (2021) Turbulence structure and longitudinal velocity distribution of open channel flows with reedy emergent vegetation. *Ecohydrology* 15(1):e2352