EFFECT OF SHEET LAYER ON THE FLOW CHARACTERISTICS IN AN ALLUVIAL CHANNEL

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ABSTRACT

An experimental study has been done to observe changes in the turbulence characteristics of flow in the presence of a sheet layer in an alluvial channel composed of a non-uniform sediment mixture. The sheet flow layer is a thin layer having few centimeter thickness comprised of moving sediment particles and suggested that the bed remains plane under sheet flow conditions and becomes independent of other bed topography features. Instantaneous velocity measurements were taken at the centre line of sheet flow layer by the Acoustic Doppler Velocimeter (ADV). The present study addresses on the flow zone in the vicinity of the bed surface. The turbulent events, such as stream wise velocity, Reynolds shear stresses, and turbulence intensities were found to be increasing and vertical velocity was found decreasing with a sheet layer. The presence of a sheet layer also affects the turbulent energy production and energy dissipation which influenced higher turbulence production and a lower TKE dissipation rate.

Keywords: Alluvial channel, Non-uniform sand, Sheet layer, Turbulence

1. INTRODUCTION

The hydrodynamics of sediment transport in alluvial channel is of crucial significance in predicting the elevation of the bed profile. The mode of sediment transport is generally in the form of saltation and changes to sheet flow, when main flow is sufficient to fully transport sediment (Bagnold, 1966). Because of the difference between tractive force and resistive force in a sand bed channel, movement of a large quantity of sediment forms a sheet layer (Gotoh & Sakai, 1997). Based on laboratory and field data, various researchers (Dingler & Inman, 1976; Conley & Inman, 1992) observed that the sheet flow layer is a thin layer having few centimeter thickness comprised of moving sediment particles and suggested that the bed remains plane under sheet flow conditions and becomes independent of other bed topography features. Based on field observations, Inman et al. (1986) found a substantial increase in the sheet flow layer thickness corresponds to the occurrence of turbulent bursting close to the point of maximum velocity.The sediment particles interaction or the interaction between the sediment particle and water in the layer of sheet flow caused high energy dissipation which may be responsible for the increase in the roughness height (Camenen et al., 2006). Jenkins and Hanes (1998) observed that the sheet flow layer affects the hydraulic flow properties in an alluvial channel.

Riverbeds are generally composed of non-uniform sediment mixtures and the corresponding grain size distribution of transported sediment is generally finer than the distribution of bed material because of selective transport (Sharma and Kumar, 2017). Flume experiments were done for non-uniform sediment to find the sediment transport rate of individual fractions of the sediment mixture (Misri et al., 1984; Samaga et al., 1986). Ghoshal (2005) and Mazumder et al. (2005) did a series of experiments in a channel and studied the influence of bed roughness on the suspension of sediment in sand–gravel mixtures. Yang et al. (2009) developed an empirical formula for the angle of repose of non-uniform sediment which is stochastically related to the size and gradation of bed materials. Wu et al. (2010) has established formulas for calculating the fractional transport rates of non-uniform bed load and suspended load iahd tested by using a large number of laboratory and field data of both uniform and non-uniform sediment transport.. Mohtar et al. (2016) did a series of field experiments to investigate the best representative grain size for the prediction of bed load transport and observed that the median grain size is suitable for the computation of bed load transport in a channel with a sediment mixture.

Considering the importance of the non-uniform sediment mixture, the current study introduces this parameter in the study of flow characteristics over a sheet layer movement. Although, there has been earlier research on sheet flow interaction, the flow structure in the occurrence of a sheet flow layer subjected to a non-uniform sand bed channel are still unexplored. In order to evaluate the effect of sheet layer, the current study emphasizes the effect of sheet layer on the flow velocity profile, Reynolds shear stress, turbulence intensities, and energy dissipation through a series of experiments done over a non-uniform sand bed channel.

2. EXPERIMENTAL SETUP AND PROGRAM

Experiments were done in a 17.24 m long, 1 m wide, and 0.72 m deep rectangular flume with an adjustable bed slope. Flow in the channel was straightened before entering the main channel by a 2.8 m long, 1.5 m wide, and 1.5 m deep tank placed at the upstream end of the flume. The length of the flume (17.24 m) is large enough to attain a fully established flow condition at the test section which is 5 m long in the streamwise direction. The test section was considered from downstream 5 m to 10 m to ensure the measurements are free from any upstream or downstream disturbance. A tail gate was used to control the flow depth in the channel. A rectangular notch with coefficient of discharge (C_d) of 0.82 was evaluated at the downstream collection tank to measure the main channel discharge. The flow depth in the channel was measured with a digital point gauge attached to a moving trolley. The water surface slope was measured by using a pitot tube connected to a digital manometer, which was assembled on a moving trolley. The bed slope of the flume was measured with the help of a total station. Further details about the basic experimental setup can be obtained in Sharma and Kumar (2016a, 2016b).

The features of the sediment mixture and flow parameters used in the current study are listed in Table 1. In Table 1, d_{50} is the median size of sediment, M = Kramer's uniform coefficient of sediment mixture, σ_g = the geometric standard deviation of sediment mixture.In the experimental run, discharge is introduced to the channel by gradually opening a valve located at the overhead tank until the required discharge, Q, and corresponding flow depth, h, are measured.

Table 1 Details of sediment mixture and flow parameters used in experiments

Sand size d_{50} (mm)	Standard Deviation σ_g	Kramers Coefficient M	Flow depth h m	Discharge, Q m^3/s
0.50	1.65	0.16	0.117	0.0488

In order to investigate the effect of the sheet layer on the turbulence structure of the flow, a four-beam downlooking acoustic Doppler velocimeter (ADV) probe, named Nortek® Vectrino, was used to measure the instantaneous velocity components at a point. A sampling rate of 100 Hz was used for the data acquisition. It worked with an acoustic frequency of 10 MHz having an adjustable cylindrical sampling volume of 6 mm diameter and 1–4 mm height. The sampling length in the near-boundary flow was set with a lowest height of 1 mm. The measuring location was 5 cm below the probe. Hence, the flow field 5 cm below the free surface could not be measured. A sampling time of 300 s was found to be sufficient to achieve the statistically time-independent time-averaged velocity. In all the experiments, the signal to noise ratio was kept at 15 or above and a signal correlation between received and transmitted signals of 70% was recommended as the cut-off value. Very near to the bed, slight deviation (±5%) in the correlation was observed (Sharma and Kumar, 2017b; Sharma and Kumar, 2018a; Sharma and Kumar, 2018b). The data measured by the ADV contained spikes, therefore, a spike removal algorithm based on the acceleration threshold method is used to filter the data (Goring & Nikora, 2002). The threshold value was maintained between 1 to 1.5 based on trial and error (Sharma and Kumar, 2017a) so that velocity power spectra should acceptably fit the Kolmogorov "-5/3 scaling law" in the inertial sub range (Lacey & Roy, 2008). Velocity power spectra, $F_{uu}(f)$, at $z = 0.01$ m is shown in the Figure 1 where, f is frequency and z is flow depth. It is observed from Fig. 3 that velocity power spectra for filtered data is in good agreement with Kolmogorov's −5/3 law in the inertial sub range.
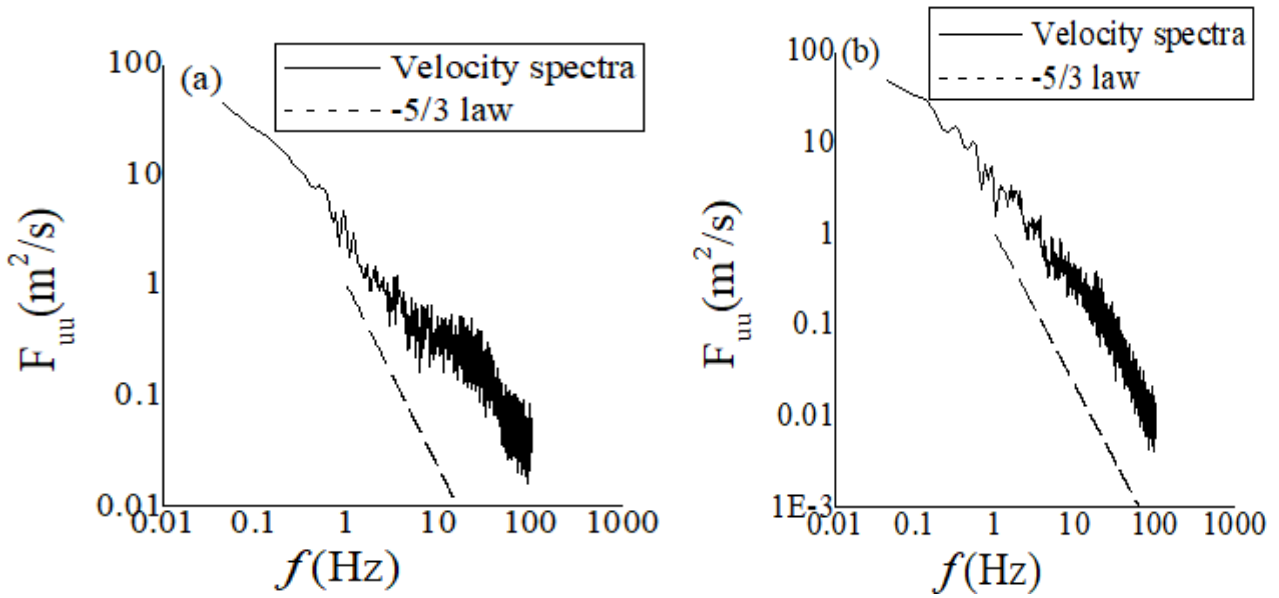
Figure 1. Velocity power spectra of (a) unfiltered data and (b) filtered data compared with Kolmogorov's -5/3 law in the inertial sub range at z = 10 mm for the presence of a sheet layer.

3. CHANGES IN THE TURBULENCE PARAMETERS IN THE PRESENCE OF A SHEET LAYER

A series of experiments were done to investigate the flow velocity, Reynolds shear stress, turbulence intensity, and energy production and dissipation in the presence of the sheet layer. Despite knowing that sheet layer affects the flow characteristics, the main objective lies in understanding the flow conditions in the absence and the presence of the sheet layer, which will enhance existing knowledge about the effects of the sheet flow layer on turbulent flow characteristics.

3.1. Time averaged velocity

Figure 2 shows the vertical distribution of the streamwise (u) and vertical (w) time averaged velocities with and without the presence of a sheet layer, where, z is the distance from the bed surface and h is the flow depth. The streamwise and vertical flow velocity at the sheet layer achieves maximum velocity near the free surface and is gradually reduced towards the bed because of the drag imposed by the sheet thickness. It can be seen that the presence of the sheet layer accelerates the velocity profiles with regard to the absence of the sheet layer while the result is the opposite in the case of flow velocity in the vertical direction. The presence of the sheet layer reduces the flow depth in the channel which suggests that velocities over the sheet layer increased in the streamwise direction and decreased in the vertical direction. Because of mass conservation, increase in the streamwise velocity tends to decrease the vertical velocity with a sheet layer. Further, quantitative analysis suggests that near to the bed, streamwise velocity increases on average by 8-12% and vertical velocity decreases by 32-40% in the presence of a sheet layer.
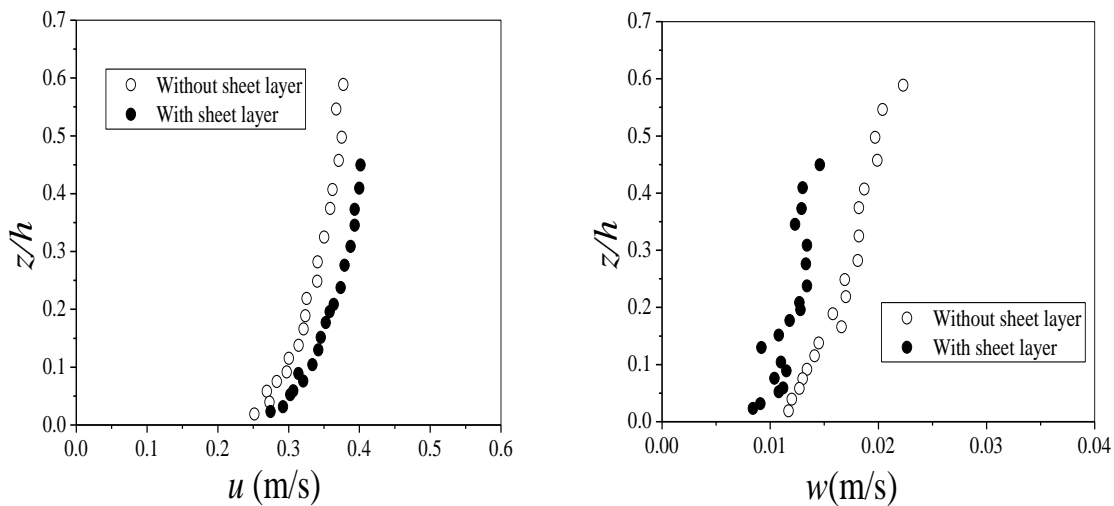

Figure 2. Vertical profiles of streamwise and vertical velocity with and without a sheet layer

3.2. Reynolds shear stress (RSS)

Reynolds shear stress indicates the momentum exchange between the turbulent flow and the sediment particles. It is, therefore, an important parameter governing the soil erosion and sediment transportation. Vertical distributions of RSS with and without a sheet layer are shown in Figure 3. RSS increases along the channel bed are associated with the momentum provided from the main flow to maintain sediment particle motion overcoming the bed resistance, which attains a maximum value between $0<z/h<0.2$ and then again decreases towards the boundary because of the presence of a roughness sublayer in the near bed region. The profiles of RSS distribution were found to be similar for the presence and absence of a sheet layer but the magnitudes are higher in the presence of a sheet layer. This leads to the occurrence of more momentum exchange in the presence of a sheet layer. Additionally, the reducing nature of RSS is recognized as the result of the fact that the farther the location from the sheet layer, the smaller is the turbulence generated by the flow due to a sheet layer. An important observation is that the maximum RSS in the presence of a sheet layer is more than the RSS without a sheet layer by a value of 16.7%.
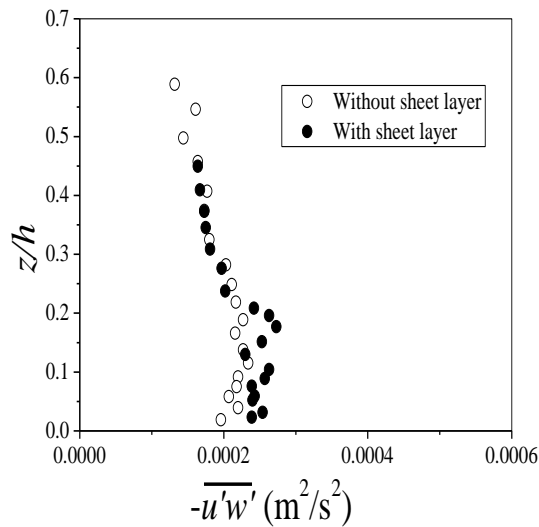

Figure 3. Vertical profiles of Reynolds shear stress with and without a sheet layer.

3.3. Turbulence intensities

Vertical distributions of turbulence intensities with and without the sheet layer are shown in Figure 4. At the location of the sheet layer, turbulence intensities show the maximum value in the range $0 <z/h < 0.2$, where the maximum RSS is achieved and it becomes stable near the water surface. In the presence of a sheet layer, it fluctuates more near the bed as compared to the free surface because of the influence of the boundary effect. An important observation is that the streamwise turbulence intensity (σ_u) in the near bed flow zone over the sheet layer is more than the turbulence intensity without a sheet layer by a value of 9-14%. In the case of vertical turbulence intensity (σ_w), the increases becomes 5-10%.
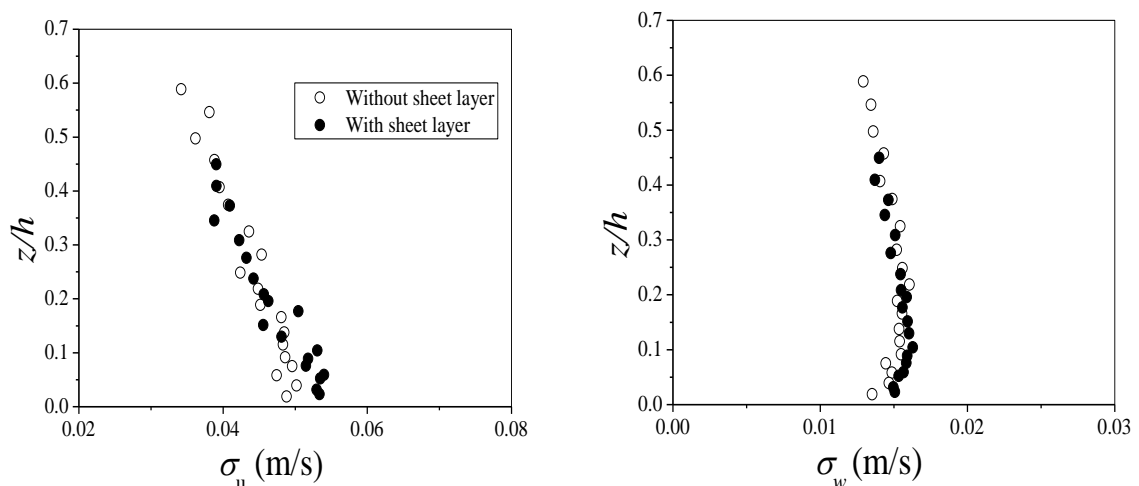

Figure 4. Vertical profiles of streamwise (σ_u) and vertical turbulence (σ_w) intensity with and without a sheet layer

3.4. Energy production and dissipation of flow

The total kinetic energy (TKE) production for uniform open channel flow is given by Nezu and Nakagawa (1993).

$$t_p = -\overline{u'w'}\frac{\partial u}{\partial z} \qquad (1)$$

Turbulence dissipation, ε, is evaluated by Krogstadt and Antonia (1999):

$$\varepsilon = \frac{15\upsilon}{u^2}\overline{\left(\frac{\partial u'}{\partial t}\right)^2} \qquad (2)$$

The TKE production (t_p) and dissipation (ε) are normalized in the form as $(T_P, E_D) = (t_p, \varepsilon) \times (h/u_*^3)$ where u_* is the shear velocity, T_P and E_D represents the non-dimensional TKE production and dissipation.

Figure 5 shows the energy production and dissipation in flows. For all profiles of T_P and energy dissipation (E_D), it is observed that maximum value is found near the bed region where there is a high velocity differential. The normalized values of T_P and E_D show that a similar pattern has been observed with and without a sheet layer. It is observed that T_P and E_D decrease rapidly with an increase in z/h becoming nearly constant (with small magnitude) for flow near the surface region. The turbulence production is increased with a sheet layer as compared to without a sheet layer because of increased Reynolds shear stress and increased momentum transfer from the flow to the sediment particles in the presence of a sheet layer. The turbulence dissipation is decreased with a sheet layer as compared to without a sheet layer which may corresponds to the increase in the turbulence production. This decreased level of turbulence dissipation is related with the increased time-averaged velocity and decreased gradient of time-averaged velocity fluctuation in the presence of a sheet layer.
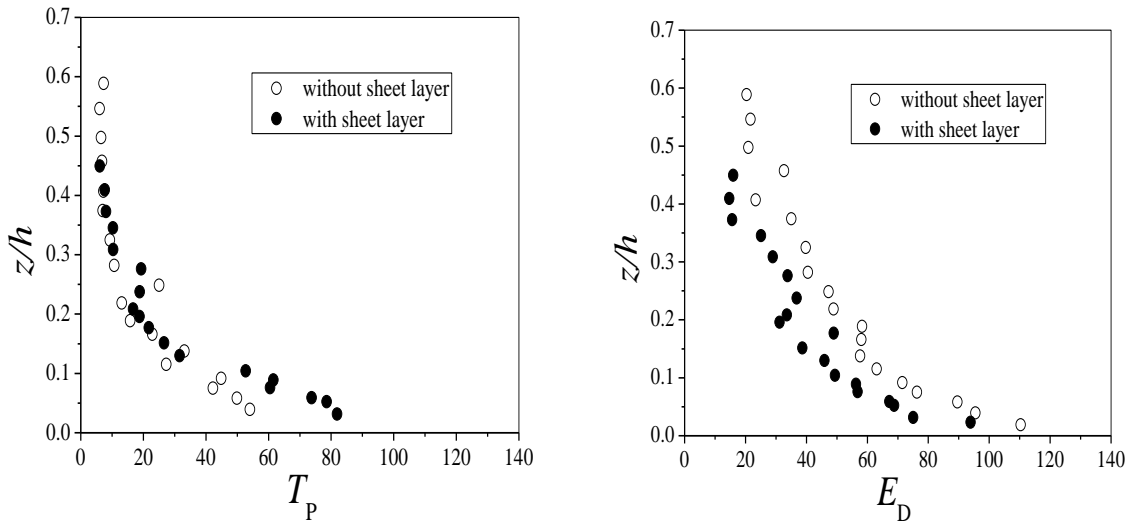

Figure 5. Vertical profiles of turbulent production (T_p) and energy dissipation (E_D) with and without a sheet layer

4. CONCLUSIONS

An experimental study has been done to observe changes in the turbulence characteristics of flow in the presence of a sheet layer in an alluvial channel composed of a non-uniform sediment mixture. The current study addresses the vertical distribution of turbulent flow. The variations of streamwise velocity with a sheet layer are greater than those without a sheet layer but the result is the opposite in the case of vertical velocity. The profiles of Reynolds shear stress are slightly scattered, in general, and increased with a sheet layer, which signifies a greater momentum transfer towards the boundary. The distribution of the Reynolds shear stress undergoes a damping due to a decreasing level of turbulence fluctuation within the wall shear layer. In presence of a sheet layer, increases in streamwise and vertical turbulence intensities are observed compared to turbulence intensities without a sheet layer. Importantly, the effect of the sheet layer on the TKE production and dissipation is pronounced. Sheet flow influenced higher turbulence production and a lower TKE dissipation rate due to which the level of turbulence in the flow is increased with the presence of a sheet layer.

REFERENCES

Bagnold, R. A. (1966). An approach to the sediment transport problem. From general Physics *U.S. Geological Survey*, *Professor paper, 422-J.*

Camenen, B., Bayram, A., & Larson, M. (2006). Equivalent roughness height for plane bed under steady flow. *Journal of Hydraulic Engineering, 132*(11), 1146-1158.

Conley, D. C., & Inman, D. L. (1992). Field observations of the fluid-granular boundary layer under near-breaking waves. *Journal of Geophysical Research: Oceans, 97*(C6), 9631-9643.

Dingler, J. R., & Inman, D. L. (1976). Wave-formed ripples in nearshore sands. In: *Coastal Engineering 1976,* (pp. 2104-2126), New York: ASCE.

Ghoshal, K. (2005). *On velocity and suspension concentration in a sediment-laden flow: Experimental and theoretical studies. (Ph.D. dissertation),* Jadavpur University, Calcutta.

Goring, D. G., & Nikora, V. I. (2002). Despiking acoustic Doppler velocimeter data. *Journal of Hydraulic Engineering*, *128*(1), 117-126.

Gotoh, H., & Sakai, T. (1997). Numerical simulation of sheetflow as granular material. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 123*(6), 329-336.

Inman, D. L., Jenkins, S. A., Hicks, D. M., & Kim, H. K. (1986). Oscillatory bursting over beds of fine sand. in *Ref. Ser. 86-13*, 16 pp., Scripps Inst. of Oceanogr., Univ. of Calif., San Diego, 1986.

Jenkins, J. T., & Hanes, D. M. (1998). Collisional sheet flows of sediment driven by a turbulent fluid. *Journal of Fluid Mechanics, 370,* 29-52.

Krogstadt, P. Å., & Antonia, R. A. (1999). Surface roughness effects in turbulent boundary layers. *Experiments in Fluids, 27*(5), 450-460.

Lacey, R. W., & Roy, A. G. (2008). Fine-scale characterization of the turbulent shear layer of an instream pebble cluster. *Journal of Hydraulic Engineering, 134*(7), 925-936.

Marsh, N. A., Western, A. W., & Grayson, R. B. (2004). Comparison of methods for predicting incipient motion for sand beds. *Journal of Hydraulic Engineering, 130*(7), 616-621.

Mazumder, B. S., Ghoshal, K., & Dalal, D. C., (2005). Influence of bed roughness on sediment suspension: Experimental and theoretical studies, J*ournal of Hydraulic Research, 43*(3), 245-257.

Misri, R. L., Garde, R. J., & Ranga Raju, K. G. (1984). Bed load transport of coarse nonuniform sediment. *Journal of Hydraulic Engineering, 110*(3), 312-328.

Mohtar, W. H. M. W., Sharil, S., & Mukhlisin, M. (2016). Representative sediment sizes in predicting the bed-material load for nonuniform sediments. *International Journal of Sediment Research*, *31*(1), 79-86.

Nezu, I., & Nakagawa, H. (1993). *Turbulence in open channels flows. IAHR Monographs.* Rotterdam, The Netherlands: Balkema,

Raja, R.K., Kumar, A., & Chhabra, S.S. (1983). Estimation of seepage losses from an unlined channel-A field study by nuclear techniques, *Proceedings, Volume II - Hydraulics, CBIP, Fiftieth Annual Research and Development Session, Simla*, Himachala Pradesh, India.

Samaga, B. R., Ranga Raju, K. G., & Garde, R. J. (1986). Bed load transport of sediment mixtures. *Journal of Hydraulic Engineering, 112*(11), 1003-1017.

Sharma, A., & Kumar, B. (2016a). Probability distribution of turbulence in curvilinear cross section mobile bed channel. *Water Science and Technology*, *73*(6), 1472-1482.

Sharma, A., & Kumar, B. (2016b). Probability distribution function of turbulence in seepage affected alluvial channel. *Fluid Dynamics and Research, 49*(1), DOI:10.1088/1873-7005/49/1/015508

Sharma, A., & Kumar, B. (2017a). Structure of turbulence over non uniform sand bed channel with downward seepage. European Journal of Mechanics - B/Fluids, 65, 530-551.

Sharma, A. and Kumar, B. (2017b). Boundary layer development over non-uniform sand rough bed channel. *ISH Journal of Hydraulic Engineering,* doi: 10.1080/09715010.2017.1391133

Sharma, A. and Kumar, B. (2018a). Sheet flow hydrodynamics over a non-uniform sand bed channel. *International Journal of Sediment Research*, doi:10.1016/j.ijsrc.2018.01.004

Sharma, A. and Kumar, B. (2018b). Flow resistance in seepage affected alluvial channel. *ISH Journal of Hydraulic Engineering*, doi:10.1080/09715010.2018.1464407

Sumer, B. M., Kozakiewicz, A., Fredsøe, J., & Deigaard, R. (1996). Velocity and concentration profiles in sheet flow layer of movable bed. *Journal of Hydraulic Engineering, 122*(10), 549-558.

Wu, W., Wang, S. S. Y., & Jia, Y. (2010). Nonuniform sediment transport in alluvial rivers. *Journal of Hydraulic Research*, *38*(6), 427-434.

Yang, F. G., Liu, X. N., Yang, K. J., & Cao, S. Y. (2009). Study on the angle of repose of nonuniform sediment. *Journal of Hydrodynamics, Ser. B*, *21*(5), 685-691.