Canadian Journal of Civil Engineering
Revue canadienne de génie civil

**Statistical description of morphological characteristics of
bedforms in seepage affected alluvial channels**

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2017-0356.R1
Manuscript Type:	Article
Date Submitted by the Author:	22-Sep-2017
Complete List of Authors:	Patel, Mahesh; Indian Institute of Technology Guwahati Majumder, Shantanaba; Indian Institute of Technology, Guwahati, Kumar, Bimlesh; bimk@iitg.ernet.in, civil Engineering; Indian Institute of Technology, Guwahati,
Is the invited manuscript for consideration in a Special Issue? :	N/A
Keyword:	erosion and sediment < Hydrotechnical Eng., bedforms

SCHOLARONE™
Manuscripts

1 Statistical description of morphological characteristics of
2 bedforms in seepage affected alluvial channels

3 1. Mahesh Patel

4 Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati-
5 781039, India

6 E-mail: p.mahesh@iitg.ernet.in

7
8 2. Shantanaba Majumder

9 Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati-
10 781039, India

11 E-mail: shantanabamajumder@gmail.com

12
13 3. Bimlesh Kumar*

14 Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati-
15 781039, India

16 E-mail: bimk@iitg.ernet.in

17 *Corresponding author. Tel.: +91-361-2582420, +91-9678000348; Fax: +91361-2582440;

18

19

20

21

22

23

24

25

Abstract

In this study, experiments were performed in a curvilinear cross-sectional threshold alluvial channel with no seepage and with seepage conditions in order to understand the influence of downward seepage in an alluvial channel. We observed that stable channel during no seepage condition started to reach in transporting stage with downward seepage. Increased value of Shields stress was observed after the application of seepage. In addition, this study deals with the effect of downward seepage on the evolution of alluvial bedforms. In this regard, multi-temporal bed elevation profiles were collected along the test section of channel, which are used to characterize migrating bedforms. Results reveal greater fluctuations and variability on the channel bed under the influence of increased seepage discharge. Slope of the power spectral density with wavenumber was significantly increased with an increment in seepage percentage, showing more inhomogeneous arrangement of bedforms and larger roughness over the channel boundary.

Keywords: turbulence; seepage; multi-scalar fluctuation; power spectral density; structure function.

52 1. Introduction

53 The intrinsic behavior of mobile beds in natural environments is complex if one attempts to
54 understand their innate creation. Mobile beds transform themselves and evolve into different
55 patterns such as sediment waves, which alter the flow and sediment transport. Understanding
56 of these intriguing patterns is significantly important for river management, bed load
57 transport, and structures in fluvial system. In this regard, the studies on fluvial bedforms are
58 widely carried out to get an insight into physics behind the initiation of bedforms over rough
59 beds in natural environments. In general, alluvial bedforms developed by unidirectional flow
60 of water over rough beds in sedimentary environments. Sand bed channel exhibits a variety
61 of bedforms, whenever the bed shear stress exceeds from its critical value. The most common
62 features of bedforms are ripple and dunes, which are formed in tranquil (Froude number < 1)
63 flow in the fluvial systems. Ripples are the small scale bed features that contribute to lesser
64 turbulence, whereas, dunes are larger structures covering a significant part of the channel bed
65 and result in macro disturbances in the flow (ASCE 2002). Best (1992) observed that ripples
66 can only form on a finer sand (median diameter < 0.7 mm) bed and grow up to a maximum
67 wavelength of approximately 0.3 m. On the other hand, dunes occur on coarser sand (median
68 diameter > 0.7 mm) bed and may grow in larger wavelength and amplitude (Allen 2009).

69 Earlier, experimental studies suggested that turbulence in the flows play an important role
70 behind the development of bedforms (Best 1992; Robert and Uhlman 2001; Schindler and
71 Robert 2005; Venditti et al. 2005). In addition to this, studies were carried out to understand
72 the formation and migration of bedforms including their linkage with the flow structure by
73 providing the excess shear stress over plane bed channels (Simons et al. 1965; Van Rijn
74 1982; Venditti et al. 2005). Some field studies on bedform dynamics such as flow structure,
75 changes in bed level, and bed load transport are presented at large scale observations (Parsons
76 et al. 2005; Kostaschuk et al. 2009; Shugar et al. 2010). Elegant work was presented by

77 Coleman and Nikora (2011) to investigate the nature of sand waves in terms of their
78 development, characterization, statistics, and flow structure. Characterization of bedforms
79 within a complex river flow system has always been a challenge to the researchers owing to
80 their complicated geometry and dynamic interaction patterns. Previous studies on bedforms
81 development and corresponding flow characteristics have shown the importance of evolution
82 of bedforms and their dynamics by increasing inflow discharge over the plane sand-bed
83 condition. However, they have not considered the cross-sectional profile of the channel and
84 temporal changes in the length scale of bedforms. Thus, one has to describe the developing
85 bedforms through statistical analysis of bed elevation series.

86 Singh et al. (2009) computed the power spectral density using data acquired from bed
87 elevation profiles along the streamwise direction and showed that the spectral densities of the
88 bed elevation time series and of spatial bed elevation transects are closely related to each
89 other. In addition to this, Singh et al. (2010) experimentally verified that smaller bedforms
90 move with a higher celerity the larger bedforms. Similar types of bedforms have been
91 observed to possess significantly different physical properties such as size and shape (Hino
92 1968; Nikora et al. 1997; Van der Mark et al. 2008; Singh et al. 2011). In alluvial channels,
93 spectral analysis of change in bed elevation profile (Nikora et al. 1997; Jain and Kennedy
94 1974; Nakagawa and Tsujimoto 1984; Nikora and Goring 2001; Aberle et al. 2010)
95 affirmatively confirmed the existence of a wide range of scaling regimes (log-log linear
96 power spectra) and a scale dependent celerity of migrating bedforms (Best 2005; Jerolmack
97 and Mohrig 2005; Nikora et al. 1997; Raudkivi and Witte 1990; Coleman and Melville 1994;
98 Schwammle and Herrmann 2004). In addition to this, Qin et al. (2013) discussed the
99 equilibrium phase of ripples with the help of a digital elevation model, where they described
100 the multi-scale behavior of sand waves by higher order structure function. Further, Singh et
101 al. (2011) quantified the multi-scale statistical structure of migrating bedforms with the help

102 of a wavelet based cross correlation analysis for understanding the complicated dynamics of
103 bedforms. Guala et al. (2014) carried out experiments over a range of Froude numbers (0.2 -
104 0.5) under varying discharges and different bed material composition. They suggested that a
105 wide range of scale dependent convection velocities is one of the governing parameters for
106 adequately describing the spatial and temporal characteristics of migrating bedforms.

107 In the present day scenario, ground water table is depleting because of the excessive use of
108 tube-wells. Therefore, the difference in ground water table and flow level in an alluvial
109 channel varies. If the level of ground water table is lower than the flow level in the channel,
110 water seeps in the downward direction causing downward seepage. The conveyance capacity
111 of the channel is reduced because of the presence of seepage (Kinzli et al. 2010; Martin and
112 Gates, 2014). Earlier studies (Chen and Chiew 2004; Patel et al. 2015; Deshpande and
113 Kumar 2016; Patel et al. 2017; Patel and Kumar 2017) observed that time-mean velocities
114 and Reynolds shear stresses are increased because of downward seepage in the alluvial
115 channels. Bedform dimensions were increased owing to the effect of seepage by considering
116 small test section in alluvial channel as discussed by Lu and Chiew (2007). Patel et al.
117 (2015) investigated that downward seepage caused deformation of banks and development of
118 a sheet layer because of increased Shields stress (bed shear stress) over coarser sand bed
119 channel.

120 Aforementioned studies have focused either on the time dependent evolution of bedforms at a
121 single point within the test section or the variation of the bed load transport rate with
122 increasing discharge. However, to the best of our knowledge, none of the earlier studies have
123 addressed the effect of seepage on the physical properties of bedform and their evolution
124 mechanism. Seepage occurs through the porous boundary of natural channels causing an
125 extra downward force to the boundary particles as well as a downward shift of the velocity
126 profile of the channel bed. Thus, seepage must be taken into account as an interfering factor,

while considering the phenomenon of bedform evolution and their characteristics, especially in alluvial channels. In addition to this, the study on bedform genesis, their complex interaction and migration patterns has not been carried out in the previous literature. Taking all these probable deficits under consideration, the main objective of this study is to quantify the effect of seepage on the physical characteristics and the evolution mechanism of bedforms. Thus, in the present study, statistical analysis has been carried to characterize the developing bedforms at different percentages of seepage.

2. Experimental setup and methodology

Experiments were conducted in a 20 m long, 1 m wide and 0.72 m deep glass-sided large tilting flume with an adjustable bed slope as shown in Figure 1. Flow in the channel was straightened before entering in the main channel by a 2.8 m long, 1.5 m wide, and 1.5 m deep tank provided at the upstream of the flume. Three pumps of 10 HP capacities each were deployed to supply the water in the overhead tank. A control valve was installed at the overhead tank, which was used to regulate the flow in the main channel. The test section was considered from downstream 4 m to 12 m to ensure the measurements free from any upstream or downstream disturbance. A seepage chamber of 15.2 m length, 1 m width and 0.22 m height was located at the bottom of the main channel, which collects and allows the seepage through the sand bed in the downward direction. Two meters of upstream length of the main channel bed was made non-porous and the remaining length of the channel was made porous by covering with a fine mesh (0.1 mm x 0.1 mm aperture size), which was supported with the help of steel tube structure of 0.22 m height, placed on the bottom of the channel. The void space between the bottom of the channel and the mesh forms a seepage chamber. The mesh hinders the bed materials from entering into the chamber. Couple of electromagnetic flow meters was installed at the downstream end of the chamber to measure and control the seepage discharge.

152 [Insert Figure 1]

153 A tail gate, which was operated manually by a geared mechanism with edges allowing
 154 precise positioning of the gate, was used in controlling the flow depth in the channel. A
 155 rectangular notch with coefficient of discharge (C_d) 0.82 was evaluated at the downstream
 156 end of the collection tank to measure the main channel discharge. Water surface slope was
 157 measured by using a pitot tube connected to a digital manometer, which was assembled on a
 158 moving trolley. Bed slope of the flume was measured with the help of total station.

159 River sand was used for all the experimental runs. Median diameter (D_{50}), geometric standard
 160 deviation, and angle of repose (ϕ) were evaluated as 0.41 mm, 1.17, and 32.55° , respectively,
 161 for the sand used in this study. Previous researchers suggested that the shape of the natural
 162 channels is curved cross section or trapezoidal (Griffiths 1983; Hey and Thorne 1986; Millar
 163 and Quick 1993). Various studies evaluated the stable shape in terms of width, depth, and
 164 slope, which was empirical or semi-empirical in nature except one proposed by Lane (1953).
 165 In the present study, a parabolic cross-sectional profile of the channel was made based on the
 166 Lane's (1953) theory, importance of which was to design the stable channel at incipient
 167 motion condition. Lane (1953) derived the equation to design of threshold channel by
 168 considering balance between the forces acting on a particle resting on the channel boundary.

$$169 \quad y_0 = h \cos \left\{ \left(\frac{\tan \phi}{h} \right) x \right\} \quad (1)$$

170 Where h is centre line depth, y_0 is lateral bank zone depth, and x is transect distance. Cross
 171 section profile of channel has been obtained by given using. For top width 0.7 m, maximum
 172 depth of flow is calculated as 0.14 m by using equation (3) (see X-X section of Figure 1).

173

2.1 Data collection

In order to understand the flow hydrodynamics, instantaneous velocity measurements were taken at the centre line of flume by the Vectrino+ Acoustic Doppler Velocimeter (ADV). Velocity samples were collected in the vertical direction for no seepage and seepage experiments (immediately after the application of downward seepage). In the no seepage experiment, when channel remained in stable condition after running several hours (10-12 h), around 20-25 velocity samples were collected at center of the cross-section 8 m from the downstream reach end. After the application of downward seepage, when measuring location of the channel was not distorted until 3 h of run, velocity measurements were taken during this period for determining the influence on flow structure caused purely by the presence of downward seepage at the same location. Once the deformation starts after 2-3 h of downward seepage, this would have an effect of the flow structure. At each vertical location instantaneous velocity samples were recorded for five minutes duration at a sampling rate of 100 Hz. Ten pulses of instantaneous velocities were recorded at 10 mm above the bed to obtain the uncertainty associated with the measured data (Table 1).

[Insert Table 1]

Geometric observations in the channel were recorded with the help of SeaTek 5 MHz Ultrasonic Ranging System that contained eight transducers. The distance between each adjacent transducer was approximately 25 mm c/c in transverse direction. The whole system was run from the upstream to the downstream of the test section for several times during experimental run of almost 31 h. The measured data of bedforms development are the streamwise spatial bed elevation profiles with the resolution of 7.8 mm in longitudinal transect. Two time intervals 9 h and 21 h are considered to analysis these recorded bed elevation profile in accordance with developing stage of bedforms. A summary of

198 experimental conditions is given in Table 2. Analysis of bedforms characteristics has been
199 carried out under both the seepage discharges (15% and 20%) at slope 0.00176 to avoid the
200 duplicity and conjunctions in the results.

201 [Insert Table 2]

202 **3. Investigation of Shields stress**

203 For validating the incipient motion condition during the no seepage run, results were plotted
204 on a Shields curve as shown in Figure 2. Mean line in Figure 2 represents the Shields curve,
205 which has been plotted by using the empirical formulation of Paphitis (2001).

206 [Insert Figure 2]

207 Shields stress provides the information regarding characteristics of bed shear stress on the
208 sediment particles. Figure 2 shows that the value of Shields parameters falls within the band
209 of Shields curve, suggesting incipient motion condition of sand particles during no seepage
210 run. Few researchers (Liu 1957; Bogardi 1959; Southard and Dingler 1971; Venditti et al.
211 2005) reported stable beds with little sediment transport and no signatures of bedforms were
212 seen. In the present experimental study, the parabolic cross-sectional shape remained stable
213 i.e. in the threshold of sediment movement for several hours (10-12 h) during the no seepage
214 run, although sediment movement was sporadic along the channel. However, when
215 downward seepage was applied to the channel, bed shear stress was increased by ~27-30%
216 from its critical values. This increase in shields shows the higher bed shear stress, resulting in
217 sediment transport and consequent deformation of cross-sectional shape of the channel.
218 Through experiments, we observed that sediment particles were detached from the channel
219 banks and collected in the form of bedforms at the center of channel. Those bedforms were

prograded from the upstream to the downstream end of the channel and resulted in the complete distortion of the cross-sectional shape of the channel.

4. Results and outcomes

Understanding of the influence of downward seepage on the turbulent flow structure is necessary for the assessment of changes in the morphodynamics of the channel. Also, statistical analysis has been carried out to quantify the effect of seepage in bedform dynamics.

4.1. Turbulent fluvial flows

In order to understand the changes in hydrodynamics of channel for no seepage and with scenarios turbulent flow parameters such as time-mean velocities, Reynolds shear stresses (RSS), turbulent production, and turbulent dissipation are evaluated in the middle of the test section (8 m from downstream end). Figure 3 (a) shows the distributions of time-mean velocities against dimensionless depth (z/h , where z is distance from channel bed and h is the depth of flow) for all the runs. We can observe that time-mean velocities are increased significantly with the application of seepage. These increased velocities cause increase in sediment movement along the flow in the channel.

[Insert Figure 3]

RSS defines the real time momentum flux of the streamwise velocity in the vertical direction caused by the fluctuating velocity field. RSS has been obtained for all the runs and the vertical distributions are shown in Figure 3 (b). Careful observation from Figure 3 (b) shows that Reynolds shear stresses are increased by ~25-40% from their no seepage values with the application of seepage, confirming increased momentum transfer toward the channel boundary in the presence of seepage. In the previous study, Patel et al. (2015) observed a

sheet layer because of increased Reynolds shear stresses in the presence of downward seepage over coarser ($D_{50} = 1.1$ mm) sand bed with curvilinear cross section channel. Here, we observed increased sediment transport and consequent development of bedforms over the finer sand bed channel with the application of seepage.

Figure 4 depicts the Profiles of turbulent production and turbulent kinetic energy dissipation for experiments on both sands under no seepage and with seepage conditions, which can be evaluated as calculated by Krogstad and Antonia (1999).

$$t_p = -\overline{u'w'} \frac{\partial u}{\partial z} \quad (2)$$

$$e_d = \frac{15\nu}{u^2} \left(\frac{\partial u}{\partial z} \right)^2 \quad (3)$$

where ν is the kinematic viscosity. Quantities t_p and e_d are normalized by multiplying with h/u_*^3 , and are expressed as T_P and E_D , respectively. Shear velocity (u_*) is obtained by the linear projection of the RSS profile to the channel bed ($u_* = (u'w')^{0.5}_{at\ z=0}$) for all the runs. Turbulent production comes from the interchange of mean flow energy to fluctuations. Here, T_P and E_D are shown for no seepage and 15% seepage at slope 0.00116 in order to avoid duplicity and to show the trend adequately in both scenarios (see Figure 4). We can observe from Figure 4 that the turbulent production is increased when the downward seepage is applied to the channel. This increased T_P is in agreement with the higher momentum transfer under the seepage condition. Also, it can be implied that larger roughness over the boundary of the channel with the application of seepage, causes more turbulent production in the flow. Further, we can observe that the turbulent dissipation is reduced when water is extracted in the vertically downward direction through the sand bed. Under the action of

downward seepage, more energy is converted to turbulent fluctuations in the flow, resulting in the reduced dissipation of the turbulent kinetic energy.

4.2. Scale dependent statistical analysis of bed elevation increments

For quantifying the effect of seepage on the bed elevation profiles as well as local fluctuations, multi scale statistical analysis has been carried out. In this analysis, wavelet coefficients, derived from Mexican hat wavelet as mother wavelet, at different length scales are obtained in accordance with Patel et al. (2017). Wavelet coefficients (fluctuations of bed elevation) can be computed as:

$$WC_f(a, b) = \frac{1}{\sqrt{a}} \int_R \psi\left(\frac{x-b}{a}\right) f(x) dx \quad (4)$$

Where a is defined as the scaling parameter, b is defined as the location parameter, and R is the set of real number. The factor $1/\sqrt{a}$ is scaling factor of mother wave as discussed in earlier studies (Mallat 1999; Kumar and Foufoula-Georgiou 1997). Some predetermined scales were chosen and the elevation series were transformed with a Mexican hat wavelet at those particular scales. For example, Figure 5 shows the wavelet coefficient computed at 20 mm and 10 mm length scales after 21 h of run for 15% seepage case.

[Insert Figure 5]

At length scale a , q^{th} order statistical moments of the absolute values of the increments can be obtained as:

$$M(q, a) = \frac{1}{N} \times \sum_{i=1}^N |dh(x, a)|^q \quad (5)$$

Where N is the number of data points of the bed elevation series at scale a . The term $M(q, a)$ is defined as the structure function or statistical moments. The statistical moments for all q values completely depict the shape of the probability density function of the bed elevation

increments at scale a . Scale invariance ensured that it varies with the following power law with scale a

$$M(q, a) \sim a^{\tau(q)} \quad (6)$$

Where $\tau(q)$ represent the scaling exponent function. In general, $\tau(q)$ follows a nonlinear relationship with q . Therefore, the following quadratic equation is used to evaluate the $\tau(q)$

$$\tau(q) = c_1 \times q - \left(\frac{c_2}{2}\right) \times q^2 \quad (7)$$

Where c_1 and c_2 are defined as average roughness of the wave series and intermittency parameter, respectively. The parameters (c_1 and c_2) signify the variations in probability distribution function of bed elevation increment over a range of length scales. From following geometrical interpretation of the statistical scaling (Frisch 1995; Venugopal et al. 2006), the parameter c_2 is related to the local roughness or degree of differentiability of the bed elevation signal. A non-zero value of c_2 symbolizes a temporally non-stationary or spatially inhomogeneous arrangement of spikes or abrupt changes along the channel. In this study, structure function has been analysed on the bed elevation spatial series after 9 h and 21 h run for both the seepage amounts (15% and 20%). Figures 6 (a) and (b) show the scaling of the statistical moments of the bed elevation variations $dh(x, a)$ as a function of scale a after 9 h run and 21 h run, respectively for 15% seepage. These plotted moments are offset vertically (along the y -axis) to get better visualization. Figures 6 (c) and (d) show the $\tau(q)$ curves obtained from the slopes of the statistical moments within the scaling range for 15% seepage. Similar explanation hold true for Figures 7 (a) to (d) for 20% seepage. From Figures 6 and 7, we can observe that the structure function follows power law in the scaling range from approximately 50 mm to 400 mm for both the seepage experiments. Additionally, the $\tau(q)$

curves have exhibit a nonlinear relationship with q , indicating the presence of multifractality in both of the seepage experiments.

[Insert Figure 6]

[Insert Figure 7]

The value of the intermittency parameter c_2 is higher for 20% seepage experiment than the value obtained for 15% seepage experiment after the 9 h run. This suggests that after increasing the seepage discharge more inhomogeneous arrangement of abrupt bed elevation fluctuations was found during developing bedforms (after 9 h run). While, the value of c_2 is nearby equal after 21 h run for both the seepage discharges, indicating bedforms arrangements achieve an equilibrium state after longer period of the seepage runs. In addition, the parameter c_1 defines the characteristics of the bed elevation fluctuation, in which greater value corresponds to smoother bed elevation. In the present study, we observe that the value of c_1 is higher after 9 h as compared with 21 h run for both the seepage discharges. This suggests that the bed elevation fluctuation is smooth in the beginning (after 9 h run) of seepage run. However, value of c_1 increases with the passage of time (after 21 h run), implying an increase of bed elevation fluctuation because of greater variability in bedforms dimensions. Therefore, the results show larger bed roughness on the channel bed at the end of seepage experiments.

4.3. Probability distribution function (pdf) of dimensionalized bed elevation increments as a function of scale

In the previous study, Wong et al. (2007) suggested that mean-removed bed elevations in plain bed channel shows nearly Gaussian distribution. For understating the patterns of bed

330 elevation series in the case of different percentage of seepage, pdf of bed elevation
331 fluctuations is analysed.

332 [Insert Figure 8]

333 [Insert Figure 9]

334 Figure 8 shows the semi-log pdfs of the bed elevation increments for 15% and 20% seepage
335 experiments after 9 h run and 21 h run, respectively. Careful observations of Figure 9 reveal
336 that the pdfs at different scales are asymmetric to each other. As the scale is increased, the
337 width of the pdfs increases and they become more skewed to the right signifying a higher
338 probability of occurrence of higher positive bed elevation fluctuations or increments. The
339 pdfs also show a significant increase in width with an increase in seepage amount, suggesting
340 larger elevation fluctuations or larger bedforms under the influence of increased seepage
341 amount. It is very important to note that earlier in the structure function analysis; we have
342 seen that the value of the roughness parameter increases with the increment in seepage
343 discharge. Further, pdf of bed elevation increments is normalized to understand the variations
344 adequately for both the seepage discharges as shown in Figure 9. We can observe that pdfs
345 are getting thinner tailed at larger length scale, which can be seen from the log-log plots of
346 the scale dependent probability of exceedance of the positive bed elevation increments.
347 Results show that the exceedance probability curves move upwards in the case of 20%
348 seepage experiment as compared with 15% seepage experiment. This suggests that the
349 existence of larger bedforms is more likely for the case of higher seepage discharge.

350 4.4. Spectral analysis

351 Power spectral density function (PSD) represents the strength of the energy as a function of
352 frequencies (or scales). In other words, it shows whether the energy is strong or weak at any

particular frequency. The PSD is the average of the Fourier transform magnitude, squared over a large time interval. The PSD, $S_x(f)$ of a random time signal $x(t)$ in the interval $(-T, T)$ can be expressed as

$$S_x(f) = \lim_{T \rightarrow \infty} E \left\{ \frac{1}{2T} \left| \int_{-T}^T x(t) e^{-j2\pi ft} dt \right|^2 \right\} \quad (8)$$

Similarly, the $S_x(f)$ can also be defined as the Fourier transform of the auto-correlation function

$$S_x(f) = \int_{-T}^T R_x(\tau) e^{-j2\pi f\tau} d\tau \quad (9)$$

Where τ is the time lag and the auto-correlation function $R_x(\tau)$ is defined as:

$$R_x(\tau) = \frac{E[(x_t - \mu)(x_{t+\tau} - \mu)]}{\sigma^2} \quad (10)$$

Where μ is the mean and σ is the standard deviation of the data series. For time series signals, the unit of the frequency response is in hertz (cycles/sec). In the present experiments, we have collected spatial data after 9 h and 21 h of seepage runs. Therefore, the representative unit of frequency is defined in terms of wave number (number of waves per unit length). Wavenumber ω is defined as the inverse of the spatial resolution ($=2\pi/\Delta x$, where $\Delta x = 7.8$ mm). It is important to note that the length scales are proportional to inversely of the wavenumbers, obtained from the PSD plots. In the spectral density plots the power spectra saturates near 1000 mm or 1 m for both the seepage experiments. This suggests that the largest amount of variance is associated with this particular length scale.

[Insert Figure 10]

Figure 10 shows the PSD versus wavenumber plots obtained from bed elevations series after 9 h and 21 h of run for 15% and 20% seepage. We can observe that the slopes of the

PSD plots are nearly equal after 9 h run for both the seepage percentages. While after 21 h, slope of the PSD for 20% seepage experiment is increased to -2.0 from -1.86 of the 15% seepage experiment. In the study of Singh et al. (2010) on a gravel bed channel, they observed that slope of the power spectra versus wavenumber increased from -1.87 to -2.06 after increasing the inflow discharge from 2 to 2.8 m³/s. In the present study, increment in the PSD slopes suggests the development of larger bedforms and more inhomogeneous arrangement of bed elevation series with the increase in seepage discharge after 21 h run.

5. Discussion

This study shows the influence of downward seepage on a threshold alluvial channel. In this regard, to understand the effect of seepage experiments were performed in no seepage and with seepage scenarios over sand bed channel. It was observed that the threshold channel remained in stable condition, while running several hours at no seepage condition (see Figure 11a). Stability of the cross-sectional shape of the channel was validated by using Shields curve as presented in Figure 2. However, with the application of downward seepage, an increased Shields stress was observed, indicating higher bed shear stress on the bed particles. Existing studies suggested that sediment transport increases when Shields stress reach towards ~20% higher than its threshold value (Diplas 1990; Ikeda et al. 1988). Bed features on the channel bed were observed when shear stress was increased from its threshold value (Kapdasli and Dyer 1986; Best 1992; Venditti et al. 2005). In recent experimental study, Pitlick et al. (2013) observed that the overbank flow caused the bank distortion because of the high Shields stress associated with it. In addition, Patel et al. (2015) observed that Shields stress increases after the application of downward seepage, causing the development of sheet flow of sediment particles. In the present study, stable particles during no seepage experiment started to detach from the banks and deposited at adjacent section because of increased Shields stress after the application of downward seepage. This process continued till the cross

section of channel distorted fully, resulting development of bedforms. Snapshots of the channel cross section obtained at the end of 15% and 20% seepage experiments are shown in Figures 11 (b) and 11 (c), respectively. Figure 11 (a) shows snapshot of the channel cross section after running the experiment for several hours under no seepage condition, where no signature of bed or bank deformation was seen. Cross-sectional shape of the channel was distorted gradually after the application of downward seepage (see Figures 11b and 11c).

[Insert Figure 11]

Further, turbulent flow parameters are evaluated for no seepage and seepage experiments to understand the mechanism behind the development of bedforms. Results show that after the application of downward seepage to the channel, increase in the time-mean velocities and RSS are observed (see Figure 2). This suggests higher flow strength in flow, which can lead to sediment transport and consequent development of bedforms. Further, we observe that turbulent production and dissipation are increased and decreased, respectively, showing greater roughness on the channel in the presence of seepage. In this regard, previous study of Sumer et al. (2003) showed that the increased turbulence in the flow may cause increase in sediment movement by six times.

The characteristic of fluvial bedforms is needed in order to understand fluvial process in seepage environment. However, development of bedforms is an intricate in nature, which cannot be defined straightforwardly. The most important characteristics of migration bedforms is its intermittency, which create deterministic approach potentially difficult. One can show its characteristics from the measurement of several bed elevation profiles at different time intervals. Therefore, one has to describe the characteristics of bedforms through statistical analysis of various bed elevation profiles. Previous literatures have focused on the statistical characterization of the physical and dynamic characteristics of bed

topography under different variable controlling parameters such as flow discharge, grain size distribution, and flow velocity (Allen 1962; Van Rijn 1982; Julien and Klaassen 1995; Coleman et al. 2006). Some advanced statistical methods such as spectral analysis and structure function analysis have also been used to characterize the variability of bedform properties over multiple temporal and spatial scales (Nordin and Algert 1966; Hino 1968; Jain and Kennedy 1974; Nakagawa and Tsujimoto 1984; Nikora et al. 1997; Nikora and Goring 2001; Aberle et al. 2010; Singh et al. 2011).

Aforementioned studies observed that the variability and celerity of developing bedforms were increased and decreased, respectively, by increasing the flow discharge over plan bed channels. Also, they have not considered the influence of seepage on statistical behavior of bedforms. In the present study, scale dependent statistical analysis has been carried out on the wavelet coefficients to quantify the developing bedforms at different scales and percentages of seepage. In this regard, bed elevation profiles were discretized into multiple scales ranging from 2 mm to 500 mm by using Mexican hat wavelet to analyse the effect of seepage over different spatial scales on bedform characteristics. Results show that variability and fluctuation over the channel boundary increases when seepage percentage increases from 15% to 20%. These observations can be linked to the study of Patel et al., (2017), they observed that eddy length and time scales of flow increases by increasing seepage discharge, causing development of larger bedforms.

This study deals with the mechanism of bedform development and the effect of seepage on their physical characteristics. It concentrates on seepage as an important controlling factor for bedform size and the distribution of their different physical parameters. Moreover, the development of a new dataset consisting of spatial arrangement of bedforms and their detailed statistical analysis is an element of interest of this work. The reason behind collecting spatial dataset was to enhance the applicability of the analysis methods to

understand the seepage affected alluvial channels. Besides, these analysis techniques can be easily applied to any real dataset of river bed profile as these are statistical analyses of bedforms dynamics. The findings of this study can be used to better understand the evolution pattern and variation in the geometry of alluvial migrating bedforms under the influence of seepage in alluvial channels.

6. Conclusions

Experimental study has been performed to understand the flow hydrodynamics and earth-surface morphology of a threshold alluvial channel under the influence of seepage environments. Experiments were carried out under no seepage and with seepage scenarios on a stable curvilinear cross-sectional shape channel. Through experiments, we observed that bed particles were stable on a channel boundary and their movement was sporadic in nature at no seepage condition. Investigation of Shields stress suggests that with the application of downward seepage bed shear increases from its critical value, leading to sediment movement and consequent development of bedforms. To get an insight behind the initiation of bedforms, turbulent flow parameters are evaluated. We have found that streamwise time-mean velocities and Reynolds shear stresses are increased with the application of seepage. This suggests that the downward seepage causes more momentum and energy transfer towards the channel bed, causing sediment transport and lead to development of bedforms. Increase in turbulent production and reduction in turbulent kinetic energy dissipation have been observed, justifying the presence of greater roughness on the channel boundary after the application of downward of seepage.

Statistical analysis was performed on the wavelet coefficients, which represents the bed elevation fluctuation at different scales. Further, higher order statistical analysis shows greater fluctuations in the elevation of bedform, as well as the presence of multi-fractal

properties, which have been described in terms of local roughness and intermittency parameters. We observed that channel bed became more inhomogeneous and rough after increasing the seepage discharge, showing greater resistance on the channel bed. The dimensionalized probability distribution functions of the bed elevation fluctuations tend to become wider after increasing the amount of seepage, indicating higher probability of larger fluctuation if the amount of seepage is increased. Logarithmic exceedance probability plots of the normalized positive bed elevation fluctuations shift upwards after increasing the seepage amount, signifying a higher probability of occurrence of larger bed elevation fluctuations. PSD analysis shows an increased slope of the power spectra indicating more inhomogeneous and rapid arrangement of bedforms in the case of increased seepage discharge.

Acknowledgements

Basic experimental data used in the paper or displayed in Figures or Tables can be obtained from any of the authors. We are very thankful to Professor Astrid Blom, Delft University of Technology for providing us with the bedform tracking tool. We also thank to Prof. Nihar Biswas for devoting his precious time and providing us with useful suggestions.

References

- Aberle, J., Nikora, V., Henning, M., Ettmer, B., and Hentschel, B., 2010, "Statistical characterization of bed roughness due to bed forms: A field study in the Elbe River at Aken, Germany," *Water Resour. Res.*, 46(3).
- Allen, J. R. L., 1962, "Asymmetrical ripple marks and the origin of cross-stratification," *Nature*, 194 (4824), pp. 167-169.
- Allen, J. R. L., 2009, "River bedforms: Progress and problems", pp. 19–33.

- 495 ASCE, T. C., 2002, Flow and Transport over Dunes, Tech. Rep. 8.
- 496 Best, J., 2005, "The fluid dynamics of river dunes: A review and some future research
497 directions," J. Geophys. Res., 110(F4). F04S02.
- 498 Bogardi, J., 1959, "Hydraulic similarity of river models with movable bed," Acta Technol.
499 Acad. Sci. Hung. 24, pp. 417–445.
- 500 Chen, X., and Chiew, Y. M., 2004, "Velocity distribution of turbulent open-channel flow
501 with bed suction," J. Hydraul. Eng., 130(2), pp. 140–148.
- 502 Coleman, S. E., and Melville, B. W., 1994, "Bed-form development," J. Hydraul. Eng.,
503 120(5), pp. 544–560.
- 504 Coleman, S. E., Nikora, V. I., McLean, S. R., Clunie, T. M., Schlicke, T. and Melville B. W.
505 2006, "Equilibrium hydrodynamics concept for developing dunes," Phys. Fluids, 18, pp.
506 105104.
- 507 Coleman, S., and Nikora, V., 2011, "Fluvial dunes: initiation, characterization, flow
508 structure," Earth Surf. Process. Landf., 36(1), pp. 39–57.
- 509 Deshpande, V., and Kumar, B., 2016, "Turbulent flow structures in alluvial channels with
510 curved cross-sections under conditions of downward seepage," Earth Surf. Process. Landf.,
511 41(8), pp. 1073–1087.
- 512 Diplas, P., 1990, "Characteristics of self-formed straight channels," J. Hydraul Eng. 116 (5),
513 pp. 707-728.
- 514 Ikeda, S., Parker, G., and Kimura, Y., 1988, "Stable width and depth of straight gravel rivers
515 with heterogeneous bed materials," Water Resour. Res. 24 (5), pp. 713–722.
- 516 Jain, S. C., and Kennedy, J. F., 1974, "The spectral evolution of sedimentary bed forms," J.
517 Fluid Mech., 63(02), pp. 301–314.
- 518 Jerolmack, D. J., and Mohrig, D., 2005, "A unified model for subaqueous bed form
519 dynamics," Water Resour. Res., 41(12).

- 520 Julien, P. Y. and Klaassen, G. J. 1995, "Sand-dune geometry of large rivers during floods," J.
521 Hydraul. Engg., 121, pp. 657-663.
- 522 Kapdasli, M.S., and Dyer, K.R., 1986, "Threshold conditions for sand movement on a rippled
523 bed," Geo Mar. lett. 6(3), pp. 161-164.
- 524 Kinzli, K. D., Martinez, M., Oad, R., Prior, A., and Gensler, D., 2010, "Using an ADCP to
525 determine canal seepage loss in an irrigation district," Agric. Water Manage., 97(6), pp. 801–
526 810.
- 527 Kostaschuk, R., Shugar, D., Best, J., Parsons, D., Lane, S., Hardy, R., and Orfeo, O., 2009,
528 "Suspended sediment transport and deposition over a dune: Rio Parana, Argentina," Earth
529 Surf. Process. Landf., 34(12), pp. 1605–1611.
- 530 Krogstad, P.Å., and Antonia, R.A., 1999, "Surface roughness effects in turbulent boundary
531 layers," Exp. Fluids 27(5), pp. 450-460.
- 532 Kumar, P., and Foufoula-Georgiou, E., 1997, "Wavelet analysis for geophysical
533 applications," Rev. Geophys., 35(4), pp. 385–412.
- 534 Lane, E. W., 1953, "Progress report on studies on the design of stable channels by the Bureau
535 of Reclamation," ASCE.
- 536 Liu, H.K., 1957, "Mechanics of sediment-ripple formation," J. Hydraul. Div., ASCE, 83, pp.
537 1–23.
- 538 Lu, Y., and Chiew, Y. M., 2007, "Seepage effects on dune dimensions," J. Hydraul. Eng.,
539 133(5), pp. 560–563.
- 540 Mallat, S., 1999, A wavelet tour of signal processing, Academic press.
- 541 Martin, C. A., and Gates, T. K., 2014, "Uncertainty of canal seepage losses estimated using
542 flowing water balance with acoustic Doppler devices," J. Hydrol., 517, pp. 746–761.
- 543 Millar, R. G., and Quick, M. C., 1993, "Effect of bank stability on geometry of gravel rivers,"
544 J. Hydraul. Eng., 119(12), pp. 1343–1363.

- 545 Nakagawa, H., and Tsujimoto, T., 1984, "Spectral analysis of sand bed instability," J.
546 Hydraul. Eng., 110(4), pp. 467–483.
- 547 Nikora, V. I., and Goring, D. G., 2001, "Extended self-similarity in geophysical and
548 geological applications," Math. Geol., 33(3), pp. 251–271.
- 549 Nikora, V. I., Sukhodolov, A. N., and Rowinski, P. M., 1997, "Statistical sand wave
550 dynamics in one-directional water flows," J. Fluid Mech., 351, pp. 17–39.
- 551 Nordin, C. F., and Algert, J. H., 1966, "Spectral analysis of sand waves," J. Hydraul. Div.,
552 ASCE, 92(HY5), 95-114.
- 553 Paphitis, D., 2001, "Sediment movement under unidirectional flows: an assessment of
554 empirical threshold curves," Coast. Eng. 43(3), pp. 227-245.
- 555 Parsons, D., Best, J., Orfeo, O., Hardy, R., Kostaschuk, R., and Lane, S., 2005, "Morphology
556 and flow fields of three- dimensional dunes, Rio Parana', Argentina: Results from
557 simultaneous multibeam echo sounding and acoustic Doppler current profiling," J. Geophys.
558 Res., 110(F4).
- 559 Patel, M., Deshpande, V., and Kumar, B., 2015, "Turbulent characteristics and evolution of
560 sheet flow in an alluvial channel with downward seepage," Geomorphology, 248, pp. 161–
561 171.
- 562 Patel, M., and Kumar, B., 2017, Flow and bedform dynamics in an alluvial channel with
563 downward seepage. Catena, 158, 219-234.
- 564 Patel, M., Majumder, S. and Kumar, B., 2017, "Effect of seepage on flow and bedforms
565 dynamics," Earth Surf. Process. Landf.
- 566 Pitlick, J., Marr, J., and Pizzuto, J., 2013, "Width adjustment in experimental gravel-bed
567 channels in response to overbank flows," J. Geophys. Res. 118 (2), pp. 553-570.
- 568 Qin, J., Zhong, D., and Wang, G., 2013, "Characterizing sand ripples at equilibrium phases".
569 J. Hydrol. Hydromech., 61(4), pp. 293–298.

- 570 Raudkivi, A. J., and Witte, H.-H., 1990, "Development of bed features," *J. Hydraul. Eng.*,
571 116(9), pp. 1063–1079.
- 572 Robert, A., Uhlman, W., 2001, "An experimental study on the ripple–dune transition," *Earth*
573 *Surf. Process. Landf.* 26 (6), pp. 615-629.
- 574 Schindler, R. J., Robert, A., 2005, "Flow and turbulence structure across the ripple–dune
575 transition: an experiment under mobile bed conditions," *Sedimentology*, 52 (3), pp. 627-649.
- 576 Schwammle, V., and Herrmann, H., 2004, "Modelling transverse dunes," *Earth Surf. Process.*
577 *Landf.*, 29(6), pp. 769–784.
- 578 Shugar, D. H., Kostaschuk, R., Best, J. L., Parsons, D. R., Lane, S. N., Orfeo, O., and Hardy,
579 R. J., 2010, "On the relationship between flow and suspended sediment transport over the
580 crest of a sand dune, Rio Parana, Argentina," *Sedimentology*, 57(1), pp. 252–272.
- 581 Simons, D. B., Richardson, E. V., and Nordin Jr, C., 1965, "Bedload equation for ripples and
582 dunes," Tech. rep.
- 583 Singh, A., Lanzoni, S., and Foufoula-Georgiou, E., 2009, "Nonlinearity and complexity in
584 gravel bed dynamics," *Stoch. Env. Res. Risk. A.*, 23(7), pp. 967–975.
- 585 Singh, A., Lanzoni, S., Wilcock, P. R., and Foufoula-Georgiou, E., 2011, "Multiscale
586 statistical characterization of migrating bed forms in gravel and sand bed rivers," *Water*
587 *Resour. Res.*, 47(12).
- 588 Singh, A., Porte'-Agel, F., and Foufoula-Georgiou, E., 2010, "On the influence of gravel bed
589 dynamics on velocity power spectra," *Water Resour. Res.*, 46(4).
- 590 Southard, J.B., Dingler, J.R., 1971, "Flume study of ripple propagation behind mounds on flat
591 sand beds," *Sedimentology*, 16 (3-4), pp. 251–263.
- 592 Sumer, B.M., Chua, L.H., Cheng, N.S., Fredsøe, J., 2003, "Influence of turbulence on bed
593 load sediment transport," *J. Hydraul. Eng.*, 129 (8), pp. 585-596.

- 594 Van der Mark, C., Blom, A., and Hulscher, S., 2008, "Quantification of variability in
595 bedform geometry," J. Geophys. Res., 113(F3).
- 596 Van Rijn, L.C., 1982, "Equivalent roughness of alluvial bed," J. Hydraul. Div., 108 (10), pp.
597 1215-1218.
- 598 Venditti, J. G., Church, M., and Bennett, S. J., 2005, "Morphodynamics of small-scale
599 superimposed sand waves over migrating dune bed forms," Water Resour. Res., 41(10).
- 600 Venugopal, V., Roux, S. G., Foufoula-Georgiou, E., and Arneodo, A., 2006, "Revisiting
601 multifractality of high-resolution temporal rainfall using a wavelet-based formalism," Water
602 Resour. Res., 42(6).
- 603 Wong, M., Parker, G., DeVries, P., Brown, T. M., and Burges, S. J., 2007, "Experiments on
604 dispersion of tracer stones under lower-regime plane-bed equilibrium bed load transport,"
605 Water Resour. Res., 43(3). W03440.
- 606
- 607
- 608
- 609
- 610
- 611
- 612
- 613
- 614
- 615

616 **List of Tables**

617 Table 1. Uncertainty associated with the ADV data^a.

618 Table 2. A summary of experimental parameters.

619

620

621

622

623

624

625

626

627

628

629

630

631

632

633

634

635

636

637

638

639 **List of Figures**

640 Figure 1. Schematic diagram of experimental setup.

641 Figure 2. Investigation of Shields stress during no seepage run and seepage runs.

642 Figure 3. Distribution of time-mean velocities and Reynolds shear stresses against normalized
643 depth for no seepage and with seepage runs. Where u is time-mean velocity, z is distance
644 from bed, and h is depth of flow.

645 Figure 4. Profiles of turbulent kinetic energy dissipation (E_D) and turbulent production (T_P)
646 for no seepage and with seepage experiments.

647 Figure 5. Wavelet coefficients computed at 20 mm and 10 mm length scales from the bed
648 elevation profile after 21 h run for 15% seepage.

649 Figure 6. Variation of statistical moments of the bed elevation increments as a function of
650 length scale (a) after 9 h run for 15% seepage and (b) after 21 h run for 15% seepage.
651 Changes in scaling exponent $\tau(q)$ obtained from the log-log linear regression within the
652 scaling regime (c) after 9 h run for 15% seepage and (d) after 21 h run for 15% seepage.

653 Figure 7. Variation of statistical moments of the bed elevation increments as a function of
654 length scale (a) after 9 h run for 20% seepage and (b) after 21 h run for 20% seepage.
655 Changes in scaling exponent $\tau(q)$ obtained from the log-log linear regression within the
656 scaling regime (c) after 9 h run for 20% seepage and (d) after 21 h run for 20% seepage.

657 Figure 8. Scale dependent pdf of dimensionalized bed elevation increments (a) and (b) after 9
658 h and 21 h runs for 15% seepage (c) and (d) after 9 h and 21 h runs for 20% seepage.

659 Figure 9. Log-log exceedance probabilities of the normalized positive bed elevation
660 increments (a) and (b) after 9 h and 21 h for 15% seepage (c) and (d) after 9 h and 21 h for
661 20% seepage.

Figure 10. Power spectral density versus wavenumber plots of bed elevations fluctuations (a) and (b) after 9 h and 21 h runs for 15% seepage (c) and (d) after 9 h and 21 h for 20% seepage experiment. x -axis denotes wave number (mm^{-1}) and y -axis denotes power spectral density.

Figure 11. Snapshots of the channel cross section after (a) no seepage run (b) 15% seepage run and (c) 20% seepage run (at the end of seepage experiment)

685 Table 1. Uncertainty associated with the ADV data^a

Parameters	u (m/s)	v (m/s)	w (m/s)	$(\overline{u'u'})^{0.5}$ (m/s)	$(\overline{v'v'})^{0.5}$ (m/s)	$(\overline{w'w'})^{0.5}$ (m/s)
Standard deviation	5.4×10^{-3}	8.08×10^{-4}	3.41×10^{-4}	1.59×10^{-3}	6.41×10^{-4}	2.5×10^{-4}
Standard uncertainty	1.7×10^{-3}	2.56×10^{-4}	1.08×10^{-4}	0.5×10^{-3}	2.03×10^{-4}	0.8×10^{-4}

686 ^aWhere u , v , and w are the time-averaged velocities in the streamwise, lateral, and vertical directions,
687 respectively. The quantities u' , v' , and w' are the fluctuating components of the instantaneous velocities in the
688 streamwise, transverse, and vertical directions respectively. The terms $(\overline{u'u'})^{0.5}$, $(\overline{v'v'})^{0.5}$ and $(\overline{w'w'})^{0.5}$ are
689 the root mean square values of u' , v' , and w' , respectively.

690

691 Table 2. A summary of hydraulic parameters^a

Experimental run	Top width B , m	Maximum flow depth, h m	Bed slope, S	Water surface slope, S_w	Inflow discharge, Q_0 m ³ /s	Reynolds no.	Seepage discharge, q_s (% Q_0)
Run 1 [*]	0.70	0.14	0.00116	0.000184	0.0175	21086.44-	15% and 20%
Run 2			0.00176	0.000151	0.0169	22920.04	
Run 3			0.00249	0.000110	0.0161		
Sand size $D_{50} = 0.41$ mm, Froude no. for no seepage was 0.30 and for seepage case it was varied from 0.38 to 0.40							
*Run used for analysing the flow and bedform characteristics.							

692 ^aValues of hydraulic parameters are given in the Table for no seepage runs where different percentages of
693 seepage were applied without stopping the no seepage experiment.

694

Figure 1

Figure 2

Figure 3

Figure 4.

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11