Effects of hydrodynamic on the mobility of phosphorous induced by sediment resuspension in a seepage affected alluvial channel

Anurag Sharma, Post-Doctoral Research Fellow, Lei Huang, Assistant Research Fellow, Hongwei Fang, Professor, Xiaocui Li, Ph.D. student

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Authors

1. Anurag Sharma
   Post-Doctoral Research Fellow, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, anu2956@tsinghua.edu.cn

2. Lei Huang [Corresponding Author]
   Assistant Research Fellow, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, huanglei2017@tsinghua.edu.cn

3. Hongwei Fang
   Professor, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, fanghw@tsinghua.edu.cn

4. Xiaocui Li
   Ph.D. student, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, lixc17@mails.tsinghua.edu.cn
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1. Anurag Sharma
   Post-Doctoral Research Fellow, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, anu2956@tsinghua.edu.cn

2. Lei Huang [Corresponding Author]
   Assistant Research Fellow, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, huanglei2017@tsinghua.edu.cn

3. Hongwei Fang
   Professor, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, fanghw@tsinghua.edu.cn

4. Xiaocui Li
   Ph.D. student, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China, lixc17@mails.tsinghua.edu.cn
Abstract

The phosphorus (P) mobility caused by sediment resuspension was investigated in a tilting flume, considering the important effect of upward seepage. The water level and velocity were observed during the experimental run, and water samples were collected for the measurement of sediment and P concentrations. A lower value of P and sediment concentrations occurred at the upstream end of the test section, and then a stable trend was gradually observed towards the downstream end due to the sediment resuspension and deposition within the test section. A lower P release was identified for the seepage run, accompanied with a lower sediment concentration in the overlying water. These phenomena were directly linked with the turbulent flow characteristics such as time-averaged velocity, Reynolds shear stresses, and turbulence intensity. Results show that the level of turbulence decreased with the upward seepage, indicating lower P and sediment concentrations. The turbulent length scale also decreased with the upward seepage, which led to a decrease in the energy and momentum transfer induced by the larger eddy size in the near-bed region, and eventually, a lower rate of sediment resuspension and P release with upward seepage.

The results of the present study are useful for civil or hydraulic engineers since the knowledge of P transport with sediment will improve the management of contaminated sediment in seepage affected alluvial channel.

Keywords: alluvial channel; turbulence; sediment resuspension; phosphorus mobility; upward seepage
1. Introduction

Most rivers generally contain a vast quantity of sediment, and sedimentation and resuspension are the key processes influencing the river morphology and water quality (Fang and Wang, 2000). The flow velocity decreases in non-flood seasons and eventually, a vast quantity of contaminated sediment is accumulated at the riverbed (Fang and Rodi, 2003). As the flow velocity increases, sediment resuspension is observed, which tends to release pollutants into the overlying water and initiates the various environmental and ecological difficulties in the river (Yao et al., 2009). Therefore, the study on the pollutant mobility in the river is important, and its chemical and sediment dynamics should be incorporated for the maintenance of the river health.

Phosphorus (P) is an important nutrient influencing water quality (Elser et al., 2007; Schindler, 2006), and the mobility of P with sediment in an alluvial channel needs to be addressed. Previous studies mostly concerned the rate and degree of P sorption in a small-scale microcosm (Krom and Berner, 1980; Wang et al., 2009; Zhang and Huang, 2011; Zhou et al., 2005), which is insufficient as a reference for P mobility in a natural river. Some of the previous literature studied the release of P with sediment from the bottom of the lakes in which the mechanics of sediment and hydrodynamics are obviously dissimilar to natural rivers (Jiang et al., 2006; Jin et al., 2006; Pedro et al., 2013; Sun et al., 2006). Barlow et al. (2004) and Ussher et al. (2011) observed that the laboratory flume experiment is an active way to incorporate the chemical and mechanics of sediment, such that the gap between the small-scale adsorption experiment and the field observation can be improved to better understand the prime phenomena corresponding to pollutant mobility. For example, Lansard et al. (2006) investigated the transport of contaminated sediment with plutonium (Pu) in a laboratory-tilting flume; and Couceiro et al. (2009) examined the movement and reactivity of nickel (Ni) bound to size-fractionated sediment from the Mersey.
estuary in a large tilting flume. However, laboratory investigation on the mobility of P with sediment is hardly reported. Huang et al. (2015) used a circulated tilting flume to examine P mobility caused by sediment resuspension, and observed a faster P release for coarse sediment and a more continuous P release for fine sediment.

Seepage is an important explicit parameter of a sand bed channel that occurs in the form of lateral flow. Seepage may get into the channel bed and banks from the groundwater (i.e. upward seepage), or it may be out of the channel bed in the form of downward seepage, depending on the water level in the stream and the ground water table (Richardson et al., 1985). If the water level in the stream is higher than the surrounding ground water table, downward seepage occurs, and vice versa. The interface between the main flow and seepage flow is important to understand the transport of sediment and contaminants and maintain a healthy river ecosystem. Nezu (1977) observed a reduction in the near-bed flow velocity profile with the application of upward seepage to the channel. Previous literature used the Prandtl’s mixing-length theory to propose a revised law of the wall boundary subjected to the upward seepage (Clarke et al., 1955; Stevenson, 1963). Cheng and Chiew (1998) proposed a revised log law of flow velocity in the inner layer when upward seepage was applied in the channel by solving the Reynolds equations and determining the unknown factors empirically. Dey and Zanke (2004) proposed an analytical model to calculate the threshold bed shear stress for non-cohesive sediment transport subject to upward seepage. Considering the Reynolds equations, Dey and Cheng (2005) developed a vertical profile of Reynolds shear stress in a non-uniform and unsteady flow in the presence of upward seepage. Bose and Dey (2007) investigated the application of upward seepage on turbulent shear flows based on Reynolds-averaged Navier-Stokes (RANS) equations, and obtained a reduction in the Reynolds shear stress with upward seepage. Dey and Nath (2010) studied the turbulent flow
characteristics in a gravel bed subjected to upward seepage and observed a decrease in
turbulence with seepage. However, with the application of upward seepage, Watters and Rao
(1971) examined the dynamic fluid forces acting on sediment particles, and observed that the
turbulence intensity increased with seepage causing a higher mass exchange between the flow
and sediment bed. Nezu (1977) measured the flow turbulence intensity with upward seepage, and
also found that the turbulence intensity increased subjected to seepage. The effects of upward
seepage on the turbulent boundary layer in a permeable strip have been investigated by other
researchers (Krogstad and Kourakine, 2000; Kim and Sung, 2003), which confirmed the
observations of Nezu (1977) that upward seepage increased the turbulence intensity. Rao and
Nagaraj (1999) used a hot-film anemometer to examine the turbulence intensities in both the
downward and upward seepage flows, and observed that the velocity fluctuations with
downward seepage flow were higher as compared to no seepage and upward seepage flows.
Thus, the turbulent characteristics are affected by the upward seepage, which may further affect
the sediment dynamics and P mobility; but there are still different conclusions in the literature,
i.e. a decrease or increase in the turbulence with upward seepage.

Aforementioned studies have focused on the P mobility with bed particle in the laboratory or in
the field condition. The release of P and its mobility due to bed material resuspension with
upward seepage remain unexplored, and the effects of turbulent flow characteristics are yet to be
investigated. Therefore, the aim of this study is to quantitatively estimate the effects of upward
seepage on P release, and particularly, explore the effects of turbulent flow subjected to no
seepage and upward seepage on the P mobility with sediment. A circulated tilting flume with
seepage arrangement was specially used to estimate the quantity of P release and its transport
caused by sediment suspension. Acoustic Doppler velocimeter (ADV) was used to measure the

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three-dimensional instantaneous flow velocities at a certain depth, which provide important results linked to the flow turbulence. The present study delivers computable mechanistic evidence for the mobility of P with sediment and can improve the management of contaminated sediment in the river.

2. Materials and Methods

2.1 Design of flume experiments

The experiments were conducted in a rectangular tilting flume with 16.0 m length, 0.5 m width, and 0.5 m depth, to investigate the P release caused by sediment resuspension and its mobility, as shown in Fig. 1(a). A pipe baffle was set at the upstream end of the channel to ensure a uniform flow. The flow was regulated by a discharge controlling system, and the water level was adjusted by a tailgate at the downstream end of the flume. The seepage chamber was formed between the stainless steel mesh and the channel bed in the test section of the flume, i.e. at $x = 10$ m with a length of 3.0 m, 0.5 m wide and 0.1 m depth, see Fig. 1. The location of the test section was selected to minimize the influences of inflow and outflow in the channel, and a flume length of 16 m was sufficient to get a fully developed flow in the test section. The function of the seepage chamber was to supply water into the sand bed channel in the form of upward seepage, which was measured by an electromagnetic flow meter. All experiments were conducted with a channel bed slope of 0.0025, and the recirculation of water was achieved using a pump system. Since the aspect ratio (i.e. the ratio of flow width to the flow depth) in the present study was greater than 6, the flow was not influenced by the side walls (Yang et al., 2004), and eventually, the flow was free from three-dimensional effect.
Figure S1 shows the particle size distributions of the used bed materials, i.e. the fine sediment placed in the testing section (the median sediment size $d_{50} = 0.27$ mm) and the boulder in the rest part of the flume. The geometric standard deviation $\sigma_g = (d_{84.1} - d_{15.9})/d_{50}$ of the used sediment was 0.93, where $d_x$ is the size for which $x$ percent of the particles are finer, indicating that it was uniform sand because $\sigma_g < 1.4$ (Marsh et al., 2004). Table 1 shows the sediment and flow arrangement.
parameters involved in the experiments. The sediment was spiked with P by stirring with a phosphate standard solution at a certain time interval for 24 h to reach a steady condition. Then, the prepared sediment sample was taken to the test section of the flume and placed on the fine stainless steel mesh to prevent its entry into the bottom seepage chamber. The thickness of the sediment layer was 10 cm, and a boulder layer of 10 cm thickness was placed in the remaining length of the flume to achieve a uniform bed level. The water tanks were installed at both the upstream and downstream ends of the flume to prevent the recirculation of the eroded sediment.

The experiments were conducted for two main flow discharge ($Q_1$ and $Q_2$), where $Q_1$ is the discharge corresponding to the incipient motion, and $Q_2$ is a greater discharge. For the discharge $Q_1$, the bed shear stress is equal to the critical value and the channel bed is in an incipient motion condition; while for the discharge $Q_2$, the bed shear stress exceeds the critical value, and therefore, the channel bed is in a mobile condition. Moreover, the experiment was done for both the conditions of no seepage (NS) and upward seepage (US). In accordance with the ranges suggested by the previous literature (Richardson et al., 1985, Dey et al., 2011) for the volumetric changes of water due to seepage and the corresponding seepage velocities, the discharge of the upward seepage was maintained at 5% of the main flow discharge. The experiment was first conducted for the no seepage condition, and then a new sediment bed channel was prepared for the upward seepage condition with the applied seepage discharge equaling to 5% of the main flow discharge.

**Table 1** Details of the sediment and the flow parameters involved in the experiments

<table>
<thead>
<tr>
<th>Sediment size, $d_{50}$</th>
<th>Geometric standard</th>
<th>Discharge, $Q$ (L s$^{-1}$)</th>
<th>Flow depth, $h$ (cm)</th>
<th>Flow Reynolds</th>
<th>Upward seepage</th>
</tr>
</thead>
</table>


<table>
<thead>
<tr>
<th>(mm)</th>
<th>deviation, $\sigma_g$</th>
<th>$Q_1$</th>
<th>$Re$</th>
<th>$q_s$</th>
<th>$5%$ of $Q_1$</th>
<th>$Q_2$</th>
<th>$7.5$</th>
<th>$18600$</th>
<th>$5%$ of $Q_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.27</td>
<td>0.93</td>
<td>7.2</td>
<td>6.5</td>
<td>14300</td>
<td>$5%$ of $Q_1$</td>
<td>9.3</td>
<td>7.5</td>
<td>18600</td>
<td>$5%$ of $Q_2$</td>
</tr>
</tbody>
</table>

### 2.2 Measurement of hydrodynamics

The water levels were measured at $x = 1.2, 2.7, 4.3, 5.8, 7.3, 8.9, 9.7, 10.4, 11.1, 12, 12.7$ and $13.5$ m from the upstream end using rulers attached to the side of the flume. The instantaneous three-dimensional flow velocities were measured by ADV at the centerline of the test section (i.e. at $x = 10$ and $11$ m). The sampling frequency of ADV was set as $100$ Hz for the data collection, and the acoustic frequency was $10$ MHz. The ADV collects the data in a cylindrical sampling volume of diameter $6$ mm and height $1$ to $4$ mm. The location of the sampling volume is $5$ cm beneath the central transmitter, thus, the velocity cannot be measured within a distance of $5$ cm from the water surface. Meanwhile, when the data collection was far away from the bed, the height of cylindrical sampling volume was maintained at $4$ mm, and it was $1$ mm in the case of near-bed data collection so that the sampling volume did not collide with the bed materials. The sampling height of $1$ mm was sufficient to achieve the real flow profiles in the inner region and near-bed zones (Sharma and Kumar, 2018a). The instantaneous velocities were measured in a vertical profile for duration of $5$ min, which was adequate to capture the time-independent time-averaged velocity.

Accordingly, the features of turbulent flow, including the time-averaged velocity, Reynolds shear stresses (RSS), turbulence intensity, and turbulent integral scale, were obtained based on the ADV measurement. The time-averaged velocity in the streamwise direction was calculated as
\[ u = \frac{1}{n} \sum_{i=1}^{n} u_i \]  

(1)

where, \( u_i \) is the instantaneous velocity in the streamwise direction, and \( n \) is the number of measurements. The Reynolds shear stress was calculated as

\[ \overline{uw} = \frac{1}{n} \sum_{i=1}^{n} (u_i - u)(w_i - w) \]  

(2)

\[ \tau_{uw} = -\rho \overline{uw} \]  

(3)

The turbulence intensity in the streamwise direction, \( \sigma_u \), was calculated as

\[ \sigma_u = \left[ \frac{1}{n} \sum_{i=1}^{n} (u_i - u)^2 \right]^{0.5} \]  

(4)

The integral length scale can be calculated by Taylor (1935)

\[ E_T = E_T u \]  

(5)

where, \( E_T \) is integral time scale

\[ E_T = \int_{0}^{T} R(t) dt \]  

(6)

where, the autocorrelation function \( R(t) \) at time \( T \) is approximately equals to zero, and the term \( dt \) represents the lag distance.

In order to check the uncertainty of the ADV measurement, ten pulses of instantaneous velocities were measured at a distance of 5 mm from the bed surface. Table S1 lists the uncertainty associated with the ADV data, where, \( u, v, \) and \( w \) are the time-averaged velocity in the streamwise, widthwise, and vertical directions, respectively, \( u', v' \) and \( w' \) are the corresponding components of velocity fluctuations, and \( \overline{u'u'}^{0.5}, \overline{v'v'}^{0.5} \) and \( \overline{w'w'}^{0.5} \) are the turbulence intensity. The uncertainty can be defined as the standard deviation of the time-averaged value of
various repeated pulses of instantaneous velocities. The standard uncertainty, \( S_u \), was calculated as:

\[ S_u = \frac{S_d}{\sqrt{n}} \quad (7) \]

where \( S_d \) represents the standard deviation, and \( n \) is the number of pulses of instantaneous velocities (i.e. \( n = 10 \) in the present study). It is observed from Table S1 that the uncertainties of time-averaged velocities and turbulence intensities were less than \( \pm 5\% \), which indicated the accuracy of ADV measurement (Sharma and Kumar, 2018 b).

The instantaneous velocity obtained from the ADV measurement contained spikes due to the interference between the reflected and transmitted pulses. The present study used an acceleration threshold method to eliminate the spikes from the velocity data (Goring and Nikora, 2002). The velocity data were filtered using the signal to noise ratio (SNR) and the correlation, which was set as 15 and 70, respectively. The correlation value was reduced to 65 in the near-bed region (Dey et al., 2012). The range of acceleration threshold value was set as 1-1.5 so that the velocity power spectra of the streamwise velocity component matched with Kolmogorov -5/3 scaling law in inertial sub-range (Lacey and Roy, 2008). In this study, the velocity power spectra \( F_{uu}(f) \) at \( z = 4 \) mm (\( z \) is a particular distance from bed surface) was calculated using the discrete fast Fourier transforms, and Fig. S2 shows the profiles of \( F_{uu}(f) \) with the frequency, \( f \). It is observed that \( F_{uu}(f) \) for the filtered data were in good agreement with the Kolmogorov’s -5/3 law

**2.3 Sampling and analysis**

A special sampling instrument was designed, see Fig. S3, to collect the water samples at the centerline of cross sections along the flume, i.e. at \( x = 9, 10, 11, 12, \) and 13 m. The water samples
collected at $x = 9$ m were used to estimate the re-circulation of particles within the flume, and the corresponding sediment and P concentrations were subtracted from the test section to eliminate the effects of recycling. Overall, the proper arrangement of upstream and downstream tanks allowed the recycling of only very few amounts of eroded sediment in the flume.

The water samples were collected at two different flow depths of a particular section, i.e. $0.1h$ near the bed surface and $0.9h$ near the water surface, where $h$ is the flow depth. Meanwhile, two water samples were collected at each depth, i.e. one sample for the measurement of sediment concentration with a photoelectric sediment concentration meter, and the other sample for the P concentration measurement by the ammonium molybdate spectrophotometric technique with a measurable range of $0.01$ mg L$^{-1}$. The efficiency of the analytical technique for P measurement was examined by the certified reagent, which had a certified P concentration of $1.58 \pm 0.06$ mg L$^{-1}$ and a measured concentration of $1.59 \pm 0.02$ mg L$^{-1}$ ($n = 6$). The recoveries ranged from 94.8% to 104%.

3. Results and Discussion

The effects of upward seepage on the channel hydrodynamics, sediment concentration, and P mobility are discussed in this section, and the interactions among turbulent flow characteristics, sediment concentration, and P mobility are explored.

3.1 Flow characteristics

Figure 2 displays the profiles of time-averaged velocity against dimensionless flow depth, $z/h$, for all the runs (including the profiles at $x = 10$ and 11 m for the flow discharge of $Q1$ and $Q2$), where the solid and open circles represent the no seepage and upward seepage runs, respectively. The time-averaged velocity was maximum at the water surface and gradually decreased towards
the bed surface due to the collision of bed particles that resulting in the deficiency of momentum.

The time-averaged velocity decreased with the application of upward seepage, which may cause a decrease in the sediment concentration in the flume. It is shown that the near-bed time-averaged velocities decreased by 4-6% when the upward seepage was applied, which was enough for the bed sediment to move slowly.

**Fig. 2** Vertical distribution of time-averaged velocity at $x = 10$ and $11$ m for the flow discharge of $Q_1$ and $Q_2$

Reynolds shear stress (RSS) is defined as the exchange of momentum from the overlying flow to the bed sediment and vice versa. RSS was calculated for both no seepage and upward seepage runs, and Fig. 3 shows the vertical distribution of RSS with the dimensionless flow depth $z/h$ for all the runs, where the solid and open circles also represent the no seepage and upward seepage runs, respectively. It is observed that the RSS increased with the water depth, indicating that the
momentum transfer was greater from the overlying flow to the bed sediment, and it could sustain the sediment transport overcoming the bed resistance. The peak value of RSS was obtained near the inner layer and then decreased towards the bed surface because of the presence of viscosity or roughness sub-layer in the near-bed region. The profiles of RSS were similar for all the experimental runs, but the magnitudes of RSS varied. Particularly, the magnitudes of RSS with upward seepage were lowered by 10-20% as compared with no seepage runs for both the discharge $Q_1$ and $Q_2$, which suggested a decreased momentum transfer towards the bed probably decreasing the sediment transport.

![Vertical distribution of Reynolds shear stress at $x = 10$ and $11$ m for the flow discharge of $Q_1$ and $Q_2$](image)

The turbulence intensity is defined as the root mean square of the fluctuating components of velocities. The streamwise turbulence intensity, $\sigma_u$, indicates the velocity fluctuation or
turbulence strength in the longitudinal direction. Figure 4 shows the vertical distributions of $\sigma_u$ at $x = 10$ and 11 m for the flow discharge of $Q_1$ and $Q_2$. Similarly, the solid and open circles represent the no seepage and upward seepage runs, respectively. The maximum value of $\sigma_u$ was observed at the water surface, while the minimum value was observed in the near-bed zone because of the decreasing RSS. The streamwise turbulence intensity decreased after the application of upward seepage, which indicated that the upward seepage reduced the velocity fluctuation, and eventually, the resuspended sediment concentration may decrease with upward seepage. The vertical distribution of turbulence intensity was important in the inner layer of the flow, and the value of damping decreased by 10-20% with upward seepage as compared with the no seepage condition.

**Fig. 4** Vertical distribution of streamwise turbulence intensity at $x = 10$ and 11 m for the flow discharge of $Q_1$ and $Q_2$
The size of large eddy in the flow represents the turbulent integral length scale, and the turnover time of the eddy at a particular point is known as the integral time scale. The larger eddies are responsible for the exchange of momentum and turbulent kinetic energy from the flow to the bed sediment. Eventually, the bed morphology is developed due to the turbulent integral scale in the near-bed flow (Venditti et al., 2005; Sharma and Kumar, 2017). Therefore, the integral length scale, $E_L$, was estimated in the near-bed region ($z = 10$ mm) using the instantaneous velocity time series data to observe the change of sediment concentration with the upward seepage. The estimated $E_L$ in the near-bed region is shown in Table S2. The results show that the value of $E_L$ decreased considerably with upward seepage by 17.5%, which indicated a reduction in the transfer of flow momentum and energy to the bed sediment.

Thus, the flow turbulence characteristics, including the time-averaged velocity, Reynolds shear stresses, turbulence intensity, and turbulent integral scale, decreased with upward seepage, probably resulting in a decrease of sediment concentration and P mobility.

### 3.2 Sediment concentration

In an alluvial channel, the incipient motion condition of sediment particles is achieved when the bed shear stress acting on the sediment particles (i.e. hydrodynamic force) is equal to the critical shear stress (i.e. resistive force). Therefore, sediment concentration directly depends on the differences between the hydrodynamic and resistive forces, and then the eroded sediment may be transported and probably deposited in the downstream sections of the flume. In this study, the bed shear stress for the discharge $Q1$ was approximately equal to the critical value (i.e. incipient motion condition), and thus, sediment particles were not yet eroded from the bed; while for the discharge $Q2$, the bed shear stress was higher than the critical value and there were sediment particles eroded from the test section. Therefore, the sediment concentration was only measured
for the $Q_2$ condition (including both the conditions of no seepage and upward seepage) due to no sediment resuspension at $Q_1$. The spatial profiles of sediment concentration at $0.1h$ near the bed surface (bottom) and $0.9h$ near the water surface (surface) for the discharge run $Q_2$ are shown in Fig. 5, where $x$ represents the distance from the upstream end of the flume.

In general, a common profile was found for both no seepage and upward seepage runs, i.e. a lower sediment concentration was found at $x = 10$ m, and then it increased and tended to be stable gradually along the test section of the flume due to the erosion and deposition. It can be found that the sediment concentration in the test section was reduced by 0-10% with upward seepage, owing to the decreased turbulent parameters such as the time-averaged velocity (4-6%), Reynolds shear stress (10-20%), turbulence intensity (10-20%), and integral length scale. Thus, sediment concentration decreased with the upward seepage, which ultimately verified that the bed shear stress decreased with upward seepage.

![Graph](image.png)

Fig. 5 The spatial variation of sediment concentration at $0.1h$ near the bed surface (bottom) and $0.9h$ near the water surface (surface) for the discharge run $Q_2$. 
3.3 Phosphorus concentration

Due to the application of hydrodynamic forces, phosphorous (P) in the contaminated sediment is released into the overlying flow together with the sediment erosion. Then, the released P is transported along the flume in the form of both particulate and dissolved phases. The longitudinal profiles of P concentration at 0.1h (bottom) and 0.9h (surface) for discharge runs Q1 and Q2 are shown in Fig. 6, and the curves for the discharge runs Q1 and Q2 are indicated by circles and triangles, respectively. As described in Section 2.3, the water samples collected at x = 9 m were used to estimate the re-circulation of P within the flume, and the corresponding P concentrations were subtracted from the test section to eliminate the effects of recycling.

Therefore, there may be some minor negative values of the presented P concentrations in Fig. 6 due to the relatively weak P release in some cases. Overall, a similar trend of P concentration was observed for no seepage and upward seepage runs (i.e. a smaller P concentration was found at x = 10 m (upstream of the test section) and then it increased and tended to be stable gradually along the flume), but with a lower magnitude of P concentration for the upward seepage run. As the P release is dominated by sediment erosion, the P release was inhibited because the turbulence was inhibited by the upward seepage with less sediment resuspension, i.e. a lower P release was observed for the upward seepage run which was consistent with the sediment concentration. Fig. S4 shows the relation between the measured sediment and P concentrations in the test section, also indicating the positive relation between sediment erosion and P release.

Moreover, it was estimated that the decrease of time-averaged velocity, RSS, and turbulence intensities with upward seepage led to a decrease of 25-40% of P release. In addition, the value of dC/dx was analyzed from Fig. 6, where dC/dx represents the net release (positive) or net deposition (negative) of P between two adjacent sections in the flume. We observed significant
positive values of $\frac{dC}{dx}$ at the upstream part of the test section suggesting a remarkable P release.

![Graph](image)

**Fig. 6** The spatial variation of phosphorous concentration at (a) $0.1h$ (bottom) and (b) $0.9h$ (surface) for the discharge runs $Q_1$ and $Q_2$

### 4. Conclusions

In this study, the release of phosphorous (P) with sediment concentration and its transport in an alluvial channel was investigated in a tilting flume. The experiments were conducted for both no seepage and upward seepage runs to examine the effects of upward seepage on the P mobility with sediment erosion. Particularly, the turbulent flow characteristics for no seepage and seepage runs were investigated to link these results with P and sediment concentration. The main conclusions are as follows:

1. The presence of upward seepage reduced the vertical profiles of RSS, which indicated a lower momentum transfer towards the bed surface. The profile of RSS had a damping nature within the inner layer of flow due to the reducing turbulent fluctuation, and thus, the turbulence intensities also decreased with the upward seepage. Meanwhile, the integral length scale was reduced by 17.5% with upward seepage.
2. The sediment concentration in the flume was smaller with upward seepage due to the decreasing turbulent parameters. A shared longitudinal profile of sediment concentration was observed for no seepage and upward seepage run, but the sediment erosion was lower for the upward seepage run.

3. The P in the sediment was released into the overlying flow together with sediment erosion, and then transported along the flow direction in the channel. A similar longitudinal profile was observed for P and sediment concentrations, which indicated a correlation between P mobility and sediment erosion.

4. In the presence of upward seepage, the time-averaged longitudinal velocity, RSS, and turbulence intensity were reduced by 4-6%, 10-20%, and 10-20%, respectively, as compared with the no seepage run; and eventually, the sediment concentration and P concentration decreased by 0-10% and 25-40%, respectively.

Overall, the upward seepage may decrease the turbulence, and eventually, affect the sediment resuspension and P release. A detailed characterization of the turbulence introduces the relation among the hydrodynamics, sediment resuspension, and P release, and may improve the existing models by delivering the effects of turbulence on P mobility with sediment resuspension under the influence of upward seepage. This study tries to establish a link among the turbulent flow characteristics, sediment and P concentrations in natural rivers with upward seepage flow, which would further help the river engineers for the management of contaminated sediment.

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References


Figures Captions

**Fig. 1** (a) Plan and side views of the tilting flume, and (b) cross-sectional profile of the seepage arrangement.

**Fig. 2** Vertical distribution of time-averaged velocity at $x = 10$ and $11$ m for the flow discharge of $Q_1$ and $Q_2$.

**Fig. 3** Vertical distribution of Reynolds shear stress at $x = 10$ and $11$ m for the flow discharge of $Q_1$ and $Q_2$.

**Fig. 4** Vertical distribution of streamwise turbulence intensity at $x = 10$ and $11$ m for the flow discharge of $Q_1$ and $Q_2$.

**Fig. 5** The spatial variation of sediment concentration at $0.1h$ near the bed surface (bottom) and $0.9h$ near the water surface (surface) for the discharge run $Q_2$.

**Fig. 6** The spatial variation of phosphorous concentration at (a) $0.1h$ (bottom) and (b) $0.9h$ (surface) for the discharge runs $Q_1$ and $Q_2$.

**Fig. S1** Grain size distributions of (a) fine sediment in the test section and (b) boulder in the rest part of the flume.

**Fig. S2** Velocity power spectra (a) before and (b) after spike removal compared with Kolmogorov’s -5/3 law in the inertial sub range at $z = 4$ mm.

**Fig. S3** A special designed instrument for water sampling (Huang et al., 2015).

**Fig. S4** Relation between the measured sediment and P concentrations in the test section.
Supplementary material for the manuscript:

Ms. Ref. No.: CHEM72128
Title: Effects of hydrodynamic on the mobility of phosphorous induced by sediment resuspension in a seepage affected alluvial channel
Journal: Chemosphere
Authors: Anurag Sharma, Lei Huang*, Hongwei Fang, Xiaocui Li

Fig. S1 Grain size distributions of (a) fine sediment in the test section and (b) boulder in the rest part of the flume

Fig. S2 Velocity power spectra (a) before and (b) after spike removal compared with Kolmogorov’s -5/3 law in the inertial sub range at z = 4 mm
**Fig. S3** A special designed instrument for water sampling (Huang et al., 2015)

**Fig. S4** Relation between the measured sediment and P concentrations in the test section

**Table S1** Uncertainty associated with ADV data

<table>
<thead>
<tr>
<th></th>
<th>$u$</th>
<th>$v$</th>
<th>$w$</th>
<th>$(u' u')^{0.5}$</th>
<th>$(v' v')^{0.5}$</th>
<th>$(w' w')^{0.5}$</th>
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<tbody>
<tr>
<td>Standard deviation</td>
<td>$4.32 \times 10^{-3}$</td>
<td>$9.65 \times 10^{-4}$</td>
<td>$4.30 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$9.39 \times 10^{-4}$</td>
<td>$3.4 \times 10^{-4}$</td>
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<tr>
<td>Uncertainty (%)</td>
<td>0.137</td>
<td>0.031</td>
<td>0.014</td>
<td>0.035</td>
<td>0.030</td>
<td>0.011</td>
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Table S2 Time-averaged integral length scale and time scale at \( z = 10 \text{ mm} \) above the bed surface

<table>
<thead>
<tr>
<th>Experimental condition</th>
<th>Eulerian time scale, ( \langle E_T \rangle ), (s)</th>
<th>Time-averaged velocity, ( u ), (m s(^{-1}))</th>
<th>Eulerian length scale, ( \langle E_L \rangle ), (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upward seepage</td>
<td>0.22</td>
<td>0.153</td>
<td>0.033</td>
</tr>
<tr>
<td>No seepage</td>
<td>0.25</td>
<td>0.160</td>
<td>0.040</td>
</tr>
</tbody>
</table>
Plan view

Side view

(a)
Highlights

• P mobility with sediment in a seepage affected alluvial channel was investigated.
• The level of turbulence decreased with the upward seepage.
• A lower P release and sediment resuspension were observed due to upward seepage.
Credit Author Statement

**Anurag Sharma:** Investigation, Formal analysis, Writing - Original Draft. **Lei Huang:** Methodology, Investigation, Writing - Review & Editing. **Hongwei Fang:** Conceptualization, Supervision. **Xiaocui Li:** Investigation, Formal analysis.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: