The effects of a low-permeability lens on hyporheic exchange intensity

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Abstract. Hyporheic exchange induced by dunes is a key process controlling water fluxes and biogeochemical process in river network, which has gained significant advances. Owing to the limitation of instrumental detection at small spatial scales, previous studies mainly focused on dune-induced hyporheic exchange in homogeneous systems and the impacts of a low-permeability lens on hyporheic process is still unknown. 2-D laboratory flume experiments were conducted in this study to quantitatively analyze the response mechanism of hyporheic exchange to the spatial locations of a low-permeability lens. Results indicated that the lens has hindering effects on the hyporheic exchange process and when located at the center of the horizontal location, the hindering effects were the weakest. The effect weakens when the vertical locations of the lens getting deeper. With the lens moving from the locations closer to the upstream face to that closer to the downstream face of the dunes, or moving from a shallow depth to a deep depth, the flowing path of hyporheic exchange become less influenced by the lens and the area of HZ is getting larger.

1. Introduction

Hyporheic exchange is an important component of groundwater-surface water (GW-SW) interactions, which means the water that flows from streams or rivers into shallow subsurface and then returns to the stream [1]. This kind of GW-SW exchange has significant influences on contaminant transport and remediation, water resources management, and the functioning of aquatic ecosystems [2]. Investigating the mechanisms that drive hyporheic exchange is very important to the further understanding of the physical, biogeochemical and thermal processes in streams, hyporheic zones and aquifers [3].

One fundamental mechanism of hyporheic exchange is the existence of pressure gradients at the streambed surface generated by surface water flowing over dunes in streambed surface [4]. Previous studies have made significant advances in the understanding of dune-induced hyporheic exchange by conducting laboratory experiments and numerical simulations. Elliott and Brooks [5, 6] provided analytical approximations of velocity fields, residence times and net mass exchange in the hyporheic zone generated by dunes. Jin *et al* [7] studied solute transport process in a streambed with dunes by combining laboratory experiments and numerical simulations.

Despite significant advances, most dune-induced hyporheic process studies have focused on homogeneous systems. However, the heterogeneity of streambed sediments is recognized to have significant effects on subsurface flow process and solute transport [8]. Especially, hydrological and

ecological processes can be significantly influenced by the presence of fine-grained sediments with low permeability [9]. To better analyze the effect of low-permeability sediments on hyporheic exchange, we focus on low-permeability lens features in this study. Such features are widespread in natural streambeds [10]. Research has suggested that in heterogeneous sediments, the transportation of aqueous solute [11] and nonaqueous solute [12] are both controlled by the presence of low-permeability lenses. Gomez-Velez *et al* [13] studied the impacts of low-permeability layers on spatial distributions of hyporheic flow. However, the mechanism of hyporheic flow under the control of a low-permeability lens is still unknown. No studies have revealed the impact a low-permeability lens with varying sizes and locations on hyporheic process.

In this study, we focus on hyporheic process at the scale of a bedform, aiming to uncover the impact of a low-permeability lens on dune-induced hyporheic exchange. The response mechanism of hyporheic exchange to a low-permeability lens was quantitatively analyzed by conducting laboratory flume experiments. One single lens with varying spatial location was imbedded in the streambed to study its effects on the hyporheic process. How hyporheic exchange intensity and hyporheic flow paths respond to the presence of a low-permeability lens was revealed in this study.

2. Methodology

2.1. Flume Setup

The dune-induced hyporheic processes was researched by a rectangular recirculating flume, shown as figure 1. The recirculating flume consisted of a 200 cm long, 10 cm wide and 120 cm high sandbox (located in the center of the flume), two rectangular water tank (located on the left and right sides of the sandbox, respectively) and a recirculating pipe system. The sandbox was filled with sand which has a mean diameter that equals to 0.5 mm and a porosity that equals 0.3. The hydraulic conductivity was estimated by the in-situ permeability testing method which equals 0.075 cm/s [14]. The sand was made as dune shaped, which had the length of 58 cm and the height of 17 cm. To keep the triangular dunes remain stationary, wet method in Jin *et al* [7] was applied when making dunes. The dunes sizes were kept unchanged along the cross section of the flume. The mean water depth was 13 cm in this study, which equals to the distance from the water surface to the average bed level. The left and right water tank represented upstream and downstream of the surface water, respectively. It can be seen from figure 1 that a centrifugal pump drives the water flow in the flume. The overlying surface water velocity was kept to be 10 cm/s, under which the dunes was found to remain stationary.
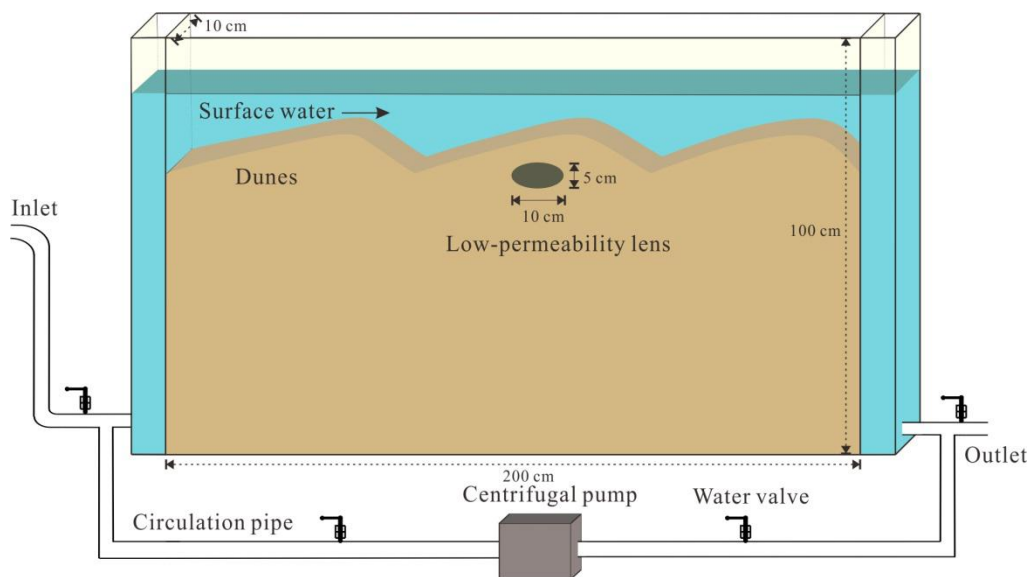

Figure 1. Schematic illustration of the experimental recirculating flume.

The low-permeability lens was made by kaoline, which could be treated as impermeable compared with its surrounding sand in the sandbox. The length and width of the lens was set to be 10 cm and 5 cm, respectively (figure 1). The thickness of the lens was 10 cm, which was equal to the width of the sandbox. The lens was placed into the sandbox with its surfaces stick to the wall, thus the water flowing and solute transportation in the sandbox can be treated as two-dimensional processes.

2.2. Hyporheic exchange

According to Fox et al [15], hyporheic exchange, or q_H, can be estimated by mass balance equations.

For a nonreactive tracer, the mass balance equations were shown as following:

$$W\frac{dC}{dt} = Aq_H(C_s - C) \tag{1}$$

$$W_s\frac{dC_s}{dt} = -Aq_H(C_s - C) \tag{2}$$

$$C(t = 0) = C_0 \tag{3}$$

$$C_s(t = 0) = 0 \tag{4}$$

where t represents the time after thorough blending of the tracer in the surface water, A represents the streambed area, W and W_s are the total volume of surface water and the water volume in the pore of sand, respectively. $C(t)$ and $C_s(t)$ represent the mean tracer concentrations in surface water and pore water, respectively.

According to Grant et al [16], during the initial periods of each experiment, the concentration within sand could be negligible ($C_s \approx 0$). Thus the concentration in stream can be simply given by:

$$\frac{dC}{dt} = -\frac{q_H}{d}C \tag{5}$$

where $d = W/A$ is the average depth of surface water. According to the equations (5) and (3):

$$C(t) = C_0\exp\left(-\frac{q_H}{d}t\right) \tag{6}$$

Equation (6) can be simplified into

$$C^*(t) = \frac{C(t)}{C_0} = \exp\left(-\frac{q_H}{d}t\right) = \exp(St) \tag{7}$$

where:

$$S = -\frac{q_H}{d} \tag{8}$$

Thus q_H can be estimated as:

$$q_H = -Sd \tag{9}$$

The conservative tracer in this study was dissolved NaCl, whose concentration was measured by a conductivity meter with an interval of 1 minutes. Water temperature was maintained at 19℃.

The red dye was injected into the dunes at multiple locations to study the flow path of hyporheic exchange (figure 2). The injected locations were equally distributed in dunes. With the centrifugal pump unopened, dissolved red dye was injected to the interior of the dunes by a transfer pipette with external diameter equals to 0.5 mm, which was smaller enough to avoid changing the structure of the dunes. After the overlying water started to flow, the flowing process of the dye was monitored by photographs taken every 10 minutes.
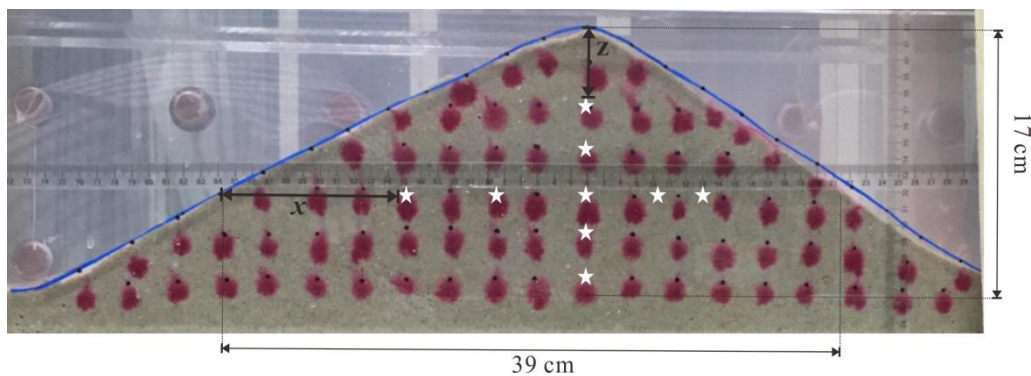
Figure 2. Schematic illustration of dye injections and the locations of the low-permeability lens.

3. Results and discussion

To research the impacts of spatial locations of lens on hyporheic exchange, the lens was imbedded at five different horizontal locations and depths (shown as white five-pointed star in figure 2). Firstly, the vertical distance of the lens to the peak point of the dunes (shown as z in figure 2) was kept to be stable and moved the lens from the upstream face of the dunes to that of the downstream face. The ratio of the horizontal distance of the lens to the upstream face of the dunes (shown as x in figure 2) to the length of dunes at this depth (39 cm here) was recorded to be the relative horizontal location of the lens to the dunes. Similarly, when changing the depth of the lens, the horizontal locations of the lens was kept at the center of the dunes (beneath the peak point) and the relative depth of the lens refers to the ratio of z to the height of the dunes (17 cm here). The relative horizontal locations and depth of the low-permeability lens is shown in table 1.

Table 1. Relative horizontal locations and depth of the low-permeability lens (dimensionless).

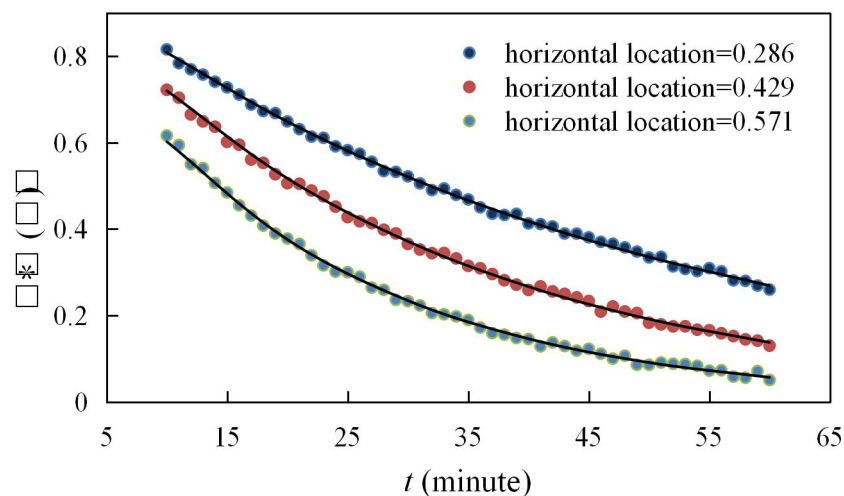| Relative horizontal locations	0.286	0.429	0.571	0.714	0.786
	Relative depth = 0.632				
Relative depth	0.316	0.474	0.632	0.779	0.947
	Relative horizontal locations = 0.571				

Figure 3. $C^*(t)$ curve at various horizontal locations.

The hyporheic exchange was estimated by equations (7) and (9). The variation of $C^*(t)$ with time was shown in figure 3. Relative horizontal locations of 0.286, 0.429 and 0.571 were selected as representatives. The $C^*(t)$ curve was fitted by the exponential function, shown as black line in figure 3. It can be seen from figure 3 that the fitted results were acceptable.

How the hyporheic exchange intensity q_H varied with the horizontal locations and depth of the lens were shown in figures 4 and 5, respectively. At each spatial location, the nonreactive tracer experiments were conducted repeatedly by 3 times. Figures 4 and 5 displayed the variation of the mean hyporheic exchange intensity and the errors bars at each spatial location. The hyporheic exchange intensity without a lens existing in the flume equals to 0.847 cm/min, which is higher than that when there is a lens in the dunes (figures 4 and 5), which means the existence of the low-permeability lens weakens the hyporheic exchange intensity. That is to say, the lens has hindering effects on the hyporheic exchange process.
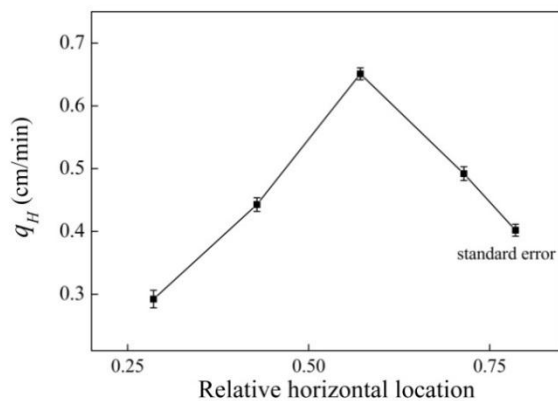

Figure 4. Variation of q_H and error bars with relative horizontal locations of the low-permeability lens.
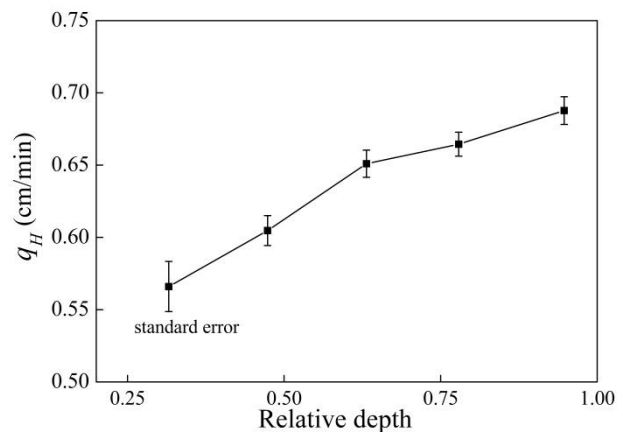
Figure 5. Variation of q_H and error bars with relative depth of the low-permeability lens.

It can be seen from figure 4 that with the lens moving from the upstream face of the dunes to the upstream face, the q_H (shown as rectangle points in figure 4) increases first until reaching its maximum value at the horizontal location of 0.571, after that, q_H decreases gradually. That is to say, the low-permeability lens has the weakest hindering effects on hyporheic exchange when located at the center of the horizontal location. The hindering effects strengthen when the lens getting closer to the upstream or downstream face of the dunes. The relative locations of 0.429 and 0.714 have the same horizontal distance to the central point (the horizontal location of 0.571), while q_H has a smaller value when the lens is closer to the upstream face of the dunes. Besides, q_H has its minimum value when the lens located at horizontal location of 0.286. Thus it can be inferred that the hindering effects of a lens located closer to the upstream face of the dunes is higher than that when closer to the downstream face of a dunes. The error bars were calculated by the stand error, which can be estimated by dividing the standard deviation by the square root of number of measurements (3 here) [16]. The error bars reflect how reliable that the mean value represents the true value. The wider the error bars, the less reliable of the results [16]. It can be seen from figure 3 that all the error bars were relatively narrow, which means the results of the physical experiments are reliable and acceptable.

The error bars are also narrow when the lens located at different depth thus the results in figure 5 are also acceptable. With the low-permeability lens moving from the shallowest depth to the deepest depth, the hyporheic exchange intensity shows a gradual increasing trend. That is to say, the hindering effect of on hyporheic process weakens with the vertical locations of the lens getting deeper.
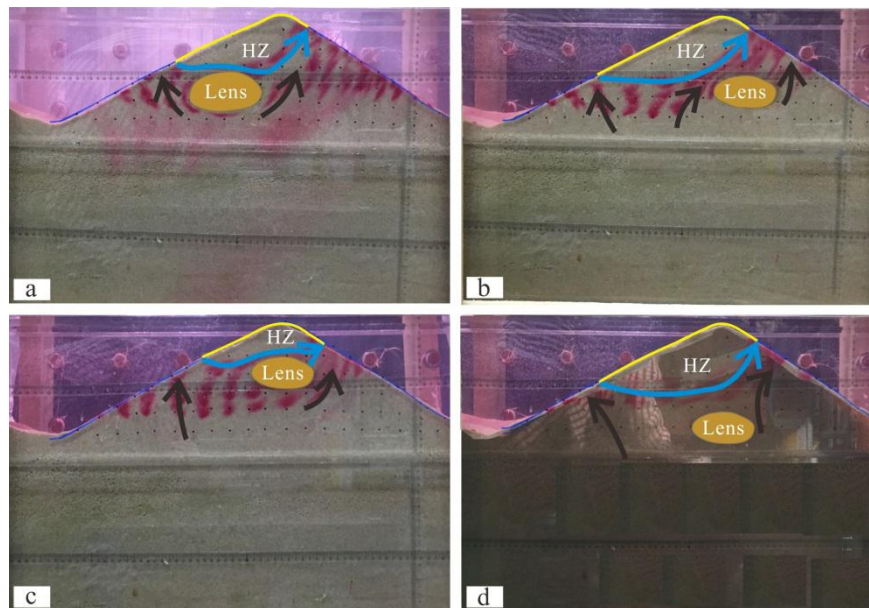
Figure 6. Hyporheic flow paths under the impact of dunes with varied spatial locations. The lines with arrows refer to the streamlines of water in the dunes. The blue lines show the deepest streamline of hyporheic exchange. The zones between the yellow lines and the blue lines refer to the hyporheic zones (HZ).

After one hour, the flow path of hyporheic exchange under the impact of dunes with varied horizontal locations (a and b) and depth (c and d) of the lens are shown in figure 6. Hyporheic exchange refers to the water that flows from the streams into the subsurface and then returns to the surface. The black lines in figure 6 only reflect the process of water in the sand bed flowing to the surface water while do not present the process of surface water flowing into the dunes, which do not belong to hyporheic exchange. Thus the blue lines in figure 6 show the deepest streamline of hyporheic exchange. It can be seen from figures 6a and b that with the lens moving from the locations closer to the upstream face to that closer to the downstream face of the dunes, the flowing path of hyporheic exchange become less influenced by the lens and the area of HZ is getting larger. Similarly, the hyporheic flow is hindered significantly by a lens that located at shallow depth while getting almost un-affected when the lens locating at deeper depth (figures 6c and d). The area of HZ also increased when the lens getting deeper. These results were consistent with the results of hyporheic exchange intensity, which have revealed that the hindering effect of the lens weakens when the horizontal locations change from upstream to downstream and the vertical locations become deeper.

4. Conclusion

This study focuses on dune-induced hyporheic processes, uncovers the impact of a low-permeability lenses on hyporheic exchange, which promotes better understanding of the impact of heterogeneity on hyporheic process at small spatial scales to some extent. The following is a summary of this study:

- The existence of the low-permeability lens weakens the hyporheic exchange intensity. The lens has hindering effects on the hyporheic exchange process.
- The low-permeability lens has the weakest hindering effects on hyporheic exchange when located at the center of the horizontal location. Meanwhile, the hindering effects weaken when the lens getting closer to the upstream or downstream face of the dunes. The hindering effect of a lens located closer to the upstream face of the dunes is higher than that when closer to the downstream face.
- The hindering effect of a lens on hyporheic process weakens when the vertical locations of the lens getting deeper.

- With the lens moving from the locations closer to the upstream face to that closer to the downstream face of the dunes, or moving from a shallow depth to a deep depth, the flowing paths of hyporheic exchange become less influenced by the lens and the area of HZ is getting larger.

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