Impact of Slightly-Curved Riparian Vegetation Distribution on Hyporheic Lateral Exchange solute migration

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Abstract. Riparian hyporheic exchange has a very important role in blocking and reducing pollution. In order to quantitatively grasp the self-purification ability of the river and predict the change of water quality, it is necessary to have a good understanding of the process that drives river water into the hyporheic layer. In this paper, the effects of slightly-curved riparian and vegetation density on the hyporheic lateral exchange of solute migration were studied in depth through model tests. The results show that: (1) The vegetation spacing d has a significant effect on the hyporheic lateral exchange. As the lateral spacing of vegetation decreases, the rate of hyporheic lateral exchange increases. (2) The amplitude a has a significant effect on the hyporheic lateral exchange. As the amplitude a increases, the faster the hyporheic lateral exchange rate on convex surface, and the larger the feather forward area of solute migration. However, due to the expansion of the volume of the retention area on the concave surface, it has a suppressive effect on the disturbance pressure and delays the solute transport. (3) There is a certain asymptotic limit for the increase of the hyporheic lateral exchange width, when the ratio of the underground pore water concentration $C'$ to the surface circulating water concentration $C_0'$ in the riparian zone is equal to 0.50, the solute transport width can be approximated as a suitable width for the hyporheic lateral exchange. The results are expected to provide a certain reference for the theoretical research of riparian hyporheic exchange.

1. Introduction
As a transition zone between water and land, the riparian surface area can effectively reduce non-point source pollution, and the riparian hyporheic layer also plays an important role. The riparian hyporheic layer is an area where surface water and groundwater are mixed with each other, and it is an ecological interlaced zone between the water area and the riparian habitat on the riparian zone[1], it provides the key solutes of hyporheic zone and riverside organisms, including nutrients and dissolved gases, and it also controls the distribution of solutes and colloids from the river scale to watershed scale [2]. In the riparian hyporheic zone, the migration and transformation of nutrients and pollutants [3-4], the water temperature regulation [5], and the abundance and distribution of organisms living in river corridors all have unique laws. The hyporheic exchange process is a basic indicator describing these unique laws, which is affected by many factors such as topography and geomorphology, heterogeneity of hydraulic conductivity [6-9]. The riparian hyporheic exchange plays a vital role in the evolution of biogeochemistry and multi-scale ecosystem functions such as local, river sections and watersheds, and it is becoming a hotspot in many disciplines [10-11]. Relevant studies have found that the transport of material in rivers is affected by physical and chemical processes, and the latter including geochemistry and biochemistry. There are four physical hydrologic processes that strongly affect the transport of solutes in stream networks: advection, dispersion, transient storage and the mixing of stream water.
with inflows [12]. Gooseff M N, Bencala K E et al [13] focused on physical hydrology to control solute transport and found that: (1) velocity, longitudinal gradient of river and channel roughness control the intensity of convection. Changes in the shape of the channel and the discharge of water from the inlet and outlet usually lead to an increase in the downstream convection rate. However, the scale changes that can be achieved by channel shapes and changes in flow over time may cause deviations in convective intensity on space and short time scales. (2) Longitudinal diffusion is the hydrodynamic diffusion of solute near the center of the solute pulse. Even the simplest channel has diffusion, and with the complexity of the channel increases, the spatial variability of the velocity distribution increases [14]. Based on the above studies on the characteristics of solute transport in river networks, X B Chen [15], J Q Lin, J H Xia [16-17] et al further explored the laws of solute transport in the riparian hyporheic zone during the physical hydrological process, and found that the riparian solute transport is influenced by morphological characteristics of riverbeds and banks and the magnitude of river flow. The research direction has gradually shifted from stream networks to riparian zones, and some results have been achieved. However, the river bank is rich in a variety of community structures of herbs, shrubs and arbor plants, and is a mosaic with variable width and complex terrain and environmental characteristics. The ecological environment of the riparian zone, such as the composition of vegetation types, the degree of vegetation canopy density, the stiffness and flexibility of the vegetation, and the spatial distribution rules, all have certain effects on the riparian zone's permeability coefficient, shoreline velocity distribution, and water flow path. Since the 1920s, research on the hydrodynamic mechanism under the action of vegetation has received international attention. The most outstanding are the Cambridge Parsons Laboratory in England (which mainly studies the impact of the degree of submersion of flexible vegetation on the hydrodynamic mechanism) and Kanazawa Hydraulic Laboratory in Japan (which mainly studies the effects of stiffness vegetation on the hydrodynamic mechanism of local sections of the river). Since then, there has been an endless research on momentum loss of vegetation to water flow[18-22]. However, the law of hyporheic exchange has not been thoroughly explored under the effect of riparian vegetation distribution and morphological characteristic. Aiming at this problem, this paper uses model experiments to deeply explore the impact of slightly-curved riparian vegetation distribution on hyporheic lateral exchange solute migration, and is hope to provide the foundation for the theory of riparian hyporheic zone.

2. Test device and method

2.1 Test device

The model test uses a dual-cycle controllable riparian zone model of the Engineering Hydraulics Laboratory of Hohai University, as shown in Figure 1 to Figure 3. The test device is mainly composed of the following parts: surface water inlet section, river bank sand trough section, surface water outlet section and water supply circulation device. The test uses non-cohesive quartz sand with median particle diameter $d_{50}$ is equal to 0.78mm, permeability coefficient $K$ is equal to 0.584 cm·s$^{-1}$, and porosity is equal to 0.45. The size of the sand trough test area is set to 10m $\times$ 2m $\times$ 0.8m. The slightly-curved riparian is laid as $y = a \cdot \sin \left( \frac{2\pi x}{\lambda} \right)$ . The river bank slope coefficient is proposed to be 3, the laying height is equal to 13 cm, and the average bank width is equal to 128 cm. The surface of the riverbed is flat and free of sand waves. The slope is equal to 0.002, the average width is equal to 35 cm, the bottom is equal to 25 cm from the top of the trough, and it can be laid into different slopes as required. The vegetation was selected as Acorus calamus L. with a total height of 1.5m, a stem height of 13 cm, an average leaf length of 0.7m, and an average width of 2 cm. The test section is arranged in the middle section of the river channel, and 5 monitoring sections are arranged at 0λ, 0.25λ, 0.5λ, 0.75λ and 1λ, and each section is arranged at a measuring point every 20 cm from the waterfront to the shore. A wire spring tube with a diameter of 1 cm and a length of 22 cm (which wrapped with nylon mesh to make it water-permeable and sand-proof) is arranged at each measuring point, and the buried depth is 20 cm. When measuring the pressure, lower the head of the pressure measuring tube on the
right side of the sand trough, and use the pressure gradient generated by the river water and the nozzle to perform the exhaust treatment.

2.2 Test method and characteristic parameters
In this physical model test, the flow rate is selected to be 40 m$^3$·h$^{-1}$, 50 m$^3$·h$^{-1}$ and 63.4 m$^3$·h$^{-1}$. The riparian amplitude is chosen to be 0cm, 4cm and 8cm. The vegetation layout selects the bare slope (None), d$_x$ is equal to 10cm and d$_x$ is equal to 5cm (maintain vertical distance d$_y$ is equal to 25cm). A total of 13 working conditions were set up in the test, and the specific characteristics of each working condition are shown in Table 1.

| Working condition | Vegetation spacing d$_x$(cm) | Riparian amplitude a(cm) | Flow Q(m$^3$·h$^{-1}$) | Water depth h(cm) | Velocity u(m·s$^{-1}$) |
|-------------------|-----------------------------|-------------------------|------------------------|------------------|----------------------|
| R1                | None                        | 0                       | 40                     | 11               | 0.2                  |
| R2                | None                        | 4                       | 40                     | 11               | 0.2                  |
| R3                | None                        | 8                       | 40                     | 11               | 0.2                  |
| R4                | 10                          | 0                       | 40                     | 11               | 0.2                  |
| R5                | 10                          | 4                       | 40                     | 11               | 0.2                  |
| R6                | 10                          | 8                       | 40                     | 11               | 0.2                  |
At the start of each set of working conditions tests, slowly adjust the tailgate and surface water pipeline valves to control the surface water flow and depth to form an approximately uniform flow, so that the bed and slope are activated without sediment, and ensure that the bed and riverbank shape are maintained intact. Adjust the opening degree of the groundwater pipeline valve so that the riparian groundwater is flush with the surface water. After the surface water and groundwater are stable, put 500g NaCl in the downstream water tank and stir. When the surface water has been circulated once or twice (about 5 minute), the conductivity of the NaCl in the river is uniform, and then the conductivity instrument is used to measure the conductivity of river and groundwater. In the initial 2 hours, measure every 5 minutes. Within 2 hours to 4 hours, measure every 10 minutes. Within 4 hours to 7 hours, measure every 20 minutes. Within 7 hours to 10 hours, measure every 30 minutes. Within 10 hours to 14 hours, measure every 60 minutes. After the end of each test, the residual salt in the previous working condition needs to be washed until the pore water concentration of the sediment drops to the background value.

### 3. Results and analysis

#### 3.1 Impact of straight riparian vegetation distribution on hyporheic lateral exchange solute migration

Under the conditions of a nearly uniform flow in a straight river bank, the hyporheic lateral exchange is mainly turbulent diffusion exchange, and the transportation of solutes from the river to the river bank is progressive. As shown in Fig.4, in the same working condition, the migration rate of each band in the unit wavelength at the same time is basically the same. But the greater the density of vegetation, the greater the solute transport rate. At t is equal to 360 minutes, the solute transport widths of working conditions R₁(None), R₄(dx =10cm) and R₇(dx=5cm) have reached 15cm, 18cm, and 20cm, respectively. At t is equal to 480 minutes, the solutes under R₄ and R₇ operating conditions began to change significantly. When t is equal to 540 minutes, it was found that the solute transport width under the R₄ and R₇ operating conditions both increased, and at this time, the operating condition R₇ basically approached the equilibrium state, and the amplitude was more severe than R₄. At t is equal to 780 minutes, the average solute transport widths of R₁, R₄, and R₇ reach 20cm, 25cm, and 35cm, respectively. It can be seen that the addition of vegetation can speed up the process of hyporheic lateral exchange. This is because with the addition of vegetation pile groups, the initial uniform flow state is changed, and a complex vortex street is generated, which causes the surface water disturbance pressure to increase and forms a lateral pressure gradient with the riparian groundwater, thereby promoting the exchange process. Moreover, at the pore scale of the riverbank, the flow path of the water flow is tortuous and divergent, which also promotes the lateral dispersion process of the solute front extending along the direction perpendicular to the flow direction, and promotes the process of solute migration to a wider gravel layer. As the vegetation spacing decreases, the pressure gradient increases and the exchange rate becomes more pronounced.
Fig. 4. Impact of straight riparian vegetation distribution on hyporheic lateral exchange solute migration

3.2 Impact of slightly-curved riparian vegetation distribution on hyporheic lateral exchange solute migration

3.2.1 Impact of slightly-curved riparian on hyporheic lateral exchange solute migration.

Fig. 5 and Fig. 6 represent the solute transport in the bare bank slope under the amplitude conditions \( R_1(a =0) \), \( R_2(a=4cm) \), \( R_3(a=8cm) \). It can be seen from Fig. 5 that with the increase of the amplitude \( a \), the rate of the hyporheic lateral exchange on the convex surface is accelerated. Because the riparian terrain with higher amplitude has greater shape resistance, the dynamic pressure difference between the convex surface and concave surface is larger. According to the basic theory of Darcy's law, the unbalanced pressure gradient distributed on the undulating river bank will strengthen the hyporheic flow of sand waves \( Q=K\alpha A J=K\alpha A \Delta P/\rho g \). Therefore, the convection-based solute transport process will be further strengthened near the convex surface, while the concave surface will be affected by the sudden decrease of the disturbance pressure caused by the riparian underground convection path and the volume expansion of the surface retention area, making the concave surface transport is affected by a certain degree of retardation in the initial, and the change is not obvious enough. It can be known from Fig. 6 that when \( a \) is greater than 0, the exchange rate of the convex surface is greater than the concave surface, and the larger the amplitude \( a \), the larger the area of the feather front. At \( t \) is equal to 780 minutes, the average exchange width of the banks under the condition \( R_1 \) is about 20 cm. On the conditions \( R_2 \) and \( R_3 \), the average exchange width on the convex surface and the concave surface are about 30 cm, 10 cm, respectively.

Fig. 5. Solute transport law of surface water in bare bank slope under different amplitudes \( a \)
3.2.2 Impact of slightly-curved riparian vegetation distribution on hyporheic lateral exchange solute migration.

There is a negative correlation between the vegetation spacing and the groundwater solute transport rate in the riparian hyporheic exchange. That is, the decrease in the lateral spacing of vegetation will promote the solute transport. However, the slightly-curved riparian banks have the effect of enhancing the convex surface and weakening the concave surface. Therefore, it is very meaningful to explore the impact of slightly-curved riparian vegetation distribution on hyporheic lateral exchange solute migration. Fig.7 selects R1 (a=0, None), R7 (a=0, dx=5cm), R3 (a=8cm, None) and R9 (a=8cm, dx=5cm) for comparison.

As shown in Fig. 7, at t is equal to 360 minutes, under the combined effect of amplitude and vegetation spacing (R9), the solute conductivity of riparian groundwater near the wave crest reached about 680μs, which was an average increase of 25.93% over the operating condition R1. Under the single factor of amplitude, the average increase in conductivity at the wave crest of the bare slope (R1, R3) is about 11.11%, and the average increase is about 17.24% when the lateral spacing of the vegetation is 5cm (R7, R9), which is larger than the bare slope. Under the single factor of vegetation spacing, the average increase of the conductivity of the straight bank (R1, R7) is only about 7.41%. When the amplitude of the bank is 8cm (R3, R9), the average increase of the conductivity of the wave crest is about 13.33%, which is greater than the straight. It can be seen that the combined effect is faster than the hyporheic exchange rate under the action of a single factor, and the vegetation and amplitude have a mutual promoting effect on the hyporheic exchange process at the wave crest of the slightly-curved bank.
conductivity of the concave surface of the bare bank slope (R3) is between 280 and 360μs, which is about 40.74% lower than the condition R1. When the lateral spacing of vegetation is 5cm (R7, R9), the average decline has rebounded by about 12.07%. It can be seen that the addition of vegetation piles can effectively promote the hyporheic exchange, but under the condition of amplitude is equal to 8cm, the concave surface still shows a reduction effect. This is because the addition of vegetation piles will generate complex vortex streets and extend longitudinally to the river, which will increase the disturbance pressure of the river flow [23] and promote the hyporheic exchange [16]. However, the riparian amplitude increases the flow velocity gradient on the convex surface and the pressure disturbance increases, but the concave surface forms a water retention zone, which makes the subsurface flow exchange blocked. In a word, the vegetation piles and the slightly-curved of the river bank can promote the hyporheic exchange on the convex surface. On the concave surface, the vortex streets produced by vegetation will offset the retardation effect of the slightly-curved of the river bank, which will cause the hyporheic exchange rate to rebound.

3.3 Impact of slightly-curved riparian vegetation distribution on hyporheic lateral exchange solute transport width

Fig.8 and Fig.9 reveal the effects of different riparian amplitudes and composite effects of vegetation and amplitude on hyporheic solute transport width. It can be seen from Fig. 8 that with the increase of the amplitude, the average exchange width of the hyporheic is gradually increasing. But comparing the exchange width difference under different working conditions at the same concentration ratio $C'/C'_0$, it will be found that the increase degree in the hyporheic exchange width gradually decreases with the increase of the amplitude. It shows that the increase of pumping exchange width has a certain asymptotic limit, which is consistent with the research results of J Q Lin [16]. It can be seen from Fig. 9 that under the combined effect of amplitude and vegetation spacing, the hyporheic exchange width is greatly increased under the effect of a single factor. But the planting density of vegetation has a certain threshold range, and excessive planting density will promote the effect of water return to river channel, which has an inverse effect on the underflow exchange [24]. It can also be found from Fig.8 and Fig.9 that when $0.50 < C'/C'_0 < 1.0$, the solute exchange distance in the equilibrium state changes very little or is basically the same. When $C'/C'_0 < 0.50$, the concentration ratio gradually decreases with increasing distance. Therefore, when the ratio of the underground pore water concentration $C'$ and the surface circulating water concentration $C'_0$ in the riparian zone is equal to 0.50, the solute transport width can be approximated as a suitable width for the hyporheic lateral exchange.

![Fig.8. Impact of slightly-curved riparian on hyporheic lateral exchange width](image-url)
4. Conclusion and prospect

4.1 Conclusion
(1) The riparian amplitude \( a \) and vegetation spacing \( d \) have significant effects on the hyporheic lateral exchange. With the decrease of the lateral spacing of vegetation, the exchange rate of hyporheic has increased. The amplitude \( a \) has a different regularity in the hyporheic exchange effect between the convex and the concave surface of the slightly-curved river bank. With the increase of amplitude \( a \), the faster the hyporheic lateral exchange rate of the convex surface, and the larger the feather forward area of solute transport. However, due to the expansion of the volume of the retention area, the concave surface has a suppressive effect on the disturbance pressure and delays the solute transport.

(2) There is a certain asymptotic limit for the increase in the hyporheic lateral exchange solute transport width. When the ratio of the underground pore water concentration \( C'/C_0' \) and the surface circulating water concentration \( C_0' \) in the riparian zone is equal to 0.50, the solute transport width can be appropriate width for hyporheic lateral exchange.

4.2 Prospect
(1) This article only discusses the hyporheic exchange pattern on the slightly-curved river bank in different vegetation arrangements represented by Acorus calamus L. in a single matrix river. However, the vegetation and matrix composition of the riparian zone in the actual river channel is more complicated. Therefore, it is necessary to further study the effect of the combined action of the composite matrix and vegetation on the hyporheic lateral exchange.

(2) Chemical reactions also exist in pollutants in rivers. This paper does not consider the adsorption of vegetation and the chemical effect of substrates on solutes. In the future, we can further study the laws of solute transport under the combined action of physics and chemistry.

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