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Effects of water flow on the uptake of phosphorus by sediments: An experimental investigation*

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Abstract: This paper investigates the effect of the water flow on the phosphorus uptake by sediments. Five experiments with different overlying flow velocities are carried out in an annular flume. The results show that the water flow significantly affects the phosphorus uptake by sediments. The sediment motion could be stationary, scroll, scroll or saltation, saltation and suspension under different flow conditions. The minimum amount of the phosphorus uptake is observed where the sediment motion is stationary. The uptake capacity of phosphorus increases with the increase of the flow velocity. However, there is no apparent difference in the uptake capacity of phosphorus between the saltated and suspended sediments. The uptake rate of phosphorus by sediments in the laboratory flume experiments is much lower than the adsorption rate in the batch experiments. There is a linear relationship between the amount of phosphorus uptake by sediments and the square root of time.

Key words: water flow, phosphorus, uptake, flume

In rivers, phosphorus transports downstream either in the soluble form with water or in the particulate form attached to the sediment. The ultimate fate of phosphorus is closely related to the sediments. For example, over 90% of phosphorus in the Yangtze River is in the particulate form[1].

Previous researches mostly focused on the factors affecting the adsorption and the desorption of the contaminant by sediments, such as the properties of the sediment, the contaminant and the environmental medium[2,3]. These studies were mainly conducted in batch reactors where the conditions were quite different from those in natural rivers. In rivers and lakes, the sediments move on or near the bed and the movements can be divided into rolling, sliding, jumping and suspending as the flow velocity increases. The uptake of phosphorus by sediments is significantly affected by various sediment motions[4-6]. But, the mechanism of the effect of the water flow on the phosphorus uptake by sediments remains not very clear.

Five independent experiments with different flow velocities corresponding to five sediment motions (stationary, scroll, scroll or saltation, saltation and suspension) are carried out. These experiments are conducted in a modified flume to simulate a river system. The sediments are collected from the Nanjing reach of the Yangtze River. The flow structures in the flume are measured by the acoustic Doppler velocimetry (ADV).

KH_2PO_4 is added into the flume to obtain an initial concentration of phosphorus of 5mg/L. 400 g sediments are placed evenly on the bottom of the flume to form a layer of about 0.003 m in thickness. Water samples are collected at 0 h, 0.25 h, 0.5 h, 1 h, 2 h, 3 h, 4 h, 6 h, 8 h, 10 h, 12 h, 15 h, 18 h, 21 h and 24 h and then analyzed for the SRP by the molybde-

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num-blue method. After each sampling, an equivalent water volume containing an appropriate phosphorus concentration is supplemented. In the meantime, the flume is supplemented with the distilled water to replace any evaporation losses at an interval of 3 h. The quantity of the phosphorus uptake by sediments is calculated by the changes of the concentration of phosphorus in the water column.

Table 1 Experimental conditions

Cases	Sediment motion	Flow velocity/ ms^{-1}	Water depth/ m
E1	Stationary	0	0.073
E2	Scroll	0.1195	0.073
E3	Scroll or saltation	0.1995	0.073
E4	Saltation	0.2450	0.073
E5	Suspension	0.3119	0.073

Table 1 lists the details of experimental conditions. The five cases of the flow velocity corresponding to five different sediment motions are determined by the combination of the theoretical formula and the experimental observation.

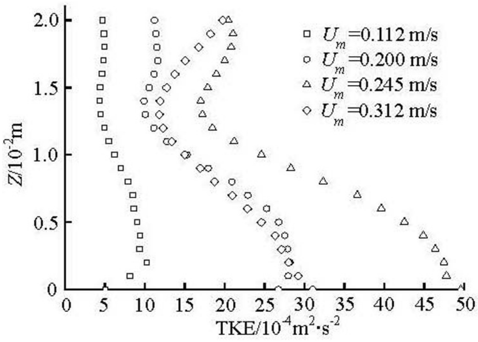

Fig.1 The distribution of TKE along vertical direction at different flow velocities

Figure 1 shows the turbulence kinetic energy (TKE) of the flow, as expressed by

$$\text{TKE} = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{1}$$

where u', v', w' are the turbulence intensities in x, y, z directions. The values of the TKE increase with the increase of the flow velocity in the Cases of E2, E3 and E4. The TKE value in the Case E5 is smaller than that in the Case E4. It is because the suspended sediment would inhibit the turbulence intensity[7].

Figure 2 shows the amount of phosphorus uptake by per unit mass of sediments at different flow velocities.

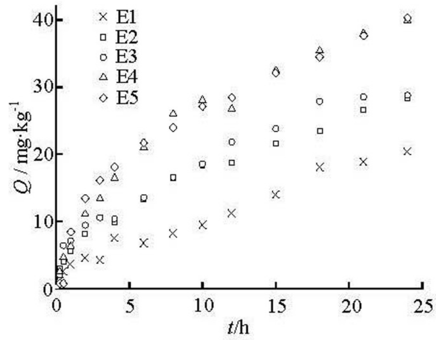

Fig.2 The amount of phosphorus uptake by sediments over time at different flow velocities

In all cases, the amount of phosphorus uptake by sediments increases significantly over time. The amount of phosphorus adsorbed by sediments ranges from 20.4 mg/kg to 40.35 mg/kg. In our previously research[8] the maximum phosphorus adsorption capacity of sediments ranges from 352 mg/kg to 803 mg/kg. This means that the net uptake of phosphorus by sediments in the flume system is in a state far from a steady-state equilibrium at the end of experiment. The minimum phosphorus uptake capacity is observed at a velocity of 0 m/s. With the increase of the flow velocity, the amount of phosphorus uptake increases. Similar phenomenon was observed by Zhang et al.[9], who found that the dynamic release of the TP of the re-suspension sediment is 6 times higher than the static release. Several factors may contribute to this result: (1) the concentration of the dissolved oxygen in the overlying water increases with the increase of the turbulence, which creates a higher redox potential and the oxidation of the soluble Fe^{2+} into Fe^{3+} could accelerate the adsorption of phosphorus by sediments[10,11], (2) as the flow velocity increases, the phosphorus uptake by bed sediments increases in response to the depth of the boundary layer[12], (3) the increased concentration of the suspended sediment increases the collision probability between the sediments and the phosphorus particles, which is favorable to the phosphorus adsorption.

It is interesting to note that there is no apparent difference between the data in the Cases E4 and E5 despite the differences of the flow conditions and the sediment motion are noticeable. This result is probably due to the compromise of the decrease of the TKE and the increase of the suspended sediment concentration.