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Measurements of In Situ Pick-up Rate of Nutrients on Riverbed

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Abstract

We measured in-situ pick-up rates of sediment and nutrients in an urban river with a new device we developed. Water quality in urban rivers may be strongly affected by the quality of sediment, which is easily suspended as flow velocity increases, during meteorological events such as precipitation. However, there is not enough field data of the pick-up rates of sediment and nutrients in rivers and lakes under various flow conditions. One reason is that there is no appropriate device for measuring in-situ pick-up rates of sediment and nutrients. Our device consists of two cylinders, and it is set at the bottom of a river. Various flow conditions are generated using a rod to stir the gap between the two cylinders at arbitrary speeds. This device directly measures the pick-up rates of sediments and nutrients. The measured results show that the pick-up rates of the particulate nutrient components and sediment increase with flow velocity. Note that the pick-up rates of the particulate nutrient components are appropriately modeled with power functions similar to that of sediment. The ratio of N to P is 1.2 – 2.2, indicating that the bed materials are a significant source of phosphorus. In contrast, the dissolved nutrient components decrease with the velocity mainly due to the absorption by the sediment.

Keywords: pick-up rate, nutrient, sediment, in-situ measurement, urban river

1. Introduction

Water quality problems in urban rivers and lakes may be strongly affected by not only the pollutant load from the watershed, but also the property of bed material, which is a non-point source (*e.g.*, [1]). Therefore, it is important to understand the vertical flux of sediment and nutrients between the water column and the bottom of rivers and lakes. Especially, the quality of sediment, which is easily suspended as flow velocity increases, significantly affects the water quality of rivers and lakes under hydrologic events such as precipitation.

Most studies have been concentrated on the nutrient release from river and lake beds as a vertical flux of nutrients between the water column and bottom. However, we poorly understand the erosion properties of sediment and nutrients in rivers and lakes under various flow conditions. The reason there are few studies on this is that there is no appropriate device for measuring the in-situ erosion rate of sediment and nutrients.

We measured the in-situ pick-up rates of sediment and nutrients in an urban river with a new device we developed [2]. The device consists of two cylinders and is set on the bottom of a river. Various flow conditions are generated using a rod to stir the gap between the two cylinders at arbitrary speeds. The pick-up rate of sediment and nutrients are then directly measured using this device. With the new device, we conducted field observations on the erosion properties of sediment and nutrients in an influent river of Lake Tega-numa, a well-known eutrophic lake in Japan. We analyzed the pick-up rate of sediment and nutrients under various flow conditions. We also modeled the pick-up rate of the nutrients.

2. Outline of field measurement

2.1 Device

To monitor the dependence of the erosion rates of sediments and nutrients on various flow conditions in an urban river, we used our device for directly observing the in-situ erosion rates. **Figure 1** shows a schematic diagram and photographs of this device, which has two cylinders in a concentric configuration. We set this device on the bed of the river. We used a rod to stir the gap between the two cylinders.

As shown in **Fig. 2**, when we stir water inside the cylinder, the velocity distribution in the radial direction is not uniform and the suspended sediment may be concentrated at the center of the cylinder. Therefore, a single-cylinder device is not appropriate for monitoring the erosion properties of sediment under various flow conditions. In contrast, using two cylinders like the present device, the width of the gap is narrower, and the velocity distribution in the gap is

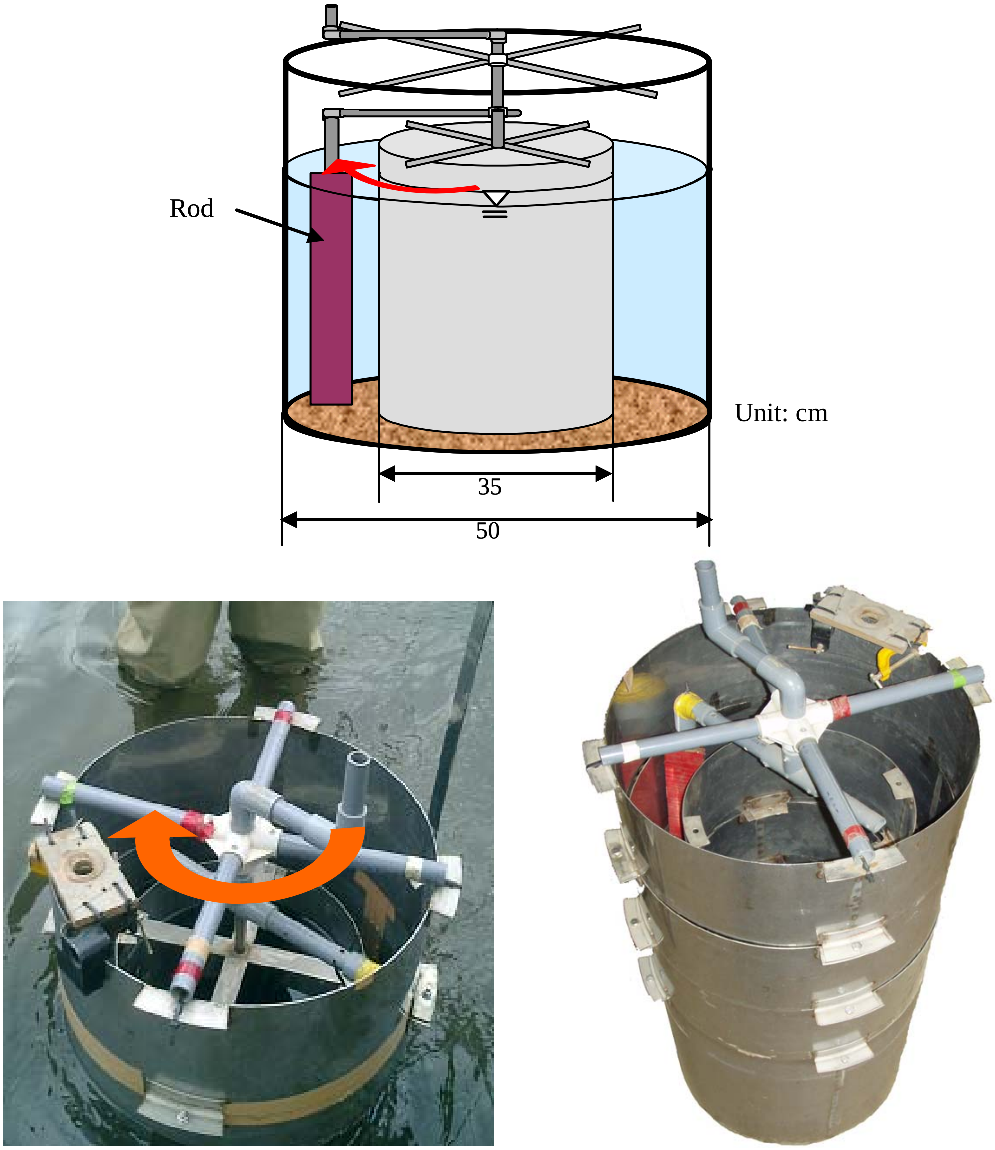


Figure 1. Schematic diagram (upper) and photographs (lower) of our new device for in-situ measuring of pick-up rates of sediment and nutrients

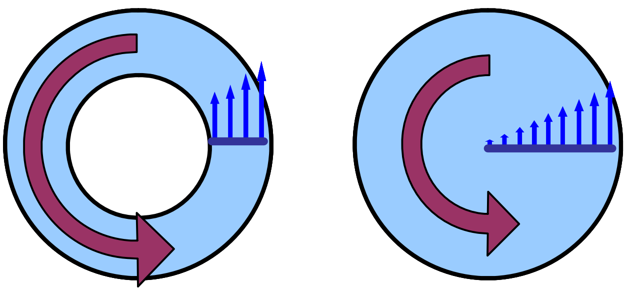


Figure 2. Velocity distribution in radial direction using two cylinders (left) and one cylinder (right)

expected to be almost uniform in the radial direction, as shown in **Fig. 2**. It is easy to control the current speeds in the gap of the device. Our two-cylinder device reproduces various flow conditions, including low flow and flooding conditions.

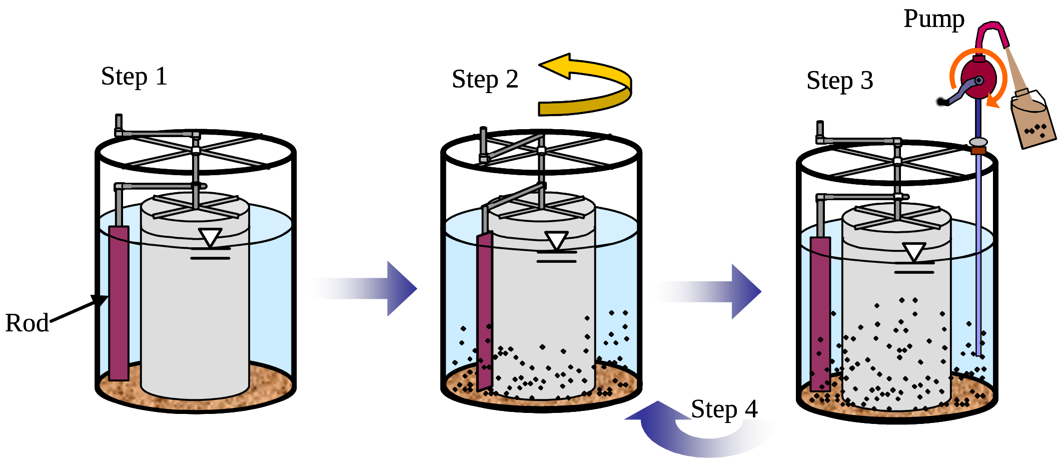


Figure 3. Procedure for in-situ measurement of erosion properties of sediment and nutrients using our new device.

2.2 Measurement procedure

The procedure of in-situ measuring of the erosion properties of sediment and nutrients using our device is described in the following four steps.

Step 1: We set the device at a prescribed position on the riverbed.
Step 2: We use a rod to stir the gap between two cylinders under a constant speed for 120 seconds.
Step 3: We sample an 800-ml volume of water from 15 cm above the bed.
Step 4: We repeat steps 2 and 3 with different rod speeds.

The current speeds in the gap, *U*, were set to be from 0.13 to 1.34 m/s to reproduce normal and flood flow conditions. We carried the water samples back to our laboratory and analyzed the turbidity, suspended solids (SS), particle-size distribution, total and dissolved components of nitrogen (T-N and D-N), nitrate (NO_2+NO_3-N), total and dissolved components of phosphorus (T-P and D-P), and phosphate (PO_4-P). Particulate components of nitrogen and phosphorus, represented as P-N and P-P, respectively, were evaluated for the difference between total and dissolved components of nitrogen and phosphorus. We analyzed all components for nitrogen and phosphorus with an auto analyzer (swAAt, BL TEC K.K., Japan) using a continuous flow analysis. The turbidity and particle-size distribution were measured with a nephelometer (WQC-24, DKK-TOA Co., Japan) and a laser diffraction particle size analyzer (SALD 3100, Shimazu, Co. Ltd, Japan), respectively.

2.3 Evaluation of pick-up rate of sediment and nutrient

For the in-situ measurements with our new device, we collected the water samples 15 cm above the riverbed. To evaluate the pick-up rate of sediment, P_{kSS}, from the SS measured at 15 cm above the riverbed, we adopted the same approach used in a previous work [2]. We assumed that the erosion and deposition rates of sediment and nutrients are equal on the riverbed:

$$P_{kSS} = w_0 SS_a \,, \qquad (1)$$

where w_0 is a setting velocity of sediments and SS_a is the *SS* concentration at a reference height *a* above the bed.

To evaluate the deposition rate of sediment shown in the right-hand side of Eq. 1, it is necessary to obtain SS_a from *SS* measured at 15 cm above the riverbed. For this, we introduced a well-known vertical distribution of SS concentration presented by Rouse [3],

$$\frac{SS(y)}{SS_a} = \left[\frac{a}{h-a}\cdot\frac{h-y}{y}\right]^Z \,, \qquad (2)$$

$$Z = \frac{w_0}{\beta \kappa U_*} \,, \qquad (3)$$

where *y* is the vertical direction, *h* is the water depth, *SS*(*y*) represents the distribution of SS in the *y* direction, U_* expresses the friction velocity, κ is the Karman constant, and a numerical constant β is set to at 1.2. The frictional velocity U_* is defined as

$$U_* = \sqrt{C_f}\, U \,, \qquad (4)$$

$$C_f = \frac{gn^2}{h^{1/3}} \,, \qquad (5)$$

where *U* is the depth-averaged velocity in the gap, C_f is the coefficient of bottom friction, and *g* represents the gravitational acceleration. The roughness coefficient of Manning, *n*, is given to be $0.025\mathrm{m}^{-1/3}\mathrm{s}$. Also, in the present study, the settling velocity w_0 was determined based on Stokes law for settling motion of sediment particles with median diameter. From Eqs. 2-5, we obtained SS_a from the measured SS, and calculated P_{kSS} with Eq.1.

To calculate the pick-up rates of the particulate components of nitrogen and phosphorus, described as P_{kN} and P_{kP}, respectively, we adopted the same procedure for the pick-up rate of sediment P_{kSS}. That is, SS concentration in Eqs 1-5 is replaced with P-N or P-P, and then P_{kN} and P_{kP}, are evaluated instead of P_{kSS}.

2.4 Field site

As shown in **Fig. 4**, the field measurements were done at the lower reach of the Oohori River, which flows into Lake Taganuma, a well-known eutrophic lake in Japan. From October 27 to December 19, 2006, a total of seven measurements were conducted. The water depth at the measuring stations was from 0.2 to 0.4 m. With the above measurements, we also collected core samples of bed material with a diameter of 4 cm and height of 10 cm in order to observe the sediment properties and interstitial water quality.

3. Measured results and discussion

3.1 Relation between nutrients and flow velocity

To grasp the fundamental features of in-situ pick-up rates of sediment and nutrients in the Oohori River, examples of SS, P-N, P-P, D-N and D-P under various flow conditions are shown in **Fig. 5**. These data were obtained on Oct. 27, 2006. The results for sediment and particulate components reveal that SS increases appreciably with flow velocity in line with the previous measurement. Furthermore, the increase in P-N and P-P was also observed as the flow velocity increased, showing the similar tendency between SS and flow velocity. At maximum velocity, P-N and P-P was 28 and 61 times as large as P-N and P-P of the ambient river water, respectively. This means that the significant increase in nitrogen and phosphorus is caused by the vertical turbulent flux from the riverbed at high flow conditions such as during flooding. It also should be noted that the ratio of N to P was 1.2 – 2.2. The N/P ratio of river water is generally about 10. This means that the bed material is a significant source of phosphorus.

In contrast, the values of D-N and D-P decrease gradually with flow velocity. This tendency was confirmed from other data.

3.2 Pick-up rates of P-N and P-P

As stated above, the evaluation for pick-up rates of P-N and P-P is similar to that of sediments. In order to confirm the evaluation for P_{kN} and P_{kP}, the relationship between SS and P-N or P-P is shown in **Fig. 6**. The result indicates good correlations between SS and the particulate components of nutrients in which the correlation coefficient is larger than 0.9. This fact indicates that the pick-up rate of sediment may be similar to those of P-N and P-P and, hence the evaluation for P_{kSS} is valid for that for P_{kN} and P_{kP}.

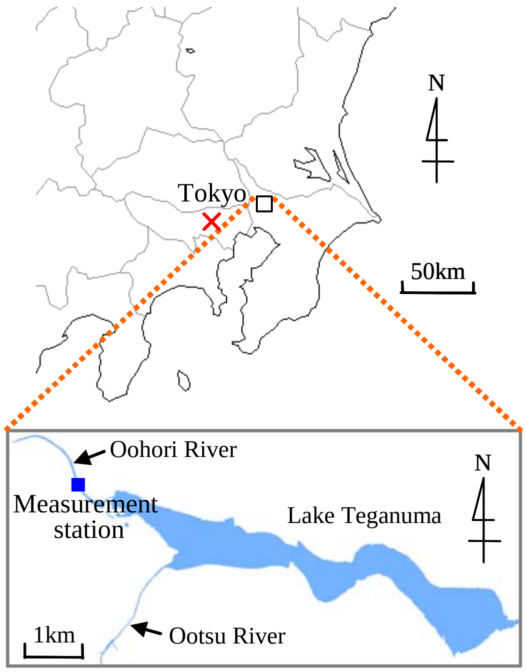
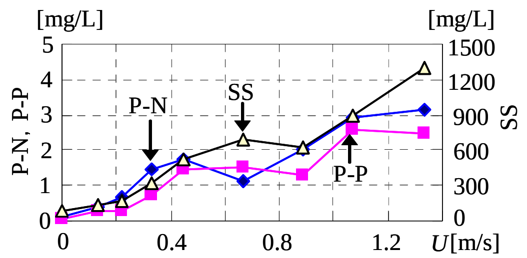
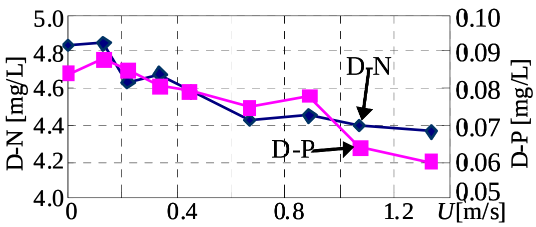


Figure 4. Location of measurement station.



(a) SS, P-N and P-P



(b) D-N and D-P

Figure 5. SS and nutrients under various flow velocity U on Oct. 27, 2006.

The relationship between the pick-up rate of P-N, P_{kN}, and bottom shear stress τ_b is displayed in **Fig. 7**. The observed data were obtained just after it rained (Oct. 30) and 5 (Nov. 1) and 10 days (Nov. 6) after the rainfall. The pick-up rate of P-N increases with the period of the rainfall event. It was also noted that there is a good correlation between the pick-up

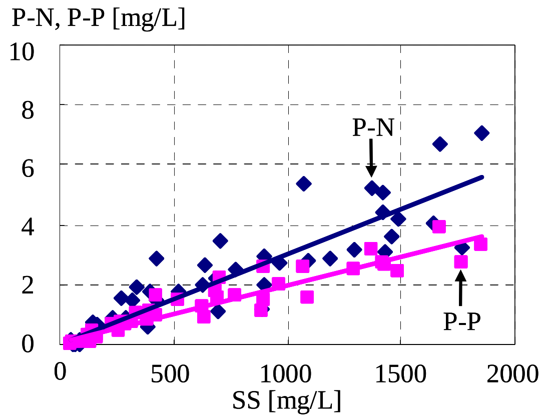


Figure 6. Relationship between SS and P-N or P-P.

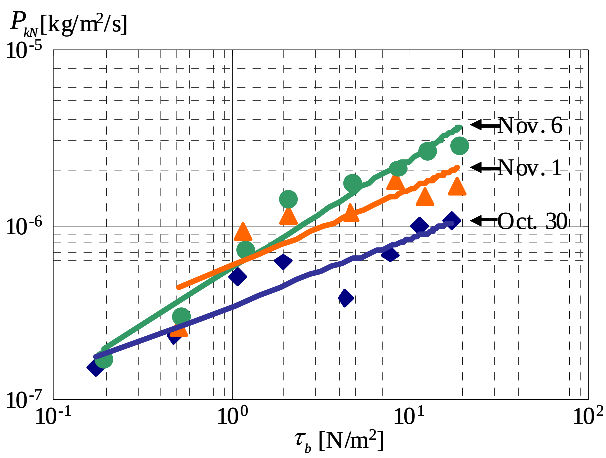


Figure 7. Pick-up rate of P-N P_{kN} vs. bottom shear stress τ_b.

rate of P-N, P_{kN}, and the bottom shear stress τ_b. The result also includes the approximations between P_{kN} and τ_b expressed as

$$P_{kN} = a\tau_b{}^{\eta}, \tag{6}$$

where a and η are constants. These approximations based on power functions are normally used for the evaluation of the pick-up rate of sediment. The results for the approximation reveal that the power function is also appropriate for the approximation between P_{kN} and τ_b. Similar results are found in the pick-up rate of P-P. This fact implies that the pick-up rate of particulate nutrient components can be modeled with the approximation based on the power function generally used for that of sediment.

3.3 Effect of interstitial water on variations of D-P and D-N

To clarify why D-N and D-P decrease as the flow velocity increases, as shown in **Fig. 5(b)**, **Fig. 8** displays the vertical distributions of D-N and D-P for river and interstitial waters on Dec. 6, 2006. In the figure, y=0 corresponds to the surface of the riverbed. The results reveal that D-N and D-P greatly decrease in the downward direction. It is expected that the interstitial water with lower D-N and D-P may decrease the D-N and D-P of river water when turbulent fluxes between the river water column and bottom are dominant under high flow conditions.

To quantitatively check the above mixing effect of river and interstitial water, we calculated D-N and D-P with the assumption that the river water may be completely mixed with the interstitial water. **Figure 9** indicates the correlation between ΔDP_1 and ΔDP_2, where ΔDP_1 is the variation of D-P before and after the in-situ measurements and ΔDP_2 is the variation of D-P evaluated when the river and interstitial water were assumed to be completely mixed. In the evaluation of ΔDP_2, the water depth was given as the measured data, and the thickness of the sub-riverbed layer was assumed to be 2 cm and 5 cm. The results indicate that the absolute values of ΔDP_2 were much lower than those of ΔDP_1, showing that the mixing effect of river and interstitial waters is negligible. This fact indicates that the dissolved component of nutrients decreases with velocity mainly due to the absorption by the sediment.

4. Conclusions

We conducted in-situ measurements of the pick-up rates of sediment and nutrients in the Oohori River with our newly developed device [2]. Using this

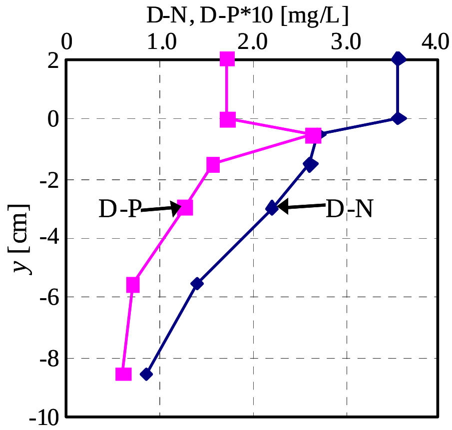


Figure 8. Vertical distributions of D-N and D-P of river and interstitial waters on Dec. 6, 2006.

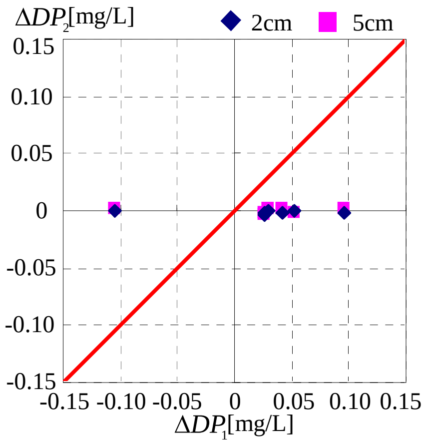


Figure 9. Correlation between ΔDP_1 and ΔDP_2 on Dec. 6, 2006. ΔDP_1 is variation of D-P before and after in-situ measurements. ΔDP_2 means the variations of D-P evaluated when river and interstitial water were assumed to be completely mixed.

two-cylinder device, the in-situ pick-up rates of sediment and nutrients were easily measured under various flow conditions.

The results show that the pick-up rates of particulate nutrient components and sediment increase with flow velocity. Note that the pick-up rates of particulate nutrient components are appropriately modeled with power functions similar to that of sediment. The ratio of N to P is 1.2 – 2.2, indicating that the bed material is a significant source of phosphorus. In contrast, the dissolved nutrient components decrease with the velocity mainly due to the absorption by the sediment.

In future work we will introduce the measured data for in-situ pick-up rates of sediment and nutrient into water quality simulations of rivers [4].

Acknowledgments

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