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Impact of the flush discharge from a dam on the biotic and abiotic river environment

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ABSTRACT: Due to regulation of river flow, there have been gradual but drastic changes on the biotic and abiotic environment of rivers. These changes may have led to lowering of the quality of ecosystem services provided by affected rivers. In this study, a flush discharge release was observed to estimate the impact of a flush discharge on the river environments of an upstream reach of the Jyouge River, which flows through the northern part of Hiroshima, Japan. The river reach that was assessed in this study is 8 km in length and is located just downstream of the Haiduka dam, which released a maximum flush discharge of 100 m^3/s. Water stage hydrographs at 21 stations were recorded using the water gauges installed in the river. At two stations, water sampling had been conducted to quantify suspended sediment (SS) and chlorophyll a (chl.a.) Two-dimensional flow simulation was performed to represent time-dependent flow and material transport processes. Using the observed and simulated results, transport of chl.a during the flush discharge was investigated. Then transport distance of chl.a and its relation to the flood duration are discussed.

Keywords: Flushing flow, Dam, Attached algae, Numerical model, Environmental impact

1 INTRODUCTION

Regulation of rivers is effective measure to reduce flood damage and utilize water resources. River regulation by dam operation has induced gradual, but drastic changes in the biotic and abiotic environment of rivers. These changes may lower the quality of ecosystem services provided by affected rivers (Tsujimoto et al. 2008).

Flushing flow is a river environmental restoration method used to mitigate the negative effects of river regulation. Impacts expected from the flushing flow include maintenance of bed sediment composition (recovering the ratio of fine and coarse sediment, e.g., Downs et al. 2009), maintenance of channel and floodplain geometry and maintenance of riparian and aquatic plants (e.g., Tsujimoto et al. 2001 for riparian vegetation, Tashiro et al. 2003 for periphyton, Battala and Vericat 2009 for macrophytes). These impacts were provided by natural floods before river regulation was initiated, but these impacts have become definitive after dam installations. Accordingly, flushing flow has been implemented to restore the river environment; however, the impact of the flush discharge on the river environment is not straightforward but complicated phenomena. For example, changes in bed sediment composition, meandering of channel geometry and plant migration interact with each other so we should evaluate those effects in comprehensive manner to assess the impact of the flush discharge on the river environment.

Hence, estimation of the effects of a flushing flow in advance of actual water release is a challenging task, and the comprehensive method to predict the impact on the river environment has been not developed yet.

The design of a flushing flow is constrained by environmental and financial considerations (Wu and Chou 2004). To optimize the design of the flushing flow, it is essential to estimate or predict the environmental effects due to the flushing flow.

In this study, a flush discharge release conducted on March 25, 2009 was observed and two-dimensional flow simulation was performed to estimate the impact of a flush discharge on the river environment of an upstream reach of the Jyouge River that flows through the northern part of Hiroshima, Japan.

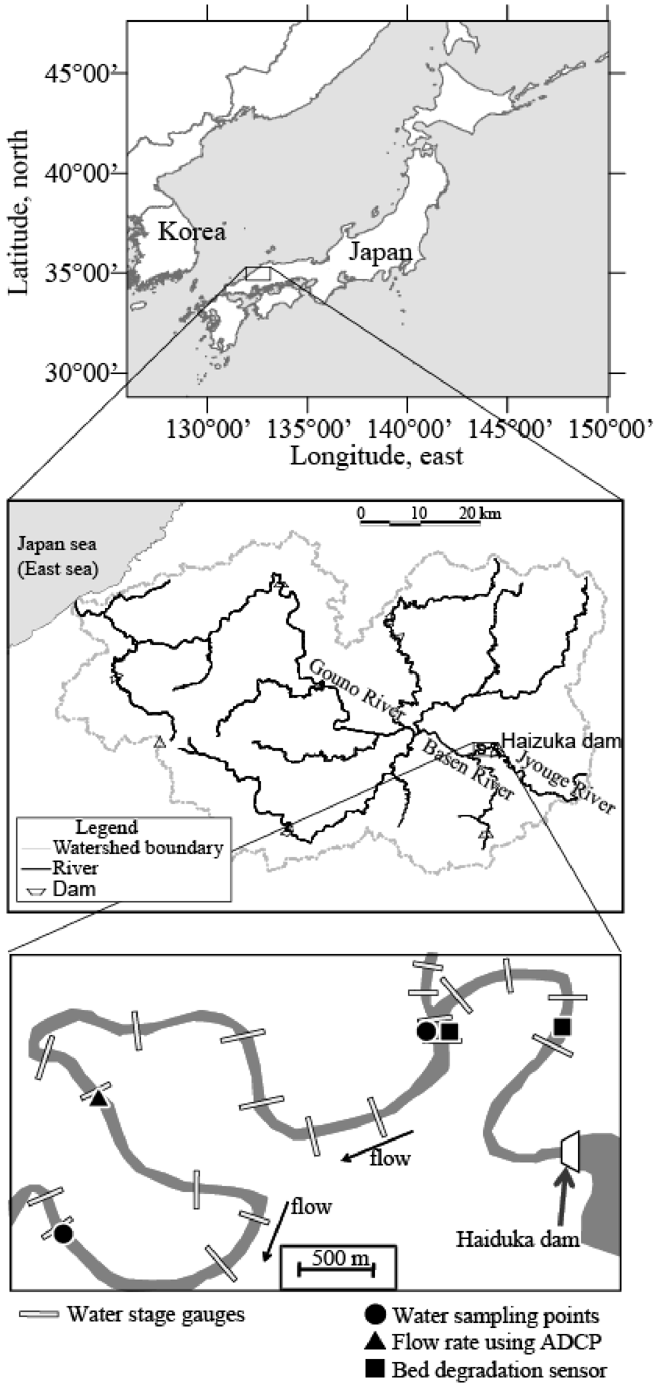


Figure 1. The study area of the Jyouge River.

2 THE STUDY AREA

The Gouno basin is located in the north area in the Chugoku district and drains an area of approximately 3,900 km^2 (Figure 1). The mountainous area accounts for 92% of the Gouno basin, and the rest consists of 7% agricultural area and 1% urban and residential area. Due to the high proportion of mountainous area, the runoff process of this basin is comparatively short and concentrated. Additionally, three large tributaries converge at the Miyoshi basin and the peak discharge of these three tributaries has been simultaneous, and this condition has caused to rapid and concentrated runoff, accordingly this area had suffered frequent flooding damage. To mitigate flooding damage, the river regulation methods such as dam construction, embankment installation and dredging of the river bed, are effective and deemed to be indispensable. However, due to river regulation, the river environment has changed. For instance, the fishery yield of the Japanese trout, *Plecoglossu altivlis*, has decreased. One of the reasons of the *Plecoglossu alivlis* population decrease is due to the reduction in the amount of fresh attached algae, which is the main food source of the Japanese trout. To increase and maintain the amount of fresh algae to feed the Japanese trout, periodical disturbance of the river bed is essential. For this reason, the flush discharge was planned and conducted in 2007.

In this study, a reach of the Jyouge River that spans 8 km and is located 1 km downstream of the Haiduka dam is explored to evaluate the impacts of the flush discharge conducted in March 25, 2009. The mean bed slope in this reach is approximately 0.33%. The discharge hydrograph of released water is shown in Figure 2. The maximum flow rate was 100 m^3/s.

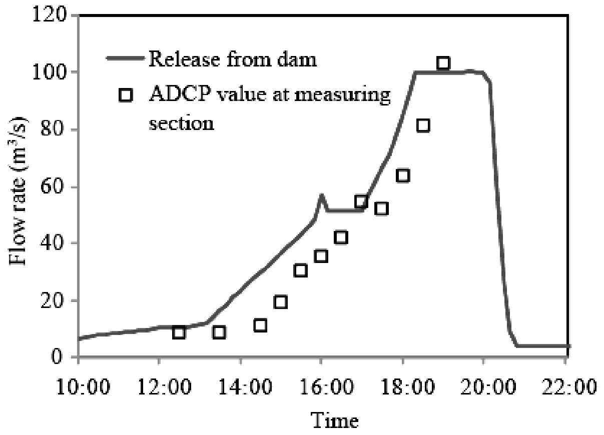


Figure 2. Released and measured discharge hydrograph. The section measured by ADCP is located approximately 7.5 km downstream from the dam, resulting in a lag time of approximately 30 min.

3 METHODS

3.1 *Bathymetry surveying*

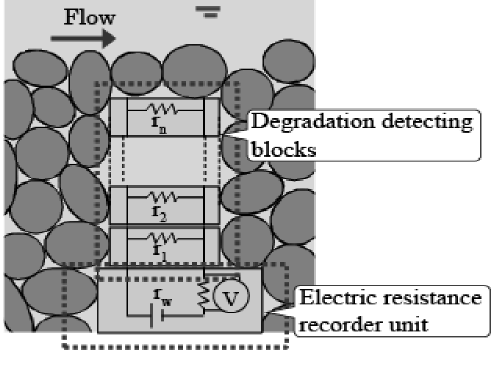
In advance of the flush release, we surveyed 70 cross-section profiles. At each cross-section, reference points for surveying were measured using RTK-GPS (Real Time Kinematic-Global Positioning System, Nikon-Trimble, 5800/R8), then cross-sectional points (13 points on an average) were measured using the total station (Nikon-Trimble Co., Ltd., NST-305CN.) The bathymetry surveying result is used to generate a flow simulation grid.

3.2 *Observation during flush discharge*

During the flush discharge, an ADCP (acoustic Doppler current profiler, RD Instruments Inc., Workhorse Monitor) was used to measure flow discharge at cross-sections in the middle of the measuring reach (symbol ▲ in Figure 1) and a small tributary. Aerial photograph surveys from low altitude using a remote control airplane were conducted before and after the flush discharge to obtain high resolution aerial images. These images were used to identify the surface cover and its change after the flush release. Water stages at 21 stations were recorded using the pressure type water gauges (Oyo Co., S&DL mini) installed in the river. Locations of water-stage stations are depicted in Figure 1.

At two stations (an upstream station and a downstream station, location of each station is depicted as symbol ● in Figure 1), we sampled one liter of water at 30 min intervals to evaluate SS (suspended sediment) and chl.a (chlorophyll a). The sampled water was analyzed at a laboratory.

(a) Photo



(b) Diagram

Figure 3. Bed degradation sensor system.

3.3 *Bed degradation sensor system*

The scour depth sensor systems (see Figure 3) was developed and installed in the bed to record morphological change during the flush flood. The sensor system is composed of an electric voltage recorder, a battery and a sequence of blocks (7.8 cm in diameter and 5 cm in height) with electric resistance. The sequence of blocks is connected to form a parallel electric circuit as shown in Figure 3b. In this circuit, a constant electric voltage is supplied and voltage recorder measures the voltage reduction by use of a parallel electric circuit of resistances. This system is installed under the river bed. If the bed surface was eroded, the top block is flown out downstream. Loss of the top block changes the electric circuit, which leads to a passing electric current reduction. A time series change of voltage indicates the bed degradation during the flood. By using this system, the unsteady process of degradation at the measuring point during the flood can be recorded.

3.4 *Flow and passive scalar transport simulation*

A two-dimensional flow simulation was performed to represent time-dependent flow and material transport processes. In this simulation, two-dimensional flow and scalar transport are modeled by solving the following fundamental equations:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + S = 0 \tag{1}$$

where

$$U = \begin{pmatrix} h \\ uh \\ vh \\ ch \end{pmatrix}, \quad E = \begin{pmatrix} uh \\ u^2 h + \frac{1}{2} g h^2 \\ uvh \\ cuh \end{pmatrix},$$

$$F = \begin{pmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g h^2 \\ cvh \end{pmatrix},$$

$$S = \begin{pmatrix} 0 \\ -gh(S_{0x} - S_{fx}) + D_x \\ -gh(S_{0y} - S_{fy}) + D_y \\ 0 \end{pmatrix}, \tag{2}$$

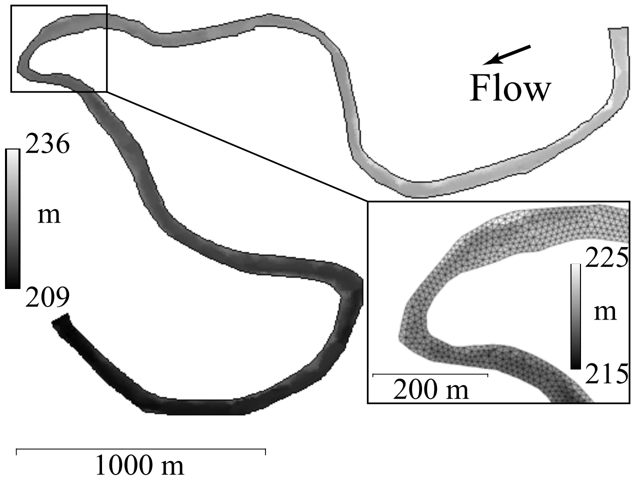
and h = water depth, u and v = velocity components for x and y directions, respectively, c = concentration of passive scalar (chl.a in this study), g = gravitational acceleration. S_{fx} and S_{fy} = bed shear stresses for x and y directions and are estimated using Manning's friction parameter as follows:

$$S_{fx} = \frac{n^2 u \sqrt{u^2 + v^2}}{h^{4/3}}, \quad S_{fy} = \frac{n^2 v \sqrt{u^2 + v^2}}{h^{4/3}} \tag{3}$$

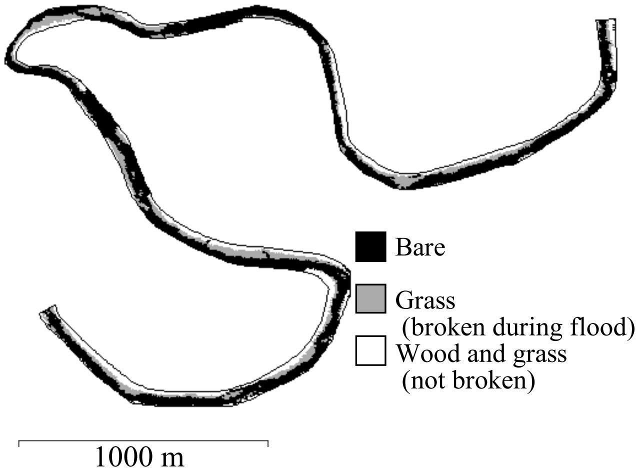
where n = Manning's friction parameter. S_{0x} and S_{0y} = bed slope for x and y directions. D_x and D_y = drag force due to vegetation, and estimated as:

$$D_x = 0.5C_d \lambda hu\sqrt{u^2+v^2},$$
$$D_y = 0.5C_d \lambda hv\sqrt{u^2+v^2} \qquad (4)$$

where C_d = drag coefficient, λ = frontal length per unit area. In this study, diffusion, settlement (sink) and pickup (source) of the scalar are not considered; only convection effect is considered. The fundamental equations are solved using the finite volume method with a triangular unstructured grid system. The flux difference scheme is used to achieve both stability and accuracy for the calculation (Shige-eda and Akiyama 2003, Benkhaldoun et al. 2007). In Figure 4a, the discretized domain used in the flow calculation is depicted.



(a) Bed elevation



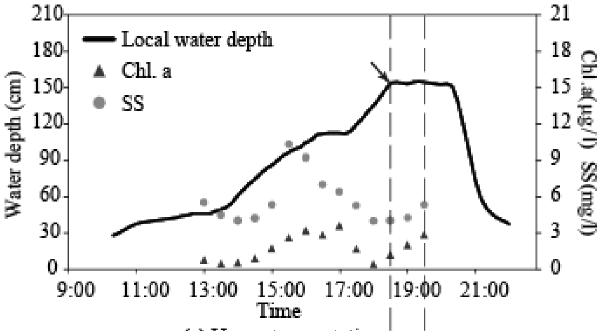
(b) Bed surface cover

Figure 4. Flow simulation grid.

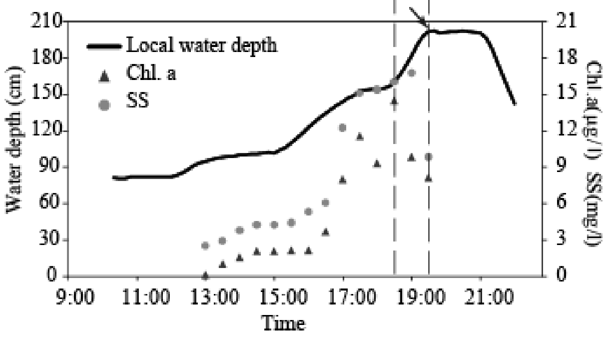
4 RESULTS

4.1 *Observed time-series changes on water depth, chl.a and suspended sediment*

In Figure 5, hydrographs of observed water depth, chl.a and suspended sediment (SS) at the upstream station (placed about 2 km downstream of the dam) and the downstream station (9 km downstream of the dam) are compared. Locations of both stations are depicted in Figure 1 using symbol ●. During the flush discharge, water depth increased from 30 cm to 150 cm at the upstream station, and increased from 80 cm to 200 cm at the downstream station. At the upstream station, water depth was accomplished to the peak discharge at about 18:30 (immediately after the peak flush-release from the dam). At the downstream station, the peak water depth was observed at 19:30. The time lag of peak water depth (and local flow rate) between the upstream station and downstream station is approximately one hour. The profiles of the chl.a and SS concentrations show clear peak during the raising stage of water depth. Concentrations of chl.a and SS at the downstream station are about twice as much as those at the upstream station. This means that the influxes of chl.a and SS are larger than those of out-fluxes in the section between the upstream and downstream stations.



(a) Upperstream station



(b) Downstream station

Figure 5. Time-series change of chlorophyll a (chl.a, μg/l) and sediment (ss, mg/l).

4.2 *Bed degradation*

In Figure 6, the time-series change in the recorded voltage of the bed degradation sensor is depicted. At 18:00, the recorded voltage abruptly declined, which indicates that the upper block of the sensor was exposed to the flow and washed out. Therefore, the bed degradation of approximately 5 cm (height of the block) occurred at that moment. It is confirmed that bed shear stress at this point

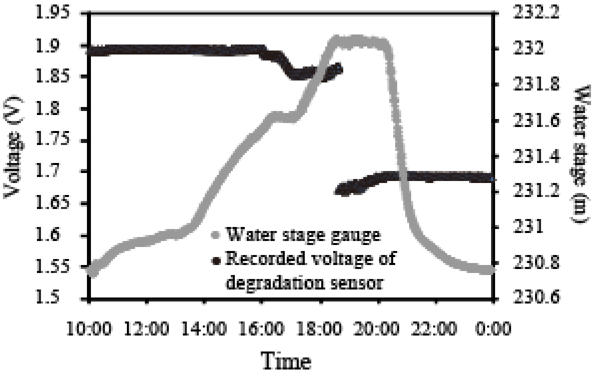


Figure 6. Recorded voltage change of bed degradation sensor during the flush event.

4.3 *Validation of simulation*

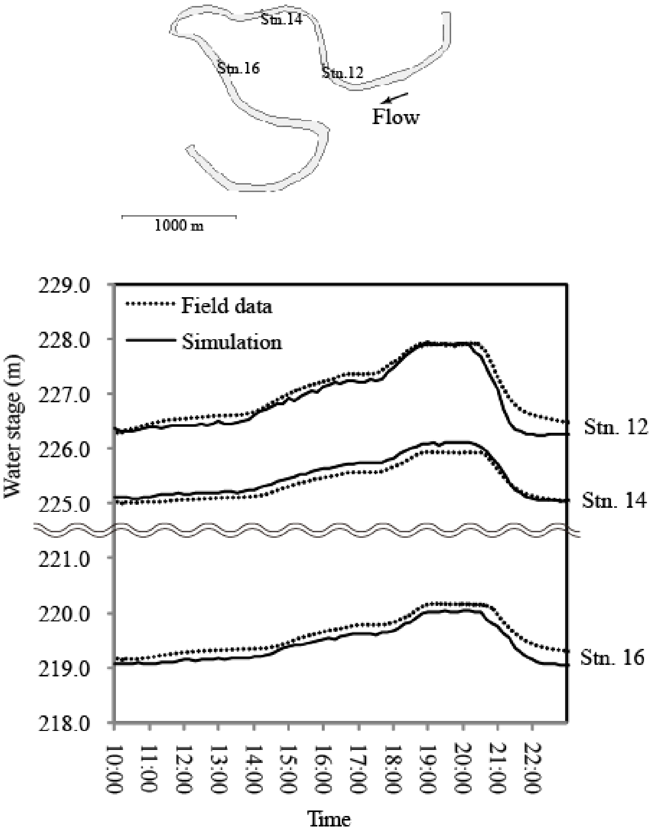


Figure 7. Comparison of simulated and measured stages at stations 12, 14 and 16.

Figure 7 presents a comparison of observed and simulated water stages at three stations. The simulated water stage hydrographs adequately represent the observed result profiles, which indicate that the general flow structure can be reproduced by the flow simulation used here.

4.4 *Transport and exchange of chl.a concentration*

Figure 8 shows simulated and observed chl.a concentrations at the upstream and downstream stations. In the chl.a transport simulation, diffusion, sink and source are neglected and pure convection is considered. Difference between the simulated and the observed values shows net gain of chl.a for the water mass convected from the upstream station to the downstream station. As shown in the lower part of Figure 8, the field sample value is about twice as much as the pure convected profile (simulated result). The net gain in chl.a concentration shows that the amount of chl.a supplied from the river bed is larger than that settling on the bed in the reach between the upstream station and the downstream station. The chl.a concentration in the dam water is 3 μg/l, namely the concentration of phytoplankton is comparatively low in the flow under stable conditions. The high concentration of chl.a is originated from the algae, which has been detached from the river bed in the reach between the dam and the upstream station. Namely, the difference between the observed and the simulated concentrations of chl.a at the downstream station shows that a net gain of chl.a originated from the attached algae removed from the river bed.

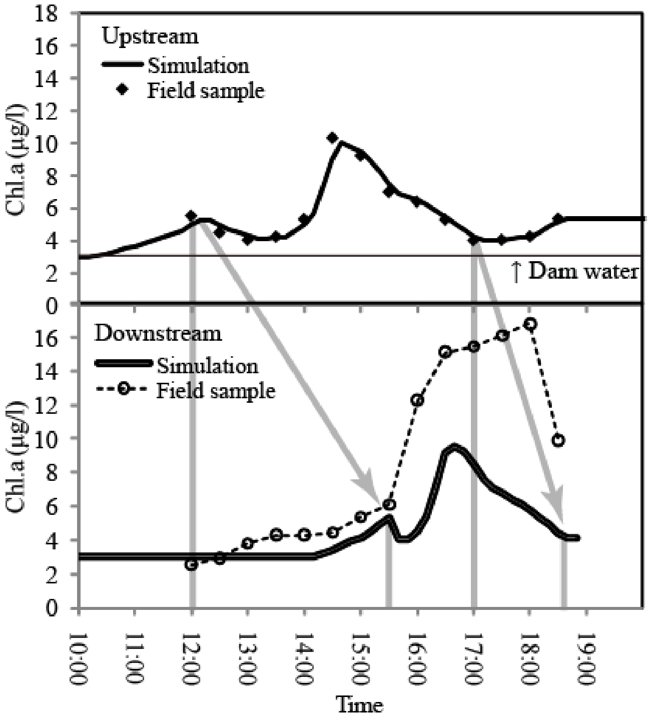


Figure 8. Comparison of measured and simulated time-series changes of chl.a.

4.5 *Transport distance of chl.a*

By comparing the chl.a profiles of the upstream and downstream sections of the simulated result, convection velocity of chl.a transport can be evaluated. The convection velocity of chl.a concentration is identical to that of water mass, namely flow velocity. The first inflection point of chl.a concentration at the upstream station takes 3.5 hours to arrive to the downstream station. The second inflection point arrives 1.5 hours later (see gray additional lines on Figure 8). As demonstrated in Figure 5, the lag time of peak water depth (and discharge) at the upstream station and the downstream station is about an hour. In the open channel flow, a flood wave travels faster than the local velocity of water (e.g., Sato and Watanabe 2000). Therefore, chl.a that has been detached from the river bed during the rising phase of the flood will settle to the river bed at a specific downstream distance L because chl.a is left behind the flood due to the difference of chl.a transport velocity C and the flood propagation velocity U. The distance of chl.a convection during the flood with duration time of T is roughly estimated as

$$L \approx \frac{C}{1-U/C}T \quad . \tag{5}$$

Namely, if the flood duration of the flush discharge is short, transported algae will settle at the point close to the detached area, and it can be said that only one-time implementation of the flush release is insufficient to flush of the organic matter from the river bed. To flush out the organic matter deposited or attached on the river bed effectively, it is necessary to conduct a long-duration flush release, or short but repetitive implementation of the flush release.

The traveling distance of the materials depends on the flush hydrograph pattern. The difference of the flood propagation velocity and the material transport velocity can be analyzed based on the hydraulics, so the traveling distance can be estimated analytically or by using the numerical flow simulation.

5 CONCLUSION

In this study, field observation was conducted to record flow and transport phenomena during the flush discharge conduced in the Jouge River on March 25, 2009. The numerical flow and transport simulation was also conducted to analyze flow characteristics and the transport mechanism. A simple equation to estimate the traveling distance of the suspended matter was proposed and framework of the hydrograph design of a flush discharge from the viewpoint of the material transport were discussed. We would like to analyze more field data to verify applicability of this concept.

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