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INFLUENCE OF SEDIMENT FLUSHING FROM RESERVOIRS ON RIVERBED VARIATIONS

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Reservoir sedimentation causes many problems, such as lowering of a riverbed and coastal erosion. Therefore, in order to alleviate negative influences of the reservoir sedimentation on the downstream reaches, the countermeasures such as sediment flushing and bypassing have been adopted to supply sediment to the downstream channel in Japan. Although various countermeasures have been adopted, the responses of the downstream riverbed to sediment supply have not been clarified enough. It is necessary to understand the responses for effective sediment management in the future. In this paper, the responses of downstream riverbed variations to sediment discharge through the sediment flushing at the Dashidaira and the Unazuki reservoirs on the Kurobe River are studied by means of a one-dimensional numerical model for riverbed variations. The responses characteristics of the downstream physical environment to the sediment flushing from these reservoirs are analyzed to acquire useful information on the sediment management.

Key Words : *Sediment flushing, Sediment management, One-dimensional numerical model, Riverbed variations*

1. INTRODUCTION

To solve problems arising from reservoir sedimentation, and alleviate its negative influences on the downstream environment, countermeasures such as sediment flushing, bypassing and sediment relocation in the river channel have been taken in Japan. It is necessary to understand the responses characteristics of the downstream riverbed to such artificial sediment supply and find effective sediment management methods. However, the practices have just begun recently and the impact of artificial sediment supply to the downstream sediment transportation and the responses of riverbed variations are not understood very well.

Understanding of the responses characteristics to sediment flushing from a reservoir is one of most important problems in sediment management. In this study, a one-dimensional numerical model for riverbed variations is used to simulate the conditions of artificial sediment supply from the reservoir based on the flushing operation and the downstream riverbed variations. Using the results of the analyses, characteristics of long-term changes of downstream riverbed level, diffusion of transported sediment, disturbances to riverbed due to sediment flushing are explained. The findings provide useful information for sediment management.

2. OUTLINE OF THE KUROBE RIVER AND COORDINATED SEDIMENT FLUSHING

In this study, the case of Kurobe River in Toyama Prefecture is selected as a research subject. The Kurobe River located in the eastern part of Toyama Prefecture, originates in Mount Washibadake,enters into the plain region at the Aimoto point 13km upstream of the estuary, and finally flows into the Sea

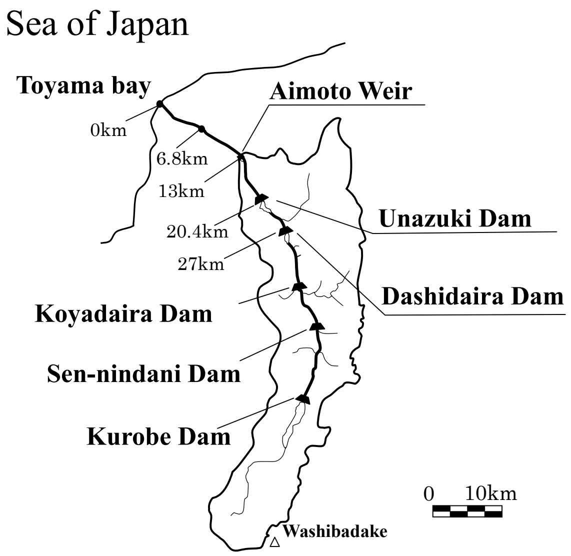

Fig.1 Location of dams in the Kurobe river basin

of Japan (**Fig.1**). The catchment area of the Kurobe River is 682km^2, and the length of the main river is 85km.The gradient of river bed is 1/5 to 1/100 which means one of the steepest in Japan. The geological condition in the river basin is characterized by weathered granite, and the sediment production potential is very high. The annual rainfall in the basin is about 4,000mm, and there is great amount of sediment flowing into the reservoirs on river course$^{1)}$.

To solve the problems of reservoir sedimentation, sediment flushing operations has been implemented at the Unazuki dam, completed in 2001, and the Dashidaira dam, completed in 1985. During the flood that satisfies a stipulated standard, reservoir water levels are lowered to increase erosion force, and the incoming sediment and deposits in the reservoirs are flushed through sediment flushing gates to the downstream channel. The sediment flushing at the Dashidaira dam has been carried out since 1991 and the coordinated sediment flushing at the Unazuki and the Dashidaira dams has been carried out since 2001. 14 coordinated sediment flushing had been implemented by December 2007$^{2)}$.

3. NUMERICAL MODEL AND CALCULATED CONDITIONS

(1) Outline of numerical model

A one-dimensional numerical model which can simulate variations of the bed load, suspended load and wash load is used in this study. Flow is calculated using a one-dimensional non-uniform flow method, which considered computational time and stability. The bed load and suspended load are defined as the grain size over 0.1mm, and wash load is as the grain size 0.1mm and less. The bed load is estimated by the Ashida and Michiue formula, and the wash load and suspended load are calculated by multiplying the mean cross-sectional concentration by the discharge of the cross section. The mean cross-sectional concentration is obtained by a one-dimensional convection and diffusion equations which consider the particle falling and pick-up. The grain size distribution is computed by multilayer model which is divided from the riverbed surface to the bottom in vertical direction and varies grain distribution of each layer in response to the bed variation. Further details can be found in the reference$^{3) 4)}$.

(2) Calculated conditions

The object domain of our concern is about 30km reach, which is from the estuary to the upstream section of the Dashidaira reservoir, as shown in **Fig.2**. There located the Aimoto weir, the Unazuki dam and the Dashidaira dam in this domain. The Kuronagi River, the main tributary, confluents around 4.5km upstream of the Unazuki dam.

The initial riverbed elevation is based on the measured value in December 2006. The initial grain size distributions of the bed materials are calculation values in December 2006. The intervals of cross section of simulation are set to be 100 to 200m.

Regarding the boundary condition of water level, the average tidal level at the river mouth in the Toyama Bay, El. 0.21m is used for the outlet section. Reservoir water level is given by the following operation rule for the coordinated sediment flushing. When floods with the discharge of more than or equal to 300m^3/s at the Dashidaira dam or more than or equal to 400 m^3/s at the Unazuki dam are observed during the period from June to August, the coordinated sediment flushing would be carried out. The sediment flushing can be carried out under the condition of the gravity flow made by draw down of the reservoir water level. After the first coordinated sediment flushing in the year, the sediment flushing

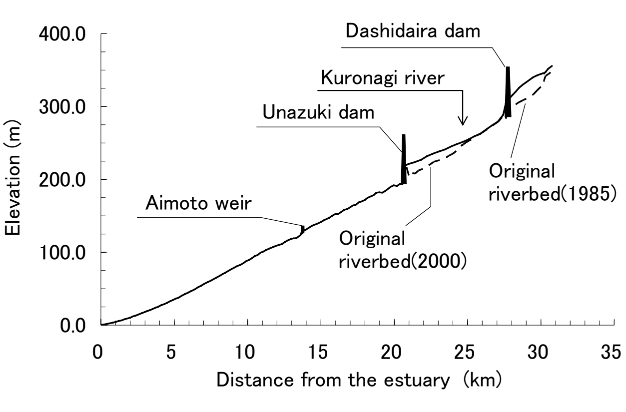

Fig.2 Object domain and initial riverbed profile

is carried out again if the flood of the Dashidaira reservoir is more than or equal to 480m^3/s, or the flood of the Unazuki reservoir is more than or equal to 650m^3/s. It should be noted that the gravity flow condition is set to be continued 12 hours in consideration of past sediment flushing practices. The details of the operation rule are mentioned in the reference$^{5)}$.

In this study, the hourly discharges for 35 years at the inlet section of the Dashidaira reservoir and those of the Kuronagi River from 1972 to 2006 are repeatedly used for computing the 100 years riverbed variations. The discharges of the Kuronagi River are estimated as the measured inflow discharges of the Unazuki dam minus the measured outflow discharges of the Dashidaira dam. However, because there are not any measured inflow data at the dams before completion, the measured discharges at the hydrological stations near the dams are transferred into the inflow data.

The sediment supply at the inlet section of the Dashidaira reservoir and the ones of the Kuronagi River are obtained by the uniform flow method and the sediment transport formulae where the bed slopes are 1/55 and 1/30 from the measured values, roughness coefficients are 0.03 and 0.04, and the grain size distributions of the bed materials are determined on the basis of the survey results. The bed load is computed by the Ashida and Michiue formula, and the suspended load is computed by the Lane-Kalinske formula. The concentration near the riverbed is computed by the Ashida and Michiue formula. However, the riverbed variations calculated by these conditions are larger than the actual ones. Therefore, the bed load and suspended load at the inlet section of the Dashidaira reservoir are modified by multiplying the calculated ones by 0.4, and the bed load and suspended load of the Kuronagi River are modified by multiplying the calculated ones by 0.6. The effective discharge of sediment transport at the inlet section of the Dashidaira reservoir and the one of the Kuronagi River are 300m^3/s and 100m^3/s, respectively. The effective discharge is the minimum discharge at which the sediment can be supplied. The wash load at the inlet section of the Dashidaira reservoir and the one of the Kuronagi River are determined on the basis of the measured SS value of turbid water from 2001 to 2006 by the function of discharge, and the effective discharge of the wash load are 100m^3/s and 35 m^3/s.

The bed material is divided into 11 classes by size, the representative grain sizes of the bed load and suspended load are 707.1mm, 361.2mm, 118.3mm, 37.42mm, 11.83mm, 3.742mm, 1.183mm and 0.374mm. The representative grain sizes of the wash load are 0.1mm, 0.0158mm and 0.0022mm.

The above model was verified to simulate the riverbed variations of both reservoirs and downstream in the reference$^{6)}$.

4. ANALYSIS OF RESPONSE CHARACTERISTICS OF RIVERBED VARIATION TO SEDIMENT FLUSHING

(1) Outline of analysis

It is very important for the comprehensive sediment management to understand the long-term riverbed variations of the downstream channel related to the sediment flushing volume, grain size and frequency of flushing, and the short-term riverbed variations due to pulsed sediment releasing by the sediment flushing. Especially, the latter has very important influence on the ecological environment because suitable disturbance on the river is necessary. Therefore, we analyze the riverbed variations not only from the aspect of the long-term characteristics by sediment flushing but also the short-term characteristics and transportation characteristics of pulsed sediment releasing.

(2) Long-term riverbed variations by the sediment flushing

Fig.3 shows the calculated annual volume of the suspended load and bed load released from the Unazuki dam. The annual sediment volume varies with the flood scale and frequency in the year. **Fig.4** indicates the calculated riverbed variations in three reaches downstream of the Unazuki dam. From the point of the long-term riverbed variations, there are no obvious changes in all the three reaches in beginning ten years. The riverbed elevation in the reach between the Unazuki dam and the Aimoto weir gradually rises after about 10th year, and the riverbed elevations in other two reaches gradually rise after about 25th year. Therefore, it can be said the rising of the riverbed due to the coordinated sediment flushing in the upstream reach occurs earlier than the ones in

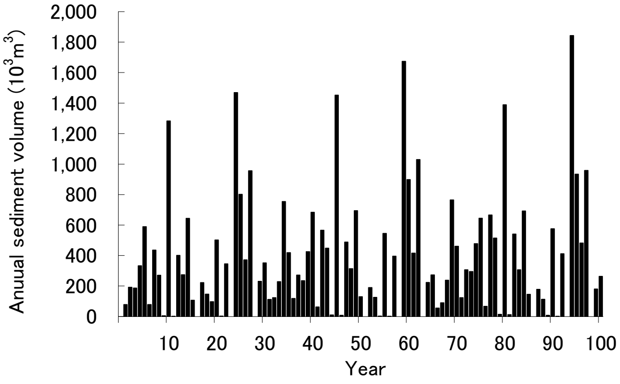

Fig.3 Annual volume of the suspended and bed load released from the Unazuki dam

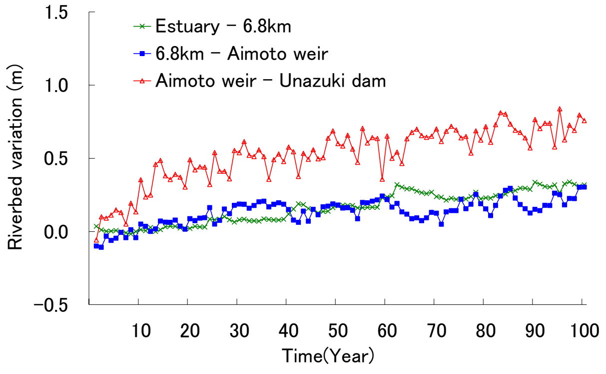

Fig.4 Time variations of calculated sediment deposition depth in the downstream from the Unazuki dam

the downstream reaches, and it requires at least 10 years.

It is necessary to study whether long-term variations due to the flushing are acceptable for flood control, water utilization, and environment conservation or not. It is one of the alternatives to modify sediment flushing operation rule, if the long-term riverbed variations are judged to be larger than the toleration range, considering time lags between the sediment flushing and aggradation of the riverbed as predicted by the above analysis.

(3) Transportation characteristics of sediment discharged in pulse

As shown in **Fig.3** and **Fig.4**, the large pulse releasing of sediments from the reservoirs have significant influence on the short-term riverbed variations in the downstream channel, and give various disturbances to the river channel. However, the riverbed variations of the channel far from the sediment supply points become relatively smooth and smaller.

Fig.5 shows the spectrum of annual amount of sediment outflow from the Unazuki dam and annual riverbed variations in three reaches downstream of the Unazuki dam. It is found that the predominant periods of annual sediment outflow are approximately 2 to 3, 5 and 18 years. The phenomena of the large sediment outflow in a period of 18 years can be also found from **Fig.3**. The predominant periods of annual riverbed variations in the reach between the Aimoto weir and the Unazuki dam are about 2 to 3, 4 to 5, 9 and 18 years. The spectrum has similar characteristics of annual amount of sediment outflow. It is concluded from the above-mentioned analyses that the river course near the dam is more responsive and sort-term riverbed variations are likely to occur.

Fig.6 shows the relationship between the annual maximum daily sediment volume released from the Unazuki dam and absolute values of the daily riverbed variations in three reaches on the day when the annual maximum sediment volume occurs. Correlation coefficients between these values are also shown in **Fig.6**. The absolute value of the riverbed variations is larger in relation to sediment outflow volume, and the correlation coefficient is also larger, in the reach immediately downstream of the Unazuki dam than in other reaches. Therefore, the response of riverbed variations to sediment supply is higher, and riverbed level varies corresponding to the volume of sediment supply in the reach immediately downstream of the dam. The riverbed variations in the other two reaches do not respond to changes in sediment supply, and the magnitude of its variations is not large.

Fig.7 indicates correlation coefficients between annual maximum daily sediment outflow volume released from the Unazuki dam and absolute values of segment averages of daily bed variations on N days after the annual maximum sediment outflow occurs. The correlation coefficient in the reach immediately downstream of the Unazuki dam is largest on the day N=0, and the correlation

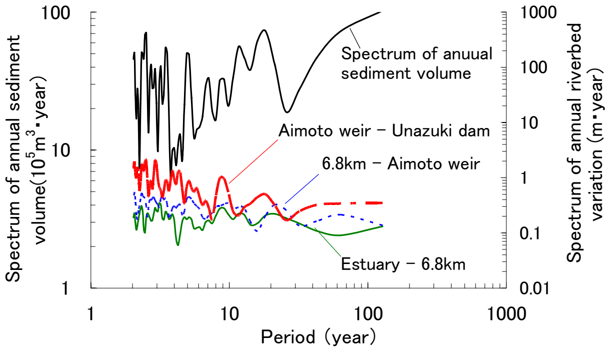

Fig.5 Spectrum of annual amount of sediment outflow from the Unazuki dam and annual riverbed variations in three reaches downstream of the Unazuki dam

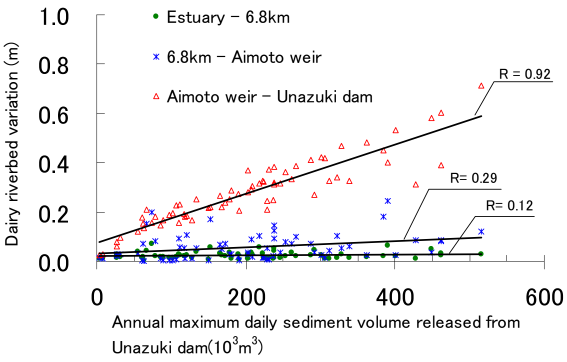

Fig.6 Relationship between the annual maximum daily sediment volume released from the Unazuki dam and absolute values of segment averages of the daily riverbed variations in three reaches when the annual maximum sediment volume occurs

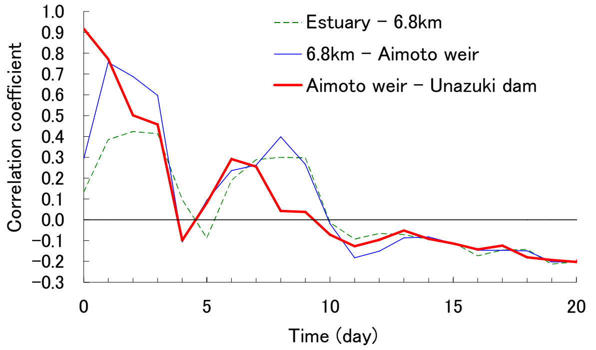

Fig.7 Correlation coefficients between annual maximum daily sediment outflow volume released from the Unazuki dam and absolute values of daily riverbed variations on N days after the annual maximum sediment outflow occurs

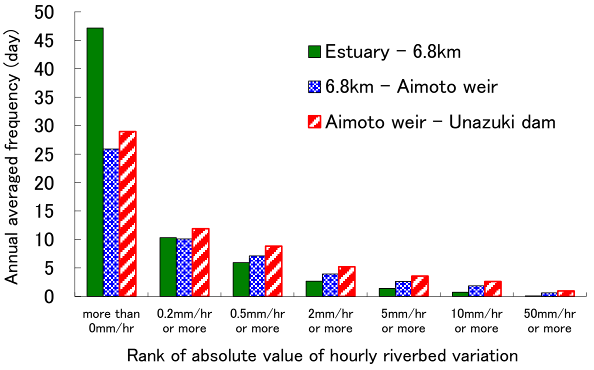

Fig.8 Relationship between the ranks of absolute values of hourly riverbed variations and their annual averaged frequencies

disappears after 5 days. Correlation coefficients in other two reaches are small on the day N=0, but those on the day N=1 and N=2 become larger. The relationship disappears after 5 days same as the case in the reach immediately downstream of the Unazuki dam. The correlation coefficient in the three reaches increase up to 0.3 on the days N=6 to 9, which is because floods after the sediment flushing induced riverbed variations. From the above-mentioned observation, it is found that the effect of sediment outflow on the riverbed variations appears later in the reaches further downstream.

(4) Short-term riverbed variations characteristics by sediment released in pulse

If sediment released in pulse gives appropriate disturbances to riverbed formation, it would be a welcome effect in terms of natural environment. To decide volume and frequency of pulse releasing appropriate for the environment, we need to know what kind of disturbances of riverbed is desired by the ecosystem, which is beyond the scope of this study. Now we have a look at the disturbances induced by sediment released in pulse on the basis of short-term riverbed variations characteristics.

Fig.8 shows the relationship between the ranks of absolute values of hourly riverbed variations and their annual averaged frequencies. The smaller variations are observed in the reach between the estuary and Section 6.8km, and larger variations in the reach between the Aimoto and the Unazuki dam. The grain sizes are smaller near the estuary and small riverbed variations are induced by weaker current. The grain sizes become larger in the upstream and small riverbed variations is less frequent, while larger riverbed variations is more frequent than in downstream reaches.

Large scale riverbed variations are frequently observed immediately downstream of the dam, which become less so in the downstream. And small scale bed variations are more frequent in the reaches near the estuary.

5. CONCLUSIONS

In this study, applying a one-dimensional numerical model for riverbed variations to the case of flushing operations in the Kurobe River, long-term river riverbed variations due to sediment flushing from reservoirs, characteristics of sediment transportation and short-term riverbed variations after sediment flushing released in pulse were investigated in order to obtain useful information in working out effective sediment management. The findings are summarized as follows:

1) The riverbed immediately downstream the Unazuki dam rises gradually.

2) Riverbed variations in the reach immediately downstream of dam occur in frequencies corresponding to sediment flushing. But those in reaches further downstream show frequencies different from sediment flushing. Riverbed variations in the reach immediately downstream of the Unazuki dam shows maximum value on the day when the annual maximum sediment releasing occurs, but that in the reaches further downstream is observed 1 to 2 days after. The characteristics of sediment transportation are different in three reaches.

3) In the reach immediately downstream of the dam, relatively large scale riverbed variations are observed frequently. This characteristic becomes weaker downstream, and in the reaches near the estuary, small variations are observed more frequently. This finding will serve evaluation of the effects of sediment flushing on the environment.

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