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Estimation of Sediment Discharge Taking into Account Tributaries to the Ishikari River

Kazutake ASAHI
Division of Environmental and Resource Engineering, Hokkaido University, Sapporo, Japan
Kazuo KATO
SUIKO Research Company, Sapporo, Japan
Yasuyuki SHIMIZU
Division of Environmental and Resource Engineering, Hokkaido University, Sapporo, Japan

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ABSTRACT

In managing the Ishikari River, it is necessary to evaluate sediment discharge along its entire length. Sediment discharge from tributaries into the main stream therefore was in vestigated. Two numerical models that take into account tributaries are proposed which were tested for the 1981 Ishikari River flood. The sediment discharges calculated with these models were compared with recoded values. Results show that it is necessary to consider tributary effects directly and that sediment discharged from tributaries contributes to the output sediment discharged from the river's mouth.

1. INTRODUCTION

The Ishikari River flows from Mt. Ishikari (elev. 1967m) in the Taisetsu Mountains and is the second-longest river in Japan (Fig.1). Its basin (14,330km^2) spreads over the west-central area of Hokkaido, northern Japan. As many as 70 tributaries flow into the Ishikari River, among them the Chitose, Yubari, and Uryuu rivers. The extensive plains along the Ishikari River are at the center of Hokkaido. Evaluation of the sediment transport rate therefore is important in managing the is river and its environment.

Flood control on the Ishikari dates from 1910, when the first development plan for Hokkaido was initiated, thereafter cutoffs were established and dredging done to prevent flooding. Dramatic flooding of the basins in the lower reaches has occurred occasionally after heavy rainfall because water does not readily infiltrate the peaty marshland and lowlands that make up the basin. Moreover a 1981 flood caused severe damage in the basins of the Ishikari River, including in Sapporo, Hokkaido's center of economy and government.

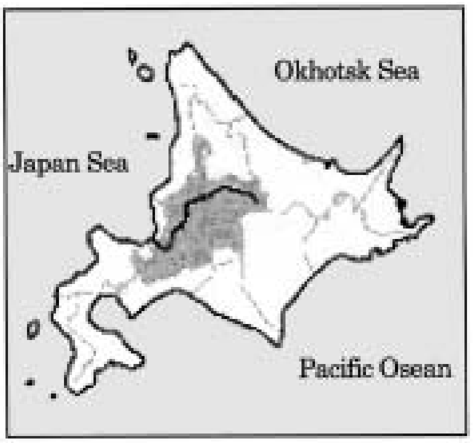

Fig. 1 Map of the Ishikari River.

A number of studies of the Ishikari River therefore have been made. Itakura, Yamaguchi et al. (1986) reported the effects of placing alternating bars in the lower reaches of the river. Shimizu (1995) used computer technology to show that grain size distribution and bed deformation could be calculated for the transport of bed and suspended loads. The relationship between sedimentation, sediment discharge and tributaries has however is unknown.

The 1-Dimensional bed variation model is a powerful tool with which to evaluate sedimentation over a long period of time in a large area. A 1-Dimensional numerical model is here used to investigate sediment discharge and sedimentation along the Ishikari River and representative tributaries.

Two models were tested with data for the 1981 flood. The first that of Shimizu (1995), models water discharge using a curve approximated from data on the main stream. The second models discharge by directly assessing the effects of tributaries. i.e., by analyzing the water discharges from the main stream and its tributaries. Based on the calculated results, a method for determining the effects of tributaries on the main stream, in terms of sediment discharge and sedimentation, is proposed.

KEY WORDS: tributaries, sediment discharge, sedimentation, the Ishikari River, numerical calculation

2. GOVERNING EQUATIONS

The numerical model used follows that of Shimizu (1995) which was verified by the use of data from the 1981 flood. However. His model however did not consider the effects of tributaries sufficiently. Our study uses numerical models to assess the effects of water and sediment discharged from tributaries into the main stream.

Change in the speed of a stream is faster than bed and grain size transformation. Generally, the kind of models used are quasi-steady state ones. Furthermore the stream is considered to be in sub-critical flow. A non-uniform flow model, in which the water level at the river mouth and discharge from the tributaries are given respective for the boundary and hydraulic conditions. Channel width, bed elevation and grain size distribution as the initial conditions are given as an approximated curve obtained from measured data. And bed valiation is conducted with bed and suspended loads.

Two models are used to from a numerical model which considers tributaries effects on flow and sediment discharges.

2.1. Outline of two models are explained as follows

(1) Model I : Input data from the approximated curve

Fig.2 shows the input discharge image for Model I. In that model, a curve approximated from existing data, that is in only for the main stream, is used for the input discharge. That is, the confluence point of the tributary is not considered directly and discharge roughly follows the curve approximated from actual measurements. Only the suspended load is considered as sediment inflow. This method is effective when observatories are located only in the main channel.

(2)Model II : Input data from measurements

Fig.3 shows the input discharge image for Model II. In that model the measured discharges, for both the main channel and the tributaries, are used directly. Increases in the discharges of the main stream are observed only at the sites of confluence.

Sediment discharge by and the sedimentation of tributaries also are calculated in this model. Only the suspended loads entering main stream from the tributaries are dealt with because bed load was not considered in Model I, and almost all sediment enters the main stream from it tributaries as suspended loads.

2.2. 1-dimensional continuity and momentum equations

The continuity and momentum equations of 1-dimensional steady flow are

$$Q=uhB \tag{1}$$

$$\frac{\partial H}{\partial x}+\frac{\partial H}{\partial x}\left(\frac{Q^2}{2gA^2}\right)+\frac{q_xQ}{gA} \tag{2}$$

where x is the distance from the river mouth, Q the discharge, u the cross-sectional averaged velocity, h the water depth, B the channel width, h the water surface elevation ($H=h+\eta$), η the bed elevation, g the acceleration due to gravity, A the cross-sectional area of flow, q_x the inflow from the side, and i_e the energy gradient. q_x comprises the inflow from tributaries, ground water, and surface runoff.

Kishi and Kuroki's formula is used to estimate bed friction;

$$\frac{u}{u_*}=6.8\left(\frac{h}{d_m}\right)^{1/6} \tag{3}$$

where u_* is shear the velocity($=\sqrt{ghi_e}$) and d_m the average grain size of the bed material.

i_e is obtained from Eqs.(1) and (3);

$$i_e=\frac{Q^2 d_m{}^{1/3}}{46.2h^{10/3}gB^2} \tag{4}$$

2.3. Sediment transport

The bed load transport rate per unit width is calculated by Ashida and Michiue's formula;

$$\frac{q_{Bi}}{\sqrt{sgd_i^3}}=p_i 17\,\tau_{*i}{}^{3/2}\left(1-\frac{\tau_{*ci}}{\tau_{*i}}\right)\left(1-\frac{u_{*ci}}{u_*}\right) \tag{5}$$

where subscript i is the grain size, s the specific gravity of the sediment particles, d_i the diameter of the bed material, p_i the volumetric fraction of the sediment particles, τ_{*i} the non-dimensional bed shear stress $[=u_{*ci}/(sgd_i)]$, τ_{*i} the non-dimensional critical shear stress $[u_{*ci}/(sgd_i)]$, and u_{*ci} the critical shear velocity calculated by Egiazaroff and Asada's formula;

$$\frac{u_{*ci}^2}{u_{cm}^2}=\frac{\log 23}{\log\left(21\frac{d_i}{d_m}+2\right)}\frac{d_i}{d_m} \tag{6}$$

where u_{*cm} is the critical shear velocity for d_m calculated by Iwagaki's formula. In this study, the effective bed shear stress equals the total bed shear stress.

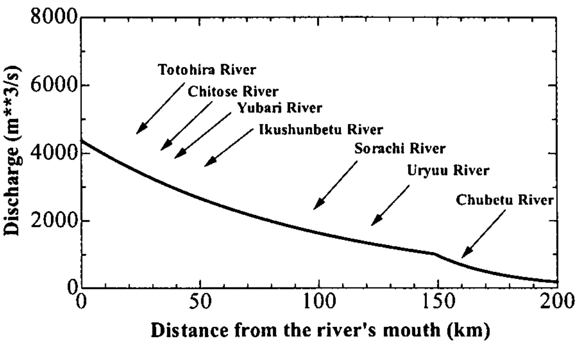

Fig. 2 Approximated curve used for input discharge: Model (I).

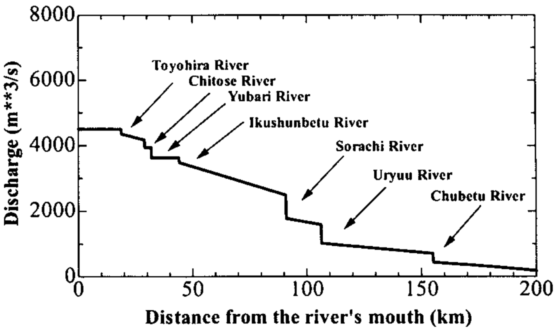

Fig. 3 Actual recorded measurements used for input discharge: Model (II).

The pick-up rate of the suspended load per unit area is calculated by the formula of Itakura and Kishi;

$$q_{sui}=p_i K\left(\alpha_*\frac{\rho_s-\rho}{\rho_s}\frac{gd_i}{u_*}\Omega_i-\omega_{fi}\right) \tag{7}$$

$$\Omega_i=\frac{\tau_{*i}}{B_{*i}}\frac{\int_{a'}^{\infty}\xi\frac{1}{\sqrt{\pi}}\exp(-\xi^2)d\xi}{\int_{a'}^{\infty}\frac{1}{\sqrt{\pi}}\exp(-\xi^2)d\xi}+\frac{\tau_{*i}}{B_{*i}\eta_o}-1 \tag{8}$$

where q_{sui} the pick-up rate, and ω_{fi} the fall velocity calculated by Rubey's formula. ρ and ρ_s are the respective specific densities of the water and sediment particles. Furthermore, $a'=B_*/\tau_*-1/\eta_0$, η_0=0,5, K=0.08, and a_*=0.14. Generally, B_{*i}=0.143, but here the shielding effect is determined using the formula of Oki and Kuroki;

$$B_{*i}=\xi_i B_{*o} \tag{9}$$

$$\xi_i=\frac{\tau_{*ci}}{\tau_{*cio}} \tag{10}$$

where B_{*0}=0.143, and $[\tau_{*cio}=u_{*ci}^2/(sgd_i)]$. u_{*cio} the critical shear velocity for d_i in the uniformity bed as calculated by Iwagaki's formula.

The continuity equation of the depth-averaged suspended sediment concentration is

$$\frac{1}{B}\frac{\partial}{\partial x}(Q<c_i>)=q_{sui}-\omega_{fi}c_{bi}-\frac{q_x<c'_i>}{B} \tag{11}$$

$$<c'_i>=\begin{cases}<c_{xi}> \text{ in Model I}\\ <c_{xi}> \text{ in Model II}\end{cases}$$

where $<c_i>$ the depth-averaged suspended sediment concentration and $<c_{xi}>$ the depth-averaged suspended concentration of the tributaries at the confluences. c_{bi} is the reference concentration of lateral flow. Here it is be obtained from

$$c_i=c_{bi}\exp(-\beta\xi) \tag{12}$$

$$<c_i>=\frac{1}{h}\int_0^h c_i dz=\frac{c_{bi}}{\beta}(1-\exp(-\beta)) \tag{13}$$

where z is the distance from the bed, $\varepsilon=ku_*h/6$, k is the Karman constant(=0.4), $\beta=\omega_{fi}h/\varepsilon$, and $\xi=z/h$. The volumetric fraction of the bed material grain size, is obtained from

$$\delta\frac{\partial p_i}{\partial t}+p_i^*\frac{\partial\eta}{\partial t}+\frac{1}{1-\lambda}\left[\frac{1}{B}\frac{\partial}{\partial x}(q_{Bi}B)+q_{sui}-\omega_{fi}c_{bi}\right.$$
$$\left.-\frac{q_x c_{Bxi}}{B}\right]=0 \tag{14}$$

p_i^* ; p_i' ; $\partial\eta/\partial t>0$

p_i^* ; p_i ; $\partial\eta/\partial t<0$, $\eta_b<\eta$

p_i^* ; p_{io} ; $\partial\eta/\partial t>0$, $\eta_b<\eta$

where δ is the exchange layer thickness, t the time, and λ is the void ratio. c_{Bxi} is the reference concentration of lateral flow from tributaries. p_i' and p_{io} are the volumetric fractions of the sediment particles in the bed and the suspended loads, and for the initial bed.

The time-dependent change in bed elevation is obtained from the continuity of bed material transport;

$$\frac{\partial\eta}{\partial t}+\frac{1}{1-\lambda}\left[\frac{1}{B}\frac{\partial}{\partial x}(\Sigma_i q_{Bi}B)+\Sigma_i(q_{sui}-\omega_{fi}c_{bi})\right]=0 \tag{15}$$

where Σ_i is the summation of the bed material transport load.

3. CALCULATION CONDITIONS

The aim of this study was to establish a numerical model takes into account the effect of tributaries on sediment discharge and sedimentation. The conditions in the two models were set to be the same.

A curve approximated from existing data was used for the initial bed elevation (= η), channel width (=B), and bed material grain size (=d_i) in the main stream and its tributaries (Figs.4 and 5). The approximate expressions for the main stream used for calculation were

$$\eta = 2.49\exp(0.0245K_p)-7 \tag{16}$$

$$B = 457.91\exp(-0.0089K_p) \tag{17}$$

where η is the bed elevation, B the channel width and K_p the distance from the river's mouth(km). Grain size profiles (d_{10}, d_{50}, and d_{90}) and of the bed materials in main stream were

$$d_{10}=0.1682\exp(0.0145K_p) \tag{18}$$

$$d_{50}=0.3883\exp(0.0273K_p) \tag{19}$$

$$d_{90}=1.4530\exp(0.0258K_p) \tag{20}$$

d_{10}, d_{50}, d_{90} respectively being the 10%, 50%, 90% grain sizes(mm) in the bed. The initial grain size distribution in the bed material is defined by those formulas as the normal distribution. Fig.6 shows the classification of bed material for the normal distribution. Bed elevation, channel width, and grain size profiles for the initial condition in the tributaries were obtained in the same way.

The two models were tested by reproducing the 1981 Ishikari River flood. Fig.7 shows a hydrograph of that flood. Ishikari Bridge, Naie Bridge, Inou Bridge, and Kamikawa are discharge observation stations in the main channel of the

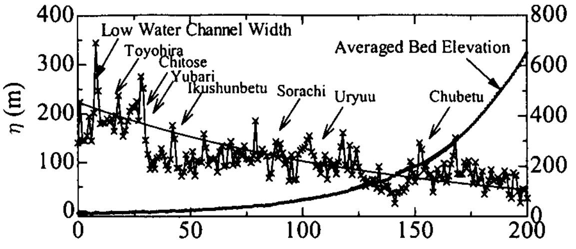

Fig. 4 Longitudinal profile of bed elevation and channel width.

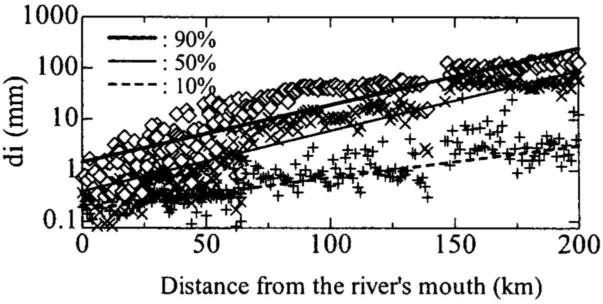

Fig. 5 Longitudinal profile of d10, d50, d90.

Ishikari River. Fig.8 shows the location of each station, and its distance from river's mouth. In advance, the discharge and water depth at the river's mouth respectively were given as the hydraulic and boundary conditions. First, the water surface elevation of the main stream was obtained from Eqs.(1) and (2). The water surface elevations of the tributaries then were calculated based on the main stream water depth at each confluence. Bed shear stress was obtained with Eq.(6), and the bed load, suspended load, and suspended concentration respectively were calculated with Eqs.(5), (7), and (11). On the basis of these values the sediment discharge, volumetric bed material fraction and bed elevation were obtained. The calculations were continued from the start to end of the hydrograph.

Flowchart

The calculation procedure is given below. Repeating these procedures were conducted in the calculation.

1) Calculation of the water surface elevation in the main channel. Eqs.(1) and (2).
2) Calculation of the water surface elevation in the tributaries; Eqs.(1), and the water surface elevation at confluence in the main channel; Eqs.(2).
3) Calculation of the bed shear stress; Eq.(6).
4) Calculation of the amount of sediment; Eqs.(5) and (7).
5) Calculation of the suspended sediment concentration; Eq.(11).
6) Updating of the bed elevation; Eq.(15).
7) Updating of the volumetric fraction of the bed material; Eq.(14).
8) Updating the of the time.

No.	Grain Size(mm)	Average Grain Size(mm)
1	~ 0.074	0.054
2	0.074 ~ 0.200	0.137
3	0.200 ~ 0.400	0.300
4	0.400 ~ 1.000	0.700
5	1.000 ~ 2.000	1.500
6	2.000 ~ 4.000	3.000
7	4.000 ~ 10.00	7.000
8	10.00 ~ 20.00	15.00
9	20.00 ~ 40.00	30.00
10	40.00 ~ 100.0	70.00
11	100.0 ~ 200.0	150.0
12	200.0 ~	300.0

Fig. 6 Grain size classification.

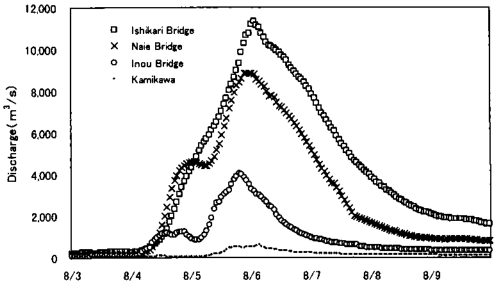

Fig. 7 The hydrograph of observation station (1981. 8).

Observation	Distance from the river's mouth(km)
Ishikari Bridge	26.6
Naie Bridge	76.8
Inou Bridge	130.2
Kamikawa	200.33

Fig. 8 Distance of Observation from the river's mouth.

4. NUMERICAL VERIFICATION AND RESULTS

Figs.9 and 10 show the longitudinal sediment discharge profile along the Ishikari River, averaged by the hour, as calculated respectively by Model I and II . The findings for each model show that sediment discharge increases in the downstream direction.

In the lower reaches the suspended load predominates, whereas in the upper reaches the suspended and bed loads are roughly equal. The effect of confluence on sediment discharge to the main stream in not found in the calculated results for Model I. Results of Model II clearly show that sediment discharge enters the main stream from its tributaries. The sediment discharge obtained for Model II is greater than that for Model I because the former model includes the inflow from the tributaries. The results show that the effects of the Chubetsu, Uryuu, and Sorachi rivers, which flow into the upper reaches of the Ishikari River have particularly marked effects, on the sediment discharge of the main

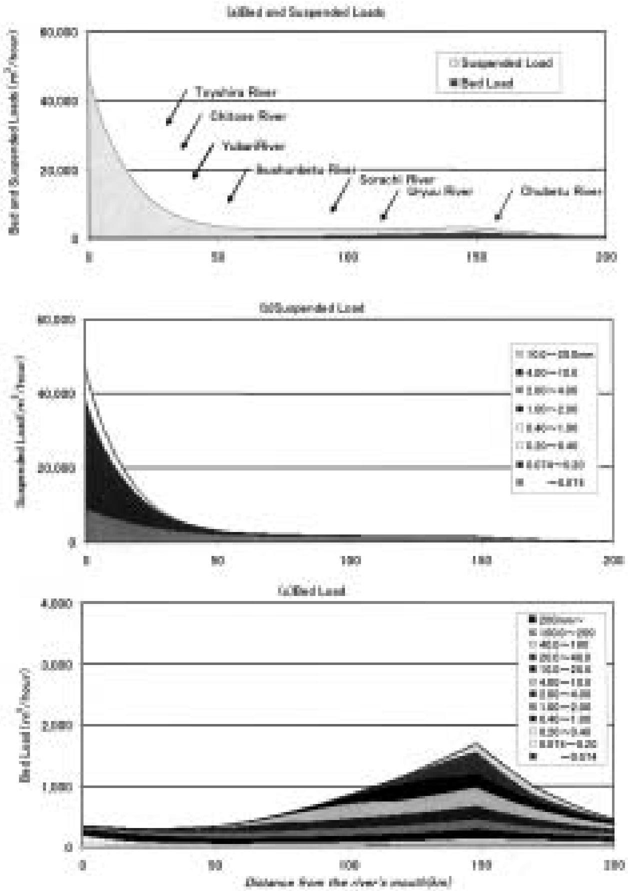

Fig. 9 Calculated Bed and Suspended Loads in the Ishikari River: Model I.

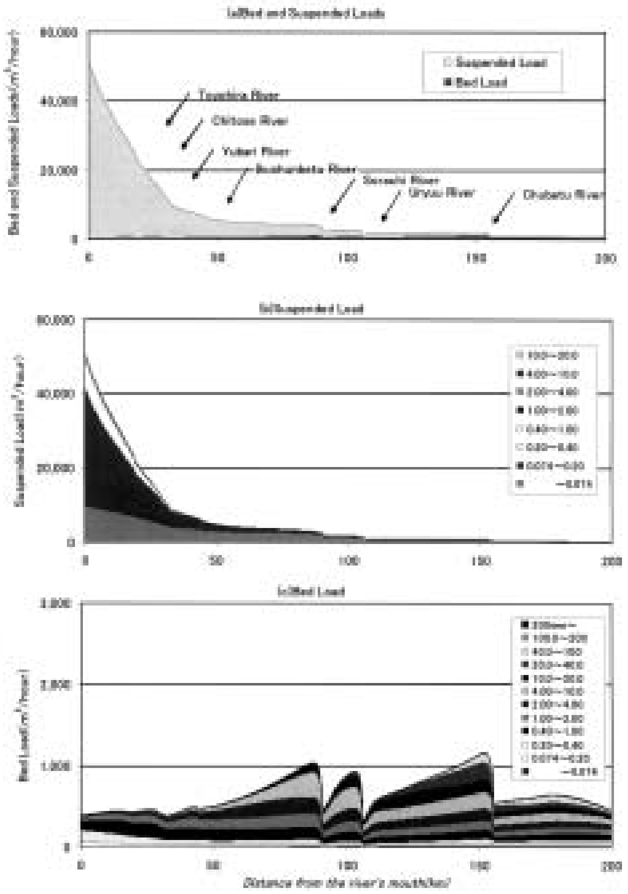

Fig. 10 Calculated Bed and Suspended Loads in the Ishikari River: Model II.

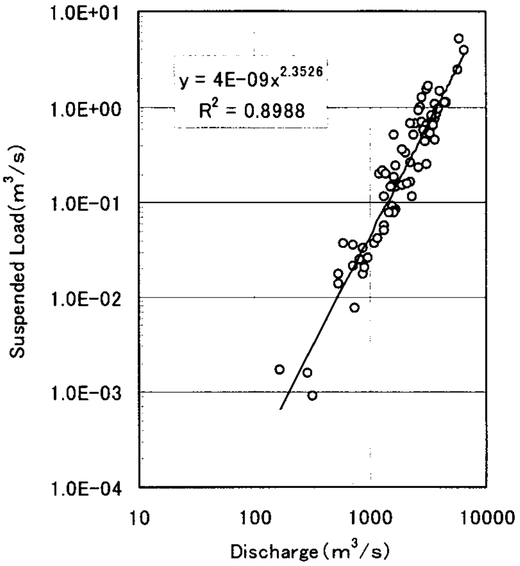

Fig. 11 Relationship between Discharge and suspended Load at Ishikari Brige.

stream.

Fig.11 shows the relationship between the discharge and suspension of sediment in the Ishikari River. An approximated curve, which agrees with the measured values, was obtained from that data. This approximate is considered to represent the actual values for the Ishikari River.

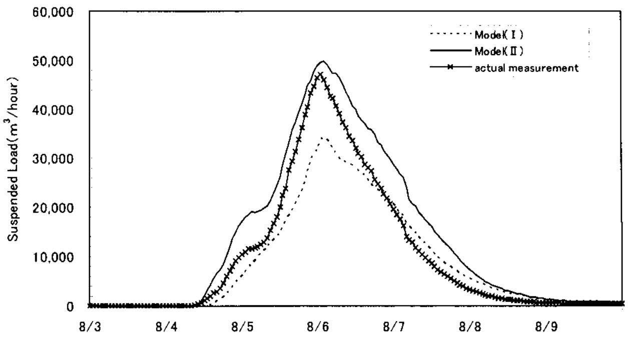

Fig. 12 Comparison of Suspended Sediment Discharges at Ishikari Brige.

The approximated curve is written

$$Q_s=4\times10^{-9}Q^{2.3526} \tag{21}$$

where $Q_s(m^3/sec)$ the suspended sediment discharge and $Q_s(m^3/sec)$ the discharge.

Fig.12 compares recorded values of the suspended sediment at Ishikari Bridge with values found with Models I and II.

The results obtained with Model II clearly agree more closely with the measured values. Because in Model II the suspended load which flows into the main stream from the tributaries is greater than that in Model I the estimation of the sediment discharge from the tributaries in Model I is litter estimation than actual phenomenon.

Model II therefore is valid. The findings of this study show the importance of tributaries in contributing to the sediment discharge of the main stream.

5. CONCLUSION

Two models that consider the effects of tributaries were examined based on records for the 1981 Ishikari River flood. It was confirmed that Model II, which directly takes into account the effects of tributaries, can be used to estimate the sediment discharge of the Ishikari River of the main channel. Because sediment eutering from the tributaries was found to contribute to the runoff sediment discharge from the river's mouth, tributary effects on flow discharge and sediment discharge mast be considered directly.

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APPENDIX-NOTATION

The symbols used in this paper are

Q = water discharge;
u = cross-sectional averaged velocity;
h = water depth;

B = channel width;
H = water surface elevation;
η = bed elevation;
g = acceleration of gravity;
A = cross-sectional area of flow;
q_x = water discharge of inflow from unit side length;
i_e = energy gradient;
d_m = averaged grain size of bed material;
d_i = grain diameter of bed material;
q_{bi} = bed load transport rate per unit width;
q_{sui} = pick-up rate from unit area;
p_i = volumetric fraction of sediment particle;
u_* = shear velocity;
u_{*ci} = critical shear velocity;
u_{*cm} = critical shear velocity for ;
τ_{*i} = non-dimensional bed shear stress;
τ_{*ci} = non-dimensional critical shear stress;
ω_{fi} = fall velocity;
s = submerged specific gravity of sediment;
ρ = specific density of water;
ρ_s = specific density of sand;
c_i = suspended sediment concentration;
c_{bi} = reference concentration of lateral flow;
k = von Karman constant;
δ = exchange layer thickness;
p_i = volumetric fraction of sediment particles and
λ = void ratio