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DEBRIS FLOWS PRODUCED BY HEAVY RAINS ON JULY 21, 2009 IN HOFU CITY, JAPAN

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ABSTRACT

In this paper, we examine the debris flows which occurred in the mountain rivers in Hofu City, Japan on July 21, 2009. We estimate velocity and discharge of the debris flows in the rivers at Manao and Ishihara districts from field survey and numerical simulation. The numerical simulation indicates that the peak discharge is 181 m^3/s in the river at Manao district and 258 m^3/s in the river at Ishihara district. It is found that sediment yield volume by riverside erosion is larger than landslide sediment volume in the both rivers. Although the landslides triggered the debris flow initiation, they did not play the major role for the sediment outflow to the residential areas. The morphological characteristics of the river at Ishihara district increase debris flow discharge

Key words: *debris flow, Hofu City, simulation, hydrograph, discharge, velocity*

INTRODUCTION

The Hofu City area in Yamaguchi Prefecture had heavy rain on July 21, 2009. The accumulated rainfall was 241mm and the largest hourly rainfall was 62mm/hour at the downtown. This rainfall caused a large number of shallow landslides on mountain slopes in the Hofu City area. Most of the landslides changed into debris flows and then moved downstream in rivers. They resulted in 14 victims. For example, 7 inhabitants were killed in the Ueda-minami river basin at Manao district, 4 inhabitants were killed in a number of river basins at Shimomigita district and 2 inhabitants were killed in a few river basins at Ishihara district.

In order to consider the measures against the debris flows in the mountain areas, it is important to know the debris flow velocity and discharge.

The purpose of the present study is to estimate velocity and discharge of the debris flows from the field survey, the theoretical consideration and the numerical simulation.

The rivers at Manao and Ishihara districts are selected as the study rivers.

First, we visited these rivers in August, September and October, 2009 to measure the cross-sectional profiles and know the river bed situation after the debris

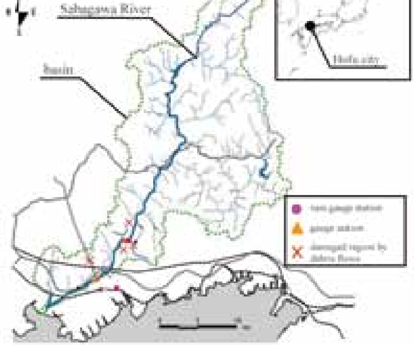

Fig. 1 - Study area.

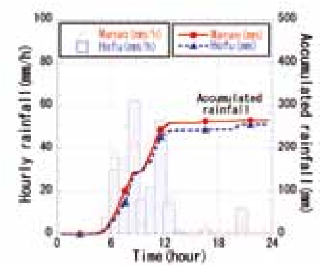

Fig. 2 - Rainfall measured at the Manao and Hofu stations on July 21, 2009

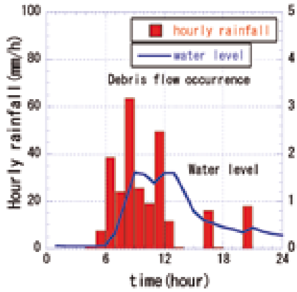

Fig. 3 - Rainfall-runoff relationship of the Mate-gawa River basin

Fig. 4 - The nursing home damaged by the debris flow (Manao district)

Fig. 5 - The house hit by the debris flow (Ishihara district)

flow event. Second, we simulated the debris flows in the rivers at Manao and Ishihara districts with the method of Takaoka, Hashimoto & Hikida (2007). Finally, we discussed the debris flow behaviour in the rivers.

OUTLINE OF THE DEBRIS FLOW DISASTER

STUDY AREA

The study area is located in Hofu City, Yamaguchi Prefecture, Japan (Fig. 1). Geology of its mountain areas is mainly composed of fresh and weathered granite. Therefore, these areas are vulnerable to landslides and debris flows. The government of Yamaguchi Prefecture has made effort to prevent landslides and debris flows. As a result, 23 check dams have been installed to control river bed erosion and bed sediment runoff in the areas. However, Manao and Ishihra district have no check dams in their mountain rivers. These are selected as the study areas.

RAINFALL CONDITION

Hofu City area had heavy rain on July 21, 2009. The situation of the rainfall at two hydrological stations is shown in Figure 2. Hofu station is located in the downtown and Manao station is near the site of the debris flow event. For example, Hofu station measurement expresses that the accumulated rainfall was 241mm from 4 a.m. to 1 p.m. The hourly rainfall had two times of peak of 62 mm from 8 to 9 a.m. and 53 mm from 11 to 12 a.m. Corresponding to such rainfall situation, flood flows arose in every river in Hofu City area. Figure 3 illustrates the rainfall-runoff relationship in a small-river basin at the downtown. In this figure, the measurement of water level of the Mate-gawa River at the downtown is plotted. We found that the flood water level of the small rivers, such as the Mate-gawa River, had also two times of peak.

OUTLINE OF THE DISASTER

This rainfall condition resulted in many shallow landslides in the mountain areas. Most of the landslides changed into debris flows and then moved down the mountain rivers. In their downstream areas, there are villages, a nursing home for elderly people, and roads. The impact of the debris flows produced 7 victims in Manao district and 2 victims in Ishihara district. Figures 4 and 5 are photos of the nursing home and the houses hit by the debris flows in Manao and Ishihra districts, respectively. Some of the witness of this event shows that most of the debris flows occurred at around 12 a.m. Therefore, we can consider that the second peak of the hourly rainfall initiated most of the landslides. The landslide sediments moved into the second peak flood flow. These transported a significant

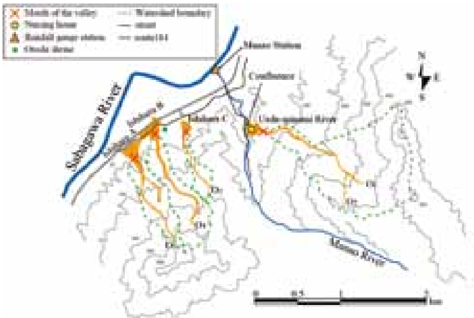

Fig. 6 - Landslides and debris flow channels at Manao and Ishihara districts

	Ueda-minami	Ishihara A	Ishihara B	Ishihara C
River basin area	1.0km^2	0.3km^2	0.3km^2	0.1km^2
Maximum elevation of river basin	610m a.s.l	460m a.s.l	460m a.s.l	240m a.s.l
River length	1,900m	1,100m	1,600m	970m
Average river bed slope	10°	14°	10°	11°

Tab. 1 - Characteristics of the Ueda-minami River, and Ishihara A, B and C River

amount of sediment to the downstream river reach.

FIELD INVESTIGATION INTO THE MANAO AND ISHIHARA DISTRICT

Figure 6 depicts plan view of Manao and Ishihara districts. At the Manao district, landslide-induced debris flows occurred in the Ueda-minami River basin; this is a tributary of the Manao River. At the Ishihara district, the debris flows occurred in three mountain rivers; for convenience, the first one is termed 'the Ishihara A River ', and the second one 'the Ishihara B River' and the third one 'the Ishihara C River'. The morphological characteristics of these rivers are shown in Table 1.

We visited Manao district on August 10 and 11, 2009 and also Ishihara district on September 4, 5 6 and 7, and on October 14. At these times, we took pictures of river situation and measured the cross-sectional profiles of the rivers at several sections. From these measurements and the observation of flow tracks, we obtained depth, width and area of debris flows during the peak period.

MANAO DISTRICT

Figure 7 shows a longitudinal profile of the Ueda-minami River and a longitudinal change of its river width, respectively. The debris flows were initiated by shallow landslides at locations O_1 and O_2 in this river basin. The slope at locations O_1 and O_2 is 27^o and 32^o,

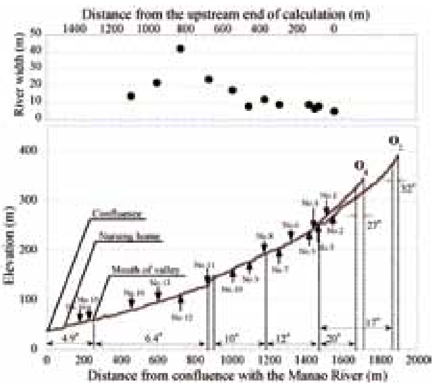

Fig. 7 - Longitudinal river bed profile and change of river bed width (the Ueda-minami River)

Fig. 8 - Eroded river bed and sides at Section 5 (xd =1,420 m)in the upper reach of the Ueda-minami River

Fig. 9 - The situation of erosion and deposition at Section 7 (xd =1,260 m)

respectively. The main debris flow from O_2 moved down the river with the slope of 17^o and the width of 5 m to the confluence with the debris flow from O^1. Figure 8 is the photo of the river bed at x_d=1,420m. Here x_d =distance measured in the upstream direction from the confluence with the Manao River. This is the view from the downstream to upstream direction; we can find the confluence of the two rivers from locations O_1 and O_2. This photo shows the situation of river bed erosion.

Figures 9 and 10 are the photos of the river bed at x_d =1,260 m and 1000 m, respectively. These photos express the situation of sediment deposition. River

Fig . 10 - Debris-flow deposit at Section 10 (xd =1000 m)

Fig. 11 - The situation of boulder deposition and driftwood accumulation on the river bed at Section 14 (xd =460 m)

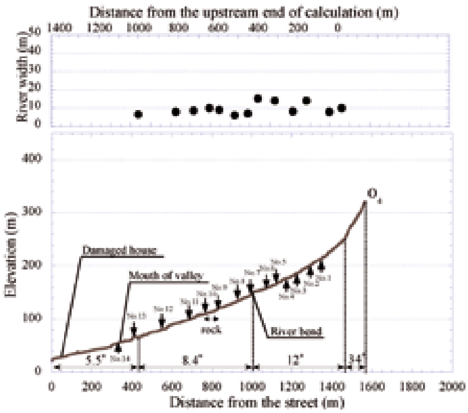

Fig. 12 - Longitudinal river bed profile and change of river bed width (Ishihara B River)

Fig. 13 - Debris-flow deposit at Section 3 (xd =1220m) in the upper reach of the Ishihara B River

Fig. 14 - Boulder deposition in the river bend at Section 7 (xd =990 m)

Fig. 15 - Scoured river bed at Section 9(xd =830m)

bed slope is 12^o ,10^o and river width is from 9 m to 24 m between x_d =1300 m and 870 m.

Figure 11 is the photo of the river bed at x_d =460m. The river bed around this position has the longitudinal slope of 6.4^o and the transverse width of 14 m to 42 m. The photo shows the situation of boulder deposition and driftwood accumulation on the river bed. Here it is emphasized that river width does not always coincide with that of debris flow. Especially in the case of larger river width, it is possible that debris flow of smaller width varies within larger river width.

ISHIHARA DISTRICT

Figure 12 depicts a longitudinal profile of the Ishihara B River and a longitudinal change of its river width, respectively.

The debris flow was initiated by shallow landslides in this river. The slope at the landslide location is 34^o. The debris flow moved down the river reach (x_d =1340~990m) with the average slope of 12^o and the width of 8~15m (Figure 13). Here xd =distance measured in the upstream direction from the street (Figure 6). Figure 13 shows the situation of sediment deposition on the river bed. At around x_d =990m (Section 7), the river is curved significantly and then boulders are deposited on the river bed, as shown in Figure 14.

The river reach such that 990m > x_d >550m has the average slope of 8.4o and the width of 6~10 m.

No sediment deposition is found on the river bed, as shown in Figure 15.

The river becomes abruptly narrow at around x_d =410m (Section 13) and then wide at around x_d = 340 m (Section 14). The river width varies rapidly from 15m to 40m and the river slope is 5.5 o on the average.

ESTIMATION OF PEAK DISCHARGE

Hashimoto & Hirano (1997) introduced a non-dimensional parameter for sediment-water mixture flow such as debris and mud flows. At smaller values of this parameter, intergranular-stress terms in the momentum equation play major role compared with the inertia terms; this shows that the effect of grain collisions becomes major. At larger values of the parameter, on the other hand, the inertia terms in the momentum equation become important relatively to the intergranular-stress terms; this means that turbulence of the mixture flows becomes dominant. Therefore, this parameter corresponds to Reynolds Number for clear water. It is defined as

$$N_h = \frac{h}{d}\sqrt{\frac{\rho_t}{\sigma F(C)}} \tag{1}$$

where h = flow depth; d = diameter of flowing sediment particles; C = sediment concentration in the flow; σ =sediment particle density; ρ=water density; $\rho t= \sigma C+\rho(1-C)$ = density of sediment-water mixture; and F(C)= a function of sediment concentration.

Assuming d =0.3m from the field survey, we can obtain N_h=5~20 corresponding to the variation of C from 0.2 to 0.5. The variation of C can be verified by the simulation in the next chapter. The smaller values of N_h indicate that the debris flow is in the laminar-flow type. From these values of N_h, we can estimate non-dimensional average velocity $\varphi = v/u*$ as φ =2~8. Here, v = cross-sectional average velocity and **u*** = friction velocity. On the average, we obtain the value of $\varphi =5$. Using the value of $\varphi =5$, we can estimate average velocity and peak flow discharge under the assumption of steady and uniform flow. The result is presented in Table 2. Section 5 is selected as the location for their estimate in the Ueda-minami River and Section 9 is selected in the Ishihara B River. It is found that the Ishihara B River had peak discharge larger than the Ueda-minami River.

	Ueda-minami R.	Ishihara B R.
Location	Section5 (x_d=1420m)	Section9 (x_d=830m)
Peak flow depth (m)	2.2	3.4
Cross-sectional area of flow (m^2)	19.8	42.3
River bed slope angle (degree)	12.5	8.7
Average velocity (m/s)	10.8	9.0
Peak flow discharge (m^3/s)	214	381

Tab. 2 - Estimated average velocity and peak discharge of the debris flows

SIMULATION OF THE DEBRIS FLOW EVENT

We simulate the behavior of the debris flows in the Ueda-minami River at Manao district and the Ishihara B River at Ishihara district. This simulation is based on the model of Takaoka *et alii* (2007). It is composed of two steps; the first one is transformation of landslide into debris flow, and the second one is numerical calculation of debris flow hydrograph along the river reach. The first one becomes the boundary condition for the second one.

TRANSFORMATION OF LANDSLIDE INTO DEBRIS FLOW

In order to know the transformation process of landslide into debris flow, we use the simple model proposed by Takaoka *et alii* (2007). When landslides occur on mountain slopes, all sediments of landslide do not change into debris flows. Since we can estimate the sediment volume of landslide from the field survey or aerial photo analysis, we can know sediment volume of initial debris flow by the concept of runoff coefficient of landslide sediment.

From mass conservation of sediment before and after the landslides, we obtain the relationship between sediment volume V_s of landslide and sediment discharge $Q_{s0}(t)$ of initial debris flow at the landslide position:

$$Q_{s0}(t) = C_0 Q_0(t) = f_s V_s u(t) \tag{2}$$

where C_0 = sediment concentration in the initial debris flow, $Q_0(t)$ = the initial debris flow discharge and f_s =sediment runoff coefficient. $u(t)$ corresponds to a response function for the transformation from landslide into debris flow.

From Eq.(2), we have

$$Q_0(t) = \frac{f_s V_s}{C_0} u(t) \tag{3}$$

River's name	Ueda-minami R	Ishihara B R.
Landslide sediment volume V_s	1,800m^3	3,600m^3
Sediment concentration of initial debris flow C_0	0.4	0.4
Landslide duration time T	60sec	60sec

Tab. 3 - Parameters on the transformation of landslide into debris flow

where the value of sediment runoff coefficient f_s is assumed equal to 1.0. The evaluation of response function *u(t)* is very difficult. In this simulation, we use the response function u(t) obtained by Takaoka *et alii* (2007):

$$u(t)=\frac{1}{T} \quad \text{for } 0\le t\le T \quad \text{and} \quad u(t)=0 \quad \text{for} \quad T<t \tag{4}$$

where T = landslide duration time.

We have estimated landslide sediment volume V_s from the aerial photo analysis. On the basis of the work of Takaoka *et alii* (2007), we have determined sediment concentration C_0 of the initial debris flows and landslide duration time T by trial and error. These parameters are summarized in Table 3.

CALCULATION OF DEBRIS FLOW HYDROGRAPH

We assume that the cross sections of the river reach are approximately rectangular and then the riversides are eroded in lateral direction with constant angle of 90 degree. The equations of mass and momentum conservation govern the flow in the river reach:

One-dimensional equation of motion

$$\frac{\partial(\rho_t Q)}{\partial t}+\frac{\partial(\rho_t vQ)}{\partial x}= -\frac{1}{2}g\cos\theta\frac{\partial(\rho_t Bh^2)}{\partial x}+\rho_t gBh\sin\theta-\rho_t(B+2h)\frac{v^2}{\phi^2} \tag{5}$$

Continuity equation of sediment-water mixtures

$$\frac{\partial(Bh)}{\partial t}+\frac{\partial Q}{\partial x}=hi_s+Bi_b+q_{in} \tag{6}$$

Continuity equation of sediment

$$\frac{\partial(CBh)}{\partial t}+\frac{\partial(CQ)}{\partial x}=C_*hi_s+C_*Bi_b \tag{7}$$

$$i_b=-\frac{\partial z}{\partial t} \tag{8 a}$$

$$i_s=\frac{\partial B}{\partial t} \tag{9 a}$$

where t = time, x = distance measured in the downstream direction, $\rho t=\sigma C+\rho(1-C)$ = density of sediment-water mixture; Q=discharge of the mixture flow; v = average velocity; h = flow depth; z = bed level; B = river bed width= debris flow width; φ = non-dimensional average velocity; C = volumetric concentration of sediment in flow; C_T = flux-averaged sediment concentration; C_* = 0.6 = the maximum possible sediment concentration and qin= lateral inflow rate of water from the slopes. Indicating friction velocity by u_*, we have $\varphi = v/u_*$.

In the discussion we assume sediment concentration profile uniform. Therefore we can have the relation of $C_T = C$.

Q, h, z, B and *CT* are unknowns in Eqs. (5), (6) and (7). Solving theses equations requires two more equations. Takaoka *et alii* (2005) derived the following two equations from laboratory experiments

Riverside bed erosion rate equation

$$i_b=k_b\left(C_{T\infty}-C_T\right)^p v \quad \text{for } C_{T\infty}>C_T \tag{8 b}$$

and

$$i_b=-k_b\left(C_T-C_{T\infty}\right)^p v \quad \text{for } C_{T\infty}<C_T\,. \tag{8 c}$$

Riverside erosion rate equation

$$i_s=k_s v \tag{9 b}$$

where $C_{T\infty}$=equilibrium sediment concentration; k_b = coefficient for bed erosion rate and k_s = coefficient for side erosion rate. We can have the values of k_b = 0.01 and p = 0.7 for Eqs. (8b) and (8c), and k_s = 0.01 for Eq. (9b).

Denoting equilibrium sediment discharge by $q_{\infty s}$, we can express the equilibrium sediment concentration as

$$C_{T\infty}\approx\frac{Bq_{s\infty}}{Q} \tag{10}$$

The equilibrium sediment discharge $q_{\infty s}$ can be evaluated by the formula of HASHIMOTO *et alii* (2003 & 2004); it is found appropriate for various kinds of sediment transport in steep rivers:

$$\frac{q_{s\infty}}{\sqrt{sgd^3}} = \frac{\overline{u}_\delta}{u_*}\tau_*^{3/2}\left(1-\frac{\tau_{*c}}{\tau_*}\right)\frac{1}{(\alpha - I_f)\cos\theta}G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) \tag{11}$$

where $s = (\sigma - \rho)/\rho$; d = sediment grain diameter; τ^*= the non-dimensional shear stress; τ^*_c = the critical non-dimensional shear stress; θ = bed slope angle; I_f = the friction slope; w_0 = the fall velocity of sediment grains in water; α =0.875 and u_δ/u^* =4.7. According to HASHIMOTO *et alii* (2003 & 2004), G is a function of If, h/d and $w0/u^*$ and can be approximated as

$$\frac{q_{s\infty}}{\sqrt{sgd^3}} = \frac{\overline{u}_\delta}{u_*}\tau_*^{3/2}\left(1-\frac{\tau_{*c}}{\tau_*}\right)\frac{1}{(\alpha - I_f)\cos\theta}G\left(I_f, \frac{h}{d}, \frac{w_0}{u_*}\right) \tag{12}$$

In the field survey, we could not obtain information about the thickness of river bed sediments. Therefore, referring to PARK & HASHIMOTO (2003), we assume that river bed was composed of cohesionless sediments 2.0 m thick.

Boundary condition

River reach for the numerical calculation is from x_d=1,552 m (x= 0) to x_d= 302 m(x= 1,250) in the Ueda-minami River and from x_d= 1,440m (x=0) to x_d=390m (x= 1,050) in the Ishihara B River.

The boundary conditions at x = 0 (position downstream immediately from the landslide location) are given by

$$Q = Q_0(t),\ h = \left(\frac{Q}{\phi B\sqrt{g\sin\theta}}\right)^{2/3} \text{ and } C_T = C_0 \text{ for } 0 \le t \le T \tag{13}$$

and

$$Q = Q_0(t),\ h = \left(\frac{Q}{\phi B\sqrt{g\sin\theta}}\right)^{2/3} \text{ and } C_T = C_0 \text{ for } 0 \le t \le T \tag{14}$$

where $Q_0(t)$=initial flow discharge,C_0=initial sediment concentration and T=landslide duration. The value of C_0 is assumed 0.4. $Q_{w0}(t)$ denotes flow discharge determined by runoff analysis.

Initial condition

It is said that the debris flow event occurred at around 12:00 on July 21, 2009 (FURUKAWA *et alii*, 2009). Therefore, the numerical calculation is made for the debris flow event from 11:00 to 13:00.

Initial river bed elevation data can be obtained from the lasar measurement of land elevation by the Ministry of Land, Infrastructure, Transport.

Initial river width can be given by that before the debris flow event. However it is difficult to know the mountainous river width before the debris flow event. Therefore, initial river width B (m) can be estimated by the empirical equation (HASHIMOTO *et alii*, 2001):

$$B = kA^{0.37} \tag{15}$$

where k = coefficient and A (km^2) = river basin area at an arbitrary river section. PARK & HASHIMOTO (2003) reviewed the work of HASHIMOTO *et alii* (2001) and then adopted k = 5.36 in runoff analysis of debris flows. In the present calculation, we determine the value of k, considering the river bed situation before and after the debris flow event. As a result, we can have k = 5.36 for the Ueda-minami River and k = 8.04 for the Ishihara B River.

The lateral inflow of rain water along the whole river reach has to be considered, because flood flow due to the heavy rainfall occurred immediately before the debris flow event. The lateral inflow rate of rain water can be evaluated by the rational equation.

Calculation condition

The calculation condition is summarized in Table 4. Time and distance step in the difference formulas of Eqs. (5), (6) and (7) can be determined from stability condition of numerical calculation. Diameter representative of bed sediment grains was estimated from the field survey. Non-dimensional average velocity φ = v/u^* was determined in the former chapter.

River's name	Ueda-minami	Ishihara B
Calculation distance	1,250m	1,050m
Calculation time	From 11:00 to 13:00	
Time step Δt	0.01sec	0.1sec
Distance step Δx	25.0m	
Bed sediment grain diameter d	0.3m	
Non-dimensional average velocity ϕ	5	

Tab.4 - Conditions for numerical calculation

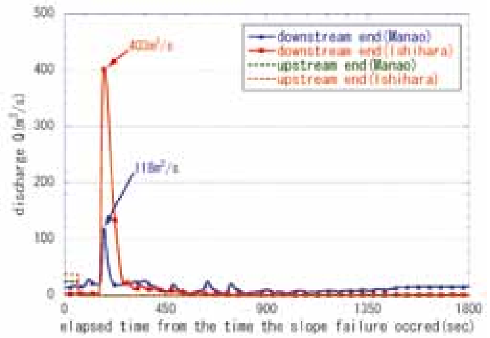

Fig. 16 - Time-variation of flow discharge

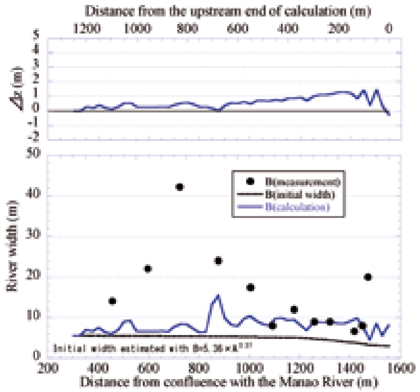

Fig. 17 - Longitudinal change in river bed elevation and river width(Ueda-minami River)

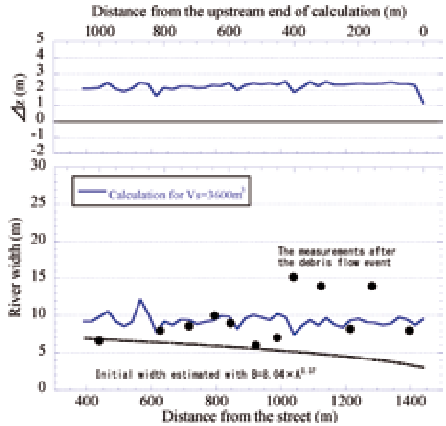

Fig. 18 - Longitudinal change in river bed elevation and river width (Ishihara B River)

	Vs(m³)	h(m)	v(m/s)	Q(m³/s)	C
Field measurement	-	2.2	10.8	214	
Simulation	1,800	2.2	7.3	182	0.36

Tab. 5 - (a)Comparison between the simulation and field measurement at Section 5 (xd=1,420m) in the Ueda-minami River

	Vs(m³)	h(m)	v(m/s)	Q(m³/s)	C
Field measurement	-	2.2	10.8	214	
Simulation	1,800	2.2	7.3	182	0.36

Tab. 5 - (b) Comparison between the simulation and field measurement at Section 9 (xd=830m) in the Ishihara B River

DISCUSSION

Figure 16 shows time-variation of flow discharge Q at Section 5 (x_d=1,420m) in the Ueda-minami River and at Section 9 (x_d=830m) in the Ishihara B River. The peak discharge is found 181 m³/s in the Ueda-minami River and 258 m³/s in the Ishihara B River. Flow discharge in the Ishihara B River is found larger than that in the Ueda-minami River. This simulation corresponds to the field observations.

The flow velocity and discharge calculated numerically are compared with their estimate based on the field measurements and uniform-flow concept (Tab. 5 (a) and (b)). The agreement between them is excellent. Furthermore, it is confirmed that sediment concentration C varies from 0.2 to 0.5.

Figures 17 and 18 express longitudinal change in river bed elevation and river width during the debris flow events. Here, it should be emphasized that calculated river width denotes flow width.

In the Ueda-minami River, the calculation of river width disagrees with its field measurements after the debris flow event except the region of small river width. This is due to the difference between river width and flow width. In the Ishihara B River, on the other hand, the calculation of river width agrees with its field measurements. Therefore, a comparison between the calculation and field measurements of river width shows the satisfactory agreement in the both rivers except the region of larger river width.

The calculation of river bed change indicates sediment deposition along the whole reach of the both rivers. In the Ueda-minami River, the field survey shows sediment deposition in the region of 460 m< x_d < 1,260 m except the small region of 1,320 m < x_d < 1,470 m. In the Ishihara B River, on the other hand, the field survey shows sediment deposition in the region of 1,040 m < x_d <1,280 m and bed erosion in the region of 350 m < x_d <990 m. Therefore, a comparison between the calculation and field observations of river bed change shows agreement in the Ueda-minami River and disagreement in the Ishihara B River.

Sediment budget within each river basin area is also examined by numerical calculation. It is found that sediment yield by riverside erosion is larger than landslide sediment volume in the both rivers, especially in the Ishihara B River. Although the shallow landslides triggered debris flow initiation, they did not play the major role for the sediment outflow to the residential areas in the Ishihara B River.

CONCLUSIONS

The results obtained in this study are as follows:

1. Flow discharge in the Ishihara B River at Ishihara district was larger than that in the Ueda-minami River at Manao district.

2. The numerical calculation of river width agrees with its field measurements in both rivers except the region of larger river width.

3. The numerical calculation of river bed change agrees with its field observations in the Ueda-minami River and disagrees with those in the Ishihara B River.

4. The shallow landslides triggered debris flow initiation, but the sediment outflow to the residential areas was mainly attributed to the riverside erosion.

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