Development of a Numerical Model for Deposition and Flood Propagation by Multiple Inflows of Debris Flows and River Floods

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When it rains over a large area, numerous mountain streams and rivers often lead to debris flows and greater river flows. Since these flows overlap at the stream and river confluences, damaged areas around the confluences may be expanded because of a flow bottleneck formed by debris flow deposition around them. To reasonably predict the processes, we require a numerical model that considers how the deposition and flood propagation of these flows occur at the confluences based on their various characteristics. Therefore, we developed a numerical model named “the multiple inflow model with debris flows and river floods.” In the developed model, the downstream ends of several 1-D calculation areas for mountain streams are connected on a 2-D calculation area for a confluence area at any selected points. With the developed model, we performed calculations to reproduce the debris flow disaster in the Nachigawa River plain, which induced by 2011 Typhoon Talas in Wakayama Prefecture, Japan. During this event, the debris flows that simultaneously flowed into the river from several mountain streams contributed to the deposition and flooding around the streams and river confluences, and the damaged areas around them expanded. The calculated result indicates that we can estimate reasonably the deposition and flood propagation of the debris flows and river flood around the confluences and their downstream areas. This also indicates that the developed model helps us to investigate how multiple debris flows inflowing from mountain streams contribute to the disaster, and develop more efficient countermeasures for these inflows.

Key words: numerical simulation, debris flow, river flood, multiple inflows, 1-D and 2-D calculations

1. INTRODUCTION

When heavy rainfall occurs over a large area, numerous mountain streams and rivers often carry significantly increased water volumes, leading to debris flows and greater river flows. Since these flows overlap at the stream and river confluences, sediment deposition around the confluences may occur. Sometimes, these deposition may block river floods and form natural dams. By 2011 Typhoon Talas, the debris flows that inflowed from several mountain streams into the Nachigawa River caused the sediment deposition and flooding around the confluences in Wakayama Prefecture, Japan, leading to expanded flood damage around the confluences [e.g., Matsumura et al., 2012; Kinoshita et al., 2013; Tsutsui et al., 2016]. These processes depend on the characteristics of the inflowing flows into the confluences, such as sediment concentration, flow depth, velocity, and particle-size distribution of material. Thus, to reasonably predict the processes, we require a numerical model that considers how the deposition and flood propagation of debris flows and river floods occur at the confluences based on their various characteristics.

Several one-dimensional (1-D) numerical models for calculating the deposition and flood propagation of debris flows and river floods at a confluence area have
been suggested [e.g., Takahashi and Kuang, 1989, Hasegawa and Ishikawa, 1990; Nakatani et al., 2012]. However, when debris flows from a sub-channel partially block a main-channel at a confluence, it is difficult to predict the sedimentation process with these 1-D models because of the complicated two-dimensional flows that occurred by the partially blocking. Furthermore, using these models, it is difficult to predict the deposition and flood propagation at confluences with various topography conditions such as connection angles, riverbed inclines and widths of main- and sub-channels. This suggests that multi-dimensional calculation models are necessary to more accurately consider these processes. Accordingly, several two-dimensional (2-D) numerical models for calculating the processes at a confluence on high-gradient streams have also been suggested [e.g., Ido et al., 1992; Chen and Peng, 2006; Deguchi et al., 2007]. However, in the models proposed by Ido et al. [1992] and Deguchi et al. [2007], only bedload sediment transportation on a high-gradient stream is considered, but a sediment-water mixture flow, such as a debris flow, is not considered. In the model by Chen and Peng [2006] with the 2-D finite volume method, sediment transport and riverbed variation are not considered. Thus, accurate calculation of the deposition and flood propagation of debris flows and river floods at a confluence with various topographies requires a 2-D debris-flow calculation model that can consider the multiple inflows of sediment-water mixtures or bedload sediment transportations from any selected point.

In this study, we developed a new numerical model, “the multiple-inflow model with debris flows and river floods,” that can calculate the deposition and flood propagation on a confluence area by river floods and debris flows from several mountain streams. Our developed model is based on “the 1-D/2-D coupled model” developed by Wada et al. [2008]. The downstream ends of several 1-D areas are connected to a 2-D area at any selected point. These 1-D areas are parts of a unified temporary 1-D area. These areas are distinguished from each other on the temporary area by setting the calculation points of their upstream (i.e., n : the 1-D area number) and downstream ends (i.e). Therefore, these areas are independent of each other within the temporary area. In our model, the calculations of both all 1-D areas and a 2-D area are carried out for each timestep. In addition, the discharge (Q), sediment discharge (Qs) and momentums of the debris flow that passes at the downstream end of the n-th 1-D area are added to the inflow point on a 2-D area, and the average bed elevation (Zb) and flow depth (Hs) at the inflow points are assigned the bed elevation and flow depth at the downstream end of the n-th 1-D area. Using our model, we can continuously calculate the flow processes of debris flows and river floods on several streams, their multiple inflows into the stream and river confluences, and the deposition and flood propagation on the confluences resulting from these inflows.

2. NUMERICAL MODEL CONSIDERING MULTIPLE INFLOWS OF DEBRIS FLOWS AND RIVER FLOODS

2.1 Outline of our developed model
Figure 1 shows the overview of our developed model. For the calculation point placement in our model, we adopt staggered grids similar to “the 1-D/2-D coupled model.” Specifically, the vector amount calculation points are placed at 1/2Δx or 1/2Δy downstream (positive directions of the x-axis or y-axis) from the scalar amount calculation points. Here, Δx and Δy are the x- and y-axis grid spacing on the 2-D area, respectively. The downstream ends of several 1-D areas are connected to a 2-D area at any selected point. These 1-D areas are parts of a unified temporary 1-D area. These areas are distinguished from each other on the temporary area by setting the calculation points of their upstream (i.e., n : the 1-D area number) and downstream ends (i.e). Therefore, these areas are independent of each other within the temporary area. In our model, the calculations of both all 1-D areas and a 2-D area are carried out for each timestep. In addition, the discharge (Q), sediment discharge (Qs) and momentums of the debris flow that passes at the downstream end of the n-th 1-D area are added to the inflow point on a 2-D area, and the average bed elevation (Zb) and flow depth (Hs) at the inflow points are assigned the bed elevation and flow depth at the downstream end of the n-th 1-D area. Using our model, we can continuously calculate the flow processes of debris flows and river floods on several streams, their multiple inflows into the stream and river confluences, and the deposition and flood propagation on the confluences resulting from these inflows.

2.2 Connection of the 1-D and 2-D areas in our developed model
Figure 2 shows the profile of a connection with the
The values on the 1-D and 2-D area show Black and Gray characters, respectively.

Fig. 2 Profile of connection with \( n \)-th 1-D and 2-D areas.

Fig. 3 Placement of inflow points connected with downstream end of the \( n \)-th 1-D area on the 2-D area.

The procedure for setting these inflow points is as follows. First, the both endpoint coordinates of the inflow axis on the 2-D area, \( B_n(x_n, y_n), C_n(x_n, y_n) \), should be calculated by \( A_n(x_n, y_n), \beta_m \), and \( B_m \). Next, the length of the \( B_nC_n(L_{\beta_m}) \) within the control area of the point \((i, j)\) should be calculated. When \( B_nC_n \) has no crossing points with the control area, \( L_{\beta_m} = 0 \) should be set. To calculate \( L_{\beta_m} \), the number of crossing points of the \( B_nC_n \) with the sidelines of the control area (the rectangular DEFG in Fig. 3) should be investigated. On the condition that no sidelines of the DEFG can completely correspond with the \( B_nC_n \) because of expeditiously adding a slight angle to \( \theta_m \), the number of crossing points is zero, one, or two. Figure 4 shows examples of DEFG and \( B_nC_n \) placements in each case of crossing point numbers. When the number of crossing points is zero, as shown in Fig. 4 (a), \( B_nC_n \) does not cross with the area of DEFG, \( L_{\beta_m} = 0 \). Otherwise, \( B_nC_n \) is completely within DEFG, \( L_{\beta_m} = B_m \). When the number of crossing points is one, as shown in Fig. 4 (b), \( B_nC_n \) contacts DEFG on only one of the DEFG vertexes \( \theta_m \). Otherwise, the one endpoint of \( B_nC_n \) is within DEFG and \( L_{\beta_m} \) is the length to the endpoint within DEFG from the crossing point \( K \) (or \( L \)). When the number of crossing points is two, as shown in Fig. 4 (c), \( B_nC_n \) goes through the area of DEFG and \( L_{\beta_m} \) is the length of the line KL.

The number of crossing points is the number of all intersections of \( B_nC_n \) with each sideline of DEFG (DE, EF, FG, or GD). When \( B_nC_n \) and a sideline intersect, the each endpoint of \( B_nC_n \) is in the above and below areas of the sideline, respectively. Therefore, we can determine the number of crossing points by investigating whether the endpoints of \( B_nC_n \) are in the above and below areas of DE, EF, FG, or GD. Now, the placement of the control volume of point \((i, j)\) (the rectangular DEFG), and the inflow axis \( B_nC_n \) are considered as shown in Fig. 3. When \( B_nC_n \) and DE intersect, that is, \( B_n \) and \( C_n \) are in the above and below areas of DE, respectively, the following expression is established:

\[
DB \times DE \cdot DC \times DE = \begin{cases} 
(x_n - x_i)(y_n - y_i) - (y_n - y_i)(x_n - x_i) \leq 0 
\end{cases} \]  

where the coordinates of \( B_n \) and \( C_n \) are \((x_n, y_n)\) and \((x_n, y_n)\), respectively, the coordinates of DEFG vertexes, D, E, F and G are \((x_i, y_i), (x_r, y_r), (x_r, y_r)\) and \((x_r, y_r)\), respectively. In this case, it is also necessary for the endpoints of DE to be in the above and below areas of \( B_nC_n \), respectively. Therefore, the following expression is also established:
When Eqs. (1) and (2) are both established, the coordinates of the crossing point K, \((x_k, y_k)\), are as follows:

\[
L_{u,j} = B_m
\]  

When the number of crossing points is one and one of the endpoints of BNC is within DEFG, \(L_{u,j}\) is as follows in the case that the crossing point is the point K \((x_k, y_k)\).
Note that our model can not describe a debris flow run-up to 1-D areas from a 2-D area since the discharge transferring is only one-way from 1-D areas to a 2-D area. Therefore, to transfer the debris flow discharge from the 1-D areas to a 2-D area without deficiency, it is necessary to set the connection point at the area that is not an extreme stream alignments such as bends and curves triggering a debris flow run-up.

We also consider transferring the momentums from the n-th 1-D area to the 2-D area in our model. First, at the inflow points, we define that the debris flow velocity \( u_{n,i+1,j} \) on the n-th 1-D area changes to \( u_{n,i,j} \) in the x- and y-direction on the 2-D area. Thus, the forces per unit time, which added to the debris flow with the changes in debris flow velocity in the x- and y-direction, \( F_n \) and \( F_s \), are as follows, with no consideration of changes in the density, depth, and hydraulic pressure of the inflowing debris flow, and gravitational influence,

\[
F_n = \rho' Q_{n,i+1,j} - M_n = \frac{\rho' L_{n,i+1,j} Q_{n,i+1,j}}{B_m} (u_{n,i+1,j} - u_{n-1,i,j} \cos \theta_m) \quad (9)
\]

\[
F_s = \rho' Q_{n,i+1,j} - M_s = \frac{\rho' L_{n,i+1,j} Q_{n,i+1,j}}{B_m} (v_{n,i+1,j} - v_{n-2,i,j} \sin \theta_m) \quad (10)
\]

where \( \rho' \) is the apparent mass density of a debris flow \( = \sigma \times C + \rho_m \times (1 - C) \), \( \sigma \) is the mass density of sediment, \( \rho_m \) is the mass density of interstitial fluid, \( u_{n,i,j} \), \( v_{n,i,j} \) are the debris flow velocities in the x- and y-direction at the inflow point \( (i, j) \), respectively, \( u_{n-1,i,j} \) is the debris flow velocity at the overlapping point \( (i+1, i) \) on the n-th 1-D area and \( M_n, M_s \) are the moments per unit time of the debris flow to a 2-D area from the n-th 1-D area in the x- and y-direction, respectively \( (M_n = \rho' Q_{n,i+1,j} M_{n-1} \cos \theta_m, M_s = \rho' Q_{n,i+1,j} M_{n-1} \sin \theta_m) \). Considering above, the opposite force \( (-F_n) \) should add to the debris flow in the control volume of inflow point \( (i, j) \), where the debris flow volume flow is \( \Delta x \times \Delta y \times h_{n,i,j} \) and the debris flow mass is \( \rho' \times \Delta x \times \Delta y \times h_{n,i,j} \). Therefore, the momentum transferring from the n-th 1-D area to a 2-D area is considered by adding the force \( -F_n \) at the inflow point \( (i, j) \) when the inflowing debris flow velocities at the point \( (u_{n,i,j}, v_{n,i,j}) \) are calculated. Note that the momentum transferring is performed under the condition where the hydrostatic pressure changes between 1-D and 2-D areas are neglected. In addition, this is only one-way from 1-D areas to a 2-D area. Thus, the transferring may not be sufficiently reasonable when the connection points are set at extreme stream alignments such as bends and curves triggering a debris flow run-up. Therefore, it is necessary to set the connection point at the area that is not an extreme stream alignment.

### 2.3 Governing equations

The governing equations for our model are the same as those used in the model by Wada et al. [2008], and are shown below. These equations for erosion/deposition and riverbed shear stress are based on the previous debris flow simulation by Nakagawa et al. [1996]. The followings are the governing equations for the 2-D area, and the equations which excluded the y-direction terms from the followings are the governing equations for the 1-D area. In 1-D areas, the longitudinal changes of stream widths can be considered by using the averaged hydraulic quantities in the stream-cross direction for calculating with the equations. Note that the loss of debris-flow energy by rapid changes of widths cannot be considered strictly in 1-D areas.

The continuity equation for the total volume of a debris flow is as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = i \quad (11)
\]

where \( h \) is the flow depth, \( t \) is the time, \( x \) and \( y \) are the coordinates in the longitudinal and transverse directions, respectively, \( M \) and \( N \) are the momentum flux in the x- and y-direction \( (M = u h, \ N = v h) \), respectively, \( u \) and \( v \) are the flow velocities in the x- and y-directions, respectively, and \( i \) is the erosion/deposition rate.

The continuity equation for the volume of sediment in a debris flow is as follows:

\[
\frac{\partial C h}{\partial t} + \frac{\partial C M}{\partial x} + \frac{\partial C N}{\partial y} = i h \quad C. \quad (12)
\]

where \( C \) is the sediment concentration in a debris flow and \( C \) is the sediment concentration in the initial mobile layer of the riverbed.

The momentum equation in the x-direction is as follows:

\[
\frac{\partial M}{\partial t} + \frac{\partial u M}{\partial x} + \frac{\partial v M}{\partial y} = -g h \frac{\partial H}{\partial x} - \tau_x \quad (13)
\]

where \( H \) is the flow surface level \( (H = z + h) \), \( z \) is the riverbed level, \( g \) is the gravitational acceleration, and \( \tau_x \) is the riverbed shear stress in the x-direction.

The momentum equation in the y-direction is as follows:

\[
\frac{\partial N}{\partial t} + \frac{\partial u N}{\partial x} + \frac{\partial v N}{\partial y} = -g h \frac{\partial H}{\partial y} - \tau_y \quad (14)
\]

where \( \tau_y \) is the riverbed shear stress in the y-direction.

The continuity equation for the riverbed level is as follows:

\[
\frac{\partial h}{\partial t} + \frac{\partial v}{\partial x} + \frac{\partial H}{\partial y} = 0 \quad (15)
\]

where \( h \) is the flow depth, \( v \) is the flow velocity in the y-direction, and \( H \) is the flow surface level.
The riverbed shear stress \( (\tau_n, \tau_v) \) is calculated by adopting three different flow resistance theories based on sediment-transport modes, that is, a debris flow, a sediment sheet flow, and an ordinary turbulent water flow including bed material load. These flow modes are classified according to \( C \) [Takahashi, 1991]. The riverbed shear stress in the \( x \)-direction \( (\tau_n) \) for each flow mode is as follows:

\[
\tau_n = \begin{cases} 
\frac{u \sqrt{u^2 + v^2} \sqrt{2}}{8h^2} \left\{ \left( C + (1-C) \frac{\rho}{\rho_m} \right) \left\{ (C/C)^{1/3} - 1 \right\} \right. & (C \geq 0.4C) \\
\frac{1}{0.49} \sqrt{u \sqrt{u^2 + v^2} \frac{g n_m^2}{h}} & (0.01 < C < 0.4C) \\
\frac{g n_m^2 u \sqrt{u^2 + v^2}}{8h^{1/3}} & (C \leq 0.01 \text{ or } h/d \geq 30)
\end{cases}
\]

where \( d \) is the diameter of the sediment and \( n_m \) is Manning’s roughness coefficient. \( \tau_n \) are expressed by changing the \( x \)-direction terms in Eq. (16) to the \( y \)-direction.

The erosion on a movable bed \( (i>0) \) is considered if \( C \) is smaller than the equilibrium sediment concentration \( (C_e) \). Conversely, if \( C \) is larger than \( C_e \), the deposition \( (i<0) \) is considered. \( i \) for a saturating movable bed without finer sediment is described as follows [Takahashi, 1991]:

\[
i = \begin{cases} 
\delta_e \frac{C - C_e}{C - C_e} \frac{q}{d} & (C \leq C_e) \\
\delta_d \frac{C_e - C}{C_e} \frac{q}{h} & (C > C_e)
\end{cases}
\]

where \( q \) is the debris flow discharge per unit width, \( \delta_e \) and \( \delta_d \) are the coefficients of erosion and deposition velocity, respectively.

The equilibrium sediment concentration \( (C_e) \) is calculated by using the following equations [Takahashi, 1991]:

\[
C_e = \begin{cases} 
0.9C & \left( \tan \theta_s > \tan \phi \right) \\
\frac{\rho_m \tan \theta_s}{(\sigma - \rho_m)(\tan \phi - \tan \theta_s)} & \left( \tan \phi \geq \tan \theta_s > 0.138 \right) \\
6.1 \left( \frac{\rho_m \tan \theta_s}{(\sigma - \rho_m)(\tan \phi - \tan \theta_s)} \right)^2 & \left( 0.138 \geq \tan \theta_s > 0.03 \right) \\
(1+5 \tan \theta_s) \tan \theta_s \left( 1 - \frac{\rho_m}{\sigma - \rho_m} \right)^2 & \left( 0.03 \geq \tan \theta_s \text{ or } h/d \geq 30 \right)
\end{cases}
\]

where \( \theta_s \) is the flow surface gradient, \( \phi \) is the internal friction angle. The riverbed shear stress \( (\tau_v) \), critical shear stress \( (\tau^*) \), and \( \alpha_e \) are as follows:

\[
\tau_v = \frac{0.04 \times 10^{10} \tan \theta_s \sin \theta_s}{1 - \sigma \tan \theta_s / (\sigma - \rho_m)}
\]

when \( \tau_v \) is larger than or equal to \( \tau^* \). \( C_e \) is zero.

For the discretization method of these equations in our model, the finite-difference method is used. The forward, upwind and centered finite-difference methods are used for the time discretization, the advective term discretization, and the spatial discretization, respectively.

3. SIMULATION EXAMPLE

3.1 Calculation conditions

Using our model, we performed calculations to reproduce the debris flow disaster in the Nachigawa River plain, which induced by 2011 Typhoon Talas. During this event, the debris flows that simultaneously flowed into the Nachigawa River from multiple mountain streams contributed to the deposition and river floods around the stream and river confluences, and the flood damaged areas around them expanded.

**Figure 5** shows the deposition of debris flow around Izeki district (the points D and E in **Fig. 6**), which suffered the most significant damage in the Nachigawa River plain by the disaster. Considering the significant deposition of sediment and woody debris in the upstream side of bridges and buildings as shown in **Fig. 5**, we inferred that these bridges and buildings contributed to partially trap the debris flow materials. Thus, the local topographies such as bridges and buildings in the inundation area affects the debris flow deposition. **Figure 6** shows the measured flow depths obtained by the post-disaster survey by Kinoshita et al [2013]. The points A–E in **Fig. 6** show the points which measured flow depths were more than 2m by the survey. These points were concentrated around the confluences of the Nachigawa River and streams. Thus, the debris flow inflows from these streams may contribute to the disaster significantly. **Figure 6** also
shows the 1-D and 2-D calculation areas, and the initial elevation for the reproduction calculation. The initial elevation was constructed using the 5-m square grid digital elevation map provided by the Geospatial Information Authority of Japan. The initial sedimentation thickness was set to 10 m for expediency because there was no observational data for it. The sabo dams in streams No. 4 and 8, and the building in the 2-D area, were considered by adding the effective height ($5 \text{ m}$) to the initial elevations at these points. The debris flow inflows from the eight streams (No. 1–8) and the river flood from upstream of the Nachigawa River (No. 9) were considered. These inflow points on the 2-D area were the confluences of the sub-streams in these catchments. The stream widths of the 1-D areas in streams No. 1–8 were set to the values measured by the disaster survey results [Kii-sanchi Sabo Office, Ministry of Land, Infrastructure, Transport and Tourism, 2012 b]. The river width of the 1-D area in upstream of the Nachigawa River (No. 9) was set to 20 m by considering the actual widths in the aerial photograph.

Figure 6 illustrates the inflow discharges from the upstream ends of streams No.1–8 and the Nachigawa River (No. 9). The calculation period is 7 hours from 0 : 00 to 7 : 00, September 4th, 2011. Inflow discharges from the upstream ends of streams No.1–8 were defined to comprise the debris flow part with a triangular-shaped peak, and the flood flow part with a constant discharge every hour, because the heavy antecedent rainfall already caused large flow rates into the river plain before the debris flow occurred. Considering the report in which the testimonies of inhabitants about the actual spread process of the disaster were organized by Tsutsui et al. [2016], the inflow starts from streams No.2–8 and stream No.1 were considered at 9000 s (2 : 30) and 10800 s (3 : 00) from the start of the calculation, respectively. Since the duration of debris flows were defined to 300 s, which is the observed debris flow duration at Kitamata Valley of the Namekawa river [Ikeda et al., 1998], the peak time of debris flow discharges from streams No.2–8 and stream No.1 are 9150 s and 10950 s, respectively. The inflow discharge from the upstream end of the Nachigawa River (No. 9) comprised only a flood flow, and the inflow start was considered identical to the start of the calculation.

The peak discharges of debris flow part ($Q_d$) were calculated using the following equations by considering with the triangular-shaped peak that the duration of a debris flow was 300 s.

$$Q_d = \frac{2}{300} \frac{V_o \times C}{C_d} \quad (22)$$

$$C_d = \frac{\theta_o \tan \theta_1}{(\sigma - \rho_w)(\tan \phi - \tan \theta_1)} \quad (23)$$

where $V_o$ is the inflow sediment volume (including porosity) from the upstream end of the stream (see Table 1), $C_o$ is the inflow sediment concentration from the upstream end (The maximum value is $0.9 \times C$), and $\theta_1$ is the riverbed gradient around the upstream end. Table 1 lists $Q_o$ for the stream No.1–8.

The discharge of flood flow part ($Q_f$) was calculated using the rational formula as follow:

$$Q_f = \frac{1}{3.6} \times f \times P \times A \quad (24)$$

where $f$ is the runoff rate for mountainous areas ($= 0.7$), $P$ is the hourly precipitation in the target basin (mm/h), $A$ is the area of the basin (km$^2$). $P$ is the hourly precipitation at the Ichinono precipitation station on the center part of the plain at the debris flow inflow period, that is, from 0 : 00 to 7 : 00, September 4th, 2011. Table 2 lists the parameters for the reproduction calculation. These parameters were set by considering the previous simulation by Nakagawa et al. [1996].
Table 3 lists the calculation cases for the reproduction calculation. To investigate how the inflows from streams No.1–8 and the Nachigawa River (No. 9) contributed to the disaster, the three inflow conditions were considered in the calculation, which were the cases considering the inflows from the river and all streams, the inflows from only the river, and the inflows from only the streams.

### Table 1 Inflow conditions of streams No. 1–8 and Nachigawa River for reproduction calculation.

| No. | Stream                | \(V_i (\text{m}^3)\) | \(C_{**}\) | \(\tan\theta_{**}\) | \(\tan\theta_{***}\) | \(Q_i (\text{m}^3/\text{s})\) |
|-----|-----------------------|----------------------|------------|---------------------|----------------------|---------------------|
| 1   | Kanayamadaniwagawa    | 49798               | 0.56      | 0.75               | 0.227                | 704.9               |
| 2   | Sharikodenanigawa     | 17203               | 0.56      | 0.75               | 0.307                | 152.8               |
| 3   | Hebinotanigawa        | 7197                | 0.56      | 0.75               | 0.417                | 53.3                |
| 4   | Nakadaniwagawa        | 11300               | 0.56      | 0.75               | 0.258                | 132.5               |
| 5   | South Hiramonogawa    | 27007               | 0.56      | 0.75               | 0.295                | 257.2               |
| 6   | North Hiramonogawa    | 2703                | 0.56      | 0.75               | 0.558                | 20.0                |
| 7   | Higashigawa           | 5827                | 0.56      | 0.75               | 0.217                | 88.1                |
| 8   | Uchinokawa            | 9443                | 0.56      | 0.75               | 0.271                | 102.9               |

* The estimated passing sediment volume near the inflow points on the streams by the disaster survey results [Kii-sancho Sebo Office, Ministry of Land, Infrastructure, Transport and Tourism, 2012].

** The values of the debris flow simulation by Nakagawa et al. [1996].

*** The value estimated with the contour lines on 1:25000 scale topographical map by Geospatial Information Authority of Japan.

### Table 2 Parameters incorporated in reproduction calculation.

| Parameters of Sediment Variables | Value | Unit  |
|----------------------------------|-------|-------|
| Total simulation time (\(T_{sim}\)) | 25200 | s     |
| Time step (\(\Delta t\)) | 0.01 | s     |
| Minimum flow depth of flux (\(h_{min}\)) | 0.05 | m     |
| Minimum flow depth (\(h_{min}\)) | 0.01 | m     |
| Manning’s roughness coefficient (\(n_{m}\)) | 0.04 | m\(^{1/3}\)s |  
| Gravity acceleration (\(g\)) | 9.8 | m/s\(^2\) |
| Diameter of sediment (\(c_i\)) | 0.10 | m     |
| Volume density of sediment (\(\sigma\)) | 2650 | kg/m\(^3\) |
| Volume density of interstitial fluid (\(\rho_i\)) | 1000 | kg/m\(^3\) |
| Sediment concentration by volume in the movable bed layer (\(C_i\)) | 0.56 | -     |
| Internal friction angle of sediment (\(\tan\theta_{**}\)) | 0.75 | -     |
| Coefficient of erosion rate (\(\alpha\)) | 0.0007 | - |
| Coefficient of deposition rate (\(\delta\)) | 0.10 | -     |

### Parameters of 1-D area

| Parameters of 1-D area | Value | Unit  |
|-----------------------|-------|-------|
| Number of 1-D calculation points (\(l_{i,1}\)) | 84 | -     |
| Interval of 1-D calculation points (\(\Delta x_{i}\)) | 10 | m    |

### Parameters of 2-D area

| Parameters of 2-D area | Value | Unit  |
|-----------------------|-------|-------|
| Number of 2-D calculation points (\(l_{i,2}\)) | 331 \times 301 | -     |
| Interval of 2-D calculation points (\(\Delta x_{i}\)) | 10 \times 10 | m   |

* The values of the debris flow simulation by Nakagawa et al. [1996].

** Numbers of 1-D calculation points are 25 on stream No. 1, 7 on streams No. 2–8, and 10 on the Nachigawa River (No. 9).

3.2 Calculation results and discussion

Figure 8 shows the area distributions of the calculated flow depths at 7680, 9480, and 11280 s from the start of the calculation in Case 1. The second and third extraction times are 8 min after inflowing the debris flows from streams No. 2–8 and stream No. 1, respectively. At the time when no debris flows inflowed from any streams (7680 s), as shown in Fig. 8(a), the calculated inundation range did not spread throughout the Nachigawa River plain. In addition, the calculated flow depths were much lower than the measured flood depths as shown in Fig. 6. These results implied that only the river flood were not sufficient to contribute to the entirely plain flooding at 2:00. At this time, considering most of the inhabitants did not begin moving to the refuge, as reported by Tsutsui et al. [2016], this results nearly corresponds with the actual situation.

When the debris flows inflowed from streams No. 2–8 (9480 s), as shown in Fig. 8(b), the calculated inundation range spread throughout the entire valley plain. The calculated flow depths increased more than those at 7680 s, but they were still lower than the measured flood depths.

When the debris flow inflowed from stream No. 1, and the river flood discharge was nearly maximum (11280 s), as shown in Fig. 8(c), the calculated flow depths increase closer to the measured flood depths around the points D and E, and at its downstream area. This area corresponds with the area which many inhabitants could not move to the refuge, as reported by Tsutsui et al. [2016]. However, around the points A–C, the calculated flow depths were lower than the measured flood depths. Considering a bridge and a river constriction existed at downstream of these points, the reason for this is that the debris flow flooding was calculated with no controls by these river local topographies. Therefore, for a more accurate simulation, we need to establish the way to reflect the river local topographies in the 2-D area setting.

Figure 9 shows the temporal changes in calculated discharges at immediate downstream of the connection points of streams No.1–8 in the 2-D area. The shapes and peak volumes of the calculated discharges are consistent with them of the inflowing debris flow discharges as shown in Fig. 7. This result demonstrates
that the connection of 1–D and 2–D areas in our model are reasonable.

**Figure 10** shows the temporal changes in calculated flow depths at points A–E. These changes are similar to the temporal changes in rainfall intensity. Considering that the river flood discharge was calculated by Eq. (24), which depended on the rainfall intensity, the factor that influenced on the temporal changes in calculated flow depths at these points was primarily the flood discharge. On the other hands, the peaks of calculated flow depths at points D and E appeared more significantly. This is because the debris flow from stream No. 1 contributed directly and indirectly to the flood around the stream and river confluences. The directly contribution means that the flow depths were increased by the debris flow flooding around the confluence. The indirectly contribution means that flow depths were increased by the river flood overflowing due to the rising riverbed by the debris flow deposit in the confluence. Thus, our model enables us to reflect the multiple complex flow at the confluence.

**Figure 11** shows the area distribution of the calculated deposit thickness at the calculation end time in Case 1. The significant deposit areas, in which deposit thicknesses were larger than 2.5 m, were within the actual ranges of debris flow pass. However, the calculated deposit areas around the confluences of streams No. 1–8 and the river did not correspond with the actual ranges. One possible reason for this is that the influence of the local topographies such as bridges, culverts, and river constriction on the flow flooding were not considered in the 2–D area setting. This also may be because boulders with several meters in diameter, that were deposited around the confluence of streams No. 1 and the river as shown in **Fig. 5(a)**.
were not considered. Therefore, the concentration of coarser materials at the debris flow front were not reflected in the calculation. Thus, the consideration of coarser materials such as boulders is necessary to more accurately simulate the flood processes and depositions of debris flows.

**Figure 12** shows the area distributions of the calculated maximum flow depths for the whole calculation periods in all cases. In Case 1, the calculated flow depths nearly corresponded with the measured flood depths at most points as shown in Fig. 6. However, around the confluences near the points A–C, the calculated flow depths are somewhat lower than the measured flood depths. The primal reason for this is, as described above, the river local topographies were not considered in the 2–D area setting. In Case 2, the calculated flow depths are lower than the measured flood depths at almost all points. At the downstream areas from the confluences near the points A–C, and D–E, the calculated flow depths were lower than the measured flood depths because of the lack of debris flows inflow from these streams. Similarly, the calculated flow depths in Case 3 were also lower than the measured flood depths at many points. These results indicated that only inflow of the debris flows from streams No. 1–8 or the river flood did not contribute to the disaster enough. Thus, the simultaneous inflow of the debris flows and the river flood significantly contributed to the disaster.

4. CONCLUSION AND FUTURE STUDY

We developed a numerical model that considered deposition and flood propagation around a confluence area due to multiple inflows of river floods and debris flows from several mountain streams. In our model, the downstream ends of all 1–D areas for mountain streams are connected to the 2–D area for a confluence area at any selected point, and calculations of all 1–D areas and a 2–D area are carried out continuously for each timestep.

Using our model, we performed calculations to reproduce the debris flow disaster in the Nachigawa River plain, which induced by 2011 Typhoon Talas. The calculated result indicated that our model can reasonably calculate the deposition and flood propagation of debris flows and river floods around the
stream and river confluences by their multiple inflows. This also indicates that our model helps us to investigate which inflow of debris flows and river floods greatly contribute to the disaster. The damage prediction for multiple debris flow and flood disasters with our model can lead to establish more efficient countermeasures for these disasters.

However, our model requires the consideration of local topographies such as bridges, culvert, and river constriction in the 2-D area setting, and the coarser materials such as boulders for more accurately simulating. These updates to our model will occur in a future study along with an investigation of the validity of our model based on more reproduction calculations for another past disasters caused by multiple inflows of debris flows and river flows.

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