Debris Flow Prevention Countermeasures with Urban Inundation in a Multihazard-Environment

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Natural disasters can strike without notice at any time, anywhere. Also these disasters can occur in multiple locations between high and low mountainous areas simultaneously with flooding in urban areas caused by heavy rainfall. However, it is becoming more and more difficult to predict heavy rainfall, and intensive rainfall could become more frequent in the future due to climate change. In order to reduce these impending disasters more effectively, it is necessary to investigate what causes the damage with an integrated model of disasters at once, and to adequately predict rainfall. The main objectives of this study are to evaluate the maximum forecast rainfall by a depth-area-duration analysis, to analyses the debris flow during urban inundation in a real basin, and to estimate the risk evaluation index according to two-dimensional debris flow with two-dimensional urban inundation models. Finally, the establishment of an evacuation time scenario is proposed, and multihazard risk and evacuation route maps combining both disasters are created using a geographic information system. The peak precipitation is estimated at 135mm/hr of torrential rainfall, and the maximum total rainfall is estimated at 544mm of typhoon-related rainfall at Ono, Japan, using depth-area-duration analysis.

Key words: debris flow, urban inundation, DAD analysis, multihazard map, GIS

1. INTRODUCTION

Natural disasters are caused by heavy rainfall, especially localised torrential downpours, due to the changing global climate and environment (i.e., global warming) as well as urbanisation (e.g., paving a road with asphalt), rapid forest development in mountainous areas (e.g., deforestation), increasing population density, and so on. Furthermore, these disasters frequently lead to the large-scale destruction of infrastructure or private property and cause psychological (or physical harm), even depth, to humans.

These disasters can strike without notice at any time, anywhere. Today, advances in science and technology have brought us many ways to mitigate the damage. However, they still require development because it is impossible to protect against all disasters by means of countermeasures. In order to protect people and property from sediment-related disaster and urban inundation, two types of preventive measures are taken: structural measures such as check dams, Sabo structures, levees, training channels, and so on, and nonstructural measures such as warning and evacuation systems, regulation, and controlling new residential land development in areas vulnerable to disasters.

Sediment-related disasters (i.e., debris flow) caused by localized torrential downpours, earthquakes, volcanic eruptions, and so on occur frequently every year, and they account for nearly half of the total human casualties from natural disasters. A sediment disaster is not as large as an earthquake, flood, storm surge, or tsunami, but its threat to human lives is very high because it can occur at multiple locations simultaneously [Kim et al., 2013a].

The basic concept of hazard assessment is shown in Fig. 1. Effective prevention of natural hazards requires a better understanding of the processes occurring in nature. The frequency of disasters and the warning time caused by debris flow is very small for sediment-related disaster in
comparison to other disasters. On the other hand, flooding provides more evacuation time than other disasters. However, in recent years, torrential rainfall has frequently caused floods, and quite a few of them have caused tremendous damage. In order to mitigate flood disasters, it is important to promote structural measures by constructing flood-control facilities such as levees. It is also important, however, to prepare nonstructural measures by improving ways to communicate disaster information and evacuation procedures, as well as by enhancing public awareness of disaster prevention.

Many researchers have developed hazard-risk maps of debris flow and urban inundation disasters independently. Nakagawa et al., [1998] presented an estimated hydrograph of debris flow by assigning an arbitrary rainfall to an arbitrary and very steep basin. Also, Thang et al., [2004] estimated the inundation process of floods due to heavy rainfall. The hazard map for flooding at Ono City in March 2007 is shown in Fig. 2. This hazard map was based on a 50-year rainfall frequency plan. Its mesh size is 50 m, and it shows the inundated area of flooding and the influence range of debris flow.

According to a recent report, the probabilities of heavy rainfall and flooding have been increasing every year due to the changing global climate. This means that the probability of occurrences of disasters in the future is very high. Therefore, hazard maps should contain potential risks for heavy rainfall. Additionally, it is necessary to consider the interaction between heavy rainfall and flooding simultaneously and to use the latest available data on current rainfall patterns when preparing a hazard map. This is because one area (i.e., where the disasters overlap) might face higher potential damage than another area (i.e., where only one disaster occurs); therefore, the risk impacts of both disasters should be considered.

The objectives of this study are to estimate the rainfall of designed storm and the probable maximum precipitation (PMP) by a depth–area-duration (DAD) analysis using 11 years of radar data (2003–2013, in flood season between May and November) predict the irregular rainfall pattern, to estimate the maximum-risk area, and to analyse the debris flow with urban inundation at the real basin. Both two-dimensional (2-D) horizontal models (i.e., 2-D debris flow with 2-D integration of flooding model) were developed to estimate the risk evaluation index and to improve applicability for the real basin. Simulations are carried out for various inflow conditions of flood hydrographs (e.g., designed storm) to understand the characteristics of flooding and the gross correlation of both disasters at multiple locations (especially neighborhoods in which debris flow and urban inundation overlap) are established. Finally, an evacuation time scenario is established, and multihazard risk and evacuation route maps combining both disasters are created using a GIS (geographic information system).

2. STUDY AREA

Ono City, which belongs to the Fukui prefecture in Japan, is located at an average elevation of about 200 m above sea level. As of June 2014, the city has an estimated population of 35,489, with 11,812 households (population density: 42.29 people/km²), and its total area is 872.3 km². The Ono City’s population is aging and has declined over the past 30 years (around 30% of the population is currently aged 65 and over). Hence, the age of the people is one of the main issues in designing an evacuation plan. The town is encircled by a ring of mountains and the only way in or out is via tunnels or
mountain roads as shown Fig. 3. The study basin has 8 major rivers namely the Hizume, Akane, Boke, Kiyotaki, Mana, Dondo, Uchi and Kuzuryu. The 7 rivers all join the Kuzuryu to become one river. The area is divided into four catchments caused by 8 rivers.

3. DAD ANALYSIS

The quantitative analysis of all rainstorms has been achieved using DAD method with standard techniques developed by the World Meteorological Organization, [1961]. The purpose of the DAD analysis is to determine the maximum precipitation amounts over various area sizes during the passage of storms over 6, 12, and 24 hr durations to aid in the computation of probable maximum precipitation (PMP) estimates.

In this study, generalised physical approach to estimating areal probable maximum precipitation (PMP) for the nonorographic region of the Ono City basin has been developed. In the DAD analysis, the highest average areal basin depths of different area size and durations of the major rainstorms (i.e., torrential rain, seasonal rain front and rainstorm due to a typhoon) were considered using 11 years of radar data (2003-2013, in flood season between May and November) from the Fukui prefecture. These precipitation data are composed by the 1 km² mesh areas and observed at every 10 min. Fig. 4 shows the calculation mesh size with basins of Ono City.

The results of the maximum precipitation in four basins were shown in Table 1. Fig. 5(a) shows the arrangement considering typhoon, front and local torrential rainfall and Fig. 5(b) shows the hourly precipitation between design rainfall (i.e., 50-year return period) and DAD analysis. In particular, the target basin regarding the occurrence of both disasters (i.e., debris flow and flooding) is analysed at the Akane River basin, where the cumulative local torrential rainfall is highest around 12 hr, and the typhoon-related heavy rainfall, above 12 hr, are the highest.

The target basin area is the smallest in comparison to the total basin of Ono City, where the peak precipitation is 135 mm/hr of torrential rainfall and the total amount typhoon-related rainfall is 544 mm. In addition, the flooding runoff discharge and the debris flow runoff discharge are calculated by the rational runoff formula with the maximum precipitation using DAD analysis.
4. NUMERICAL MODEL

Debris flow is a rapidly moving mixture of sediment and water that occurs in a wide variety of environments throughout the world. To understand the formation process of the debris flow, this study uses a numerical simulation of debris flow analyse the mechanism and hydraulic characteristics of the interaction for real basins. A 2-D numerical analysis model is developed to analyse for onsite applications based on an existing 2-D numerical model [Kim, 2013b].

4.1 Debris flow model

4.1.1 Governing equation

The basic equations used to compute the behaviour of flow motion of debris flow are the 2-D momentum equations, continuity equation of flow, continuity equation of sediment and riverbed surface equation.

\[ \frac{\partial M}{\partial t} + \beta \frac{\partial (uM)}{\partial x} + \frac{\partial (vM)}{\partial y} = -gh \left( \frac{\partial (z_b + h)}{\partial x} \right) - \frac{\partial \tau_{bx}}{\partial x} \]

\[ \frac{\partial N}{\partial t} + \beta \frac{\partial (uM)}{\partial x} + \frac{\partial (vM)}{\partial y} = -gh \left( \frac{\partial (z_b + h)}{\partial y} \right) - \frac{\partial \tau_{by}}{\partial y} \]

\[ \frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = i_b \]

\[ \frac{\partial (C_CH)}{\partial t} + \frac{\partial (C_CH \cdot M)}{\partial x} + \frac{\partial (C_CH \cdot N)}{\partial y} = \begin{cases} i_b C_{DL} & (i_b \geq 0) \\ i_b C_{DL} & (i_b < 0) \end{cases} \]

Here, \( M = (uh) \) and \( N = (vh) \) are the flow discharge per unit width in \( x \) and \( y \) directions, \( u \) and \( v \) are the velocity components in \( x \) and \( y \) directions, \( h \) is the flow depth, \( z_b \) is the erosion or deposition thickness of the bed measured from the original bed surface elevation (mesh size : 5 m, elevation data based on the Geospatial Information Authority of Japan), \( \beta \) is the momentum correction factor equal to 1.25 for stony debris flow [Takahashi et al., 1992] and equal to 1.0 for both an immature debris flow and a turbulent flow, \( i_b \) is the erosion (\( \geq 0 \)) or deposition (\( < 0 \)) velocity, \( g \) is the acceleration due to gravity, \( \tau_{bx} \) and \( \tau_{by} \) are the bottom shear stresses in \( x \) and \( y \) directions, \( \rho_r \) is the mixture density (\( \rho_r = \sigma C + (1 + C) \rho \)), \( \sigma \) is the density of the sediment particles, \( \rho \) is the density of the water, \( C \) is the sediment concentration in the flow, \( C_l \) is the volumetric sediment concentration of the coarser fraction in the flow, \( C_{DL} \) is the volumetric concentrations of the coarser and fine fractions in the original bed, and \( C_{DL} \) is the volumetric concentration of the coarser fraction in the static bed produced by deposition of the debris flow.

4.1.2 Bottom shear stress equation

The bottom resistance for a 2-D flow is described as follows.

[Stony debris flow: \( C_l \geq 0.4C \)]

\[ \tau_{bx} = \frac{u}{\sqrt{u^2 + v^2}} \tau_{yx} + \rho f_b u \sqrt{u^2 + v^2} \]  \( \tag{5} \)

\[ \tau_{by} = \frac{v}{\sqrt{u^2 + v^2}} \tau_{yx} + \rho f_b v \sqrt{u^2 + v^2} \]  \( \tag{6} \)

[Immature debris flow: \( 0.02 \leq C_l < 0.4C \)]

\[ \tau_{bx} = \rho f_b \frac{d_m}{0.49 \ h} \ u \sqrt{u^2 + v^2} \]  \( \tag{7} \)

\[ \tau_{by} = \rho f_b \frac{d_m}{0.49 \ h} \ v \sqrt{u^2 + v^2} \]  \( \tag{8} \)

[Turbulent flow: \( 0.02 < C_l \)]

\[ \tau_{bx} = \rho g n^2 \frac{u \sqrt{u^2 + v^2}}{h^{1/3}} \]  \( \tag{9} \)

\[ \tau_{by} = \rho g n^2 \frac{v \sqrt{u^2 + v^2}}{h^{1/3}} \]  \( \tag{10} \)

where \( \tau_{yx} \) and \( \tau_{xy} \) are the yield stresses in \( x \) and \( y \) directions, \( C_l \) is the maximum sediment concentration in the bed, \( f_b \) is a coefficient of resistance, and \( n \) is the roughness coefficient.

4.1.3 Erosion and deposition velocity equations

The bed erosion or deposition velocity \( i_b \) is a source term. The dependence of this quantity with the basic set of dependent variables has to be modelled, which can be done using the model proposed by Takahashi et al., [1992]. The erosion

| Duration  | 10min | 20min | 30min | 1hr  | 2hr  | 3hr  | 4hr  | 5hr  | 6hr  | 12hr | 24hr | 48hr |
|-----------|-------|-------|-------|------|------|------|------|------|------|------|------|------|
| Managawa  | 21    | 40    | 60    | 99   | 153  | 193  | 221  | 244  | 252  | 335  | 430  | 545  |
| Kiyotaki  | 32    | 60    | 79    | 116  | 181  | 218  | 260  | 283  | 294  | 423  | 501  | 619  |
| Akane     | 36    | 59    | 83    | 135  | 195  | 235  | 278  | 320  | 332  | 482  | 544  | 602  |
| Ono City  | 19    | 36    | 53    | 86   | 143  | 179  | 204  | 222  | 248  | 339  | 426  | 536  |
and deposition velocity are described as follows.

[Erosion velocity]

\[ i_b = \delta_e \frac{C_w - C_L}{C_w - C_e} \sqrt{\frac{\mu^2 + v^2}{d_m}} \]  

(11)

[Deposition velocity]

\[ i_b = \delta_d \left( 1 - \frac{\sqrt{\mu^2 + v^2}}{pU_e} \right) \frac{C_w - C_L}{C_L \Delta t} \sqrt{\mu^2 + v^2} \]  

(12)

where \( p = (2/3) \) is a numerical constant and \( U_e \) is the equilibrium velocity at which neither erosion nor deposition takes place, as follows:

\[ U_e = \frac{2}{5d_m} \left[ \frac{g \sin \theta}{\alpha_m \sin \alpha_i} \left( C_L + (1 - C_i) \frac{\rho_m}{\sigma} \right) \right]^{1/2} \]  

\[ \times \left( \frac{C_{60}}{C_L} \right)^{1/3} \left( C_i - C_e \right) \]  

(13)

where \( \theta_e \) is the channel slope in which coarser sediment concentration is in equilibrium, which can be obtained as follows:

\[ \tan \theta_e = \frac{C_L(\sigma - \rho_m) \tan \phi}{C_L(\sigma - \rho_m) + \rho_m} \]  

(14)

where \( \phi \) is the internal friction angle of the sediment, \( d_m \) is the mean diameter of the sediment, and \( C_e \) is the equilibrium sediment concentration, described as follows [Nakagawa et al., 2003]. If \( \tan \theta_e > 0.138 \), a stony-type debris flow occurs, and

\[ C_w = \frac{\tan \theta_e}{(\sigma - \rho_m)(\tan \phi - \tan \theta_w)} \]  

(15)

If \( 0.03 < \tan \theta_e \leq 0.138 \) an immature-type debris flow occurs, and

\[ C_w = 6.7 \left( \frac{\tan \theta_w}{(\sigma - \rho_m)(\tan \phi - \tan \theta_w)} \right)^2 \]  

(16)

If \( \tan \theta_e \leq 0.03 \), a turbulent water flow with bed load transport occurs, and

\[ C_w = \frac{(1 + 5 \tan \theta_e) \tan \theta_w}{\sigma / \rho_m - 1} \left[ 1 - \alpha_0^2 \frac{\tau_w}{\tau_c} \right] \left( 1 - \alpha_0^2 \frac{\tau_c}{\tau_v} \right) \]  

(17)

where \( \theta_w \) is the water surface gradient, \( \rho_m \) is the density of the water,

\[ \alpha_0^2 = \frac{2 \left[ (\sigma / \rho_f) \tan \theta_w / (\sigma / \rho_f - 1) \right]}{1 - (\sigma / \rho_f) \tan \theta_w / (\sigma / \rho_f - 1)} \]  

\[ \tau_c = 0.04 \times 10^{0.7 \tan \theta_w} \]  

(18)

\[ \tau_v = \frac{h \tan \theta_w}{(\sigma / \rho_f - 1)d_m} \]  

(19)

\[ \tau_w = \frac{h \tan \theta_w}{(\sigma / \rho_f - 1)d_m} \]  

(20)

where \( \tau_w \) is the non-dimensional critical shear stress and \( \tau_v \) is the non-dimensional shear stress.

### Table 2: Conditions used in debris flow simulation

| No. | Occurrence Point | Supply time(s) |
|-----|-----------------|----------------|
| Case1 | A               | 10, 20, 30, 40, 60 |
| Case2 | B               | 10, 20, 30, 40, 60 |
| Case3 | A&B             | 10, 20, 30, 40, 60 |
| Case4 | A&B             | A:33 B:38       |

### Table 3: Parameters for debris flow simulation

| Parameter                | Unit | Value     |
|--------------------------|------|-----------|
| Basin Area               | km²  | 1.262     |
| Calculated duration      | min  | 30        |
| Input discharge (Qᵢ)     | m³/s | 223.03    |
| Mesh size (Δx, Δy)       | m    | 5         |
| ΔT                       | s    | 0.01      |
| Mean diameter (D₅₀)      | m    | 0.1       |
| tanφ                     | -    | 0.7       |
| Cᵣ                       | -    | 0.65      |

#### 4.1.4 Estimation of Debris Flow Discharge

The estimation of debris flow peak discharge is obtained using empirical equations. This study analyses the runoff discharge that was estimated based on the method proposed by the New Integrated Lowland Inundation Model [NILIM, 2007].

\[ P_r = \frac{10^3 R_f A}{1 - \lambda} \left( \frac{C_d}{1 - C_d} \right) f_r \]  

(21)

\[ f_r = 0.05 \log A - 2.0 \]  

(22)

\[ Qᵢ = \frac{C_w}{C_w - C_d} Q_p \]  

(23)

where \( P_r \) is the possible runoff of sediment volume, \( R_f \) is an accumulated of rainfall during 24 hr, \( A \) is basin area, \( \lambda \) is porosity (=0.4), \( Qᵢ \) is peak discharge of debris flow, \( Q_p \) is peak discharge by rational formula. \( C_d \) is the sediment concentration and \( f_r \) is the correction factor of outflow. The conditions and parameters used in debris flow simulation are shown in Tables 2 and 3, respectively. The topography of the study basin for
debris flow simulation at Ono City is shown in Fig. 6, and the sewerage system domain of urban inundation as shown in Fig. 7.

### 4.2 Introduction of Inundation Model

A 2-D inundation model is used in this study with various components for simulating the complex flow phenomena in urban drainage basins. The inundation of underground infrastructure during a flood is also considered in the model. The concept of the integration flooding model is showed Fig. 8. This study analyses the mechanism and hydrodynamic characteristics of the interaction between flooding inundation, river network and sewerage system by applying the NILIM 2.0 [MLIT, 2012]. The total number of meshes is 104,996 (mesh size: 25 m)

#### 4.2.1 Governing Equation for Flood Plain Area

The 2-D unsteady flood flows with consideration of rainfall intensity and drainage capacity can be described by a system of shallow water equation, as bellow:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} &= q_e - q_{out} + q_{over} \\
\frac{\partial M}{\partial t} + \frac{\partial uM}{\partial x} + \frac{\partial vM}{\partial y} &= -gh\frac{\partial h}{\partial x} + \frac{1}{\rho} \tau_{hx} \\
\frac{\partial N}{\partial t} + \frac{\partial uN}{\partial x} + \frac{\partial vN}{\partial y} &= -gh\frac{\partial h}{\partial y} + \frac{1}{\rho} \tau_{hy}
\end{align*}
\]

where:

\[
\begin{align*}
\tau_{hx} &= \rho g n^2 u \sqrt{u^2 + v^2} \\
\tau_{hy} &= \rho g n^2 v \sqrt{u^2 + v^2} \\
n^2 &= n_0^2 + 0.02 \times \frac{\theta}{100 - \theta} \times h^{3/4}
\end{align*}
\]

and

\[
q_e = \left\{ \begin{array}{ll}
\lambda r & \text{if } r \\
(1-\lambda)q_e & \text{otherwise}
\end{array} \right.
\]

where \(u\) and \(v\) are the x and y-components of flow velocity, respectively; \(M\) and \(N\) are the x and y-components of discharge per unit width, respectively; \(q_{out}\) is the drainage discharge per unit area from computational mesh into sewerage system; \(q_{over}\) is the overtopping flow discharge per unit area of computational mesh from the river network; \(r\) is rainfall; \(n_0\) is the roughness coefficient; \(n\) is the roughness coefficient to consider the share rate of buildings; \(\theta\) is the share rate of buildings; \(q_e\) is the runoff rainfall of discharge per unit width; \(r_e\) is effective rainfall.

#### 4.2.2 Governing Equations for the River Network

In the river network, the following St. Venant momentum equations solved by the characteristics method.

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{in} - q_o
\]

\[
1 \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + u \frac{\partial h}{\partial x} = S_o - S_r
\]

where \(A\) is the cross sectional area of flow, \(Q\) is the discharge, \(u = Q/A\) is velocity averaged over the cross-section, \(S_o = \sin \theta\) is the riverbed slope, \(S_r = n^2 \sqrt{gR^{4/3}}\) is the friction slope, \(R\) is the hydraulic radius, \(g\) is the gravitational acceleration, and \(q_o\) is lateral inflow per \(x\)-directional unit width from the pump stations and drainage channels.

#### 4.2.3 Governing Equation for Sewerage System

Rainwater on the flood-plain area is drained into the river network through the sewerage system. This system consists of sewers and a pump station. The rainfall in the sewer pipe is dynamically calculated based on the following continuity and momentum equations:
\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{33}
\]
\[
\frac{\partial Q}{\partial x} + \frac{(u)Q}{x} = gA\frac{\partial H}{\partial x} - \frac{g n^2 |Q|}{R^{1/3} A} \tag{34}
\]
where \(A\) is the cross sectional area of flow, \(Q\) is discharge, \(q\) is the lateral inflow, \(u\) is the flow velocity, \(n\) is the roughness coefficient, \(R\) is the hydraulic radius, \(H(z+h)\) is water level, \(z\) is the elevation of sewer pipe bottom and \(h\) is the water depth.

5. RESULTS AND DISCUSSIONS

The results are generated in the form of hazard maps of the study area, one considering both debris flow and the inundation, and the other considering inundation only. The description of the hazard map will be done in later projects. The development of such hazard maps consists of different processes which are described briefly as below:

5.1 Final Deposition of Debris Flow

First, the supply time needed to generate debris flow in the model is estimated by comparing results from different supply times with the potential volume obtained from the \(P_r\) equation (21). Fig. 9 shows the result of obtaining suitable supply time for the model analysis for all four cases. The times for the first three cases (1, 2 and 3) are calculated using the process below. The fig shows that a suitable supply time is calculated by solving the horizontal straight line of volume generated by the empirical equation and the volume-supply time curve generated by model. The results obtained are 33 s for Case 1 (accumulated sediment volume: 251,982 m³), 38 s for Case 2 (accumulated sediment volume: 250,528 m³) and 21 s for Case 3 (accumulated sediment volume: 249,907 m³). But Case 4 is estimated on the basis of a worst-case scenario taken as 33 s for the occurrence of point A and 38 s for occurrence of point B (accumulated sediment volume: 482,901 m³).

After estimating the supply time, the model is run with the respective supply times for all cases, and the resulting debris flow depositions are generated. The study basin is classified into three sections: source area, main pathway, and depositional area. Fig. 10 shows the gradation of the mountain stream bed in sediment displacement morphology. The parameter of moving velocity is very important to the establishment of a hazard map of the direct damage area. The access times of debris flow at the collecting point under the four cases were investigated. As a result, Case 1 through 4 are 340 s, 380 s, 320 s and 220 s, respectively. Fig. 11 shows the debris flow deposition at the final stage based on the rainfall obtained from the DAD analysis.

5.2 Inundation map

The inundation map of the study area is generated based on two scenarios: a) by using return period 1/50 and b) by using rainfall through DAD. The results are prepared using one inundation event at the maximum depth and another at the peak hydrograph time 12 hr (see Fig. 5b). The results are shown in Fig. 12. The results clearly show that the inundation area in the DAD analysis is larger than that of return period analysis.
The results of risk area obtained from the inundation analysis of the study area are as shown in Fig. 13. The inundation map is generated by considering the risk factor to the people according to the guidelines in Table 4. This figure also shows that the DAD method generates a larger risk area than return-period analysis. Areas at risk levels I and II are estimated as safe zones without human injuries, but areas at risk levels III and IV are estimated as very dangerous areas with potential risk to people. Therefore, areas at risk levels III and IV require evacuation and preferential treatment when disasters occur.

### 5.3 Hazard Map

Finally, a hazard map is prepared, considering two cases: one with the combination of debris flow and inundation and another with only inundation, calculated by DAD analysis. The complete map is shown in Fig. 14. The figure also shows the evacuation route for people living near the foot of a mountain (i.e., Area-II). As a result, 2 routes are proposed below: Route-A (by foot 21 min, by car 3 min) and Route-B (by foot 35 min, by car 5 min). Additionally, the results show 2 viewpoints. First, in terms of Area-I (i.e., people living near the river), this area will be influenced by flooding from the surrounding river more than by the impact of debris flow. Therefore, Route-A’s evacuation route can be determined by accessibility and movement time. Second, in terms of Area-II, there is no necessity for residents to take shelter from the flood. However, if considering both disasters simultaneously, Route-A will lose its evacuation function due to flooding before debris flow occurs (generated based on two scenarios). Therefore, it can be determined that Route-B is safer, even though it takes more time than Route-A in these areas.

The evacuation time scenario was also developed under the impact of debris flow, which is shown in Fig. 15, and the target basins (near debris flow only: A, B, C, D, E, and F) for the evacuation time scenarios shown in Fig. 16, based on an analysis combining both disasters.
6. CONCLUSION AND RECOMMENDATIONS

In this study, the hazard map is prepared considering debris flow and inundation simultaneously. The hazard map is an important tool that highlights areas that are affected by or vulnerable to a particular hazard. Hazard maps help prevent serious damage and deaths. From the above analysis, it can be inferred that combining one or two disasters in a multihazard environment provides a clearer picture of an inundation scenario than independent analysis. In our case, also, the two-disaster scenario shows a greater risk area than a single-disaster scenario. Thus, the 2007 hazard map of Ono City is revised to consider a two-disaster scenario. Based on the above analysis, Route-A is the optimal evacuation route for Area-I. If only considering flooding at Area-II, there is no necessity for residents to take shelter from the flood. However, when considering both disasters at Area-II, Route-B will be safer in terms of debris flow impact because Route-A will have already been inundated by flooding before debris flow.
occurs. Therefore, these results indicate a need to consider both disasters. Furthermore, evacuation planning involves an iterative process to identify the best routes and to estimate the time required to evacuate the at risk areas. Therefore, the various conditions (i.e., impacts of disasters) should be considered when providing estimates for evacuation planning.

The target basin is the smallest basin in the total basin area of Ono City; the current 1 h and 30 min rainfall duration produces rainfall as heavy as 135 mm and 83 mm, respectively (see the Table 1). If we consider a 30 min case, the precipitation becomes 166 mm/hr, compared to 1 hr of rainfall at 135 mm/hr. Since debris flow time advances in minutes, the 30 min analysis should be done in the future regarding the development of a hazard map.

In the future, more disasters like landslides, dam failure, slope failure, etc. can be incorporated into one map to show a clear picture of the problem. The debris flow reaching the river forms a temporary dam to obstruct river flow, and the river flow happens by overtopping such dams. Hence, such scenarios should also be included in future studies.

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Fig. 15 Established evacuation time scenario

Fig. 16 Target of evacuation basin