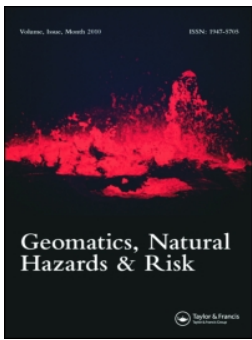# Estimating woody debris recruitment in a stream caused by a typhoon-induced landslide: a case study of Typhoon Lionrock in Iwaizumi, Iwate\nprefecture, Japan

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Estimating woody debris recruitment in a stream caused by a typhoon-induced landslide: a case study of Typhoon Lionrock in Iwaizumi, Iwate prefecture, Japan

Thapthai Chaithong[a] (iD), Daisuke Komori[b], Yuto Sukegawa[b] and Satoshi Anzai[b]

[a]Department of Frontier Sciences for Advanced Environment, Graduate School of Environmental Studies, Tohoku University, Sendai, Japan; [b]Department of Civil and Environmental Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan

ABSTRACT

A landslide can generate large amounts of debris in the form of boulders, cobbles, soil, and wood. The woody debris produced by a landslide flows into a downstream river or village; it can form obstructions in the stream and destroy houses. In this study, we aimed to develop a procedure for estimating woody debris recruitment into streams following a landslide. Understanding the volume of woody debris can help predict and prevent hazards from this debris. The proposed procedure combines a shallow landslide model, tree density data, and observational data following landslide occurrence. The study site is a sub-watershed of the Omoto River watershed in the town of Iwaizumi in Iwate prefecture in Japan; this town was affected by Typhoon Lionrock in 2016. Typhoon Lionrock delivered over 200 mm of rainfall in 24 h and induced many landslides. Based on field surveys, we found that approximately 524 m^3 of woody debris jammed the narrow section under a railway bridge (including voids) and approximately 178 m^3 of woody debris to formed a dam in the stream channel of the target watershed (including voids). Using the proposed protocol, we estimate that woody debris recruitment to the stream was approximately 638 m^3.

Introduction

On 30 August 2016, Typhoon Lionrock struck the Pacific coast of north-eastern Japan; it was the first tropical cyclone to make landfall in this region. The typhoon caused flash flooding, landslides and debris flows in the north-eastern part of Japan (the Tohoku region), destroying houses and infrastructure. The mechanism of typhoon induced-landslides can be summarized as follows: rain water infiltrates into a sloping surface, thereby recharging the groundwater or increasing pore water pres-

sure (decreasing negative pore water pressure). These factors reduce the effective stress and shear strength on the potential failure plane. (Ng and Shi 1998; Orense 2004; Rahardjo et al. 2005; Chaithong et al. 2017)

Generally, landslides occur on steep slopes; thus, landslide-prone areas tend to be mountainous and covered by natural or artificial forests. When landslides occur, the slope movement disturb tree roots, causing the trees to collapse. The fallen trees become woody debris; some of the woody debris remains on the hillslope, and some of it is entrained by debris flows, landslides or flash floods that flow downstream through the watershed. The woody debris, which can be defined as downed wood, branches, roots, stumps, snags (standing dead trees), plays a significant role in the area's ecosystem and hydrology. Numerous researchers have reported woody debris recruitment and transport into a catchment following landslides or flooding during or after a tropical cyclone or heavy rainstorm. For example, Chen et al. (2013) reported that 603 m^3 of woody debris was transported in the Qijiawan catchment in Taiwan after Typhoon Morakot in August 2009. Ruiz-Villanueva et al. (2014) reported that flash flooding in Spain caused several woody debris traps and blocks, creating critical obstructions in a stream. Additionally, Comiti et al. (2016) studied the total amount of large woody debris recruited by large floods in the Gravegnola and Pogliaschina sub-catchment areas of the Magra River; they found that woody debris accounted for approximately 4,500 m^3 in the Pogliaschina sub-catchment and 9,400 m^3 in the Gravegnola sub-catchment. While, woody debris is a natural hazard that can destroy infrastructure and threaten human lives it also provides habitat for vertebrates, insects, and microorganisms (Triska and Cromack 1980). Decaying woody debris is supplies soil organic matter by returning nutrients to the soil (Wu et al. 2005). Moreover, previous research has shown that the pools created by woody debris are an important habitat for overwintering salmon (Fausch and Northcote 1992).

Hence, woody debris recruitment is the initial data used in the analysis and modelling of the effects of woody debris on an ecosystem. Several researchers have presented methods for estimating the inputs from fallen trees in a channel. Sickle and Gregory (1990) developed a model for fallen trees delivered to a stream that estimates the number of trees falling into the stream using the stand density, the probability of one tree falling, and the fall direction. Mazzorana et al. (2009) developed hazard index maps for woody material recruitment and transport. To generate these maps, they combined Sickle and Gregory's (1990) method of determining the probability of one tree falling with debris flow, overbank sedimentation, and land-use maps. They used these maps to identify five zones of woody material recruitment: the stream influence zone, active wood buffer, recharging wood buffer, preferential recruitment paths, and preferential contributing area. Similarly, Ruiz-Villanueva et al. (2014) proposed a method to evaluate woody debris recruitment from landslides, bank erosion, and floods based on geographic information system and multi-objective assessment tools using fuzzy logic principles. However, few researchers have used post-disaster observational data to estimate woody debris recruitment. Therefore, this paper aims to use data collected after a landslide to develop a method of estimating woody debris recruitment. We combine an analytical shallow landslide model, tree density data, and a geographic information systems database after a landslide occurrence.

Description of the study site and the aftermath of Typhoon Lionrock

The study site is a sub-watershed of the Omoto River catchment located in the town of Iwaizumi in Iwate prefecture in the north-eastern part of Japan (Figure 1). The total area of the study site is approximately 0.87 km^2, and the total length of the stream is approximately 3.75 km. Land cover in the study area is an artificial forest, with the main tree species being Hinoki (*Chamaecyparis obtusa*) and Sugi (*Cryptomeria japonica*). A post-disaster survey showed that woody debris and sediment created a dam in a narrow downstream section; upstream of the study area, we found woody debris dams and slope failures along the stream, as well as fallen trees on the hillslope. Figure 1 shows the study site and the locations of the slope failures and woody debris dams in the catchment. Figure 2 shows the dam formed by woody debris and sediment at the narrow section. For field-surveying techniques, lengths, widths, and thickness of woody debris dams were measured by laser distance measure and levelling staff, moreover, we also checked the geometric shape of woody debris dams. The total amount of woody debris in this dam was approximately 524 m^3 (including voids). The woody debris recruitment rate per channel length was 139.7 m^3/km and the woody debris
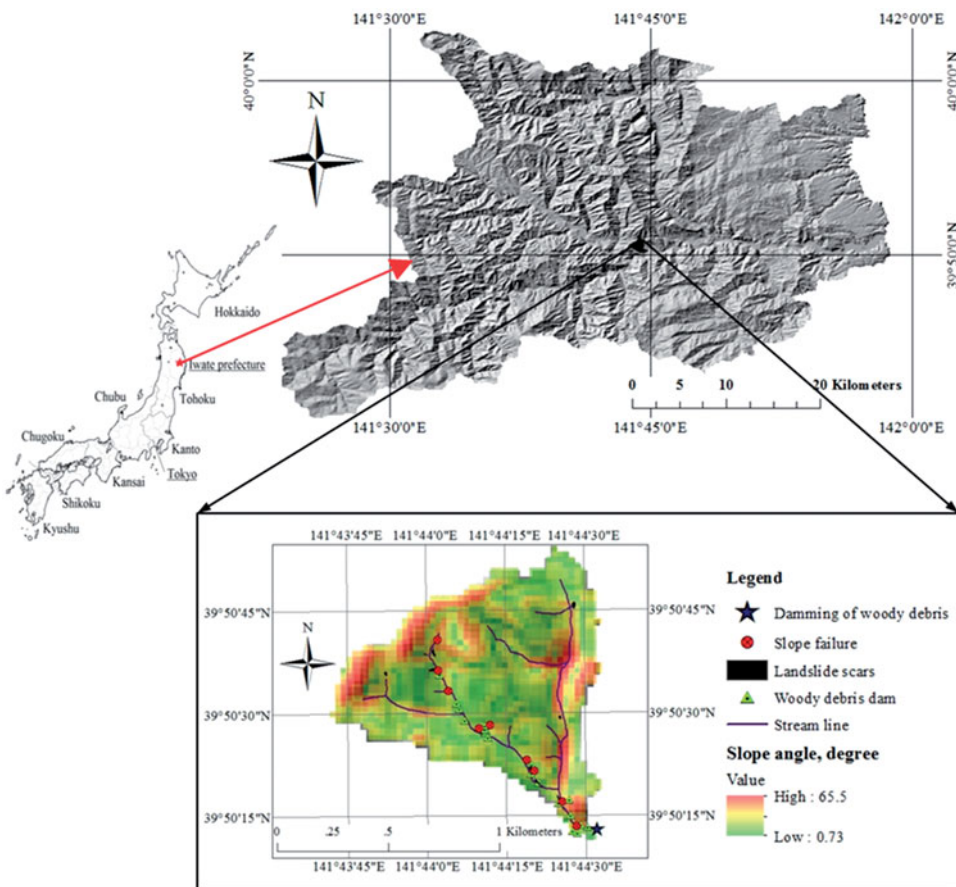

Figure 1. Geographic setting of the study site and locations of the slope failures and woody debris dams in the catchment area.
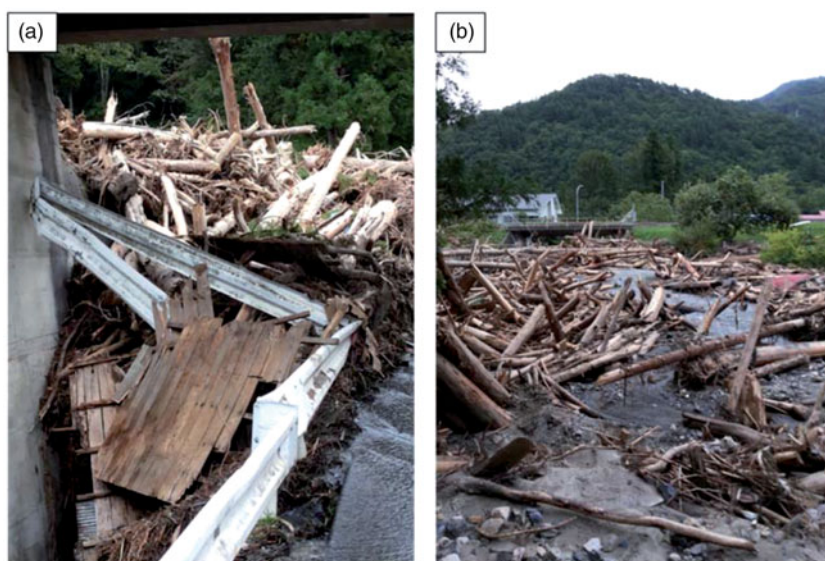
Figure 2. Damming of the woody debris and sediment at a narrow section of the stream.

recruitment rate per catchment area was 602.3 m^3/km^2. The mean length of the woody debris was 5.2 ± 4.8 m, and the mean diameter of woody debris was 0.22 ± 0.1 m. The total volume of woody debris dams in the upstream part of the study area was approximately 668.5 m^3 (including voids); this number includes approximately 178 m^3 (including voids) for the dam located in the stream channel and approximately 490.5 m^3 (including voids) for the dam located on the hillslope. The mean height of the woody debris dams was 2.7 ± 1.6 m, the mean width was 5.9 ± 2.8 m, and the mean depth 4.7 ± 2.5 m. The field survey showed that a total of 18 woody debris dams were present in the studied site, of which 8 dams were located in the stream channel and 10 dams were located on the hillslope. The occurrence rate woody debris dams in the stream channel rate per channel length was approximately 2 dam*km^{-1}.

Considering the size of sediment deposited behind the woody debris jamming the narrow section, we collected 15 sediment samples to determine their grain size distribution. Laboratory tests classified the sediments as gravel and sand, with diameters ranging from 53 to 0.075 mm. The fine particle content of sediments deposited near the dam and the particle size increases with distance from the dam. Figure 3 shows the distribution of sediments with a D50 grain size that is called median diameter.

Figure 4 shows plots of the hourly rainfall and the cumulative rainfall from 5 rain gauges operated by the Japan Meteorological Agency (JMA) and Iwate prefecture. The maximum 24-h rainfall when Typhoon Lionrock hit the east coast of the Tohoku region of Japan on 30 August 2016 in Iwaizumi was 208 mm at the Iwaizumi (JMA) rain gauge (the maximum hourly rainfall was 66 mm). The rainfall peaked from 15:00 to 19:00. Approximately 160 mm fell over these 4 h, which is greater than the average monthly rainfall in Iwaizumi (JMA); the average August rainfall in Iwaizumi (JMA) from 1976 to 2015 was 156.9 mm. Figure 5 shows the of 24-h rainfall in the town of Iwaizumi.
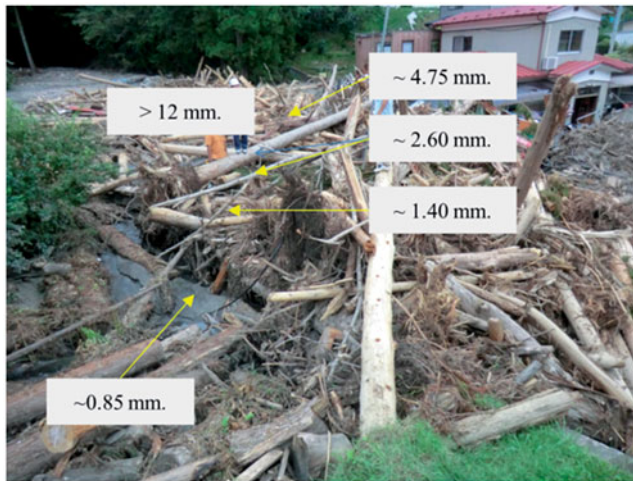
Figure 3. Distribution of sediments with a D50 grain size behind the woody debris dam.
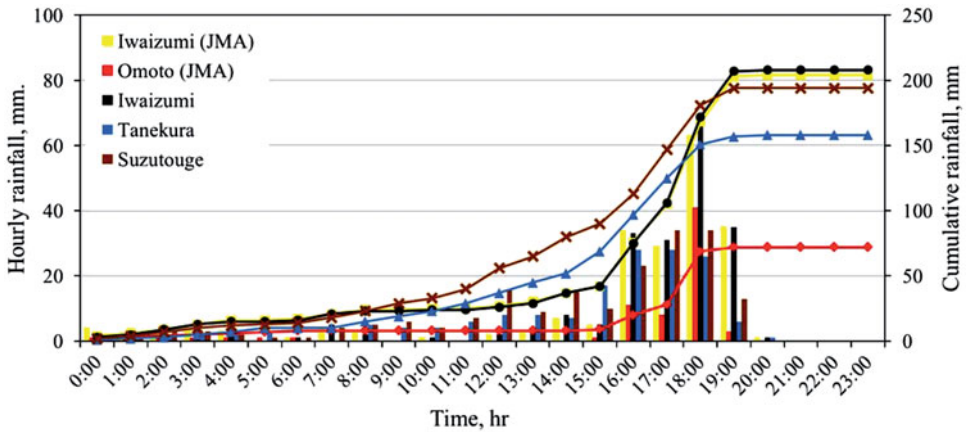

Figure 4. Plots of hourly rainfall and cumulative rainfall from five rain gauges in the town of Iwaizumi on 30 August 2016.

Methods and dataset

The proposed procedure can be divided into four steps. The first step involves simulating the unstable area (landslide areas) with an analytical shallow landslide model that describes the source of woody debris recruitment to the watershed. The second step is performing forest analysis to determine tree diameters and height and trees density, as well as estimating the volume per piece of downed woody debris. The third step is using the satellite images and aerial photography to identify the width of the active stream channel following the debris flow. In the final step, we use these parameters the unstable areas, the volume per piece of downed woody debris and the tree density, and the width of the active stream channel to estimate woody debris recruitment into the stream channel caused by the Typhoon Lionrock induced landslide. To estimate woody debris recruitment, we calculate the volume of woody debris
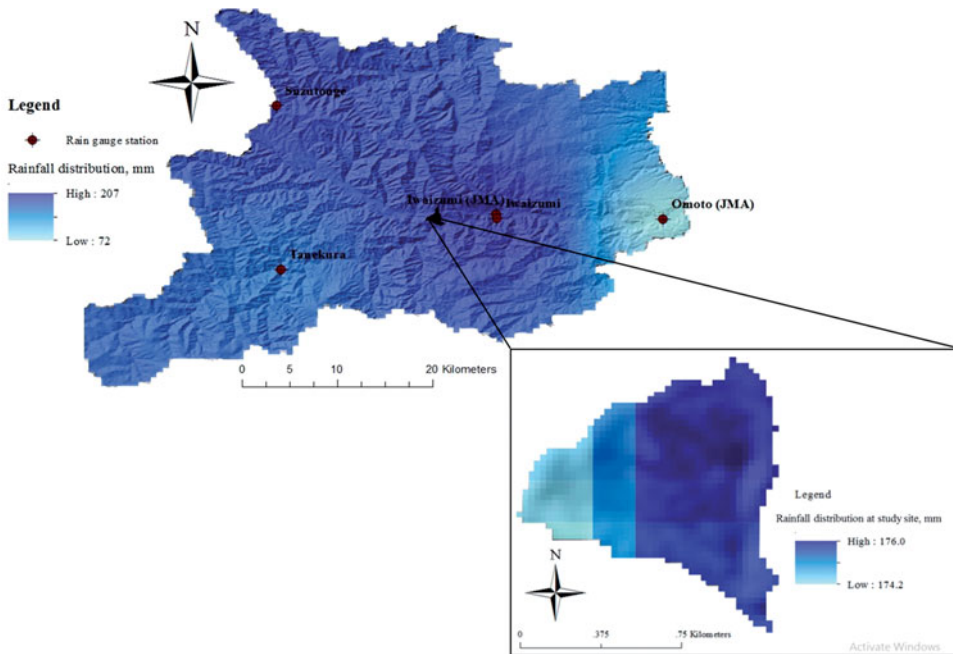
Figure 5. 24-hour rainfall distribution in the town of Iwaizumi on 30 August 2016.

in area of the overlap between the unstable area and the active channel area, assuming that only woody debris in the active channel zone could be entrained into the stream channel.

We validate the performance of this procedure by comparing the amount of woody debris estimated using the proposed method and the total woody debris in the stream determined during a field survey.

Analytical shallow landslide model

The shallow landslide model used in this study makes two major assumptions: (1) the landslide characteristics are based on an infinite slope and (2) the hydrological conditions are based on steady state subsurface flow and infiltration. The model is analytical and simulates the physical process of slope destabilization caused by an increase in groundwater.

Hillslope hydrology model

The hillslope hydrology model used in this study consists of two parts. One part simulates the saturated subsurface flow (groundwater flow), and the other part simulates rainfall infiltration into the sloping surface. The equation for saturated subsurface flow is based on Darcy's law, and the equation for rainfall infiltration into the sloping surface is based on the modified Green–Ampt equation that was proposed by Chen and Young (2006). In the modelling framework, groundwater is recharged by rainwater infiltration, and overland water flow occurs once the infiltration capacity is exceeded. The subsurface flow is parallel to the slope surface, the flow through soils

occurs through the interconnected voids in the soil mass, the base rock is the imper-meable layer at shallow depth and the hydraulic gradient is equal to the slope. The catchment topography is represented using a digital elevation model (DEM). From the water balance equation and Darcy's law, the following expression can be obtained:

$$I \cdot A = \eta \cdot m \cdot b \cdot k \cdot \sin \beta \tag{1}$$

where I is the rainwater infiltration, A is the catchment area, η is the porosity of the soil, m is the steady water table height, b is the width of the topographic elements, k is the saturated hydraulic conductivity, and β is the slope angle.

From Equation (1), the steady water table height can be expressed as follows:

$$m = \frac{I \cdot A}{b \cdot \eta \cdot k \cdot \sin \beta} \tag{2}$$

The Green–Ampt equation is a simplified mathematical expression that represents the infiltration process. The rate of infiltration for the sloping surface and the cumulative infiltration are as follows:

$$i = k \cdot \left[\cos \beta + \frac{(\psi \cdot \Delta\theta)}{I(t)} \right] \tag{3}$$

$$I(t) - \frac{(\psi \cdot \Delta\theta)}{\cos \beta} \cdot \ln \left[1 + \frac{I(t) \cdot \cos \beta}{(\psi \cdot \Delta\theta)} \right] = k \cdot t \tag{4}$$

where i is the infiltration rate at time, $I(t)$ is the cumulative infiltration at time, $\Delta\theta$ is the volumetric water content deficit, ψ is the suction at wetting front, and t is the time.

Infinite slope stability model

Based on field observations, a shallow slip-type landslide occurred and was parallel to the slope surface; thus, the infinite slope stability model can be used to analyse the stability of the slope based on the factor of safety (FS). FS is the ratio of the shear strength of soil to the mobilized shear force. The shear strength of soil used in this study is based on the Mohr–Coulomb failure criterion and can be expressed as follows:

$$\tau_f = c + \sigma \tan \phi \tag{5}$$

where τ_f is the shear strength of soil, c is the total soil cohesion, σ is the normal stress, and ϕ is the total friction angle.

Effective normal stress resists downslope movement and can be expressed as follows:

$$\sigma = \left[(m \cdot \gamma_{sat}) + (D - m) \cdot \gamma_t \right] \cdot \cos^2 \beta \tag{6}$$

where D is the depth of soil, γ_{sat} is the saturated soil unit weight, and γ_t is the submerged soil unit weight.

The mobilized shear force developed along the potential failure plane consists of the weight of the soil mass and the seepage force and can be expressed as follows:

$$\tau_d = \left[(m \cdot \gamma_{sat}) + (D - m) \cdot \gamma_t \right] \cdot \sin\beta + \gamma_w \cdot m \cdot \sin\beta \tag{7}$$

where τ_d is the mobilized shear force, and γ_w is the water unit weight.

By substituting the equations for shear strength and the mobilized shear force, the FS can be written as follows:

$$FS = \frac{c + m \cdot \left[\gamma_{sat} + (D - 1) \cdot \gamma_t \right] \cdot \cos^2\beta \cdot \tan\phi}{m \cdot \left[\gamma_{sat} \cdot \gamma_w + (D - 1) \cdot \gamma_t \right] \cdot \cos\beta \cdot \sin\beta} \tag{8}$$

For the shallow landslide model, elevation data was obtained from the ASTER Global Digital Elevation Model (GDEM) version 2 that was jointly developed by the National Aeronautics and Space Administration (NASA) of the United States and the Ministry of Economy, Trade, and Industry of Japan. The slope angle was calculated from 30 m resolution ASTER GDEM version 2 data using the Spatial Analyst Tool in ArcGIS, as shown in Figure 1. The soil parameters at this site are used in the landslide analysis presented in Table 1. For the rainfall dataset, the rainfall intensity used to analyse the landslide are extracted from 5 rain gauges in the Iwaizumi town and interpolated to determine the spatial distribution of rainfall with a resolution of 30 m using the Inverse distance weighted (IDW) method in the Spatial Analyst Tool of ArcGIS as shown in Figure 5. Chaithong and Komori (2017) validated the accuracy of the analytical shallow landslide model by using the historical landslide case in Thailand; the accuracy of the analytical shallow landslide model was 0.737.

Forest analysis

Forest analysis is a survey of the height, diameter of trees and tree density to analyse the potential volume of downed woody debris in the study site. The forest analysis is the second step of the proposed method used to estimate the volume of downed woody debris; we also used a global tree density dataset. In this study, we measured the heights and diameters of trees in the study area to estimating the volume of

Table 1. Parameters of the analytical shallow landslide model.

Parameters	Unit	Value
Cohesion of soil	kPa	10.8
Friction angle	Degree	29.7
Saturated soil unit weight	kN/m³	16.7
Water unit weight	kN/m³	9.81
Hydraulic conductivity	cm/hr	2.99
Soil porosity	–	0.437
Suction at wetting front	cm	6.13
Volumetric water content deficit	–	0.27

downed woody debris. We used a laser meter to measure the height of each tree and girthing tape to measure the girth of each tree. The girth of the tree is measured at 1.35 metres above the ground and then is converted to the diameter at breast height (DBH).

To determine the volume of downed woody debris in this study, we used Huber's formula because it is suitable for observational data. Huber's formula is given in Equation (9). In this study, we modified Huber's formula to reflect a standing tree that will become downed woody debris. The modified formula is given as

$$V = L \cdot A_m \tag{9}$$

$$V = H \cdot A_{(DHB)} \tag{10}$$

where V is the volume of standing trees, L is the length of a downed woody debris piece, A_m is the cross-sectional area at the longitudinal midpoint, H is the height of the tree, and $A_{(DHB)}$ is the cross-sectional area at breast height.

Tree density is a key parameter for calculating the volume of trees in each unstable area. We obtained tree density data from the global scale tree density map developed by Crowther et al. (2015); they used 429,775 ground-sourced measurements to generate a global map of tree density. In addition, predictive regression models for forested areas were generated to correlate tree density with climate, topography, vegetation characteristics, and land use. Figure 6 shows the tree density map for the study site obtained from the global map of tree density.

Active stream channel identification

The active stream channel zone is the area directly exposed to debris flows or flash floods. The extent of the active stream channel was determined using satellite images
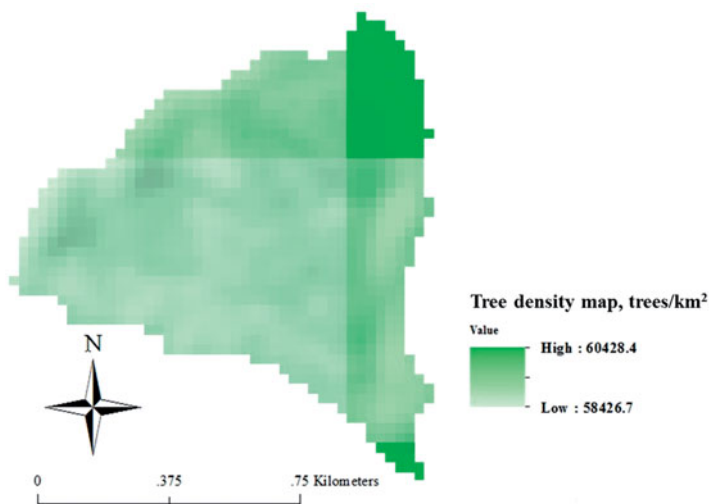

Figure 6. Tree density map of the study site obtained from the global map of tree density.

and aerial photography. The satellite image and aerial photography were provided by Google Earth and the Geospatial Information Authority of Japan, both of which include photographs of the area after the typhoon and the subsequent landslide. We extracted the width of the active stream channel from the pictures and determined the width of the active channel in ArcGIS.

Results and discussion

Figure 7 shows tree heights and diameters. The tree height data are found to be normally distributed ($P = 0.461$). The tree diameter shows a right-skewed distribution a Weibull distribution showed the best fit to these data ($P = 0.183$). As mentioned previously, we used a modified version of Huber's formula to calculate the potential volume of standing trees. We found that two parameters in the modified Huber's formula had high variability: while the minimum tree height was approximately 5 m, the maximum tree height was approximately 25 m. Therefore, tree height and diameter were treated as uncertain variables in the formula. Monte Carlo methods (MCMs) were used to estimate the volume of standing trees. The values for each parameter were generated using random and independent but non-identical distributions; we generated 10,000 random values for each parameter. Table 2 shows mean and coefficient of variation values for the tree height and tree diameter in the study area. Figure 8 shows the distribution of the volume of standing trees based on the MCMs. The peak of the distribution curve for the volume of standing trees is approximately 0.75 m³; thus, we used this value for the calculations in this study.

Figure 9 shows the FS map for 30 August 2016 and the locations of the shallow landslides. The black labels indicate the scars of shallow landslides obtained from aerial photographs, and the red points are the locations of shallow landslides from surveys. The red areas are unstable areas for which the FS is less than 1. On the map, the unstable areas are located on steep hillslope (with a slope angle exceeding approximately 30°), which is consistent with results of the field survey. The field surveys showed that slope failures occurred along the channel banks and in high elevation areas with steep slopes. Compared to the actual landslide scars, the GIS-Based Shallow model overestimated the unstable areas. This overestimation may have occurred because the spatial variance of the soil parameters was limited; additionally access to the study site was difficult because of the mountainous terrain and dense
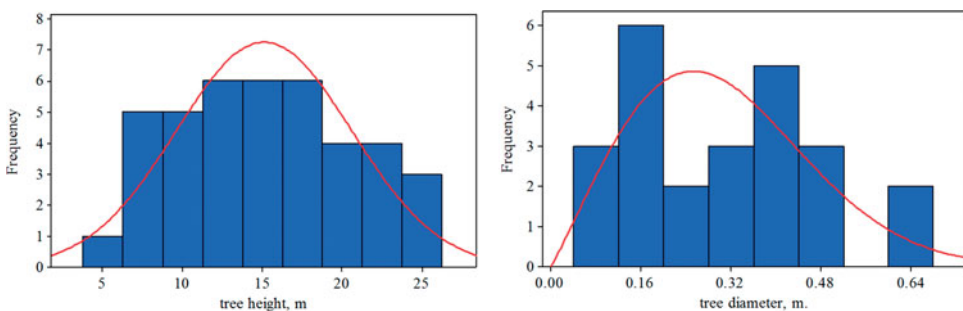

Figure 7. Distribution of the height and diameter of the trees in this study.

Table 2. Mean and coefficient of variation values for the tree height and tree diameter in the study area.

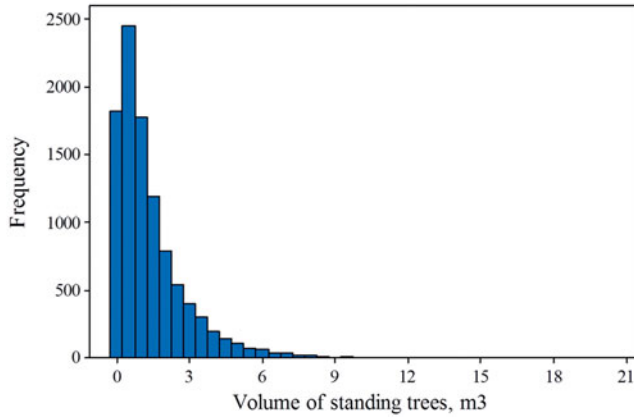| Parameters	Mean	Coefficient of variation
Height, m	15.09	0.39
Diameter, m	0.30	0.52

Figure 8. Distribution of the volume of standing trees calculated using from MCMs.
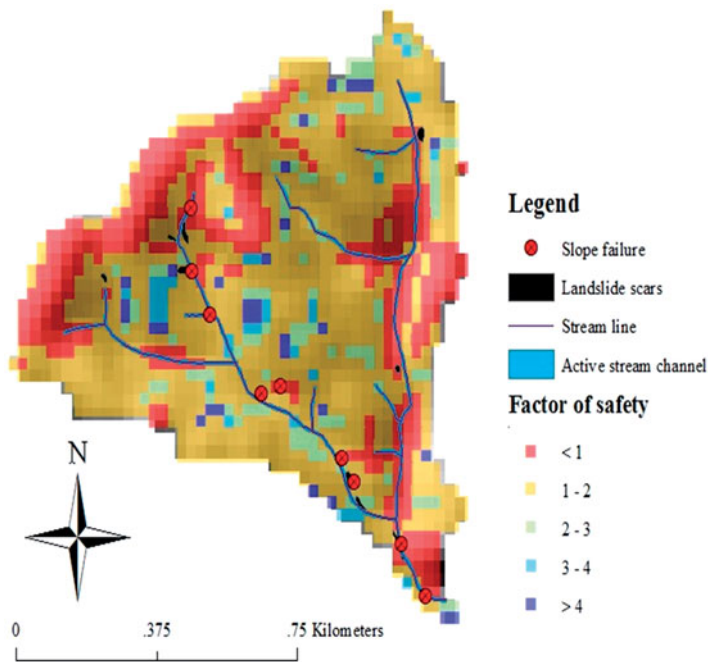

Figure 9. Map of the FS, the locations of shallow landslides and the active stream channel due to the debris flow at the study site on 30 August 2016.

Table 3. Analytical results for woody debris recruitment caused by the Typhoon Lionrock induced landslide.

	Unit	Value
Volume of the dam formed by woody debris caused by the Typhoon Lionrock-induced landslide (including voids)	m^3	524
Volume of the woody debris dam located in the stream channel caused by the Typhoon Lionrock-induced landslide (including voids)	m^3	178
Volume of woody debris in the stream caused by the Typhoon Lionrock-induced landslide (including voids)	m^3	702
Unstable area (FS <1)	km^2	0.42
Potential volume of fallen tree in the unstable area	trees	25,350
Potential woody debris recruitment in the unstable area	m^3	19,010
Woody debris recruitment in active channel	m^3	638

forest, which inhibited finding slope failure locations. Moreover, determining landslide scars from aerial photographs will miss some landslides because of the effects of tree cover. The unstable areas simulated by the model in this study cover a total area of 0.42 km².

Figure 9 shows the area of the active stream channel based on debris flows during the event. The yellow labels indicate the active stream channel caused by debris flows. We used Google Earth to draw the active stream channels and overlaid the FS in ArcGIS. The maximum width of the active stream channel is approximately 15 m, and the minimum width of the active channel is approximately 8 m.

As mentioned previously, woody debris recruitment was calculated based on the volume of standing trees, the unstable areas, the tree density, and the width of the active stream channel. In addition, the field survey showed that woody debris dams were present along the stream channel and on slopes. We estimate that the total volume of woody debris dams in the site was approximately 668.5 m³ (including voids). The volume of the woody debris dam located in the stream channel was estimated to be approximately 178 m³ (including voids). We note that there were voids between the pieces of woody debris that formed the dam.

Based on our analysis, woody debris recruitment in the active channel resulting from the debris flow was approximately 638 m³. The volume of woody debris deposited downstream was approximately 524 m³ (including voids) and the volume of woody debris dam in the stream channel was approximately 178 m³ (including voids). In total, the volume of woody debris in the stream caused by the Typhoon Lionrock-induced landslide was 702 m³. We conclude that the model proposed in this study underestimated the woody debris entrained downstream approximately 9.1%. Table 3 summarizes the simulated results for woody debris recruitment caused by the Typhoon Lionrock-induced landslide.

Conclusion

In this study, we developed a procedure to analyse the amount of woody debris that could be transported downstream. The proposed procedure can estimate the woody debris recruitment a watershed; however, we found that the procedure underestimates this amount compared to field-based measurements. Uncertainties with regard to input parameters such as soil parameters and tree density, may affect the estimated

results. Hence, increasing the accuracy of the procedure will require decreasing the uncertainties associated with the input parameters. However, our results demonstrated that the landslide or slope failures are a significant procedure of woody debris in the catchment area, which was confirmed by field surveys following the landslide.

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Disclosure statement

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ORCID

Thapthai Chaithong http://orcid.org/0000-0001-8989-8942

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