Prediction of debris flows in the Korean Oship River based on climate change scenarios

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ABSTRACT
The purpose of this study is to predict the behaviour of debris flow under climate change. The behaviour of debris flow on the slope and its mechanism is evaluated through numerical simulations using the climate change scenario Representative Concentration Pathways (RCP) 4.5 and RCP 8.5, and the developed numerical model is applied to the analysis of real areas. The results from the application of the numerical model based on climate change in this study to the Gangwon region in Korea indicated that the flow discharge and flow depth of debris flow increase drastically as the return period is longer, and the Future 2 case, a future target period, showed the largest peak value of the flow discharge of debris flow with a large value of wave amplitude on the distribution curve for the debris flow discharge. In the case of flow depth, even though the wave amplitude of flow depth slightly increased as the year increased, its distribution shared a similar tendency. The value of flow depth was high. It is expected that the results of this study will provide information necessary to predict damage due to debris flow in the climate-changing future, and to prevent damage to human life in coastal areas.

KEYWORDS
Climate change; behaviour of debris flow; finite difference method; disaster; peak flow discharge

1. Introduction
Recently, super typhoons due to climate change caused by global warming have been occurring frequently worldwide. Heavy rainfall caused by strong tropical depression has given rise to massive sediment transport in mountainous terrains with many slopes (Li et al. 2003; Chen et al. 2006). This type of sediment transport is called debris flow, which contains various types of mud, sand, and rocks, and disasters caused by debris flow have been increasing by urbanization, reckless development in mountain terrains, etc. (Chen et al. 2006). In particular, damage due to debris flow is significant in countries such as Korea, where a large part of the country is mountainous, and dry and rainy seasons are distinctive.

To prevent or reduce these disasters, sediment transport needs to be controlled by structures, or forecasting systems in accordance with local features are required. In addition, to improve the safety of an area, hazardous map by sediments is required. For such measures to be effective, numerical simulation software regarding debris flow based on the prediction of climate change in the future will be very important.

For the prediction scenarios of climate change, Kim et al. (2008) analyzed the variation and distribution of extreme rainfall events in accordance with climate change using the SRES B2 scenario.
Furthermore, to analyze the effects of climate change on hydraulic structures, Kim et al. (2011) proposed an estimation method for probable rainfall suitable for each area by estimating the amounts of local probable rainfall and then comparing these with the variation rates of previously observed rainfall. To estimate design rainfall with climate change taken into consideration, Seo et al. (2012) proposed an estimation method for ensemble probable rainfall by connecting annual rainfall time series of the GCM, observed annual maximum rainfall time series, and population parameters of probability distribution function through a regression model. To evaluate the effects of climate change on drainage systems, Kim and Ha (2013) estimated design rainfall by applying the nonstationary frequency analysis technique using the representative concentration pathways (RCP) 8.5 scenario. To evaluate the variation of extreme rainfall due to climate change in the future, Mailhot et al. (2007) proposed I–D–F curves for different durations by applying local frequency analyses.

Various models for the numerical approach to debris flow have been proposed and developed, and they can be in general classified into Newton, Bingham, Herschel–Bulkley, dilatant, dispersive stress, and frictional model (Wang et al. 2008). Takahashi and Tsujimoto (1984) developed a two-dimensional finite difference method (FDM) based on the fluid expansion model, and Egashira et al. (1997) proposed a Newtonian model with regard to the flow of sediment-water mixtures. McDougall et al. (2003) developed a depth-averaged model to simulate slope failures, and Calligaris et al. (2008) simulated the debris flow in the Italian Alps using a numerical computer program. Martinez et al. (2008) analyzed debris flow using the Non-Newtonian Bingham model with the shallow water wave equation and compared these results with the ones obtained by the finite element method. Nakataini et al. (2008) developed a computer program that can consider check dams with the one-dimensional depth-averaged model using the erosion/deposition model developed by Takahashi et al. (1992), and applied it to Cipanas, Indonesia. Armanini et al. (2009) obtained a two-dimensional Godunogo-type solution for a partial differential equation for small-scale mountainous catchments with possible erosion, set the spatial model using the finite volume method, and examined if it would be available for disaster prediction on a disaster map.

Even though various numerical analysis have been studied with regard to debris flow as above, the prediction of debris flow at a time in the future through the forecasting of future climate has not been studied at all. In this study, the amounts of probable rainfall were estimated using the RCP scenario from the new greenhouse gas scenario by Intergovernmental Panel on Climate Change (IPCC), a well-known climate change scenario. With these results, the behaviour of debris flow at present and in the future was investigated by applying the erosion/deposition model developed by Egashira et al. (1997) to the FDM. The Oship River basin located at the eastern coast of Gangwon Province, South Korea was studied, and the sediment discharge was investigated.

### 2. Theoretical backgrounds

#### 2.1. Climate change scenario data

To predict extreme rainfall in Korea in the future, the local climate change scenario data of the RCP 8.5, produced at HadGEM3-RA with 12.5 km resolution, were bi-linearly interpolated to the locations of the weather stations (Figure 1). To study the future variation of climate (2011–2040) in contrast to climate at present (1980–2005), the RCP 8.5 and 4.5 data were used. As no policy to reduce greenhouse gases is assumed in the RCP 8.5, it is a discharge scenario in contrast to A2–A1FI of the SRES.

#### 2.2. Conditional GEV distribution and nonstationary frequency analysis

The stationary frequency analysis technique is the most common until now, and it generally presents extreme rainfall through the Generalized Extreme Value (GEV) probability distribution (Coles 2001). The accumulated density function of the GEV probability distribution is shown in
Equation (1), and the extreme rainfall for a recurrence interval ($T$) can be estimated as seen in Equation (2):

$$F(z) = \exp\left\{-\left[1 + \xi\left(\frac{z - \mu}{\sigma}\right)\right]^{-1/\xi}\right\},$$

$$T = \frac{1}{1 - F(z)},$$

where $\mu$ is the location parameter, $\sigma$ is the scale parameter, and $\xi$ is the shape parameter. The recurrence interval is independent from time on the basis of stationarity, and this concept has been used to evaluate the service level of hydraulic structures. For example, a hundred-year recurrence interval means that a structure is designed in a way in which it can endure an event that can possibly occur once in a hundred years on average. However, on the basis of non-stationarity, the frequency of extreme rainfall varies and the recurrence interval is not a constant any more but a time-dependent variable. As mentioned in Section 1, as climate change will not follow the tendency of extreme rainfall in the past, the series of annual maximum will not conform to the assumption of stationarity anymore. Non-stationarity can be presented by simplifying the first moment, secondary moment, etc. of probability distribution in a way in which they are time-dependent. In this study, non-stationary frequency analyses were performed using the conditional GEV probability distribution, and they are presented as the form in Equation (3):

$$F(z, t) = \exp\left\{-\left[1 + \xi(t)\left(\frac{z - \mu(t)}{\sigma(t)}\right)\right]^{-1/\xi(t)}\right\},$$

where $\mu(t)$ is the location parameter dependent on time, $\sigma(t)$ is the scale parameter dependent on time, and $\xi(t)$ is the shape parameter dependent on time. In this study, an external variable was reflected using a linear model for each location parameter and scale parameter. The location parameter dependent on time $\mu(t)$ and the scale parameter dependent on time $\sigma(t)$ can be presented as follows:

$$\mu(t) = \mu_o + \mu_1 x(t),$$

$$\log\sigma(t) = \sigma_o + \sigma_1 x(t),$$

$$\xi(t) = \xi,$$
where \( x(t) \) is the external variable. The maximum temperature data in the past were used in this study.

### 2.3. Governing equation for debris flow

The purpose of this study is to examine the effects of climate change on debris flow, and the flow discharge and flow depth of debris flow on slopes in mountainous areas were investigated based on the climate change scenario of RCP. The governing equation for debris flow satisfies the mass and momentum conservation with erosion/deposition taken into account, and it can be presented as follows:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \nabla \cdot (\nabla \varphi h) &= B_v, \\
\frac{\partial (ch)}{\partial t} + \nabla \cdot (c \nabla \varphi h) &= C_c B_v, \\
\frac{\partial (\nabla \varphi h)}{\partial t} + \nabla \cdot (\nabla \varphi h) &= gh \left( \sin \theta - \cos \theta \cdot \frac{\partial h}{\partial x} \right) - \frac{\tau_b}{\rho_m}, \\
\frac{\partial \zeta_b}{\partial t} + B_v &= 0,
\end{align*}
\]

where \( h \) is the water depth and \( \varphi \) is the velocity potential; the flow velocity and flow discharge per unit width can be obtained with the water depth and velocity potential. \( B_v \) is the erosion velocity or deposition velocity, \( c \) is the sediment concentration in debris flow, \( C_c \) is the maximum sediment concentration in bed, \( g \) is the gravity acceleration, \( \theta \) is an angle between bed slope and water surface elevation, \( \rho \) is the water density, \( \rho_m \) is the mixture density of water and sediment \( (\rho_m = (\sigma - \rho)c + \rho) \), \( \sigma \) is the density of sediment particle, \( \tau_b \) is the bottom shear stress, \( \zeta_b \) is the deposition thickness in bed measured from the original bed surface elevation. In Equation (9), shear stress and pressure were presented by Equation (11) proposed by Egashira et al. (1997), and bottom shear stress can be calculated through the following equation:

\[
\tau = \tau_y + \tau_k + \tau_e,
\]

where \( \tau_y \) is the yield stress, \( \tau_k \) is the kinetic stress due to migration of particles in one layer to other layer, and \( \tau_e \) is the shear stress due to inter-particle collision, and they are presented as follows:

\[
\begin{align*}
\tau_y &= p_w \tan \Theta, \\
\tau_k &= \rho k_f d^2 (1 - c)^{5/3} / c^{2/3} (du / dz)^2, \\
\tau_e &= k_e \sigma (1 - e^2) d^2 c^{1/3} (du / dz)^2,
\end{align*}
\]

where \( d \) is the mean diameter of sediment, \( p_w \) is the hydrostatic pressure, \( \Theta \) is the internal friction angle of the sediment, \( e \) is the restitution of sediment particles, \( k_f \) and \( k_e \) are empirical constants of which the values are 0.16 and 0.0828, respectively. The equation for bottom shear stress can be derived by arranging Equations (11)–(14), and it can be presented as follows in Equations (15) and (16):

\[
\tau_b = (\sigma - \rho)c \left( \frac{1}{1.25} \right) gh \cos \theta \tan \Theta + \rho f v |v|,
\]

\[
f = \frac{25}{4} \left\{ k_f \frac{(1 - c)^{5/3}}{c^{2/3}} + k_e \frac{\sigma}{\rho}(1 - e^2) c^{1/3} \right\} \left( \frac{d}{h} \right)^2.
\]

Egashira et al. (1997) proposed an equation regarding erosion/deposition as follows:

\[
B_v = v \tan (\theta - \theta_e),
\]
where $\theta_e$ is the equilibrium slope with regard to sediment concentration in debris flow $c$ at each position; it is expressed as follows:

$$\tan \theta_e = \frac{(\sigma / \rho - 1)c}{(\sigma / \rho - 1)c + 1} \tan \varphi.$$  \hspace{1cm} (18)

In Equation (18), deposition occurs when $\theta > \theta_e$, erosion occurs when $\theta < \theta_e$, and neither of them occurs when $\theta = \theta_e$.

### 2.4. Numerical analysis

The purpose of this study is to predict debris flow at present and in the future on the basis of a climate change scenario, and the numerical model for the prediction of debris model used in this study.
Figure 3. (a) Sediment discharge in Oship River, South Korea, (b) topographic map of The Oship River in South Korea.
was the FDM. The FDM is suitable for the prediction of the behaviour of debris flow by time elapse, and the location level on the slope and time level can be presented with grids. Flow discharge and flow depth of debris flow by the elapse of time downstream or on slopes in mountain areas and can be analyzed in accordance with four types of time level. These four types of time level are time interval, flow supply period, numerical simulation period, and the time estimated after flow discharge reaches the downstream or a specific location (Kim and Lee 2015). Figure 2 shows the numerical calculation procedure to analyze the behaviour of debris flow. As seen in Figure 2, when interfaces had better input conditions, flow discharge ($q$) and flow velocity ($u$) were allocated on the grid line, and sediment volume concentration ($c$) and water depth ($h$) were allocated on the centre of a cell. In Figure 2, $I, I + 1,...$ mean the position level on a channel, and the distance between upstream and

![Figure 4](image_url)

*Figure 4.* (a) Annual maximum rainfall series in the past and at present (RCP8.5), (b) comparisons of stationary and non-stationary (RCP8.5).
Figure 5. (a) Stationary frequency analysis results using data in the past, (b–d) non-stationary frequency analysis results using the RCP8.5 scenario.

Figure 6. Distribution of flow discharge for about 300 s after debris flow reaches river mouth ((a) 30-year frequency, (b) 50-year frequency, (c) 80-year frequency, (d) 100-year frequency, (e) 200-year frequency).
downstream at a mountain river can be segmented at a constant interval. \( J, J + 1, \ldots \) mean the time variation (\( \Delta t \)) during the performance by the numerical model. With the numerical model used in this study, the behaviour of debris flow can be displayed in accordance with the variation of input values by time terms. In this study, there in as the level for time, the time of water supply discharge \( (t_1) \), computational execution time of numerical model \( (t_2) \), calculation time after debris flow reaches the downstream stage or a specific location \( (t_3) \), numerical model calculation time interval \( (t_4) \), set as \( t_1 = 490 \text{ s}, t_2 = 1470 \text{ s}, t_3 = 300 \text{ s}, t_4 = 5 \text{ s} \), respectively.

3. The selected study area

3.1. Target area and hydrometeorological data for the analysis of debris flow

In this study, the effects of climate change on design flood discharge were investigated with the Oship River basin in Gangwon Province, South Korea. The Oship River basin is located at the southern part of the eastern coast in Gangwon Province between 129°01’55” and 129°59’56” degrees eastern longitude and between 37°11’36” and 37°59’54” degrees northern latitude, with its river length 46.06 km and its area 350.16 km². Table 1 includes Past, Future 1, Future 2, and Future 3, and the behaviour of debris types for four types are presented in Section 4.
In this study, basic and governing equations concerning debris flow (Kim and Lee 2015) and the equations above proposed by Egshira et al. (1997) were applied, and the FDM as a numerical model was adopted to examine the effects of climate change. In addition, the evaluation results of flood discharge in the future by the RCP 8.5 scenario were set as the flood discharge supply for the calculation of debris flow to examine the effects of climate change. Applied to the Oship River basin, located at the eastern coast of Gangwon Province, South Korea was the numerical model in this study concerning the governing equation of debris flow in accordance with the climate change scenario. Most damage due to debris flow in South Korea resulted from heavy rainfall and occurred in Gangwon Province. Among them, a lot of debris flow occurred in 2002 and 2003 because of Typhoon Rusa and Maemi, respectively. Figure 3(a) shows soil outflow to the East Sea that connects to the Pacific Ocean, through the Oship River. The origin point for the simulation of debris flow at the Oship River was located at the river mouth, and the drainage area of the Oship River that can affect urban areas and the river mouth was 2.79 km² with its length 8 km. Figure 3(b) shows the topography of the drainage area of the Oship River. For the flow discharge from upstream as a calculation condition for debris flow, the peak flood predicted by the climate change scenario was determined for the frequencies of 30, 50, 80, 100, and 200 years, for the examination of the discharge of sediment and flow depth with regard to Current, Future 1, Future 2, and Future 3.

Figure 8. Distribution of flow depth for about 300 s after debris flow reaches river mouth ((a) 30-year frequency, (b) 50-year frequency, (c) 80-year frequency, (d) 100-year frequency, (e) 200-year frequency).
4. Results and discussion

4.1. Comparison between stationary and non-stationary frequency analyses

Figures 4 and 5 show the comparison between the stationary and non-stationary frequency analyses for each rainfall observatory in the Oship River basin. Overall, the results tended to increase more on the non-stationary frequency analysis than the stationary ones, particularly at higher frequencies.

4.2. Analysis of debris flow in accordance with the climate change scenario

The debris flow discharge and flow depth were analyzed for the return periods of 30, 50, 80, 100, and 200 years to predict the behaviour of debris flow in the future in accordance with the climate change scenario RCP 8.5. The conditions for performing the simulation calculations are as follows: the supply water discharge is calculated for the rainfall intensity and rainfall runoff and is based on the flood discharge shown in Figure 5. The predicted rainfall intensity for Typhoon Rusa was 98.2 mm/h. Suspended sediments exist at a depth of DP = 10 m, where sediments saturated with water stably exist. The mean diameter of the sediment is $d_m = 20$ cm, while the volume concentration of sediment in the static bed is $C_v = 52\%$. Meanwhile, the density of the sand particle is set as $\sigma = 2.65$ g/cm$^3$, and the internal friction angle of sand is expressed as $\tan\psi = 0.7$.

Figure 9. Peak flow depth of debris flow at river mouth ((a) 30-year frequency, (b) 50-year frequency, (c) 80-year frequency, (d) 100-year frequency, (e) 200-year frequency).
Figures 6 and 7 show the flow discharge of debris flow and flow depth at the river mouth of the Oship River for each target period in the future, and the longer the frequency period, the far more the flow discharge of debris flow and flow depth increased. As seen in Figure 6, in the case of Future 2 among the future target areas, the peak value of the flow discharge of debris flow was the largest, and the wave amplitude of the distribution curve of the flow discharge of debris flow was also large. This means that the energy of the flow discharge of debris flow was high with a large variability, which was likely to cause a lot of damage. In other words, debris flow with high energy would develop at a mountain upstream, pass through the downstream or be deposited with continuous erosion and deposition, which result in a lot of damage at the downstream. In the cases of Current and Future 2, the wave length of debris flow was short, which means that debris flow with high energy continued to reach the river mouth at early stages. Figure 7 shows the peak flow discharge for the future target periods at each frequency. As also seen in Figures 6 and 7, the longer the frequency year, the far more the peak flow discharge increased, and the largest peak flow discharge was 14,892.11 m$^3$/s in Future 2 at the 200-year frequency. As the value of the peak flow discharge was large at the 100-year frequency, which is the main design frequency year in designing hydraulic structures, damage is likely to occur at the Oship River basin and measures are required for its prevention.

![Figure](image.png)  
**Figure 10.** Distribution of flow discharge for about 300 s after debris flow reaches 6000 m point ((a) 30-year frequency, (b) 50-year frequency, (c) 80-year frequency, (d) 100-year frequency, (e) 200-year frequency).
Figure 8 shows the flow depth of debris flow at the river mouth. For the flow depth, as the period of frequency is longer, the magnitude of the wave length increased slightly, and its tendency showed a similar distribution. In the case of the flow depth, it decreased to a constant value as time went by in Future 1 and Future 3, and in Current and Future 2, the wave amplitude of the flow depth was large and the flow depth tended to be high at early stages. This means that damages occurred through a debris flow will be quite extensive because debris flow continues to flow during a short amount of time.

Figure 9 shows the peak flow depth for the future target periods at each frequency. Apart from the peak flow discharge, the value of the peak flow depth was overall large regardless of the frequency year, and the deviation was found to be small in the distribution of the peak flow depth for the target periods. The largest value of the peak flow depth was 18.4 m at the 200-year frequency in Future 2. This indicates that when debris flow occurs in this area, a check dam is likely to overturn or fail because a large peak flow depth will impact on the dam.

Figures 10 and 11 show the flow discharge and depth of debris flow at each frequency for the future target periods at the 6000 m point (Figure 5) at the Oship River basin. As seen in Figures 10 and 11, both the flow discharge and depth increased after 120 s. This trend increased as the frequency year increased, and the increase was the largest in Future 2 among the target periods.
4.3 Analysis of debris flow in accordance with the climate change scenario for each location and comparison of each scenario

The flow discharge and depth were analyzed for the analysis of debris flow at each location of the Oship River basin. Figure 12 shows the flow discharge and depth for the future target periods (Current, Future 1, and Future 2) at the Oship River basin. As seen in Figure 12, the peak flow discharge was the largest and the wave form width was short in Future 2. This indicates that debris flow with high energy continuously reaches at early stages. In addition, in the cases of Current and Future 2, the energy of debris flow seemed to decrease as time went by as the flow approached the river mouth, but it tended to increase again a few minutes later. In the case of the flow depth, the range of increase was larger than the flow discharge. This means that debris flow does not desist as time goes by but can resume even after a certain amount of time.

By comparing the RCP 8.5 and RCP 4.5 climate change scenarios, this study analyzed how much debris flow increases. To analyze the debris flow at each point, this study analyzed the discharge and flow depth of the debris flow at 100-year cycles, with the target period of Future 1 and Future 2 (see Figure 13). RCP 8.5 showed higher peak discharge and peak flow depth compared to RCP 4.5, along with a greater wave fluctuation. Comparing the peak discharge with Figure 14 shows an increase of

![Figure 12](image-url) Distribution of flow discharge at each location at 100-year frequency ((a) Current, (b) Future 1, (c) Future 2) and distribution of flow depth at each location at 100-year frequency ((d) Current, (e) Future 1, (f) Future 2).
23.3% for RCP 8.5 at Future 1 and a 22% increase for Future 2. RCP 8.5 also showed a greater increase at a peak flow depth of 10% for Future 1 and 7.3% for Future 2.

5. Conclusion

Recently, heavy rainfall events have been frequent due to climate change caused by global warming, resulting in debris flow at mountainous terrains with a lot of slopes, causing great damage of property and loss of life. As disasters due to debris flow are connected with heavy rainfall, it is important to predict the behaviour of debris flow in accordance with climate change scenarios. In this study, probable rainfall was estimated using a well-known climate change scenario RCP 8.5, and the behaviour of debris flow was investigated at present and in the future by applying the erosion/deposition model to the FDM. The Oship River basin, surrounded by mountain terrains, located at the eastern coast of Gangwon Province, South Korea was selected for the subject of this study.

The flow discharge, flow depth, peak flow discharge, and peak flow depth of debris flow were analyzed when the flow reached the river mouth, and the behaviour of debris flow was analyzed when the flow reached the middle point and for each location at a 100-year frequency.
The analysis of debris flow indicated that the longer the frequency year was, the far more the flow discharge and depth increased. Among the future target periods, the peak flow discharge was the largest with a large value of wave amplitude on the distribution curve for the debris flow discharge in Future 2. This means that the energy of the flow discharge of debris flow was high with a large variability, which was likely to cause a lot of damage. In the cases of Current and Future 2, the wave length of debris flow was short, which means that debris flow with high energy continued to reach the river mouth at early times.

In the case of flow depth, even though the wave amplitude of flow depth slightly increased as the frequency year increased, its distribution shared a similar tendency. As the flow depth is mostly high, damage can be quite extensive because debris flow continues to flow during a short amount of time. The peak flow depth was overall high without a large deviation. This indicates that when debris flow occurs in this area, as the value of the peak flow depth of debris flow is high, a check dam is likely to overturn or fail because a large peak flow depth will impact on the check dam, which controls debris flow. Comparing the climate change scenarios RCP 8.5 and RCP 4.5, it was found that RCP 8.5 showed higher discharge and flow depth of debris flow.

Therefore, measures are required for disasters due to debris flow based on the results of this study. Additionally, the effects of sediment outflow to the sea, caused by debris flow, on the environments of the sea need to be studied.

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