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A Study on the Application of Flash Flood Guidance with Predicting the Risk Level of Guerrilla Heavy Rainfall

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Synopsis

To alert flash flood warnings on the watersheds of the Toga River basin in Japan, flash flood guidance (FFG) was considered to determine the criteria for whether flash floods occur. FFG is the amount of precipitation needed in a specific period of time to initiate flooding on the watershed. FFG was estimated based on Threshold Runoff (TR) and Soil moisture Deficit (SD) using the Storm Water Management Model (SWMM). In this research, using topographic (i.e., DEM, land use, cross-section, etc.) and meteorological (i.e., radar rainfall intensity) data, FFG was estimated on the mixed land use consisting of the rural and urban areas. So, FFG can issue flash flood warnings without running the entire hydro-meteorological process in the region where flash floods frequently occur. As a result of the calculation of the flash flood guidance, the value at 10 minutes rainfall duration ranges from 9.97 to 23.89 mm when flash floods occur in the Toga River basin.

Keywords: Guerrilla heavy rainfall, Flash Flood Guidance, Rainfall-Runoff model

1. Introduction

Flash floods caused by heavy rainfall are recognized as one of the world's most costly and fatal natural disasters (Saharia et al., 2017). Especially, Guerrilla heavy rainfall (abbreviated as GHR) by isolated rapidly growing single cumulonimbus is one of the phenomena triggering flash floods. Flash floods often accompany other disasters such as landslides, bridge collapses, and casualties. The magnitude of flash floods depends on several natural and human factors, including the duration and intensity of precipitation, soil moisture, land use, soil, and watershed characteristics. For disaster prevention, it is necessary to detect the GHR earlier and issue a flash flooding alert in short duration to save evacuation time to escape from danger.

In the previous studies, Nakakita et al. (2017) found that vertical vortex tubes exist in the most developed heavy rainfall. Then, Kim and Nakakita (2021) developed a quantitative risk prediction method. This method can predict whether or not the early detected cells become high risk levels (i.e., heavy rainfall). Also, flash floods occur under complex conditions that integrate meteorological, geomorphological, and hydrological processes. So, Carpenter et al. (1999) also warned about an imminent flash flood by developing Flash Flood Guidance (FFG). The flash flood guidance is the amount of precipitation needed in a specific period of time to initiate flooding on a watershed. The flash flood guidance provides usefulness by simplifying the hydro-meteorological conditions of the watershed. In the Toga River basin, flash floods occur frequently, but few studies have been conducted on quantitative criteria for flash floods. Therefore, this research aims to apply the flash flood guidance and use it to alert flash flood events in Toga River, Kobe city.

2. Data and Study Area

Rainfall and soil moisture were the primary datasets to estimate the flash flood. Collecting reliable rainfall data is most important. To provide high spatiotemporal observation data throughout Japan, MLIT has been operating the X-band polarimetric RAdar Network (XRAIN) since 2010. Four radars (Rokko, Katsuragi, Jubusan, and Tanoguchi) were used in the Kinki region.

From 2012 to 2020, the four flash flood events were collected for calibration and verification of Storm Water Management Model (SWMM). The rainfall-runoff model can estimate soil moisture. It represents a hydrological cycle in watersheds based on geomorphology. So, a Digital Elevation Model (DEM) with 5m resolution was obtained from the Geospatial Information Authority of Japan. The land use and land cover map with 500m resolution was collected from Global Land Cover by National Mapping Organizations (GLCNMO) and Food and Agriculture Organization (FAO). Then, the channel cross-section was obtained from Hyogo prefecture to estimate effective rainfall on a small stream. Figure 1(a)-(c) shows the digital elevation model, land use, and impervious area in the Toga River basin.

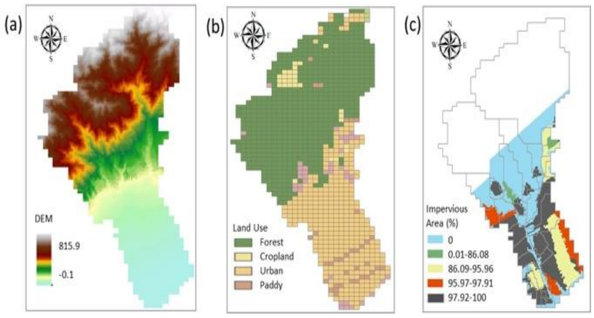

Fig. 1 Topographical data for threshold runoff and rainfall-runoff model; (a) is digital elevation model, (b) is land use, and (c) is impervious area in the Toga River basin.

3. Methodology

Figure 2 represents the procedure for estimating the flash flood guidance for flash flood warnings. To obtain flash flood guidance at a specific time, the estimation of Threshold Runoff (TR) and Soil moisture Deficit (SD) is needed as components of flash flood guidance. The threshold runoff was estimated using topographic data (i.e., digital elevation model, soil map, land use, etc.) and watershed and river characteristic factors (i.e., area of the watershed, river width, river slope, etc.). Also, the soil moisture conditions were simulated by using a rainfall-runoff model.

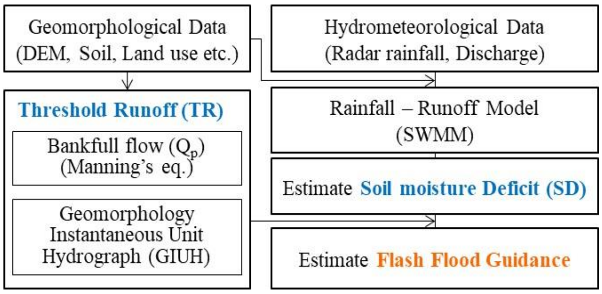

Fig. 2 Flowchart of Flash Flood Guidance (FFG) estimation.

3.1 Threshold Runoff (TR)

The threshold runoff represents the amount of effective rainfall accumulated during a given time t_r [hr] over a basin that is enough to cause flooding at the outlet of the draining stream. Effective rainfall is rainfall leading to direct runoff, excluding rainfall loss. Threshold runoff values are based on the flood flow Q_p [cms] unit hydrograph peak q_{pR} [cms/km^2/cm] and watershed area A [km^2]. The bankfull flow Q_{bf} [cms] is used as flood flow. The calculations of Q_{bf} and q_{pR} require the channel cross-section parameters. Direct measurements of channel cross-sections are performed through local surveys. The bankfull width B [m], hydraulic depth H [m], and local channel slope S_c [-] can be obtained from on-site measurements. Assuming that watersheds respond linearly to excess rainfall, threshold runoff can be estimated by equating the peak discharge determined from the unit hydrograph over a given duration to the bankfull discharge at the outlet. Mathematically, this is expressed as follows:

$$TR = Q_p/(q_{pR} \cdot A) \,, \qquad (1)$$

where Q_p [cms] is the flood flow, q_{pR} [cms/km^2/cm] is the unit hydrograph peak for a specific duration t_r [hr], A [km^2] is the watershed area, and TR [cm] is the threshold runoff.

Carpenter et al., 1999 presented the flood flow (Q_p) and the unit hydrograph peak (q_{pR}) to estimate threshold runoff. The flood flow Q_p was calculated as physically bankfull discharge Q_{bf} using Manning's equation. The bankfull discharge was computed from channel geometry and roughness characteristics for steady, uniform flow. However, most of the stream flows under the non-uniform flow. So, this research assumed the flow characteristic factors (velocity, water depth, pressure, etc.) are constant in the river section, where the cross-sectional shape and slope of the river do not change significantly in the longitudinal directions and are less affected by the upstream or downstream. Then, the flood can be calculated under uniform flow. Also, Henderson, 1966 proved that the resistance equation in turbulent flow and the Manning equation have mathematically the same characteristics. Therefore, the flow can be calculated by applying Manning's equation when the embankment begins to overflow.

To obtain the peak discharge, the unit hydrograph can be derived using the geomorphologic instantaneous unit hydrograph (GIUH) method (Rodríguez-Iturbe et al., 1979). An instantaneous unit hydrograph is a hydrograph that shows the flow to the watershed outlet when the unit effective rainfall falls to the watershed over time. The general unit hydrograph has the same duration as the duration of the effective rainfall. Still, the instantaneous unit hydrograph is a hypothetical concept in which the duration of the unit effective rainfall is close to zero. By combining the instantaneous unit hydrograph and the topographical characteristics, Rodriguez-Iturbe and Valdes, 1979 presented the GIUH method statistically by applying the travel times until the outlet of the watershed when the rainfall particles fall into the watershed. These methods have the advantage of accurately extracting geomorphological variables with the GIS and extracting parameters on a physical basis.

3.2 Soil moisture Deficit (SD)

The soil moisture deficit is the amount of soil moisture remaining after subtracting the current soil moisture from the maximum amount. Since the amount of soil moisture and insufficient soil saturation change over time under the influence of rainfall, continuous simulation should be possible. As a method, there are direct methods (i.e., lysimeter, neutron probe, Time domain reflectometry, etc.) and an indirect method simulated by a rainfall-runoff model.

In this research, the soil moisture was calculated using a rainfall-runoff model, SWMM. The runoff is estimated by a non-linear reservoir method, considering infiltration, depression loss, storage, and evaporation. SWMM has three methods to simulate infiltration from the surface-watershed to a sub-watershed: Green-Ampt infiltration, Horton infiltration, and Curve Number infiltration. In this research, the Green-Ampt infiltration method was used because this is physically based and easier to use for a single event and continuous simulation. Three parameters are important as the hydrologic components of the method: saturated hydraulic conductivity, initial moisture deficit, and suction head at the wetting front.

Then, the soil moisture deficit was calculated as follows,

$$TSAT = (FC - WP) \cdot Z \,, \qquad (2)$$

$$SD = TSAT - CSAT \,, \qquad (3)$$

where $TSAT$ [mm] is the soil moisture in the completely saturated state, FC is the field capacity, WP is the permanent wilting point, Z [mm] is the soil depth, $CSAT$ [mm] is the current soil moisture, and SD [mm] is the soil moisture deficit. The saturated soil moisture is that the outflow starts when the soil is completely saturated.

3.3 Flash Flood Guidance (FFG)

Flash flood guidance is the amount of rainfall needed in a specific period of time to initiate flooding on a small stream. Flash flood guidance and threshold runoff formed a non-linear relationship depending on the amount of moisture absorbed in the soil. If soil moisture is fully saturated and evapotranspiration does not occur, infiltration does not occur, and the flash flood guidance is the direct runoff. FFG is the same as the threshold runoff, which is the effective rainfall calculated assuming that the soil is saturated. In other words, threshold runoff calculated by GIUH and Manning's bankfull overflow has a constant value for a watershed unless the cross-section of the stream changes. However, since the moisture in the soil is not always completely saturated, rainfall that falls on the watershed causes loss due to infiltration and evaporation. So, flash flood guidance does not always correspond to direct runoff. Because flash floods occur when the overflows arise under the current soil moisture condition, direct runoff can occur when more rainfall equals the threshold runoff and insufficient current soil moisture. Therefore, flash flood guidance is calculated in a time series according to the soil moisture condition, and the threshold runoff has a constant value for the watershed.

Since flash floods are caused by localized heavy rainfall of short duration, soil moisture loss due to evapotranspiration rarely occurs. Therefore, flash flood guidance was calculated as the amount of rainfall required for the soil to become fully saturated. Also, flash flood guidance was calculated as the amount of rainfall required to bankull overflow, assuming that the soil is saturated. The formula determines the flash flood guidance:

$$FFG = SD + TR\,, \qquad (4)$$

where FFG [mm] is flash flood guidance, SD [mm] is soil moisture deficit, and TR [mm] is threshold runoff.

4. Result and Discussion

4.1 Estimation of Threshold Runoff (TR)

The digital elevation model can separate a basin, and the hydrological data (i.e., the watershed area, slope, etc.) can be extracted. This data calculated watershed characteristics parameters (i.e., the area of watersheds, slope, stream length). The data on the cross-section of the river is composed of natural and artificial cross-sections. The artificial cross-section considers the sewer system prepared for damage from floods in advance. So, it is not suitable for the definition of the threshold runoff. However, the mountainous watersheds in Rokko and Somatani Rivers affect the Toga River. The watershed in Rokko and Somatani River is composed of a natural stream. Also, the threshold runoff in the Toga River was estimated by applying the 50% of high water level. So, this research can calculate the threshold runoff in mountainous and urban areas.

The threshold runoff was calculated with Manning's equation and geomorphologic instantaneous unit hydrograph method using 10 minutes of rainfall observation data. The threshold runoff was reflected by watershed and channel characteristics parameters. As a result, the value of the threshold runoff on 10 minutes of rainfall observation data has the range of 4.05 to 19.48 mm, and the mean and standard deviation were calculated to be 13.43 mm and 6.34, respectively. Figure 3 shows the threshold runoff value for each watershed. The streams on 1 and 4 watersheds are small mountainous streams, so these have narrow streams and are highly affected by soil moisture. That is why the value of threshold runoff on 1 and 4 watersheds has a smaller value than the other watersheds.

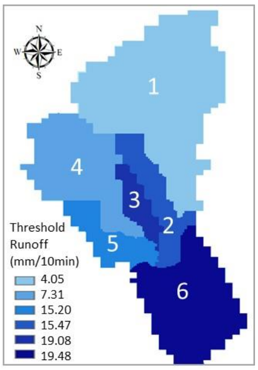

Fig. 3 Threshold Runoff (TR)

4.2 The soil moisture deficit on each watershed

The SWMM was constructed using radar rainfall as input data on the Toga River basin. The rainfall datasets were used to conduct event-based simulations to analyze the hydrological outputs, including infiltration and runoff. Detailed infrastructure characteristics were needed as input data in the SWMM, such as basins, pipes, maintenance holes, natural channels, pumps, etc. In this research, the SWMM contained 37 watersheds, 37 junction nodes, 16 links consisting of conduits, and an outlet. The Green-Ampt infiltration model, non-linear reservoir method, and kinematic wave approach were selected to compute the infiltration losses, overland flow, and routing of conduits flow, respectively. Figure 4 shows the division of watersheds and networks used to construct the SWMM. The Toga River basin is a mixed land use watershed where the rural and urban land uses affect the flood runoff analysis. In urban flooding, some sewage pipe networks and urban rivers are interconnected. To represent the accurate rainfall-runoff characteristics of urban areas, the SWMM integrates inland and river floods. In urban areas, the influence of soil moisture is low because of its high imperviousness. Leach and Coulibaly (2020) aim to identify the feasible imperviousness range to use soil moisture for improving hydrologic forecasting in an urban watershed. According to this research, soil moisture does not need to be considered in the impervious area of 65 - 75% or more. In this study, the effect of soil moisture was considered except for the watershed, where the impervious area was 79.7% in the urban area.

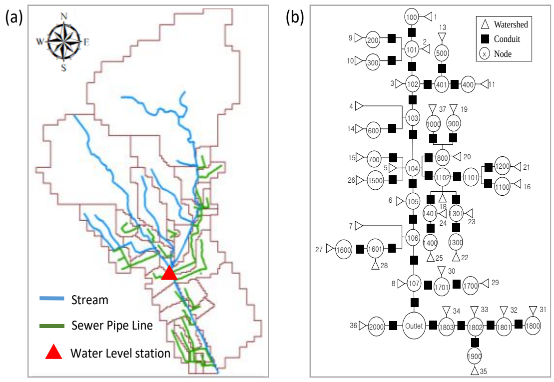

Fig. 4 Division of watersheds and networks used to construct the SWMM: (a) pipe line (green line) and stream line (blue line); (b) channel network in the Toga River basin.

The rainfall-runoff model is useful to simulate the effect of watershed processes and management on soil and water resources. Four flash flood events were selected to optimize the parameters of the SWMM. Figure 5 presents the calibration and verification results from two events each at the water level station (kabutobashi) using the radar rainfall data.

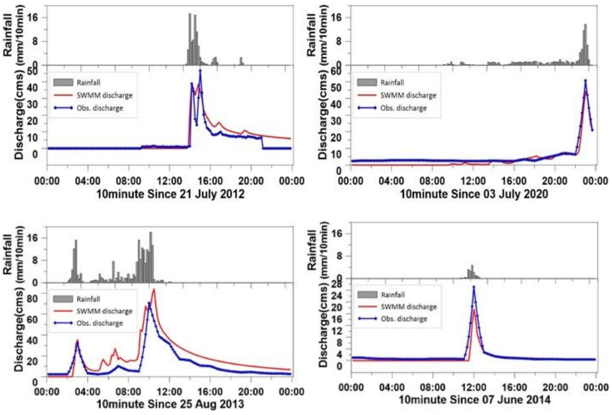

Fig. 5 Results of model simulation: (Upper) calibration results (21th July 2012 and 3rd July 2020), (Lower) verification results (25th August 2013 and 7th June 2014).

After the performance assessment of the SWMM was evaluated using three statistical indices: Nash Sutcliffe Efficiency (NSE), correlation coefficient (R), and RMSE (Root Mean Square Error), the soil moisture deficit was calculated for each flash flood event. The simulated soil moisture was applied to calculate the soil moisture deficit, which is insufficient for the soil to reach full saturation. Soil moisture was calculated for the 37 watersheds of the Toga River basin. Flash flood guidance is most affected by the watershed's topographical characteristics and the stream's cross-section. So, using the area-weighted average, the soil moisture value was calculated for six watersheds according to the threshold runoff.

4.3 Estimation and evaluation of Flash Flood Guidance (FFG)

The threshold runoff and soil moisture deficit were estimated to calculate the flash flood guidance on four flash flood events. The selected flash flood events are the cases that assumed flash floods have actually occurred. To evaluate the flash flood guidance, it was assumed that the actual flash flood happened when the water level exceeded or closed to half of the needs for observation designated by the water level observation station. This is because, based on the events reported by the media as flash floods, the watershed is small, and flash floods in the mainstream are uncommon. The time at which the rainfall on the watershed exceeded the flash flood guidance was judged as the occurrence of the flash flood. In Figure 6, the mean area precipitation of the watershed is indicated by a blue hyetograph and flash flood guidance by solid red lines as representative examples of flash floods with a duration of 10 minutes.

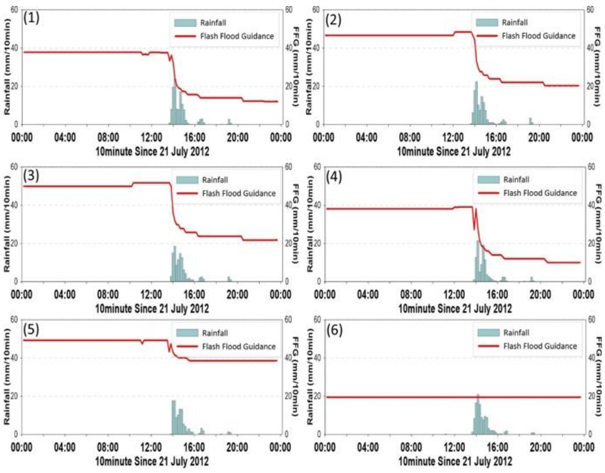

Fig. 6 Evaluation of Flash Flood guidance on the watersheds.

As a result of analyzing the collected flash flood events, the flash flood guidance of 1, 4, and 6 watersheds exceeded the mean area precipitation. In other flash flood events, it was confirmed that flash floods occurred in 1 and 4 watersheds. When the threshold runoff was estimated, the stream was divided into small mountainous streams and mainstreams, considering the channel characteristics of the Toga River basin. In the case of small streams in mountainous areas, the threshold runoff is calculated based on a 0.5 m rise in water level to prevent damage to campers and hikers in the valleys. On the other hand, an artificial embankment is constructed in the mainstream to avoid damage to the human life and property of users using the stream. The threshold runoff was calculated based on the mainstream's 50% high water level. The small mountainous streams 1 and 4 watersheds have narrow streams and are highly affected by soil moisture. This makes the watersheds vulnerable to flash floods. The flash flood guidance at 10 minutes rainfall duration on the watersheds ranges from 9.97 to 23.89 mm when the flash floods occur. The mean area precipitation exceeded the estimated flash flood guidance for the events assuming a flash flood occurred. This means that the estimated flash flood guidance was reliable and has appropriate flash flood guidance.

5. Conclusions

To minimize human injury such as isolation, death, and disappearance due to flash floods, this study proposed applying flash flood guidance to predict the risk level for the Toga River in Kobe, Japan. The FFG provides a criterion that can be used to determine whether a flash flood will occur intuitively. As the next step of this research, quantitative risk prediction (meteorology) and flash flood guidance (hydrology) will be combined. Flash floods happen when meteorological and hydrological circumstances coexist. Therefore, future research aims to bridge the gap between quantitative risk prediction and flash floods. If these methods are applied to the field, it is possible to secure enough time for disaster prevention and evacuation with high accuracy.

There are still many things to consider for warning about flash floods in real-time. To issue the flash flood warning practically in real-time, the quantitative risk prediction (meteorology) and flash flood guidance (hydrology) should be simulated at the same time. Unfortunately, this research cannot yet conduct the flash flood prediction in real-time by comprehensively considering meteorological and hydrological circumstances simultaneously. In further research, for combining the quantitative risk prediction (discretized results) and flash flood guidance (continuous results), the flash flood warning system should alert the danger by considering the ensemble of possible flash flood occurrences. Also, depending on the area of watersheds, it is necessary to estimate the concentration-time because it could affect the peak discharge.

However, this research is valuable in terms of developing the quantitative risk prediction method and establishing criteria for how much rain is dangerous in the Toga River basin. Suppose further research and analysis on various watersheds and rainfall periods are conducted. In that case, this research will propose the accuracy of guerrilla heavy rainfall prediction as useful information for flood forecasting and warning systems. It will be helpful to provide information about flash floods. In addition to representing the forecast uncertainty, a range of possible forecast outcomes will be produced to predict the risk in different events. The uncertainty could consider a broader range of variables by assuming meteorological and hydrological conditions. It is expected to contribute to the reduction of flash flood damage.

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