Analysis of extreme daily rainfall in southeast Asia with a gridded daily rainfall data set

KEISUKE ONO & SO KAZAMA

Department of. Civil Engineering, Tohoku University, Aoba 6-6-06, Sendai, Miyagi, 980-8579, Japan

ono@kaigan.civil.tohoku.ac.jp

Abstract The objective of this study is to estimate the daily extreme precipitation distribution in an Asian monsoon region considering orographic precipitation in mountainous areas. For this purpose, the APHRODITE data set and precipitation observations from 150 raingauges throughout Thailand were used as the main input. First, a bias-correction for underestimated precipitation in the APHRODITE data set was conducted based on the raingauge data. Secondly, a frequency analysis for estimating the extreme precipitation for different return periods was performed based on the bias-corrected APHRODITE data set and the raingauge data. For taking orographic precipitation effect into account, a regression relationship between the calculated extreme precipitation, elevation and latitude was developed using 150 raingauge data. Our results show that when orographic rainfall was incorporated, the extreme rainfall distribution was improved to show the characteristic of rainfall in mountainous areas.

Key words APHRODITE data set; extreme rainfall; slope failure; orographic rainfall

INTRODUCTION

The latest report from the Intergovernmental Panel on Climate Change (IPCC AR4, Parry *et al.*, 2007), along with many other studies, predicts increases in the frequency and intensity of heavy rainfall under enhanced greenhouse conditions. Those heavier rainfalls will likely increase the number of natural disasters, e.g. flash floods and slope failures (Jakob & Lambert, 2009). At the same time, social and economic activities are expanding to hilly areas, leading to a higher potential for heavy-rainfall-attributed disasters. Especially in developing countries in southeast Asia, the mitigation of slope failure hazards has not been well-developed and they are easily affected by the slope failure hazards (Tanavud, 2008).

In the past Thailand has experienced many slope failure events, causing substantial damage in many regions. Most of these slope failures have been triggered by heavy rainfall. However, only a little effort has been made to assess or predict these events which caused serious damages. Through scientific analyses of these slope failures, one can assess and predict slope-failure-susceptible areas, and thus reduce slope failure damage through proper preparation and/or mitigation. Therefore, understanding the slope failures and prevention of them is one of the important challenges, not only for Thailand but across the world.

There have been several studies on slope failure hazard mapping in southeastern Asia (Apiniti *et al.*, 2008). However, no study has considered extreme-rainfall-driven slope failures attributed to possible climate change in the future. Kawagoe *et al.* (2010) developed a probability model of slope failures considering daily rainfall, and produced a slope failure hazard map for several return periods in Japan. The Kawagoe *et al.* (2010) method can show the hazard with quantitative probability, which has a unique advantage compared with other past studies of qualitative slope failure hazard mapping.

Prediction of slope failure hazard due to heavy rainfall requires the temporal and spatial distribution of daily extreme rainfall. Developing countries in Asia often suffer from a lack of meteorological stations and quality data to produce reliable rainfall distribution data. Yatagai *et al.* (2009) developed a gridded precipitation data set in the APHRODITE Water Resources (Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) Project. That is the first rainfall data set produced to cover all of southeastern Asia with long-term daily rainfall data. This data set provides a unique advantage in regions lacking data for estimating the reliable distribution of rainfall. However, care should be taken when using the APHRODITE data set because the data set was generated by temporal-spatial interpolation based on rainfall data of raingauges and 20-km mesh MRI-AGCM (Atmospheric General Circulation Models from Meteorological Research Institute, Japan) (Nakaegawa, 2010). Moreover, due to its coarse resolution, the APHRODITE data should be downscaled to match with local precipitation patterns.

The objective of this study is to make a daily extreme rainfall distribution data set through combining the raingauge data and the latest gridded rainfall data. Validation of the distributed extreme rainfall has been done through comparison with extreme rainfall observations and past studies of rainfall in Thailand. Our final goal is to derive the distribution of slope failure hazard susceptibility using the extreme rainfall over southeastern Asia.

DATA SET

Gauged daily rainfall data

The daily rainfall data for 20 years (1987–2006) were used from 150 raingauges of the Thailand Meteorological Department (TMD). The raingauges were selected such that they do not include consecutive errors over one week.

Gridded daily rainfall data

The APHRODITE data set Ver.1003R1 for Monsoon Asia, which has 57 years data (1951–2007), was used to obtain gridded daily rainfall data. It covers the area 60.0°–150.0°E and 15.0°–60.0°N, and has a resolution of 0.25° × 0.25° (decimal degrees). Considering the data availability of the TMD gauges, the APHRODITE data from 1987 to 2006 were used.

Elevation data

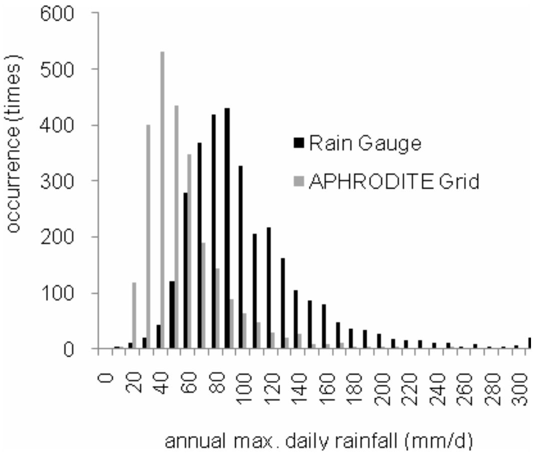
HYDRO1k from the US Geological Survey, which has a horizontal resolution of 1 km × 1 km and vertical resolution of 1 m, was used for elevation data. For the analysis in our study, this original grid of 1 km × 1 km was regridded to 0.05° × 0.05°.

METHODOLOGY

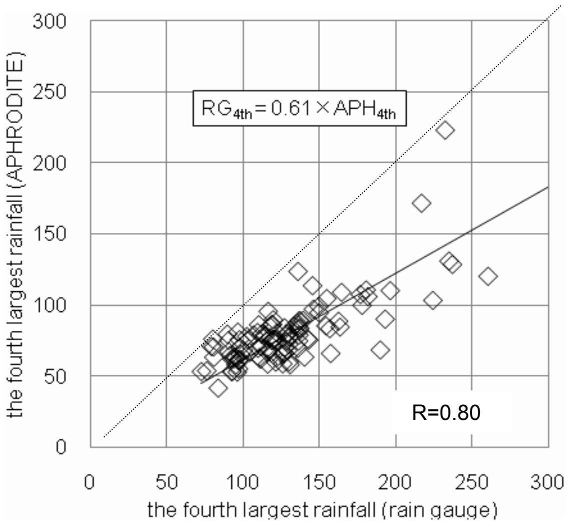
The working procedure for estimating the daily extreme rainfall for a return period in Thailand is as follows (we considered 5-year return period only): (a) the extraction of annual maximum daily rainfall for 20 years (1987–2006) from all of the TMD gauges and the APHRODITE grids, (b) the comparison of the annual maximum daily rainfall between the APHRODITE grids and the raingauges, and bias-correction based on the comparison, and (c) a frequency analysis based on the bias-corrected APHRODITE data to estimate the extreme daily rainfall of 5-year return period.

Comparison of annual maximum daily rainfall

Raingauges provide local rainfall data, while the APHRODITE data set is interpolated rainfall observation data. Therefore, the APHRODITE data set gives spatially-averaged rainfall values. To reveal the effect of the averaging in the APHRODITE data set, annual maximum daily rainfall in the APHRODITE data set and the raingauges were compared in each grid cell. When there are more than two raingauges in one APHRODITE grid cell, their maximum values were averaged for the comparison. The histogram of the annual maximum daily rainfall is shown (Fig. 1(a). In Fig. 1(a), the APHRODITE grids underestimated the mean rainfall amount by about 34% compared to raingauges (mean rainfall value is 101.7mm/d for the raingauge data set and 67.1mm/d for the APHRODITE data set). The fourth largest daily rainfall over the 20 years was selected as a parameter of the extreme rainfall of 5-year return period. The fourth largest value in 20 years is a representative value of 5-year return period, because the rainfall happens four times (or every 5 years) in 20 years on average. To prove that these underestimations happened equally



(a)



(b)

Fig. 1 (a) The histogram of annual maximum daily rainfall in the APHRODITE data set and in the raingauge data set. (b) Comparison of the fourth largest rainfall over 20 years (1987–2006) in the APHRODITE data set and the raingauge dataset (APH_{4th}: the fourth largest rainfall in the APHRODITE dataset, RG_{4th}: the fourth largest rainfall in the raingauge data set).

in every grid, the fourth largest values in the raingauge and the APHRODITE data sets were compared. In Fig. 1(b), most of the plots are near the regression line, showing the underestimated ratio occurs equally among all the grids with a correlation coefficient of 0.80. According to Yatagai *et al.* (2009), gridded rainfall data amounts are generally smaller than local rainfall observations because of the temporal-spatial interpolation. The base data of the APHRODITE data set had a resolution of 0.05° × 0.05°, but has been regridded to 0.25° × 0.25° in the data publishing process. Therefore, upscaling of the APHRODITE data set may have been the reason for underestimation of extreme rainfall in the APHRODITE data and TMD raingauges.

Bias-correction of annual maximum daily rainfall

According to Fig. 1(a), the annual maximum daily rainfall in the APHRODITE data set was 34% underestimated when compared to the mean value of the raingauge data set. Therefore, a bias-correction was performed based on:

$$ExP_{adj} = [(100\%)/(100\% - 34\%)] \times ExP \qquad (1)$$

where ExP is the annual maximum daily rainfall in APHRODITE data set (mm/d), and ExP_{adj} is the bias-corrected APHRODITE data set (mm/d).

Frequency analysis to estimate extreme daily rainfall

The final objective of our study is to derive a distribution of slope failure hazard susceptibility in southeastern Asia. For the hazard mapping, the return period of extreme rainfall is needed. Kawagoe *et al.* (2010) estimated extreme rainfall for different return periods in Japan by using a frequency analysis based on 24-hour rainfall data for 20 years (1980–2000). They considered the General Extreme Value (GEV) probability distribution function and the Probability Weighted Moment (PWM) method for universal prediction method. Then, using the extreme daily rainfall as a hydraulic input, the distribution of slope failure hazard susceptibility was assessed for the whole of Japan. Following a similar procedure for making a slope failure hazard map in southeastern Asia, a frequency analysis of the bias-corrected APHRODITE data set for each grid cell was performed. For validation, the same frequency analysis was done for the raingauge data. GEV is commonly used for estimating the return period of the extreme rainfall and flood event. An explanation of GEV analysis and PWM for parameter calibration can be found in Kawagoe *et al*. (2010).

RESULTS AND DISCUSSION

Estimated extreme daily rainfall of 5-year return period

The estimated extreme daily rainfall of 5-year return period and the corresponding SLSC (Standard Least-Squares Criterion) value in the frequency analysis are shown in Fig. 2(a) and (b), respectively. In general, fitting of a probability distribution function is adequate when the value of SLSC is less than 0.04 (Takara, 1988). In the frequency analysis of the APHRODITE data in each grid cell, the grids with an SLSC value between 0 and 0.04, 0.04 and 0.06, and over 0.06 were 62%, 31% and 7%, respectively. The extreme daily rainfall of the 5-year return period derived from the raingauge data and the bias-corrected APHRODITE data were compared in Fig. 2(c). Comparing Fig. 2(c) with Fig. 1(b), the plots are nearer the one-to-one line in Fig. 2(c), showing the effect of the bias correction. This means that the extreme rainfall of 5-year return period from the bias-corrected APHRODITE data set was almost equal to that from actual raingauge observations. With the problem of the calculated SLSC value in mind, this result is useful for us to estimate the extreme daily rainfall based on the APHRODITE data set. The results of the extreme rainfall in Fig. 2(a) were as follows:

(a) The largest amount of rainfall was found in low-latitude areas of the Malay Peninsula, a reflection of the circulation of water vapour being more active in low-latitude areas because of higher temperature, resulting in more rainfall. For example, the extreme rainfall in Malay Peninsula is over 160 mm/d, while the value in the central fan around Bangkok is only about 100 mm/d.

(b) A reliable distribution of extreme rainfall was estimated even near the borders of neighbouring countries by using the global gridded rainfall data set. For example, there are large values around the Laos border because of the wet monsoon wind flowing from Vietnam. The APHRODITE data set was developed based on the combined international raingauge data set. Therefore, it can help to make a global rainfall distribution.

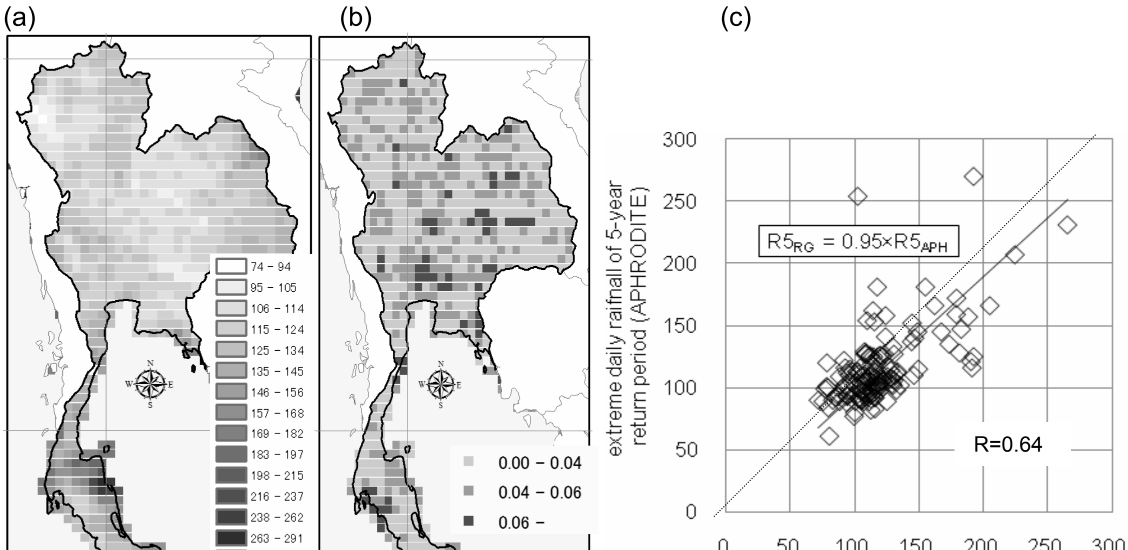


Fig. 2 (a) The distribution of extreme daily rainfall of 5-year return period (mm/d). (b) The SLSC value in the frequency analysis. (c) The comparison of the extreme daily rainfall of 5-year return period based on the APHRODITE data ($R5_{APH}$) and the raingauged rainfall ($R5_{RG}$).

(c) Even though it is known that there is orographic rainfall in Thailand (Dairaku *et al*., 2004), evidence of significant orographic rainfall around mountainous regions was not found. Because of the coarse resolution, the APHRODITE data set does not properly reflect the orographic rainfall in mountainous regions. For example, other research revealed that the extreme daily rainfall in the northern mountains is often over 200 mm/d, but Fig. 2(a) depicts a value of only about 120 mm/d.

For developing a distribution of slope failure hazard susceptibility, orographic rainfall is important. Therefore, in the next section, we developed a methodology to account for the orographic rainfall in the estimation of extreme rainfall distribution.

Incorporating orographic rainfall

Dairaku *et al.* (2004) found a relationship between downpour events and geography based on ground-based raingauge data in Thailand. Kuraji *et al.* (2004) also presented a study of orographic rainfall in Indochina Peninsula. According to Fig. 2(a), the orographic rainfall effect is not properly expressed in mountainous areas. Therefore, a methodology was developed to account for the effect of orographic rainfall in Thailand. At the same time, downscaling was done as follows, by using the elevation data, which has a finer resolution of 0.05° × 0.05°. First, a regression analysis was performed assuming that extreme rainfall in Thailand depends on latitude and elevation. As a result, the extreme rainfall of 5-year return period was expressed by:

$$R = \beta_{Ele} \times Ele + \beta_{Lat} \times Lat + b \qquad (2)$$

where R is the extreme daily rainfall of 5-year return period (mm/d), Ele is the elevation (m), Lat is the latitude (decimal degree), β_{Ele} is the coefficient of elevation, β_{Lat} is the coefficient of latitude, and b is the intercept. The regression coefficients are shown in Table 1. Therefore, the extreme daily rainfall of 5-year return period in Thailand can be explained with latitude and elevation, even though there are various parameters which can relate to rainfall event.

Table 1 The result of regression analysis.

Return period	Item	Elevation	Latitude	Intercept
5 years	Coefficient	0.051	–5.57	195
	p value	0.004	0.000	
	Standardized coefficient	0.251	–0.646	

As mentioned, Fig. 2(a) did not reflect the orographic rainfall. Therefore, a new parameter α was defined to incorporate this orographic effect in the distribution of extreme rainfall of 5-year return period:

$$\alpha = (\beta_{Ele} \times Ele + \beta_{Lat} \times Lat + b)/(\beta_{Lat} \times Lat + b) \qquad (3)$$

where α denotes the ratio of the orographic rainfall in the extreme daily rainfall of 5-year return period in Thailand. In other words, this can explain the magnitude of orographic effect in each area. The parameter α was calculated using the elevation data with the resolution of 0.05° × 0.05° as an input for downscaling. The distribution of the parameter α is shown in Fig. 3(a). The value of α is 1.0 where the orographic rainfall is negligible. The value of α in the northern mountains is over 1.75, reflecting significant orographic rainfall. Multiplying α by the extreme rainfall in Fig. 2(a), the distribution of extreme rainfall including orographic effect was estimated (Fig. 3(b)). In Fig. 3(b)), large amounts of extreme rainfall attributed to orographic rainfall were found in several high elevation areas, i.e. in the Malay Peninsula and in the northern part of Thailand. In the future, it will be important to validate these estimates by using additional raingauges or radar observations in mountainous regions. The result for orographic rainfall was compared with past rainfall research in Thailand. According to Dairaku *et al.* (2004), in the Mae Chaem area, observed rainfall in mountain ranges was approximately two-times the rainfall in the plain area due to the longer

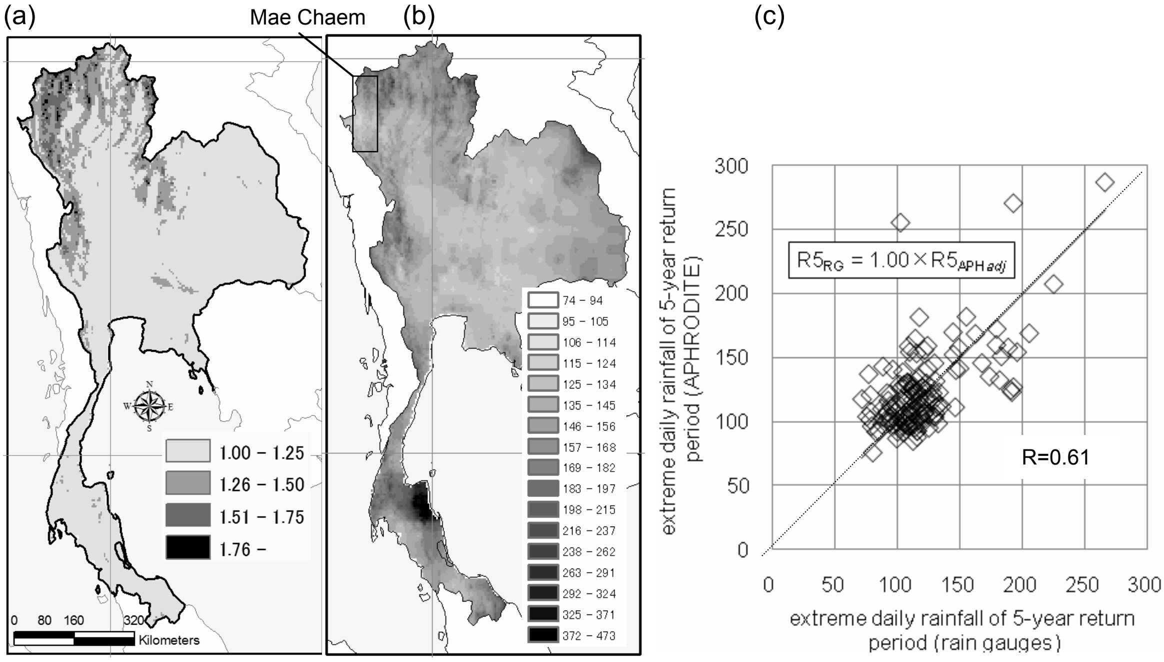


Fig. 3 (a) The distribution of *α*. (b) The estimated distribution of extreme daily rainfall of 5-year return period including the orographic rainfall (mm/d). (c) Comparison of the extreme daily rainfall of 5-year return period in the APHRODITE data including the orographic rainfall ($R5_{APHadj}$) and the gauged rainfall ($R5_{RG}$).

duration of rainfall. At Mae Chaem area in Fig. 3(b), the extreme daily rainfall in low-elevation areas and in mountain ranges is about 80 mm/d and 160 mm/d, respectively, thus confirming the consistency of our result with Dairaku *et al.* (2004) estimates. For validation, the extreme daily rainfall of 5-year return period from the APHRODITE data set (Fig. 3(b)) and the value estimated from the raingauges were compared (Fig. 3(c)). Upon incorporation of the orographic rainfall, the slope changed from 0.95 (Fig. 2(c)) to 1.00 (Fig. 3(c)). This proved that the extreme 5-year return period rainfall from the APHRODITE data set has better represented that from actual observations of the raingauges.

CONCLUSION AND REMARKS

We developed an extreme daily rainfall distribution in Thailand combining raingauge data and the latest gridded rainfall data, called the APHRODITE data set. Using the APHRODITE data set, the extreme rainfall was estimated even in areas lacking gauge data. As an example, large rainfall due to monsoon rain from Vietnam was estimated around the border between Thailand and Laos. To account for orographic rainfall in the estimated extreme rainfall, a new parameter *α* was defined and employed in our analysis. As a result, the estimated extreme daily rainfall in the mountainous areas in Malay Peninsula was over 300 mm/d, while, the value in the northern mountainous areas was over 200 mm/d. Validation of the distributed extreme rainfall has been done by comparison with extreme rainfall observations and past studies of rainfall in Thailand. Even though further validation with additional observations is needed, this study is useful to estimate extreme rainfall with the APHRODITE data set.

Acknowledgement This research was supported by the Environment Research and Technology Development Fund (S-8) of the Ministry of the Environment, Japan. This research was carried out by the IMPAC-T project supported by JST/JICA, SATREPS (Science and Technology Research

Partnership for Sustainable Development), Japan. We wish to thank Dr Chaiwat Ekkawatpanit in King Mongkut's University of Technology in Thailand for his helpful support.

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