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Prediction of extreme floods and risk curve development under a changing climate

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Abstract To estimate probabilistic characteristics of extreme floods and to predict the magnitude of largest-class floods under a changing climate are key issues for impact assessment studies on water resources. In this research, a non-stationary hydrologic frequency analysis was introduced to future extreme rainfall GCM outputs to evaluate the change of extreme rainfall and flood characteristics. Then, a physically-based method to estimate a probable largest-class flood was shown. Finally, a probabilistic method to evaluate economical loss due to flood inundation was proposed to assess adaptation measures to cope with flood disasters.

Keywords *Climate change; non-stationary hydrologic frequency analysis; largest-class flood; flood risk curve*

Introduction

To estimate probabilistic characteristics of extreme floods and magnitudes of largest-class floods under a changing climate is a key issue for building up an adaptation strategy. To evaluate the change of extreme rainfall and flood characteristics, a non-stationary hydrologic frequency analysis was applied to future extreme rainfall outputs projected by MRI-AGCM 3.2S, 20km resolution atmospheric general circulation model developed by Metrology Research Institute in Japan (Mizuta *et al*., 2012). The results showed that the magnitudes of the annual maximum short-term rainfall increase for the near future in most parts of Japan and this tendency was intensified in the end of the 21st century (Hayashi *et al*., 2014).

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As well as a non-stationary hydrologic frequency analysis, the magnitudes of largest-class floods caused by typhoons under a changing climate scenario were examined by using numerical typhoon simulation outputs. The rainfall data used for the flood simulation was developed by a physically-based course ensemble typhoon experiment for the Ise Bay Typhoon in 1959 under a pseudo global warming condition (Takemi *et al.*, 2013). The simulated rainfall data was given to a distributed rainfall-runoff model considering flood regulation with dam reservoir operations and flood control basins. It was revealed that the largest flood discharge at the Hirakata station, located at the upper part of the Osaka City area happened at the flood simulation using the typhoon course closest to the best track of the Ise-Bay Typhoon, which means the actual Ise Bay Typhoon course was the worst course for flood disaster in the Osaka area; the peak discharge in the pseudo global warming experiment showed 10% increase than the control experiment.

Finally, a method to construct a flood risk curve, a relation between the annual maximum damage due to flood inundation and its exceedance probability, was developed for a probabilistic assessment of economic loss by flood disasters (Tanaka *et al*., 2015, 2016; Tanaka, 2016). The flood risk curve was obtained by integrating the exceedance probability of the annual maximum rainfall that causes a given inundation damage for all historical spatio-temporal rainfall patterns. A flood risk curve was constructed in the Yodo River basin using the latest climate change projection database, d4PDF, the database for Policy Decision making for Future climate change (Mizuta *et al*., 2016).

Non-stationary hydrologic frequency analysis

Non-stationary hydrologic frequency models with time dependent parameters (Coles, 2001) were introduced to assess the change of probabilistic characteristics of extreme rainfall (Hayashi *et al*., 2014). The non-stationary hydrologic frequency models used here were a non-stationary GEV model, a non-stationary Gumbel model, a non-stationary SQRT-ET model, and a non-stationary lognormal model. A cumulative distribution function (CDF) and a probabilistic distribution function (PDF) for these models are represented as below:

1) CDF of the non-stationary GEV model

$$F(x_{t_i}|\boldsymbol{\theta}) = \exp\left\{-\left[1+\xi\left(\frac{x_{t_i}-\mu(t_i)}{e^{\sigma(t_i)}}\right)\right]^{-1/\xi}\right\}$$

2) CDF of the non-stationary Gumbel model

$$F(x_{t_i}|\boldsymbol{\theta}) = \exp\left[-\exp\left(-\frac{x_{t_i}-\mu(t_i)}{e^{\sigma(t_i)}}\right)\right]$$

3) CDF of the non-stationary SQRT-ET model

$$F(x_{t_i}|\boldsymbol{\theta}) = \exp\left[-e^{a(t_i)}\left(1+\sqrt{e^{b(t_i)}x_{t_i}}\right) \times \exp\left(-\sqrt{e^{b(t_i)}x_{t_i}}\right)\right]$$

4) PDF of the non-stationary lognormal model

$$f(x_{t_i}|\boldsymbol{\theta}) = \frac{1}{\sqrt{2\pi}e^{\sigma(t_i)}x}\exp\left[-\frac{1}{2}\left(\frac{\log x-\mu(t_i)}{e^{\sigma(t_i)}}\right)^2\right]$$

The time dependent model parameters for each hydrologic frequency model are modeled using the polynomial equation as

$$\mu = \mu(t_i) = \sum_{k=0}^{p}\mu_k t_i^k, \ \sigma = \sigma(t_i) = \sum_{k=0}^{q}\sigma_k t_i^k$$

The coefficients of the polynomial equation were identified by using the maximum likelihood method. The best fitted model was selected using the Takeuchi information criterion TIC and the Akaike information criterion AIC, which were analytically confirmed for model selection criteria for non-stationary sequences.

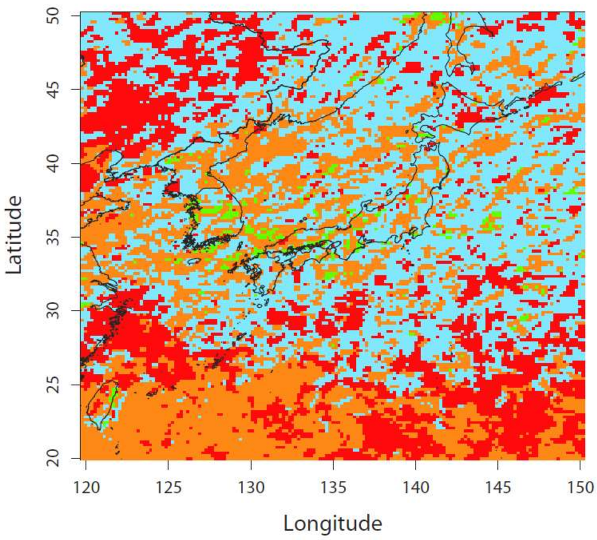

Fig. 1 The best fitted non-stationary frequency model for the annual maximum daily rainfall projected by MRI-AGCM3.2S with 20km spatial resolution. Red: non-stationary GEV model; Green: non-stationary Gumbel model; Right Blue: non-stationary SQRT-ET model; and Orange: non-stationary lognormal model.

The non-stationary four models were applied to GCM rainfall time series to examine the future change of extreme rainfall intensity. The GCM outputs used were the time series of annual maximum daily rainfall data having 20km spatial resolution for the present climate experiment (1979-2003), the near future climate experiment (2015-2044) and the end of the 21st century climate experiment (2075-2099) projected by MRI-AGCM3.2S (Mizuta *et al*., 2012).

Figure 1 shows the spatial distribution of the best fitted non-stationary frequency model evaluated by the AIC for the annual maximum daily rainfall of each grid having 20km resolution. Using the best fitted model, the change of the 100-year annual maximum daily rainfall was analyzed as shown in Figure 2.

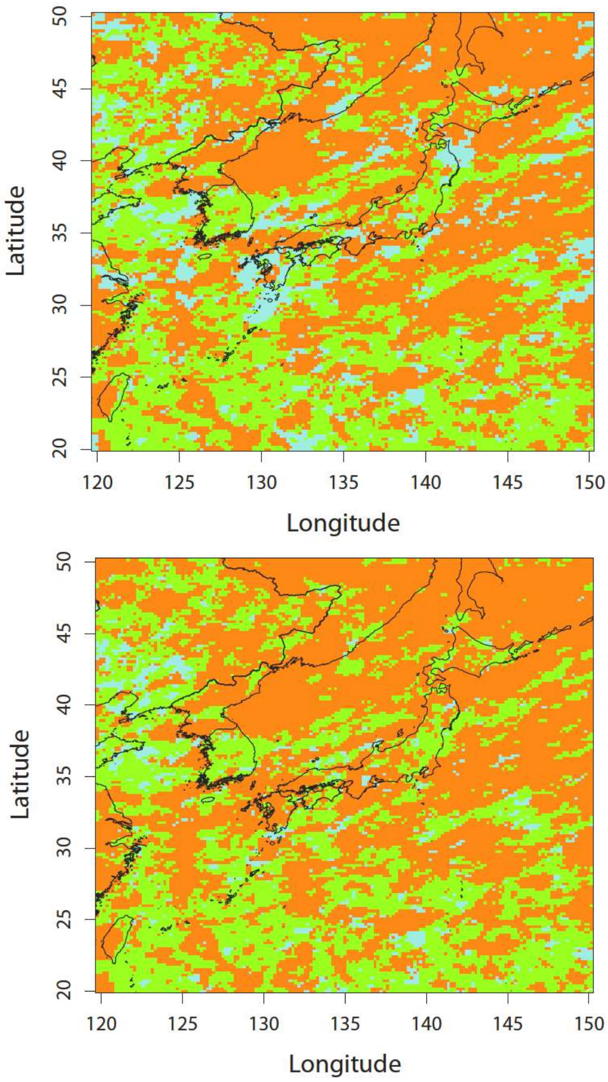

Fig. 2 Change of the 100-year annual maximum daily rainfall. Orange, green, and right blue show increase, no change, and decrease, respectively. The above figure shows the change between 2029 at the middle of the near future experiment and 1993 at the middle of the present climate experiment. The below shows the change between 2089 at the middle of the end of the 21st century climate experiment and 1993.

As shown in Figure 2, we found that the annual maximum daily rainfall around Japan shows an increase tendency and the increase tendency is intensified at the end of 21st century.

Largest-class flood prediction

A largest-class flood caused by a typhoon under a climate change condition at the Yodo River basin is examined by using rainfall data developed by a physically-based course ensemble typhoon experiment for the Isewan Typhoon in 1959 and a distributed rainfall-runoff model including flood regulation with dam reservoir operation (Tachikawa *et al*., 2014, Miyawaki *et al*., 2016).

Takemi *et al*. (2013) developed a heavy rainfall dataset based on an ensemble simulation of the historical extreme typhoon, the Ise-Bay Typhoon (1959) using a meso-scale meteorological model, the Weather Research Forecasting (WRF) model version 3.1.1. The ensemble simulation method realizes to generate different typhoon tracks perturbed from the original track of the typhoon by applying a potential vorticity inversion (PVI) method (Ishikawa *et al*., 2012). Figure 3 shows the typhoon tracks simulated by the PVI method for the Ise-Bay Typhoon in 1959. The ensemble simulation approach was also applied to the typhoon under a pseudo global warming condition by setting a different sea surface temperature. The difference of the sea surface temperature was given based on the difference of the monthly mean SST in September between the end 21st century climate experiment (2075-2099) and the present climate experiment (1979-2003) simulated by MRI-AGCM3.2 (Mizuta *et al*., 2012).

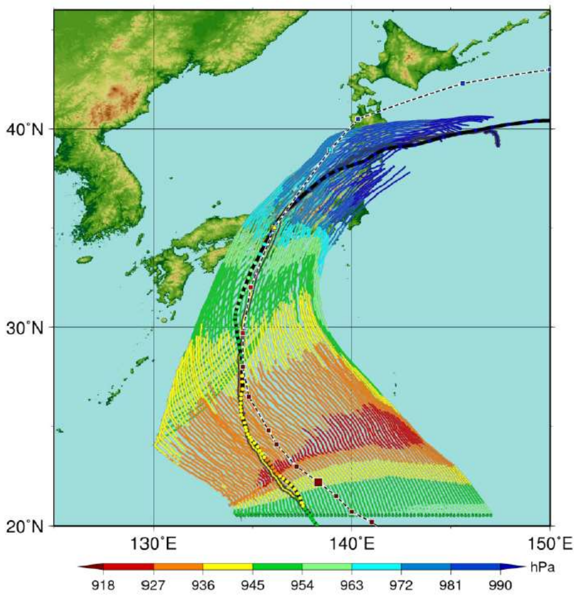

Fig. 3 Virtual shifting of typhoon's initial position for the Ise-Bay Typhoon in 1959 (Takemi *et al.*, 2013).

The simulated rainfall data was given to a distributed rainfall-runoff model with 1km spatial resolution, 1K-DHM (Tachikawa and Tanaka, 2014) developed for the Central and Kansai regions in Japan as shown in Figure 4. The simulated discharge for each typhoon track was stored with about 1km grid resolution.

Figure 5 shows the largest river discharge at the Hirakata station (7,281km^2) in the Yodo River basin for each typhoon track.

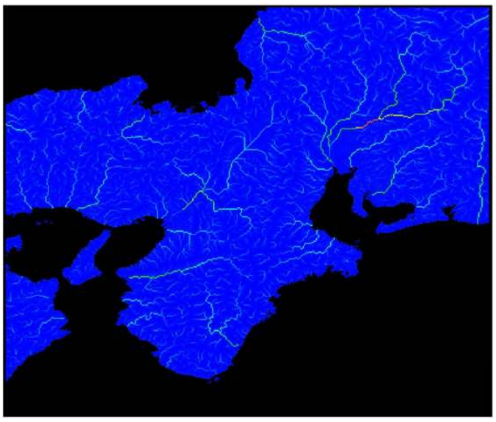

Fig. 4 Spatially distributed river flow for the Central and Kansai regions in Japan simulated by a distributed hydrologic model, 1K-DHM.

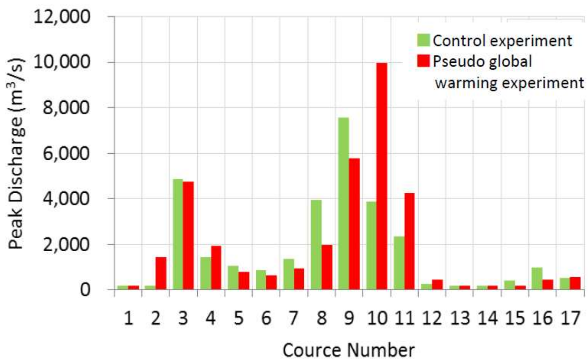

Fig. 5 The largest river discharge at the Hirakata station (7,281km^2) in the Yodo River basin for each typhoon track.

We found that the simulated typhoon track No. 9 which caused the largest river discharge at the Hirakata station was the closest track to the best track of the Isewan Typhoon in 1959, which means the Isewan typhoon took the worst course for the Yodo River basin; and the largest river discharge at the Hirakata station under a pseudo global warming condition showed about 10% increase. We also found that the peak flood discharge at the Typhoon 18 in 2013 was larger than the largest peak discharge estimated by the Isewan Typhoon course ensemble simulation under a pseudo global warming condition.

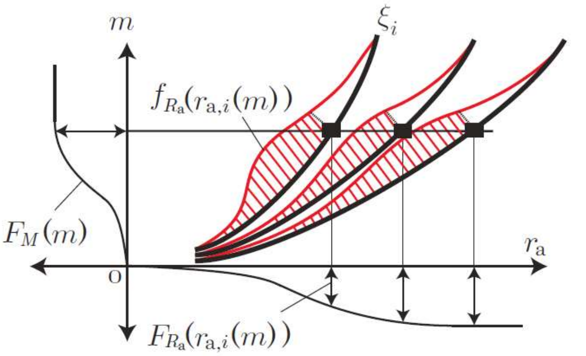

Fig. 6 Schematic explanation of the translation of a distribution function of the *D*-day annual maximum rainfall r_a to a distribution function of inundation damage *m* through various rainfall patterns (Tanaka *et al*., 2015).

Development of flood risk curve: probabilistic assessment of economic loss due to flood

To realize an integrated economic risk assessment by flood disasters, a flood risk curve plays an important role. A flood risk curve provides a relation between economic loss due to flood disaster and its exceedance probability. A method to obtain the flood risk curve considering the uncertainty of spatio-temporal rainfall distribution is newly proposed (Tanaka *et al*., 2015, 2016; Tanaka, 2016).

A flood risk curve is generated from a probability distribution function of the annual maximum rainfall distribution through the following processes (Figure 6): 1) to prepare typical extreme rainfall patterns ξ_i; 2) to obtain a probability distribution of the annual maximum rainfall $F_R(r_a)$ from the historical data; 3) to obtain relations between *T*-year annual maximum rainfall and the maximum inundation water depth through a rainfall-runoff and inundation simulation; and 4) the economic damage *m* is estimated for each maximum inundation depth caused by the *T*-year annual maximum rainfall r_a. These procedures are conducted for each typical extreme rainfall pattern. Finally, the relation between economic damage *m* and its exceedance probability $F_M(m)$ is obtained by integrating the exceedance probability of each inundation damage. This method requires many rainfall-runoff and inundation simulations, thus a nesting runoff-inundation simulation method to reduce computational costs was also developed.

The method was applied to the Yodo River basin in Japan (Figure 7). Rainfall-runoff simulation was applied to the entire Yodo River basin using a distributed hydrologic model 1K-DHM with about 1km spatial resolution. Then, inundation simulations were applied to the central part of the Yodo River basin which is the most vulnerable area for flood inundation. The estimated spatial distributions of inundation depth were used to calculate the economic loss due to inundation using a guideline to estimate the economic damage (MLIT, 2005).

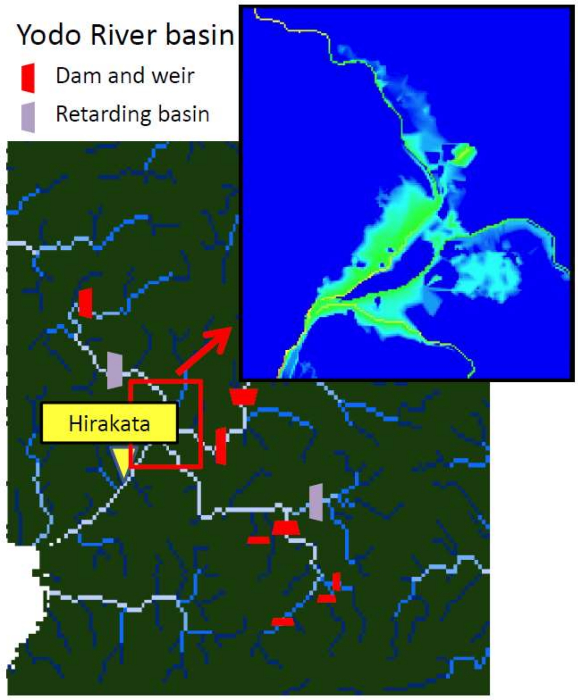

Fig. 7 Yodo River basin and an example of estimated inundation at the central part of the Yodo River basin.

To estimate the risk curve, the latest climate change projection data, d4PDF (database for Policy Decision making for Future climate change (Mizuta *et al*., 2016) was used. The d4PDF was simulated by using MRI-AGCM3.2H and 3.2S, which includes the historical experiment from 1951 to 2011 with 50 ensemble members which is equivalent to 3,000 years simulation. For the future experiment, d4PDF assumes the four degrees increase condition, which corresponds to the end of 21st century of the RCP8.5 scenario experiment. The future data consists of 15 ensemble experiments form 2051 to 2111 for six different SST patterns, which means 900 years simulation for each SST pattern.

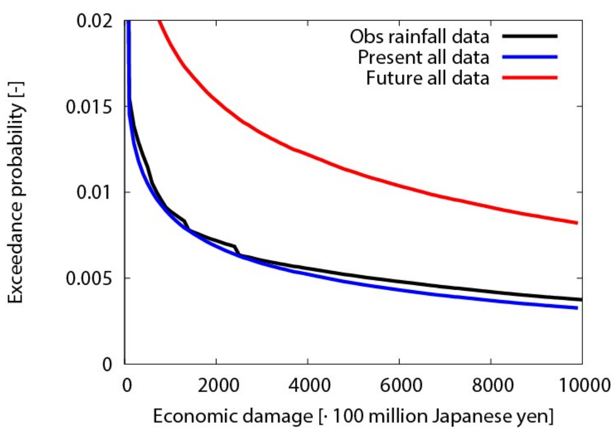

Fig. 8 Estimated flood risk curve at the Yodo River basin.

Figure 8 show a flood risk curve at the central part of the Yodo River basin derived using the observed rainfall data and d4PDF rainfall projection data. The flood risk curve estimated by using observed rainfall data well matched to the one using the d4PDF historical data set. Figure 8 clearly shows that the predicted economic loss due to flood inundation becomes larger at the end of the 21st century under the climate change scenario.

Summary and conclusions

In this study, characteristics of extreme rainfall under a climate change scenario was analyzed using a non-stationary hydrologic frequency analysis. It is found that the annual maximum daily rainfall around Japan shows an increase tendency and the increase tendency is intensified in the end of 21st century. Then, a largest-class flood was estimated using a rainfall-runoff simulation with the multi-track ensemble numerical typhoon simulation under a pseudo global warming condition. It is found that the Isewan typhoon took the worst course for the Yodo River basin and the largest river discharge under a pseudo global warming condition showed about 10% increase. Finally, a probabilistic method to evaluate economical loss due to flood inundation was demonstrated using the latest climate change projection data d4PDF.

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References

Coles, S. (2001) An introduction to statistical modeling of extreme values, Springer.

Hayashi, H., Tachikawa, Y. and Shiiba, M. (2015) Non-stationary hydrologic frequency analysis using time dependent parameters and its model selection, Journal of Japan Society of Civil Engineers, B1 (Hydraulic Eng.), 71(1), 28-42 (in Japanese).

Ishikawa, H., Oku, Y., Kim, S., Takemi, T. and Yoshino, J. (2013) Estimation of a possible maximum flood event in the Tone River basin, Japan caused by a tropical cyclone, Hydrological Processes, 27(23), 3292–3300.

Ministry of Land, Infrastructure, Transport and Tourism of Japan, Water and Disaster Management Bureau (2005) A guideline of economic survey for flood control (in Japanese).

Miyawaki, K., Tachikawa, Y., Tanaka, T., Ishii, D., Ichikawa, Y., Yorozu, K., Takemi, T. (2016) Flood runoff simulations in the yodo river basin assuming largest-class typhoons, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), 72(4), I_31-I_36 (in Japanese).

Mizuta, R., Yoshimura, H., Murakami, H., Matsueda, M., Endo, H., Ose, T., Kamiguchi, K., Hosaka, M., Sugi, M., Yukimoto, S., Kusunoki, S. and Kitoh, A. (2012) Climate simulations using MRI-AGCM3.2 with 20-km grid. J. Meteor. Soc. Japan, 90A, 233-258. doi:10.2151/jmsj.2012-A12.

Mizuta, R., Murata, M., Ishii, M., Shiogama, H., Hibino, K., Mori, M., Arakawa, O., Imada, Y., Yoshida, K., Aoyagi, T., Kawase, H., Mori, M., Okada, Y., Shimura, T., Nagatomo, T., Ikeda, M., Endo, H., Nosaka, M., Arai, M., Takahashi, C., Tanaka, K., Takemi, T., Tachikawa, Y., Temur, K., Kamae, Y., Watanabe, M., Sasaki, H., Kitoh, A., Takayabu, I., Nakakita, E., and Kimoto, M. (2016) Over 5000 years of ensemble future climate simulations by 60 km global and 20 km regional atmospheric models, Bulletin of the American Meteorological Society, BAMS-D-16-0099.

Tachikawa, Y., Ishii, D. and Yorozu, K. (2014) Probable maximum flood estimation by extreme typhoons under a changing climate, International Conference on Ecohydrology (ICE) in Conjunction with the 22nd Meeting of UNESCO IHP Regional Steering Committee (RSC) for South Asia and Pacific, Yogyakarta, Indonesia, 10-12, November 2014.

Tachikawa, Y. and Tanaka, T. (2014) 1K-FRM/DHM, A distributed river discharge simulation model based on kinematic wave theory using HydroSHED topography data, http://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K-DHM.htm.

Takemi, T, Ishikawa, T., Oku, Y. and Okada, Y (2013) Ensemble experiment for the Ise-Bay Typhoon, SOUSEI Program for Risk Information on Climate Change, Research Report, Heisei 24, 16-18 (in Japanese).

Tanaka, T., Tachikawa, Y. and Yorozu, K. (2015) A flood risk curve development for inundation disaster considering spatio-temporal rainfall distribution, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), 71(4), I_1483-I_1488 (in Japanese).

Tanaka, T., Tachikawa, Y., Ichikawa, Y., and Yorozu, K. (2016) A flood risk curve development using conditional probability distribution of rainfall on duration, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), 72(4), I_1219-I_1224 (in Japanese).

Tanaka, T. (2016) Development of a flood risk curve considering spatial-temporal rainfall variability and its application to actual river basins, Dissertation for Doctor of Engineering, Kyoto University, Japan.