Study on PMP estimation for the flood risk evaluation of hydropower dams in consideration of the future climate change

Étude sur l'estimation du PMP pour l'évaluation des risques d'inondation des barrages hydroélectriques en tenant compte du changement climatique futur

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Abstract. It is important for hydropower dams to estimate PMP (Probable Maximum Precipitation) appropriately and to prepare the plan of facilities modification and operational changes in advance, because the future flood risk by climate change influence is getting higher. In this paper, we compared three methods of PMP estimation, the conventional method applying DAD (Duration Area and Depth) analysis based on the experienced rain results, the product of d4PDF (database for Policy Decision making for Future climate change) that is the latest climate model ensemble prediction, and the pseudo-global warming experimental results on the typhoon. It was showed that PMP by d4PDF and the pseudo-global warming experimental results were larger than that by DAD analysis and fluctuated smoothly and reasonably over time. It is preferable and reasonable to evaluate the PMP risk applying DAD analysis at the rough examination, and the estimations applying d4PDF or pseudo-global warming scenario is suitable for more detailed examination.

Résumé. Il est important pour les barrages hydroélectriques d'estimer correctement les précipitations maximales probables (PMP) et de préparer à l'avance la modification des installations et les changements d'exploitation, car le risque futur de crue sous l'influence du changement climatique est de plus en plus élevé. Dans cet article, nous avons comparé trois méthodes de

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l'estimation PMP : la méthode conventionnelle appliquant l'analyse de la durée et de la profondeur (DAD) basée sur les résultats de pluie observée, les résultats de d4PDF (base de données pour la prise de décision politique pour le changement climatique à venir) qui est la dernière prédiction du modèle climatique global, et les résultats expérimentaux du pseudo réchauffement global (PGW) sur le typhon. Il a été montré que les valeurs de la PMP obtenues par le d4PDF et les résultats expérimentaux du pseudo-réchauffement global étaient plus importants que ceux obtenus par l'analyse DAD, et fluctuaient de manière régulière et raisonnable au fil du temps. Il est préférable et raisonnable d'évaluer le risque PMP en appliquant l'analyse DAD lors de l'analyse préliminaire, tandis que les estimations appliquant le d4PDF ou l'expérience de pseudo-réchauffement global conviennent pour une analyse détaillée.

1 Introduction

Due to the progress of global warming, it is anticipated that Probable Maximum Flood (PMF) that will exceed the current facility capacity will occur in the future. In order to conduct a sustainable hydropower operation, it is important to properly set and evaluate the PMF at the hydropower dam site, and plan and prepare facility modifications and operational changes in advance. Electric Power Development Co., Ltd., (J-POWER) is working on the development of a PMF setting method and a study method related to the planning of optimal intangible and tangible measures based on the PMF in order to carry out risk assessment for the PMF at all dam sites under operation.

When setting the PMF, it is necessary to reasonably estimate PMP at each dam site in consideration of future climate change impacts. For estimation of PMP, there are a statistical method by Hershfield [1], a method using the Duration Area and Depth (DAD) analysis result of Kuwahara [2], a method of maximizing meteorological conditions, a method of using a meteorological model, and the like. As a method of maximizing the meteorological conditions, there is a method developed by the World Meteorological Organization (WMO) [3] that uses the amount of precipitation as an index. As a study using meteorological models for river basins in Japan, Kobayashi et al. [4] used a virtual typhoon scenario in which the initial position of a typhoon (Owen in 1979) was longitudinally relocated using the potential vorticity inversion method, conducted the Pseudo-Global Warming (PGW) scenarios and flood assessment in the Yodo River basin. In addition, Hashimoto et al. [5] used the Weather Research and Forecasting (WRF) model to evaluate the effects of water vapor fluxes and other factors on the temporal distribution of rainfall in the upper Tone River basin by changing the relative humidity of the atmospheric field for typhoon and frontal heavy rainfall occurred in recent years, and tried to estimate PMP.

Nowadays, highly accurate climate change forecast information is being created both in Japan and overseas, and it is becoming possible for general companies to utilize it. Based on these circumstances, in this paper, aiming to establish a rational PMP estimation method considering the impact of climate change, targeting Ikehara Dam and Kazeya Dam in the model basin (Kumano River) we compared three methods of PMP estimation, the conventional method applying DAD analysis based on the experienced rain results, the product of d4PDF that is the latest climate model ensemble prediction, and the PGW experimental results on the typhoon. Finally, we have summarized the characteristics and issues of each method and considered the condition of their usage.

1.1 Power stations and dams

Kumano River in Shingu River water system where we have installed hydropower stations, is a river which has 183 km length and 2,360 km2 catchment area, and flows through the southern Kii Peninsula. A total of 11 dams have been installed in Kumano River basin (Figure 1), and all the dams are for water resources, and there is no flood control dam. J-POWER has six hydropower dams here. In the Kumano River basin, heavy flood disasters have frequently occurred in the past. Among the dams owned by J-POWER installed in the basin, Ikehara Dam and Kazeya Dam have larger reservoir than the others and can be expected to reduce discharge. Therefore, the both dams have helped flood-control operation to reduce flood damage to the lower river basin with lowering reservoir water level to the aim water level, which is below the "preliminary release" water level, during flood season. For the purpose of mitigating flood disasters, Ikehara Dam and Kazeya Dam have been independently operated. In response to the heavy flood damage in the Kii Peninsula caused by the heavy rain of the typhoon Talas in 2011, the flood damage mitigation measures that have been implemented for a long time have been strengthened.

In this paper, to prepare for PMF, we selected Kumano River basin as a model basin and estimated PMP for Ikehara Dam and Kazeya Dam. The specifications and photos of Ikehara Dam and Kazeya Dam are shown in Table 1 and Figure 2.

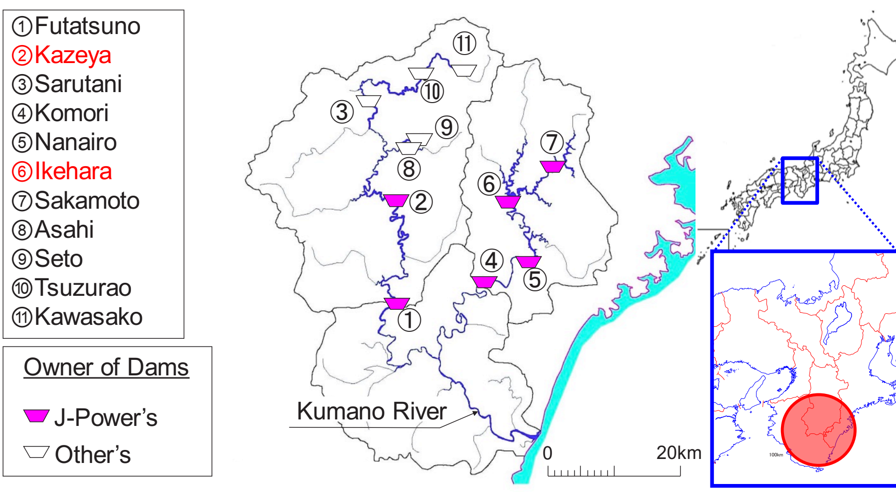

Fig. 1. Location of the Ikehara and Kazeya hydropower stations and dams.

Table 1. Specification of Ikehara Dam and Kazeya Dam.

Item	Ikehara Dam	Kazeya Dam
Completion	Sep.1964	Oct.1960
Purpose	Power	Power
Dam type	Arch	Gravity
Dam height	111 m	101 m
Crest length	460 m	329.5 m
Catchment area	354 km^2	660 km^2
Total capacity	338,373×10^3 m^3	130,000×10^3 m^3
Effective capacity	220,083×10^3 m^3	89,000×10^3 m^3
Installed capacity of power station	350,000 kW	75,000 kW

Fig. 2. Ikehara Dam(left) and Kazeya Dam(right).

2 Study procedure, method and conditions

2.1 Study procedure

Figure 3 shows the study procedure. First, the past maximum rainfalls data are listed and ranked, and PMP is estimated by the conventional method applying DAD analysis using the data. Next, PMP is estimated using a meteorological model to consider the climate change impact. As the estimation method, the latest climate change model product d4PDF and the typhoon PGW experimental results are used. Finally, we compare the three PMP estimation methods, sort out the characteristics and issues, and consider the direction of usage of each method.

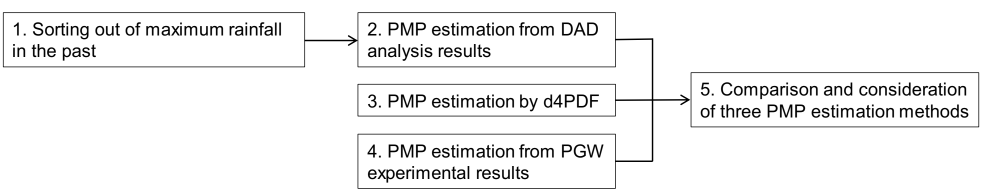

Fig. 3. Study procedure.

2.2 Study method and conditions

2.2.1 Sorting out of maximum rainfall in the past

Table 2 shows the past major flood records of the Ikehara Dam and the Kazeya Dam from the completion of these dams to 2018. It can be seen that the meteorological factors for floods are mainly typhoons at both Ikehara Dam and Kazeya Dam.

Table 2. Major flood records of Ikehara Dam and Kazeya Dam.

a) Ikehara Dam

Number	Occurrence year and month	Maximum inflow		Total rainfall		Flood factor
		m^3/s	(Rank)	mm	(Rank)	
1	Aug.1975	3,382	(7)	723	(4)	typhoon
2	Sep.1990	6,246	(2)	916	(2)	do.
3	Sep.1994	6,318	(1)	425	(8)	do.
4	Jul.1997	4,288	(5)	715	(5)	do.
5	Aug.2004	4,329	(4)	730	(3)	do.
6	Sep.2011	4,244	(6)	1,807	(1)	do.
7	Aug.2018	4,640	(3)	499	(7)	do.

b) Kazeya Dam

Number	Occurrence year and month	Maximum inflow		Total rainfall		Flood factor
		m^3/s	(Rank)	mm	(Rank)	
1	Aug.1975	3,326	(7)	768	(2)	typhoon
2	Jul.1986	4,452	(5)	252	(8)	frontal rain
3	Sep.1990	4,529	(3)	743	(3)	typhoon
4	Jun.2001	4,501	(4)	352	(7)	frontal rain
5	Aug.2004	1,566	(8)	675	(4)	typhoon
6	Sep.2011	4,962	(2)	1,317	(1)	do.
7	Oct.2017	3,770	(6)	520	(5)	do.
8	Aug.2018	5,323	(1)	442	(6)	do.

In this paper, the analytical rainfall data {hourly gridded precipitation analysis using meteorological radar and surface meteorological observation [Automated Meteorological Data Acquisition System (AMeDAS)] data owned by Japan Meteorological Agency} for the past 19 years from 2000 to 2018 that are available in Japan are used. Based on these data, the past maximum rainfall was listed and ranked for the case where the inflow of dam at each of Ikehara Dam and Kazeya Dam exceeded the fixed quantity. The sorting result was used for PMP estimation based on the DAD analysis result in the next section.

2.2.2 PMP estimation from DAD analysis results

Using the DAD analysis method organized by the Ministry of Land, Infrastructure, Transport and Tourism [6] for preparing inundation assumptions, etc., PMP at Ikehara Dam and Kazeya Dam were estimated. This method is based on the idea that Japan is divided into 15 regions with similar rainfall characteristics and that maximum rainfall in neighboring rivers in the same region will also occur in that river. For the extension to the assumed maximum scale rainfall waveform, the method of uniformly stretching the actual rainfall waveform within the planned rainfall duration is adopted. This method is a DAD formula based on the maximum envelope of actual rainfall, and does not consider the impact of climate change. Figure 4 shows the procedure for studying PMP estimation based on DAD analysis results.

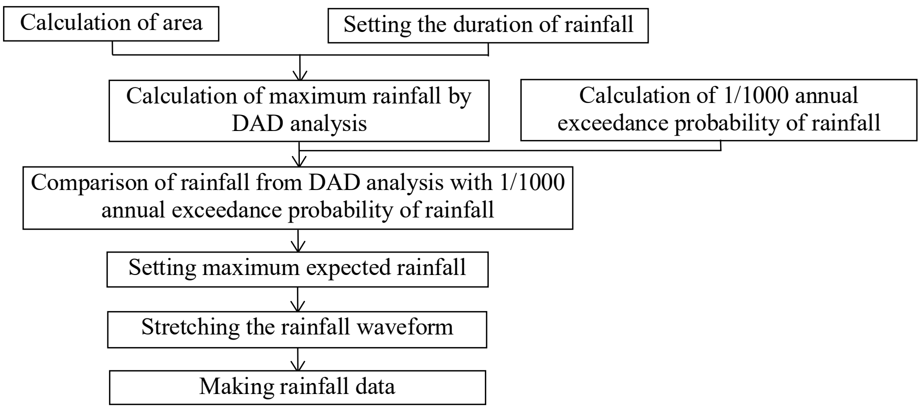

Fig. 4. Procedure for studying PMP estimation based on DAD analysis results.

For the area of the upper basin of dams, the rainfall duration of Ikehara Dam and Kazeya Dam was determined by the duration of the dominant flood peak flow (flood arrival time), which was calculated as 3 and 12 hours, respectively, using the kinematic wave method. The maximum rainfall in the southern Kii region, where Ikehara Dam and Kazeya Dam are located, was calculated based on the envelope curve diagram based on the DAD analysis results (Figure 5), and the maximum rainfalls for each dam were compared with the 1/1000 annual exceedance probability of rainfall to determine the maximum rainfall (Table 3). For both dams, the maximum rainfall based on DAD analysis results was less than the 1/1000 annual exceedance probability of rainfall, so the 1/1000 annual exceedance probability of rainfall was set as the maximum rainfall. The 1/1000 annual exceedance probability of rainfall is calculated based on the annual maximum rainfall in the rainfall duration, which is based on approximately 40 years of rainfall data from AMeDAS stations of the Japan Meteorological Agency representing each dam.

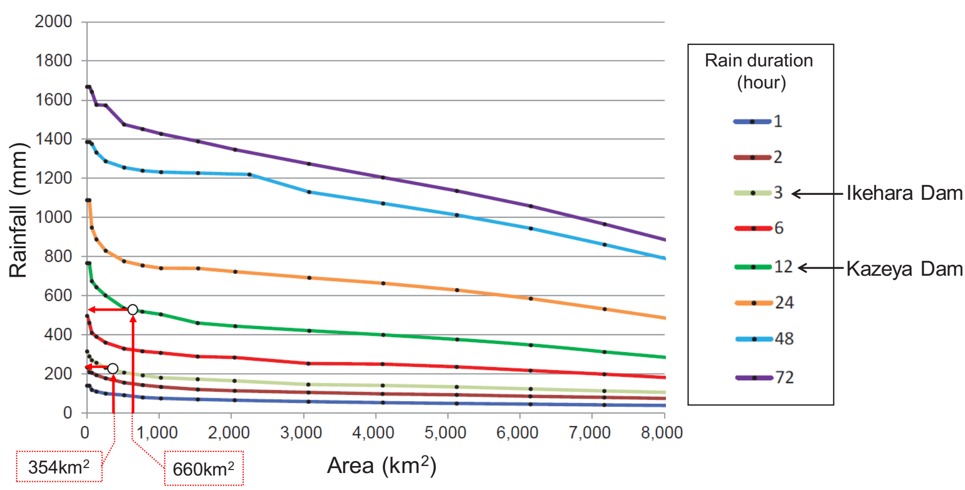

Fig. 5. Envelope curve diagram based on DAD analysis of maximum rainfall in the southern Kii region.

Table 3. Setting maximum rainfall by comparing maximum rainfall of each dam with 1/1000 probability rainfall based on DAD analysis results.

Item		Ikehara Dam	Kazeya Dam
Rain duration (hour)		3	12
Maximum rainfall (mm)	Calculation method: DAD analysis	222	526
	Calculation method: 1/1000 probability rainfall	300	598
	Determined rainfall	300	598

The rise in dam water level during floods, which is related to dam safety, is affected not only by the peak inflow value, but also by the total inflow over a long duration. Based on these, the rainfall waveforms with the maximum short- and long-duration rainfall were selected for each dam from the previous maximum rainfall results, and the rainfall data were compiled by stretching the waveforms based on the set maximum rainfall.

2.2.3 PMP Estimation by d4PDF

The d4PDF is a climate projected dataset from the Atmospheric Global Climate Model (AGCM) with a horizontal resolution of about 60 km and a regional climate model covering the Japanese region, using the information on global warming with 4K based on the data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Program (WCRP) as a boundary condition (Mizuta et al. [7]). For a regional prediction, dynamical downscaling was carried out from the global model scenario to a horizontal resolution of about 20 km, and the results of the past (3,000 years: 1951-2010 × 100 members) and future (5,400 years: 2051-2110 × 90 members) scenarios were used in this paper. In this paper, based on the topographical conditions of the mountainous Kumano River basin, we further dynamically downscaled to a horizontal resolution of about 5 km using a regional model of the Kumano River basin in order to reproduce more accurately the three-dimensional structure of meteorological phenomena, such as typhoons and fronts, and estimated PMP.

The study procedure is shown in Figure 6. PMP estimation was performed by extracting the top heavy rainfall cases from the d4PDF data and dynamic downscaling only the selected cases, since it is difficult to dynamic downscaling all the data because of the large amount of data, which requires a lot of time and money for calculation.

1. Extraction of heavy rainfall cases in d4PDF
↓
2. Dynamic downscaling
↓
3. Making rainfall data
↓
4. Selection of PMP

Fig. 6. Procedure for studying PMP estimation with d4PDF data.

As an extraction rule, we first focused on short- and long-duration rainfall for the d4PDF data in Kumano River basin, and selected the heavy rainfall cases that included the top 10 rainfall cases for each duration (1, 2, 3, 6, 12, 24, 48, 72, 96, and 120 hours). In order to extract cases of heavy rainfall as objectively as possible with no leaks, we covered up to 120 hours of rainfall with reference to the past flood records. This resulted in the extraction of d4PDF data from 48 past cases and 37 future cases. Furthermore, the cases extracted only in the lower rankings (6th to 10th; variable for each case) were excluded and narrowed down to 20 cases for each of the past and future cases. Next, we performed dynamical downscaling on these 20 extracted past and 20 future cases using the WRF model. The computational domain and physical processes required to ensure reproducibility were based on the conditions of the PGW scenario described below (Table 4). In order to eliminate the noises caused by inadequate initial values, the spin-up time was considered and the start time was set to 12-18 hours before the start of rainfall in d4PDF.

Table 4. Calculation conditions for dynamic downscaling of d4PDF.

Item	Calculation conditions
Horizontal Grid Size	5 km
Initial and boundary values	d4PDF (20 km mesh)
Elevation and Land Use	United States Geological Survey (USGS) 30 s
Physical Processes	Cloud Physics: WRF Single-Moment 6-class scheme Cumulus parameterization: Kain-Fritsch scheme Atmospheric Boundary Layer: Yonsei University Scheme Grounded realm: Monin-Obukhov (Janjic) schema Land surface processes: 5-layer Thermal Diffusion Scheme Atmospheric Radiation: Rapid Radiative Transfer Model for GCMs (RRTMG) Shortwave and Longwave Schemes

An example of rainfall distributions and hyetographs before and after dynamical downscaling is shown in Figure 7. The dynamical downscaling provided a more detailed representation of the topographic rainfall distribution.

Figure 8 shows the maximum rainfall intensity (maximum values) for the duration of rainfall before and after dynamic downscaling for each dam in the past and future cases. The dynamic downscaling in both past and future cases increased the rainfall intensity (maximum values) at each duration by about 1.3 times on average for both Ikehara Dam and Kazeya Dam. The maximum rainfall intensity (maximum value) at each duration in the future events was about 1.4 and 1.7 times larger at Ikehara Dam and Kazeya Dam, respectively, than that of the past events.

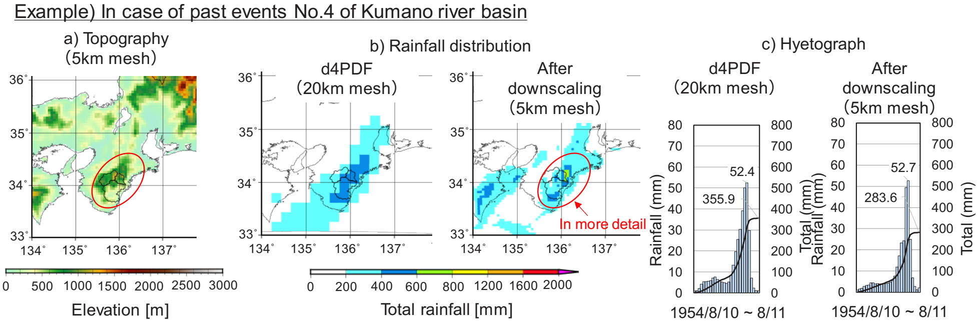

Fig. 7. An example of rainfall distributions and hyetographs before and after dynamic downscaling.

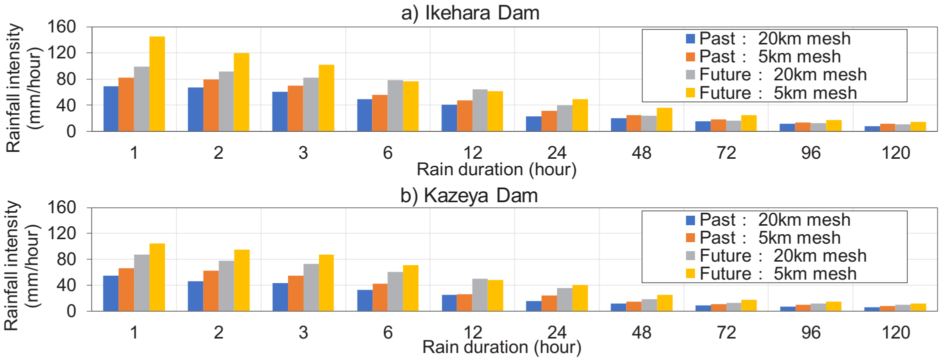

Fig. 8. Maximum rainfall intensity (maximum value) for each dam for the duration of rainfall in each case.

Finally, the relationship between rainfall intensity and duration was compiled based on the rainfall data after dynamical downscaling, and the heavy rainfall cases with the maximum short- and long- duration rainfall were selected as PMP, two for each dam. The relationship between rainfall intensity and rainfall duration for each dam in future events is shown in Figure 9.

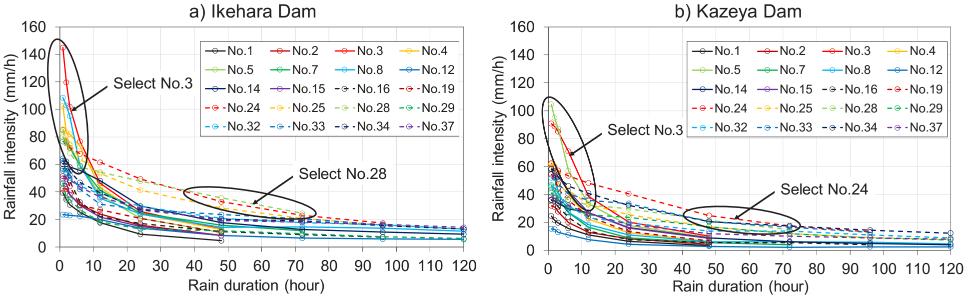

Fig. 9. Relationship between rainfall intensity and rainfall duration in future events.

2.2.4 PMP Estimation from the PGW experimental results

Most of the large flood flows in the Kumano River basin were caused by typhoons. In Ikehara Dam and Kazeya Dam, the largest inflow ever recorded was caused by Typhoon Talas (2011), which brought more than 2,000 mm of rainfall to the southern part of Kii Peninsula.

Takemi [8] conducted a PGW scenario by simulating typhoon paths in the atmospheric field of future climate to investigate the effects of global warming on the extreme rainfall of Typhoon Talas (2011). By varying the nudging parameters (i.e., wave number and time coefficients), the path and movement speed of the typhoon were accurately reproduced in the present climate scenarios, and were also reproduced in the PGW scenarios. In this paper, the results of these scenarios were used to estimate PMP at the dams.

The main conditions of the PGW scenario are shown in Table 5 and the calculation cases are shown in Table 6. The Japanese 55-year Reanalysis (JRA-55) refers to the long-duration reanalysis data provided by Japan Meteorological Agency. As for the PGW scenarios, four cases were conducted under the current climate (2011) and seven experiments were conducted under the PGW condition. The global warming increments used in the cases were generated from the output of the Representative Concentration Path-8.5 (RCP-8.5) scenario.

Table 5. Calculation conditions for the PGW scenarios.

Item	Calculation conditions
Usage model	The Advanced Research Weather Research and Forecasting Model (WRF-ARW) Version 3.3.1
Computational domain	Domain1: 5 km, Domain2: 1 km (2-way nesting)
Initial and boundary values	JRA-55 1.25 deg. equi-latitude and longitude grid data
Typhoon bogus	2011 Typhoon Talas: None (due to the representation of typhoon-like eddies in JRA-55)

Table 6. The list of the numerical scenarios.

	Case	SST in PGW	Wave number	Time coefficients (/s)
Present climate	CASE000	-	5	0.00028
	CASE001	-	5	0.00014
	CASE010	-	4	0.00028
	CASE020	-	6	0.00028
PGW climate	CASE100	CNTL	5	0.00028
	CASE101	CNTL	5	0.00014
	CASE110	CNTL	4	0.00028
	CASE120	CNTL	6	0.00028
	CASE200	C1	5	0.00028
	CASE300	C2	5	0.00028
	CASE400	C3	5	0.00028

The future climate data were driven either with the ensemble mean sea surface temperature (SST) averaged for the CMIP5 coupled models (referred to as CNTL) or other different-type sea SST pattern derived from the cluster analysis on the CMIP5 models (referred to as C1, C2, or C3).

We used the experimental results of these cases to perform rainfall calculations for the considered basins and organize each hourly rainfall at each dam point. The results of the PGW scenario were similar to the actual rainfall by Typhoon Talas, with all cases resulting in long rainfall with large total rainfall, but also large short-duration rainfall. Therefore, PMP for the maximum case of long-duration rainfall as well as the maximum case of short duration rainfall were selected for each dam based on the results of the organization (Table 7). The maximum short- and long-duration rainfall cases at Kazeya dam were both CASE 101 and were the same.

Table 7. PMP selected from the results of PGW scenarios.

	Ikehara Dam	Kazeya Dam
Short-duration rainfall maximum case	CASE110	CASE101
Long-duration rainfall maximum case	CASE101	CASE101

3 Results of the study

3.1 Sorting out of maximum rainfall in the past and PMP estimation from DAD analysis results

As a representative of the results, the maximum past rainfall and PMP based on DAD analysis results at Ikehara Dam are shown in Figure 10 (see 3.4 for the PMP of Kazeya Dam).

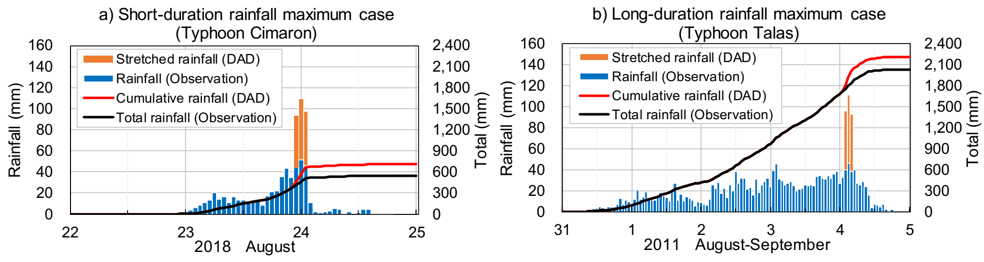

Fig. 10. Maximum rainfall and PMP based on DAD analysis results at Ikehara Dam

Typhoon Cimaron (2018) was selected as the largest case of short-duration rainfall and Typhoon Talas (2011) as the largest case of long-duration rainfall for both Ikehara Dam and Kazeya Dam for the past rainfall cases to be stretched.

PMP estimated from the DAD analysis results stretch the past rainfall waveforms and may result in a distorted and irrational rainfall waveform. PMP produced by this method consist of relatively long periods of heavy rain followed by short periods of more intense rainfall, so it is necessary to verify whether the waveform is meteorologically possible.

3.2 PMP Estimation by d4PDF

As a representative of the results, the PMP of Ikehara Dam estimated by d4PDF are shown in Figure 11 (see 3.4 for the PMP of Kazeya Dam).

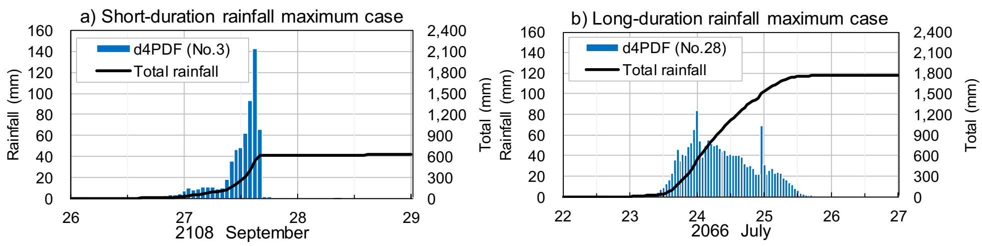

Fig. 11. PMP estimation result from d4PDF in Ikehara Dam basin.

Although it would be preferable to dynamically downscale all cases if computational resources were sufficient, in this study we narrowed down the target of dynamic downscaling from the vast amount of data in d4PDF, using the relationship between rainfall intensity and rainfall duration to rationally extract heavy rainfall cases based on certain rules. Although there is an advantage of effective process, it should be noted that there are cases where rainfall characteristics, especially rainfall intensity for short duration, can change significantly before and after dynamical downscaling, and thus may be missing rainfall cases, which may be critical for dams.

3.3 PMP Estimation from the PGW experimental results

As a representative of the results, the PMP of Ikehara Dam estimated by the PGW experimental results are shown in Figure 12 (see 3.4 for the PMP of Kazeya Dam).

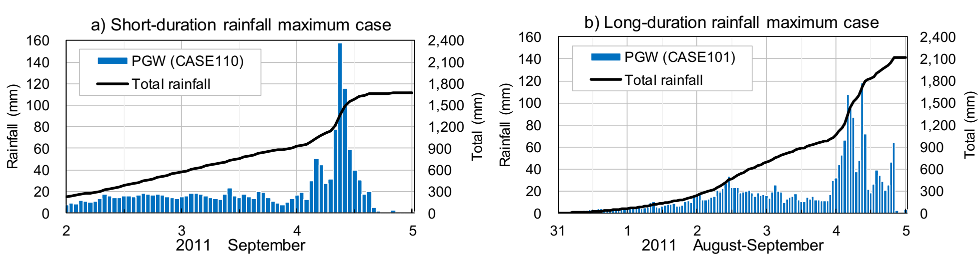

Fig. 12. PMP estimation result from PGW scenarios in Ikehara Dam basin.

PMP estimated from the Typhoon Talas (2011) PGW scenarios for Ikehara Dam and Kazeya Dam resulted in basin-averaged hourly rainfall exceeding 100 mm in the latter half of the rainfall period. Analysis of the rainfall distribution during the period of more than 80 mm showed that the typhoon, which was moving northward, stagnated near Seto Inland Sea, where the typhoon structure collapsed, resulting in heavy rainfall.

3.4 Comparison of PMP in each method

A comparison of PMP for each method at Ikehara Dam and Kazeya Dam is shown in Figure 13, Figure 14 and Table 8. The PMP from the three methods are shown on the hyetographs with the same peak rainfall point for each method.

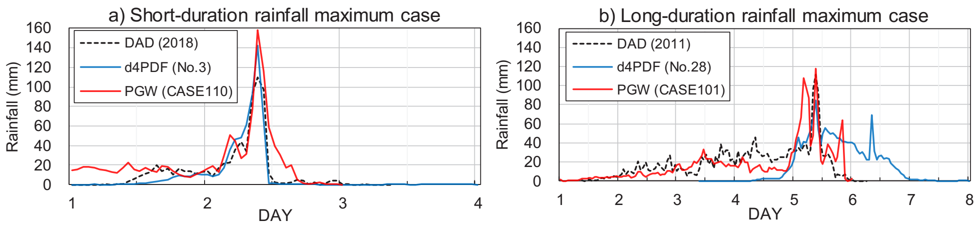

Fig. 13. Comparison of PMP for each method at Ikehara Dam.

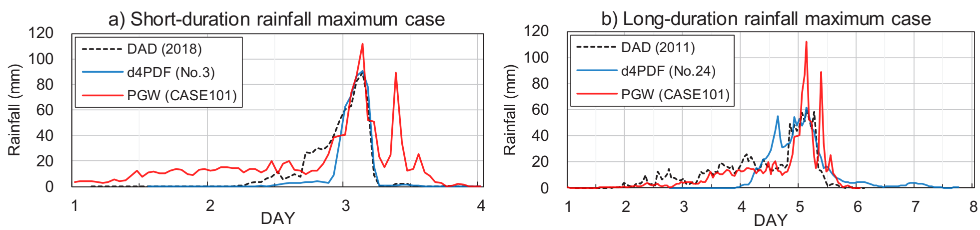

Fig. 14. Comparison of PMP for each method at Kazeya Dam.

Table 8. Peak and cumulative rainfall of PMP for each method.

		PMP for short-duration rainfall cases			PMP for long-duration rainfall cases		
		DAD	d4PDF	PGW	DAD	d4PDF	PGW
Ikehara Dam	Peak rainfall (mm)	109	143	158	111	84	118
	Cumulative rainfall (mm)	709	627	1,671	2,212	1,775	2,121
Kazeya Dam	Peak rainfall (mm)	89	91	112	60	62	112
	Cumulative rainfall (mm)	682	495	1,339	1,425	1,278	1,339

The peak rainfall in the maximum short-duration rainfall case was larger in the d4PDF and PGW scenarios than in the DAD analysis. The waveforms of PMP in the long-duration maximum rainfall case were similar for all three methods, with peaks in the second half of the rainfall. For peak rainfall, PMP from the PGW scenarios were the largest, and for total rainfall, the DAD analysis results were the largest.

A detailed comparison of PMP for Ikehara Dam based on the DAD analysis and the PGW scenarios for the same rainfall event (2011 Typhoon Talas) is shown in Figure 15. It can be seen that the PMP from the DAD analysis rises rapidly at the points of stretched rainfall, whereas the PMP from the PGW scenario rises relatively slowly and continuously. The d4PDF and the PGW scenarios have smoother waveforms and are more explanatory in that they reproduce physical phenomena by calculation. On the other hand, PMP based on the DAD analysis is similar to PMP based on the PGW scenarios, although the physical phenomena are not reproduced by the stretched waveforms of the past rainfall events. Based on the above, it is preferable to use the conventional method of applying DAD analysis for the rough examination, and to use a meteorological model such as d4PDF or PGW scenarios for the detailed examination.

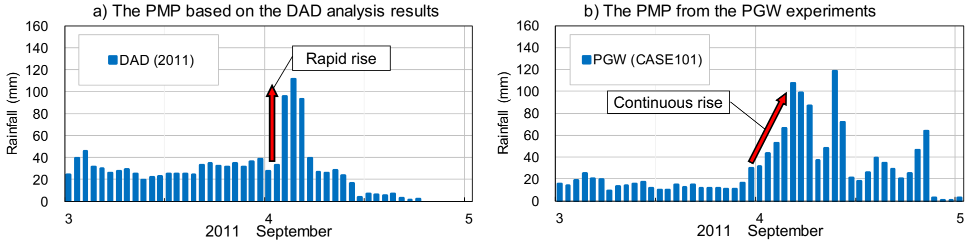

Fig. 15. Detailed comparison PMP for Ikehara Dam based on the DAD analysis and the PGW scenarios for the same rainfall event (2011 Typhoon Talas).

4 Conclusions and next steps

In this paper, we estimated the PMP at the dam site from each of the DAD analysis results, the d4PDF, and PGW experimental results for river basins in Japan, and compared those PMP. As a result, the following was clarified.

- The peak rainfall of the PMP was larger in the d4PDF and PGW experimental results than in the DAD analysis.
- The PMP rainfall waveforms from the d4PDF and PGW experimental results are smooth and highly descriptive in that they reproduced physical phenomena by calculation.
- The PMP rainfall waveforms based on the DAD analysis were similar to those of the PGW experimental results, although the physical phenomena were not reproduced because they were stretched from the past rainfall waveforms.
- Since the calculation of PMP based on the results of the DAD analysis is simple, it is preferable to use the conventional method of applying DAD analysis for the rough examination and to conduct detailed examination by numerical simulation using a meteorological model such as d4PDF and PGW scenarios.

In the future, outflow analysis and dam operation simulations should be conducted to re-evaluate PMP in terms of dam safety and set the PMF. In this paper, PMP was estimated using meteorological models under the global warming conditions of the RCP-8.5 scenario and the warming scenario of 4K increase in CMIP5 for the purpose of planning facility modifications and other measures. As well as the d4PDF, projections of climate conditions in the near future (around 2030-2050) with 2K increase in global average temperature (d2PDF) are now available. Since a long period of time is expected to be required before the modification of facilities, etc., even after the modification of facilities is planned, it is considered necessary to prepare for tentative dam operations based on d2PDF data and other data before the modification in practical terms.

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References

1. D. M. Hershfield, Estimating the probable maximum precipitation, J.Hydraul.Civ.Am.Soc.Civ. Eng., 87(HY5), 99-106 (1961)
2. H. Kuwabara, An empirical study on the temporal and spatial concentration of the largest downpours in Japan (in Japanese), Doctoral dissertation, University of Tokyo (1986)
3. World Meteorological Organization: Manual on Estimation of Probable Maximum Precipitation (PMP) WMO-No.1045 (2009)
4. K. Kobayashi, Y. Oku, H. Ishikawa, T. Takemi, E. Nakakita, Flood Assessment of the Yodo River Basin Using Dynamic Downscaling Method for Extreme Typhoons (in Japanese), Annual Report of Disaster Prevention Research Institute, Kyoto University, No. 55B, pp. 9-14 (2012)
5. K. Hashimoto, H. Yajima, Estimation of probable maximum precipitation through maximization of moisture fluxes over the upper Tone River basin (in Japanese), Journal of Hydraulic Engineering, vol. 71, pp. 487-492 (2015)
6. Ministry of Land, Infrastructure and Transport (MLIT), Method of setting assumed maximum external force for making inundation assumptions (flood, inland water), etc. (in Japanese) https://www.mlit.go.jp/river/shishin_guideline/pdf/shinsuisoutei_honnbun_1507.pdf (2015)
7. Mizuta, Ryo et al., Over 5000 years of ensemble future climate simulations by 60 km global and 20 km regional atmospheric models, Bulletin of the American Meteorological Society (2016)
8. T. Takemi, Impacts of Global Warming on Extreme Rainfall of a Slow-Moving Typhoon: A Case Study for Typhoon Talas (2011), SOLA, 15, 125–131, doi:10.2151/sola.2019-023 (2019)