Impact of Climate Change on Discharge in Small Mountainous Mizoguthi Catchment, Japan

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Abstract: This paper presents a comprehensive analysis of climate change impacts on the discharge in the small mountainous Mizoguthi Catchment, Japan, using a large ensemble of climate simulations from the Database for Policy Decision Making for Future Climate Change (d4PDF) through the TOPMODEL hydrological model. Two sets of experiments for a 60-year period were conducted using d4PDF data: historical and 4-K-warmer climate simulation experiments. The precipitation and discharge analyses were based on cumulative frequency, box-whisker plots, flow duration curves, and return periods under historical and 4-K-warmer climate conditions. Results showed that irrigation periods with low precipitation occurred more frequently, and the catchment was more likely to become more seriously dry than it is at present. Finally, the return period results showed that droughts are likely to have major impacts due to the expected decrease in discharge. These results suggest severe challenges to water resources in the catchment under 4-K-warmer climate conditions and should be used to mitigate the adverse effects of drought in the study area by adopting appropriate adaption strategies.

Keywords: d4PDF; Flow duration curve; Hydrological simulation; TOPMODEL; Return period

1 Introduction

The Earth's climate is changing because of increased atmospheric greenhouse gas concentrations. The IPCC (2014) has reported that the global average temperature has risen by more than 0.76 °C over the last century and is expected to increase by between 1.5–4.5°C over the next century due to the doubling of atmospheric CO₂ concentrations. Driven by increased average temperatures, climate change is expected to strongly affect the global hydrological cycle in the coming decades (IPCC, 2014).

Hence, a number of studies have projected that climate change is likely to significantly impact on precipitation patterns, including increased occurrences of extreme weather events, such as flooding and drought (Kazama *et al.*, 2009; Tachikawa *et al.*, 2010; Reshmidevi *et al.*, 2018). Takeshita *et al.* (2010) reported that the total amount of precipitation and number of rainy days over the past 30 years in Miyazaki Prefecture, Japan, has significantly decreased, especially in spring.

Variations in precipitation patterns are largely linked to changes in stream flows, especially in forested mountainous catchments (Viessman and Lewis, 2003; Shinohara *et al.*, 2009). Some Japanese studies have confirmed that the total precipitation is expected to change significantly, resulting in significant changes in water resources (Sayama *et al.*, 2008; Takara *et al.*, 2009; Kim *et al.*, 2010). Recent experiments on water resource changes have used predicted hydrological

data from large datasets from the Database for Policy Decision Making for Future Climate Change (d4PDF), which considers reported climate change uncertainties (Mizuta *et al.*, 2016).

Changes in water resources significantly impact agricultural irrigation water use (Kudo *et al.*, 2012; Kudo *et al.*, 2017). For example, there are over 20,000 ha of terraced paddy fields in Japan, most of which are located on mountain slopes and are irrigated from mountain streams with small catchments (Nakajima, 1999). However, most studies have analyzed large river basins with reservoirs or diversion weirs, and large areas of farmland use irrigation canals without water storage facilities.

To assess the changes in streamflow due to climate change that affect terraced paddy fields requiring irrigation, the decreased streamflow in light rain events was analyzed in this study. Climate change prediction data from ensemble data from d4PDF experiments (Mizuta *et al.*, 2016) were used for sensitivity analyses, and the streamflow under different climate change scenarios, historical and predicted scenarios was calculated and compared.

2 Methods

Mizoguthi Catchment, Japan, was used as the study area, and the discharge was calculated using the TOPMODEL hydrological model (Beven and Kirkby, 1979). The climate change impact assessment used the discharge calculated from the historical experimental dataset and 4-K-warmer climate simulation experimental dataset from d4PDF.

2.1 Study area and observational data

The mountainous Mizoguthi Catchment (0.396 km²) is located in the Sakatani River Basin in southern Miyazaki Prefecture, Kyushu Island, Japan (Fig. 1), and is characterized

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by natural forestland and mountainous topography. The elevation ranges from 330 to 960 m a.s.l, and the average temperature and total annual precipitation are approximately 16.7 °C and 4780 mm, respectively. There is almost no snow cover. This study focused on the streamflow of the Mizoguthi Catchment, which is used to irrigate the Sakamoto terraced paddy fields (*tanada*).

The discharge measurements were conducted in 2011 at the irrigation diversion weir. The rain gage and meteorological observation station were located in the Sakamoto terraced paddy field, about 800 m southwest of the diversion weir. Evapotranspiration was estimated using the Penman–Monteith method (Ward and Trimble, 2003) from the average temperature, solar radiation, relative humidity, and wind speed.

2.2 Hydrological model

The stream flow was simulated using the hydrological runoff model, TOPMODEL, developed by Beven and Kirkby (1979). TOPMODEL is a semi-distributed, mass conservative model that relies on a simple representation of basin characteristics and runoff mechanisms (Beven, 1997), compared to other fully distributed models that are more complex and require higher-quality data. This model simulated the catchment based on the topographic index and calculates the discharge considering the variable source area. TOPMODEL has many applications for studying mountainous catchments (Tada *et al.*, 2002; Okada *et al.*, 2005). The topographic index of Mizoguthi Catchment was calculated using a 5 m mesh digital elevation model (Fig. 1). This topographic index was used for the discharge calculations.

Since this hydrological model is based on the variable source area, it is often used to analyze the behavior of runoff in the basin during heavy rain. This model was used because changes in discharge during heavy rain under different climate change scenarios, historical and predicted scenarios were analyzed. However, this study analyzed runoff during lighter rain. Climate change prediction data were used as input data for the calculations, and observational data were used to verify the accuracy of the runoff calculations.

The parameters of TOPMODEL were adjusted so that discharge could be reproduced under both current and future climate conditions. TOPMODEL contains seven types of parameters: m [mm] is a scaling parameter of the exponential transmissivity function, which is a function of local storage deficit or depth of the water table; T_0 (m^2/h) is the transmissivity of the soil profile at full saturation; t_d is a time delay constant for routing unsaturated flow; RV (m/h) is the channel flow inside the catchment; SR_{MAX} (mm) is the maximum value of the root zone capacity; SR_{ZO} (mm) is the initial value of the root zone capacity; and UZ_{MAX} (mm) is the maximum value of the unsaturated zone capacity. These parameters were optimized using observational data, such as precipitation (mm/d), evapotranspiration (mm/d), and discharge (mm/d), collected during 2011–2012. The parameter optimization method was performed using the evolution strategy algorithm, which is a type of genetic algorithm (Fujihara *et al.*, 2003; Hansen *et al.*, 2013; Salimans *et al.*, 2017).

Figure 1: Overview of Mizoguthi Catchment (left) and topographic index map (right)

The two objective functions were used to decide the goodness-of-fit of the parameters, including the root mean square error (RMSE, mm/d) and coefficient of determination (R^2 , nondimensional). The parameter set was determined using these objective functions, where the weights of the RMSE and R^2 were the same. RMSE, emphasizing the errors at high flow, and R^2 , emphasizing the errors at low flow, were used as objective functions (Tanakamaru and Fujihara, 2006). Furthermore, goodness of fit for TOPMODEL evaluated the reproducibility of the model using the Nash–Sutcliffe coefficient (nondimensional; Nash and Sutcliffe, 1970), which has been widely used to evaluate the performance of hydrological models (Wilcox *et al.*, 1990; Legates *et al.*, 1999). An optimized parameter set from 100 trials was based on different initial values.

Observed data from 2015–2016 were used for model validation, and the results were plotted on a hydrograph (Fig. 2) and optimized parameter values (Table 1). The results indicated that the calculated discharge using TOPMODEL with the aforementioned parameter set was appropriate.

The results indicated that the base flow and rising and recession limbs of the calculated stream flow matched the observed stream flow. The hydrograph showed slight overestimations of the highest peak flows but excellent timing of the peak flows. The RMSE, R^2 , and Nash–Sutcliffe coefficient were 7.03, 0.71, and 0.74, respectively, indicating good model performance in simulating the stream flow of Mizoguthi Catchment. These results support the application of TOPMODEL to the external independent dataset.

Table 1: Parameter values used in the model

Parameter	Optimized value
SR_{ZO} [mm]	0.00072
SR_{MAX} [mm]	17.47
UZ_{MAX} [mm]	0.5240
m [mm]	0.0627
T_0 [m^2/h]	1.25
t_d [h/m]	0.6720
RV [m/h]	583.3

Figure 2: Comparison of observed and calculated discharges during validation period (2015–2016)

2.3 Climate simulation

The climate simulation (i.e., precipitation) data were input into the hydrological model to simulate the stream flow in order to assess the climate change impact on stream flow in the Mizoguthi Catchment. The general circulation model outputs used in this study were archived in the d4PDF (Mizuta *et al.*, 2016).

The d4PDF is a large ensemble of climate forcing simulations from the Japanese Meteorological Research Institute atmospheric general circulation model 3.2 (with a horizontal resolution of 60 km) and was dynamically downscaled for Japan using a 20 km resolution regional climate model developed by the Meteorological Research Institute. The d4PDF ensembles comprise historical and future atmospheric general circulation model simulations. The historical ensembles for the 60-year period of 1951–2010 were simulated with 50 regional climate models. The future ensembles for 2051–2110 (60 years) were simulated with 15 members of the +4 K global warming taken from six sea surface temperature patterns (CCSM4, GFDL-CM3, Had-GEM2-AO, MIROC5, MPI-ESM-MR, and MRI-CGCM3) and using the 2090 conditions of the RCP8.5 scenario (Van Vuuren *et al.*, 2011). Therefore, the historical ensembles spanned 3000 years (50 members $\times$ 60 years), and the future (4-K-warmer) ensembles spanned 5400 years (6 sea surface temperature patterns $\times$ 15 members $\times$ 60 years).

Precipitation (mm/day) and latent heat flux (W/m^2) data based on the historical and 4-K-warmer ensembles were used in the study. These values are the means of the four points in the study area (Fig. 3). The d4PDF regional climate model data cannot describe the impact of small topography with sufficient accuracy. If the prediction of the hydrological quantity is investigated, a large river basin should be selected as study area. However, the purpose of this study was to investigate changes in the quantity of the irrigation source of the mountainous terraced paddy fields. Therefore, the problem of using the d4PDF data needed to be considered. We decided not to use the d4PDF data for predictions in the Mizoguthi Catchment. Instead, this study should be viewed as a sensitivity analysis using a dataset from southern Miyazaki Prefecture.

Historical precipitation data (1979–2017) from the d4PDF dataset were compared to Fukase AMeDAS observation data. This comparison revealed that the shapes of the probability

Figure 3: Location of study area and position of calculated points of d4PDF

density distribution were generally similar. However, precipitation from the d4PDF dataset was underestimated by around 19.5%. The highest underestimations were observed in June and September, possibly because of the rainy season and typhoon rainfall, respectively. Therefore, the d4PDF dataset showed a high degree of consistency for periods with less precipitation, despite some inconsistencies during periods with high precipitation. However, since these data were not considered as predicted values in this study, the bias was corrected by adjusting the differences in the mean value with the observed value of every month.

The analysis of climate change impact on stream flow was based on the calculated stream flow dataset. This dataset was compiled by inputting the climate change dataset (d4PDF) into TOPMODEL. Therefore, the historical and 4-K-warmer climate stream flow datasets contained 3000- and 5400-year experiments, respectively.

3 Results and discussion

3.1 Changes in precipitation

Figure 4 shows a comparison of the annual cumulative frequency of precipitation and that in the irrigation periods from the historical and 4-K-warmer data ensembles. Regarding annual precipitation, there was almost no difference between the two curves below 2200 mm. Above that, the 4-K-warmer curve was to the right of the historical curve. This shows that the frequency of precipitation of 2200–3800 mm decreased due to climate change, whereas rainfall of more than 4000 mm occurred increasingly frequently.

Figure 5 shows the changes in seasonal historical and 4-K-warmer precipitation using box-whisker plots. The seasonal interquartile ranges were larger for the 4-K-warmer precipitation in all seasons. Similarly, the upper whiskers were longer for the 4-K-warmer climate precipitation, except in spring. The highest upper whisker of seasonal precipitation was projected during summer, as was the most noticeable decrease in average precipitation. The lower whiskers showed no major differences.

Regarding precipitation during the irrigation period, the 4-

Figure 4: Comparison of cumulative frequency of annual precipitation in irrigation (Irr) periods between historical and 4-K-warmer precipitation

Figure 5: Box-whisker plots of historical and 4-K-warmer seasonal precipitation

k-warmer curve below 1200 mm in Fig. 4 was to the left of the historical curve, indicating that irrigation periods with low precipitation occurred more frequently

3.2 Changes in discharge

Since discharge was calculated using precipitation as an input value, the characteristics of the calculated cumulative frequency graph of discharge were similar to those of precipitation. The flow duration curve was used to analyze the difference between historical and 4-k-warmer climate conditions.

Figure 6 shows the plotted annual flow duration curves using box-whisker plots, revealing a substantial increase in peak discharge but no major changes in lower discharge under 4-K-warmer climate conditions. Figure 7 shows the flow duration curves during the irrigation periods. This graph also shows a large difference in peak discharge under the 4-k-warmer climate conditions and hardly any differences at a lower discharge. This study assumed that the characteristics of the catchment did not change, and the model parameters were consequently the same for both climate conditions. Therefore, it was further assumed that there were no differences in flow characteristics, especially lower discharge.

3.3 Drought frequency during irrigation period

Quantile 95 (Q95) during the irrigation period corresponded

Figure 6: Box-whisker plots of historical and 4-K-warmer climate annual flow duration curves

Figure 7: Box-whisker plots of historical and 4-K-warmer climate flow duration curves during irrigation period

to the drought flow rate in the flow duration curve. The cumulative frequency of Q95 is shown in Fig. 8. No clear difference was found in Fig. 7, but Fig. 8 shows that the positions of the two curves differed. Under 4-k-warmer climatic conditions, the occurrence frequency of low discharge was higher than that under historical conditions. Specifically, the frequency of low discharge in the range of 2.5–4.5 mm/day was 10% higher under 4-k-warmer climate conditions.

TOPMODEL calculated the soil moisture conditions in the catchment and, specifically, the soil moisture contents of the unsaturated zone in Q95 (Fig. 9). According to Fig. 9, the incidence of soil moisture contents of 30–35% was higher under 4-k-warmer climate conditions than under historical conditions. This indicated that the catchment was likely to become much drier than it is at present.

Finally, the analysis of low discharge (Q95) during the irrigation period was performed because extremely low discharge conditions can have negative impacts on agricultural systems, such as terraced paddy fields. Figure 10 shows a slight decrease in the low discharge in return periods under the 4-K-warmer climate conditions. The 10-year return period of low discharge decreased under these conditions, and the 2.5 mm/day return period decreased from 9.6 to 5.5 years, which might present major challenges to water resources in the catchment under 4-K-warmer climate conditions.

4 Conclusions

This study comprehensively analyzed climate change impacts on precipitation and discharge in the Mizoguthi Catchment in Japan using a large ensemble of d4PDF historical

Figure 8: Comparison of cumulative frequency of low discharge (Q95) during irrigation periods under historical and 4-K-warmer climate conditions

Figure 9: Comparison of cumulative frequency of soil moisture (Q95) under historical and 4-K-warmer climate conditions

Figure 10: Return periods of discharge (Q95) during irrigation period under historical and 4-K-warmer climate conditions

and 4-K-warmer climate simulations and the TOPMODEL hydrological model. Climate change prediction data based on ensemble data from d4PDF experiments were used for sensitivity analysis, and the streamflow under different climate change scenarios, historical and predicted scenarios was calculated and compared.

Based on cumulative frequency, the results showed that the frequency of precipitation of 2200–3800 mm decreased and

that of more than 4000 mm increased under the 4-K-warmer climate conditions. Irrigation periods with low precipitation occurred more frequently.

Finally, the return period results showed that droughts had notable impacts due to the expected decrease in low discharge. This might present major challenges to water resources in the catchment under 4-K-warmer climate conditions.

To assess the impacts of climate change on discharge in small mountainous areas more comprehensively, the uncertainty in hydrological modeling and simulation should be considered. This is especially important during peak discharge event analysis. Therefore, in this study, the d4PDF dataset was used for sensitivity analyses of, not for predictions in, the study area and further focused on the low discharge. These results could be used to mitigate the adverse effects of drought in the study area by means of appropriate adaption strategies.

Acknowledgements

This research was supported by the Integrated Research Program for Advancing Climate Models (TOUGOU program) from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

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Discussion open until June 30, 2020