FLOOD RISK ANALYSIS FOR THE ISHIKARI RIVER CONSIDERING RAINFALL PATTERNS USING DOWNSCALED D4PDF DATA

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ABSTRACT

This study evaluated the flood risk of the Ishikari River basin under various climate change scenarios by using a large-ensemble dataset (d4PDF) with a high resolution of 5km. The top 20 and the top 36 rainfall events (corresponding to a return period of 150 years for the historical and future simulations, respectively) were selected. The Integrated Flood Analysis System (IFAS) was applied to simulate the flood risk under climate change scenarios after calibration and validation with observed discharge. After validation, we used the rainfall data from a large-ensemble dataset (d4PDF) as input to the IFAS model to assess the future flood risk. We found that the flood risk is expected to increase due to increases in rainfall for both historical and future simulations in the target basin. Moreover, the year of maximum rainfall (372 mm/72hr) does not agree with the year of greatest discharge of 17,982 m^3/s under the historical simulation. In the future simulation, we obtained two cases with the same maximum rainfall amount (454 mm/72hr), but the peak discharges differed (30,018 m^3/s versus 22,444 m^3/s, respectively). This shows that the ranking of rainfall for a certain event does not necessarily coincide with the peak discharge ranking. As a result, river discharge volume depends not only on the total rainfall, but also on the temporal and spatial rainfall distribution. These results of this study will be helpful in developing flood disaster prevention plans in the target basin.

Keywords: Flood risk, d4PDF, IFAS, river discharge, climate change

1. INTRODUCTION

In recent years, severe floods have occurred frequently throughout Japan, including in Hokkaido, where they have caused great loss of life, injury, and property damage. For example, in October 2019, super-typhoon Hagibis has been described by meteorologists as the strongest typhoon to hit the Kanto region of Japan in the last six decades. This typhoon brought strong winds and torrential rainfall, which led to severe flooding and landslides (NHK World-Japan, 2019). Additionally, in Hokkaido, the northern Japanese island (Figure 1), the consecutively four typhoons made landfall this island within two weeks in August 2016, caused enormous damage. Climate change due to global warming is considered to be the main cause of the extreme weather events of recent years.

According to the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC), severe natural disasters due to climate extremes have been occurring more often since 2000 (IPCC, 2012). Several studies have discussed climate change as a direct factor in flood risk from heavy rainfall (Fleming et al., 2012; Hirabayashi et al., 2008).

Therefore, a better understanding of river flooding trends and characteristics is a crucial concern for future flood prevention and mitigation. Recently, attempts have been made to estimate flood risk under various climate change scenarios (eg., Kimura et al., 2014; Yamada et al.,2018). Most of the results show that the flood risk is projected to increase as a result of extreme precipitation in the future in each study area. For example, Yamada et al. (2018) evaluated flood risk for two river basins (the Tokachi and Tokoro river basins) in Hokkaido under the climate change scenarios. This study used the rainfall data extracted from the "database for Policy Decision making for Future change" (d4PDF) with a high resolution of 5 km. The results indicated that flood risk is predicted to increase in both river basins due to increases in rainfall under climate change scenarios. These results promise to be useful in investigations on practical flood control plans that consider a high spatial and temporal resolution for a basin-scale. Therefore, in this study, we used the large-ensemble rainfall data from d4PDF with a high resolution of 5 km (Yamada et al.,2018). The hydrological model named the Integrated Flood Analysis System (IFAS) is used to simulate flood risk in the target basin. The model was developed by the International Centre for Water Hazard and Risk Management (ICHARM) (IFAS, 2014).

Currently, many studies have addressed flood evaluation and prediction under the impact of climate change. However, the simulation and prediction of flood risk for the Ishikari River basin, which is the most important river in Hokkaido, has not been studied. Therefore, the main objective of this study is to estimate flood risk in the Ishikari River basin with the following objectives: (1) to calibrate and validate the hydrological model (IFAS), (2) to simulate flood risk for the top 20 rainfall cases under historical simulation and the top 36 rainfall cases under future simulation.

2. METHODOLOGY

2.1 Study area

The target basin is the Ishikari river basin, which covers the central and western areas of Hokkaido. It flows through 48 municipalities (cities, towns, villages) that account for roughly 52 percent of Hokkaido's population. Sapporo, the thriving capital of Hokkaido, is at the lower reaches of the river. The basin is occasionally subject to heavy rainfall in summer, caused by typhoons and atmospheric depressions. The average annual rainfall is 1300 mm, and hydrologic peaks occur in August and September, the rainy season. The Ishikari river basin plays an important role in economic development in Hokkaido. At 268 km long and with a drainage area of 14,330 km^2, the river is the longest in Hokkaido and the second largest in the basin area in Japan (The Ishikari River, 2003). Figure 1 shows the location of the Ishikari river basin.

2.2 Characteristics of the d4PDF dataset

The "database for Policy Decision making for Future climate change" (d4PDF) consists of outputs from global warming simulations by a global atmospheric model with a horizontal grid spacing of 60 km (Mizuta et al., 2016) and from regional downscaling simulations covering the Japan area by a regional climate model with 20 km grid spacing (Sasaki et al., 2011). The dataset covers 60 years (1951-2010) x 50 members (total: 3,000 cases) for the historical climate simulation and 60 years (2051-2110) x 90 members (total: 5,400 cases) for the +4K future climate simulation.

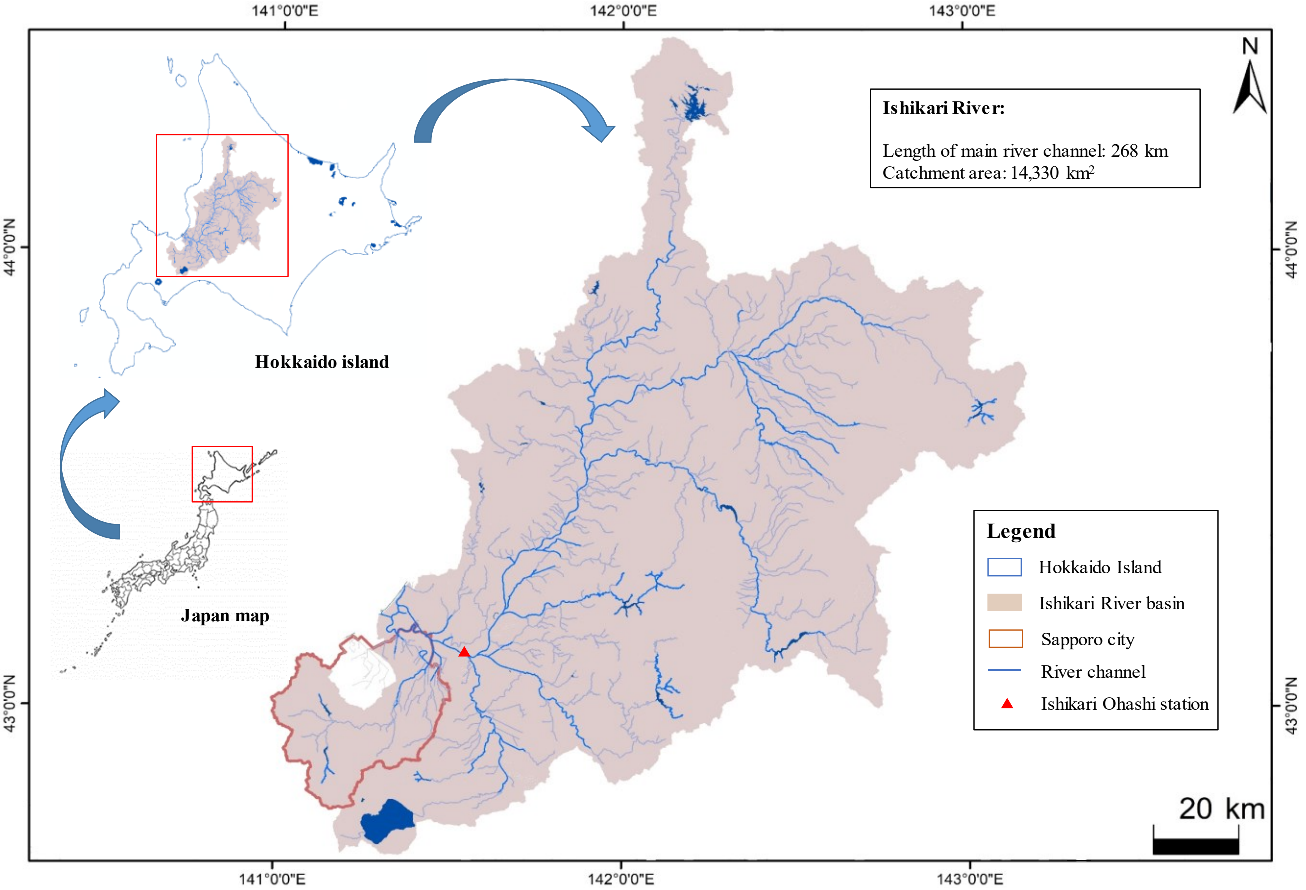


Figure 1. The Ishikari River basin, Hokkaido, Japan

In this study, we used 5 km resolution d4PDF data after dynamical downscaling from a previous study (Yamada et al., 2018). The rainfall dataset includes the 15 days of maximum rainfall for each case in Hokkaido region for 3,000 cases under the historical simulation and 5,400 cases under the future simulation. The rainfall data for simulation is selected with three steps. (1): we selected the rainfall data for locations within the Ishikari river basin. (2): we selected 72 hours as the annual maximum rainfall over the target basin. (3): the top 20 rainfall events and the top 36 rainfall events (corresponding to a return period of 150 years for the historical simulation and future simulation, respectively) are selected.

2.3 Hydrological model

The hydrological model was carried out using the Integrated Flood Analysis System (IFAS). This model was developed by the International Centre for Water Hazard and Risk Management (ICHARM) (IFAS, 2014). The IFAS is effective as a tool for simulating flood risk. IFAS uses Public Works Research Institute (PWRI) – distributed hydrological model as the runoff simulation engine. The model consists of a distributed hydrological model based on the tank model and a routing model based on a kinematic wave hydraulic model. IFAS has the capacity to input ground-based rainfall, radar rainfall, satellite-based rainfall, and a geographic information system (GIS) function. Hence, the IFAS system can be applied to predict flood risk for the basins with insufficient hydrologic data. A schematic of the IFAS model is shown in Figure 2. IFAS model has been successfully applied in many basins in the world and with satisfactory simulation results (eg., Aziz and Tanaka, 2011; Kimura et al., 2014). In this study, the IFAS model was calibrated with observed discharge data for a historical flood event in August 1981 and was validated for the flooding event in August 2016. We simulated the river discharge at the Ishikari Ohashi station, which is about 26.6 km upstream from the river amount (Figure 1). The rainfall data for the flood in August 1981 were provided by the Hokkaido Regional Development Bureau, and those for the flood in August 2016 are radar rainfall. After validation, IFAS model was applied to estimate river discharge under historical and future climate simulations derived from d4PDF.

The performance of the IFAS model can be evaluated by two indices: the Nash-Sutcliffe coefficient (*NS*) (Nash and Sutcliffe, 1970), and the peak discharge error (E_p) (Aziz and Tanaka, 2011). Each indicator can be described as below:

$$NS = 1 - \frac{\sum_{i=1}^{n}\left[Q_{M(i)} - Q_{C(i)}\right]^2}{\sum_{i=1}^{n}\left[Q_{M(i)} - Q_{AVG(i)}\right]^2} \tag{1}$$

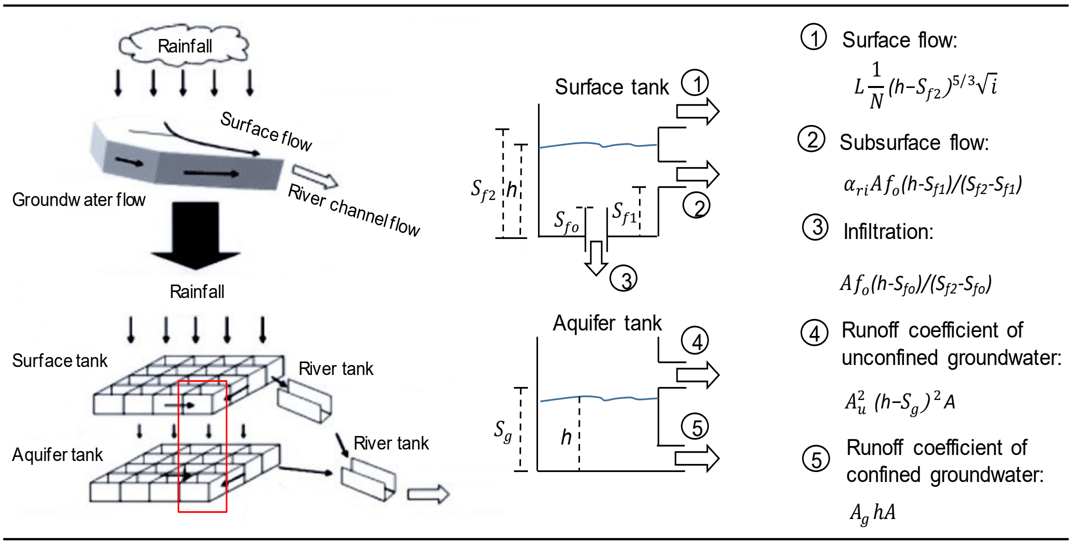
$$E_p = \frac{Q_{MP} - Q_{CP}}{Q_{MP}} \tag{2}$$

where Q_M: the observed discharge (m^3/s), Q_c: the simulated discharge (m^3/s), n: the number of data, Q_{AVG}: the average discharge for the observation (m^3/s), Q_{MP}: the peak value of observed discharge (m^3/s), Q_{CP}: the peak value of simulated discharge (m^3/s). The simulation model is acceptable if $NS>0.7$, and the smaller the E_p errors are, the better the model is.

3. RESULTS AND DISCUSSION

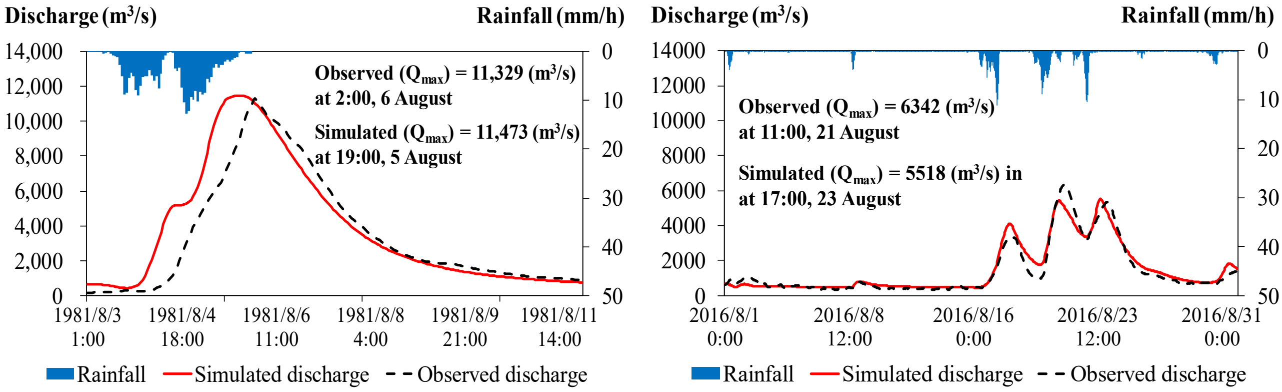
3.1 Hydrological model validation

Figure 3(a) compares the simulated and observed discharges for the historical flood in August 1981 after calibration. Figure 3(b) compares the simulated and observed discharges in the validation process for the flooding event of August 2016. In Figure 3(a), the simulated discharge at the Ishikari Ohashi station shows close agreement with the observed values, with a Nash-Sutcliffe (*NS*) of 0.81 in Eq.(1) and a peak discharge error (E_p) of -0.02 in Eq.(2). As a validation, IFAS well captured the flood duration and the peak discharge for the flood of August 2016, with a *NS* and an E_p of 0.94 and -0.13, respectively. These results suggest that the IFAS model can perform reasonably well in the Ishikari River basin.



where *L*: the length of cell (m), *N*: roughness coefficient of surface ($m^{-1/3}s$), *h*: the height of stored water (m), S_{f2}: maximum storage height (m), *i*: the gradient of slope, α_{ri}: the regulation coefficient for rapid intermediate flow, *A*: the area of cell (m^2), f_o: the final infiltration capacity (cm/s), S_{f1}: rapid intermediate flow (m), S_{fo}: the height where ground infiltration occurs (m), A_u: runoff coefficient of slow intermediate outflow ($m^{-1/2}s^{-1/2}$), S_g: height where slow intermediate outflow occurs (m), A_g: coefficient of base outflow (s^{-1}) (IFAS, 2014)

Figure 2. Schematic diagrams of the IFAS model



(a) (b)

Figure 3. Comparison of observed and simulated discharge at Ishikari Ohashi station for (a) the 1981 flooding event, (b) the 2016 flooding event.

3.2 Evaluating flood risk under the examined climate change scenarios

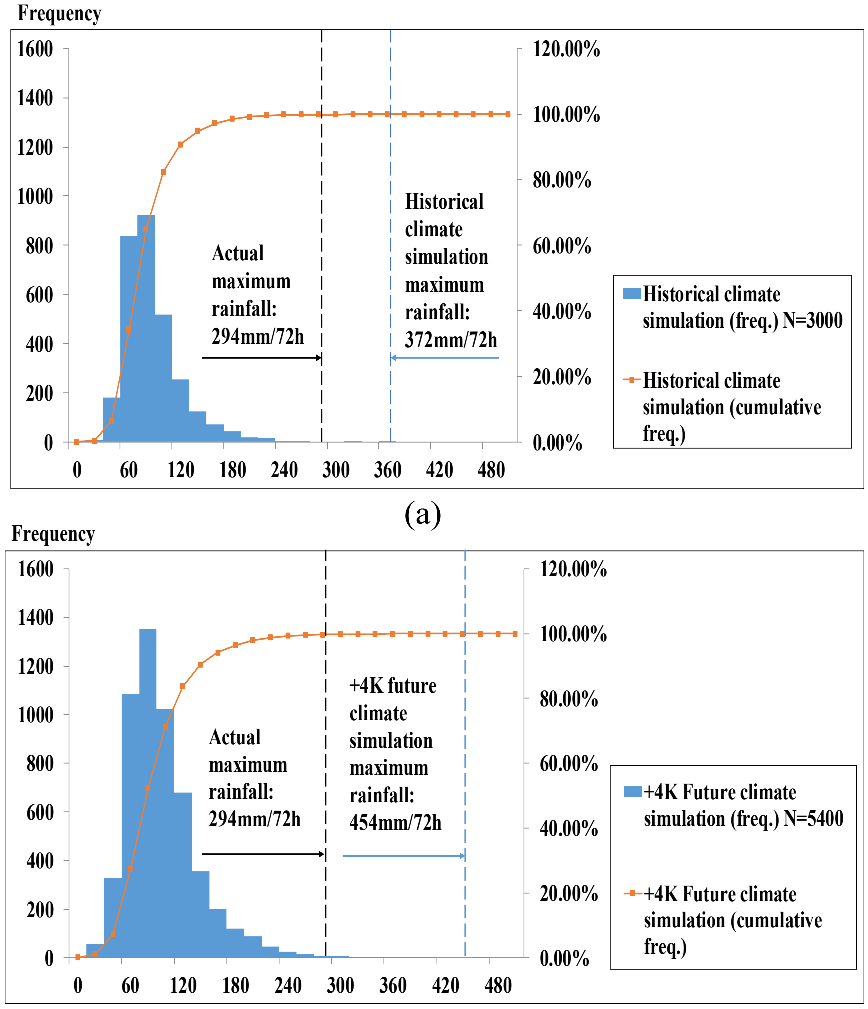
Figure 4 shows histograms for annual maximum rainfall (mm/72hr) in the Ishikari River basin for the historical (Figure 4a) and future simulations (Figure 4b). The results indicate that under the influence of global climate change, the rainfall amount is projected to increase for the historical and future simulations in the target area. The top 20 and the top 36 rainfall events and the peak discharge results for each event are defined in Table 1 and Table 2, respectively. From these tables, it can be seen that flood risk from heavy rainfall is projected to increase significantly. Moreover, the year of maximum rainfall does not coincide with the year of greatest discharge for either the historical or the future simulation.

In Figure 5, there are the simulated discharge results for the four cases including the years of maximum rainfall and the years of greatest discharge under the historical and future simulations. This difference can be explained by the distribution of annual maximum rainfall. From the annual maximum rainfall distribution for four cases in Figure 6, it can be seen that the large rainfall amount in the HPB_m004_1957 pattern (Figure 6b) is more evenly distributed in the target basin than the HPB_m043_2006 pattern is (Figure 6a). Additionally, for the HPB_m004_1957 pattern, the heavy rainfall is predominantly distributed in the southern part of the basin, close to the calculation station, whereas the heavy rainfall in the HPB_m043_2006 pattern occurs in the southwest area. Furthermore, by the time the peak discharge has occurred, the cumulative rainfall in the HPB_m004_1957 pattern is 346 mm, whereas the cumulative rainfall in the HPB_m043_2006 pattern is 290 mm. Therefore, even though the HPB_m043_2006 pattern has a higher total rainfall amount than the HPB_m004_1957 pattern, the estimated peak discharge at the Ishikari Ohashi station is lower for the former pattern than for the latter pattern.

As seen in Figure 5(c), and (d) for the future simulation, two cases with the same maximum rainfall amount (454mm/72hr) were obtained, but the peak discharge differed (30,018 m^3/s versus 22,444 m^3/s). The difference in peak discharge is also primarily due to the rainfall distribution pattern.

In Figure 6(c), which shows the HFB_MP_m112_2062 pattern, the large rainfall amount is evenly distributed from the upper reaches to the lower reaches of the basin, and heavy rainfall occurs in the southern area (which is close to the calculation station). Therefore, the peak discharge is predicted to be 30,018 m^3/s, which could cause a severe flood in the future. For the HFB_MI_m108_2094 pattern (Figure 6d), although heavy rainfall is also distributed in the southern part of the basin, the upper reaches have low amounts of observed rainfall. Moreover, by the time the peak discharge occurs, the cumulative rainfall in the HFB_MP_m112_2062 pattern is 400 mm, whereas the cumulative rainfall in the HFB_MI_m108_2094 pattern is 390 mm.

These results can be explained by the fact that the two cases have the same total rainfall, but that the peak discharges are obtained differently. The results show that the spatial and temporal rainfall distribution plays a vital role in the simulation of river discharge. Therefore, determining the impact of the spatial and temporal of rainfall distribution on flood risk by using large-ensemble data is necessary to achieve accurate prediction results.



(b)

Figure 4. Histograms of annual maximum rainfall (mm/72hr) in the Ishikari River basin for (a) the historical simulation, (b) the future simulation

Table 1. The top 20 rainfall events and the peak discharge results for each event

	Name of the year	Annual maximum rainfall (mm/72h)	Q_{max} (m^3/s)	No.	Name of the year	Annual maximum rainfall (mm/72h)	Q_{max} (m^3/s)
1	**HPB_m043_2006**	**372**	**12,789**	11	HPB_m005_2005	221	6,229
2	**HPB_m004_1957**	**346**	**17,982**	12	HPB_m084_1955	220	7,774
3	HPB_m063_1968	314	12,268	13	HPB_m088_1955	218	9,458
4	HPB_m010_1976	303	16,654	14	HPB_m006_1994	216	8,371
5	HPB_m089_2002	254	10,350	15	HPB_m061_1964	214	6,949
6	HPB_m065_2007	244	10,665	16	HPB_m064_1987	211	6,135
7	HPB_m086_1988	238	9,566	17	HPB_m024_1996	208	8,219
8	HPB_m045_1957	237	7,670	18	HPB_m025_1962	207	8,714
9	HPB_m004_2000	234	9,325	19	HPB_m046_1980	206	7,058
10	HPB_m007_1970	233	10,552	20	HPB_m043_1995	204	5,990

Table 2. The top 36 rainfall events and the peak discharge results for each event

No	Name of the year	Annual maximum Rainfall (mm/72h)	Q_{max} (m^3/s)	No	Name of the year	Annual maximum rainfall (mm/72h)	Q_{max} (m^3/s)
1	**HFB_MP_m112_2062**	**454**	**30,018**	19	HFB_MP_m103_2078	271	11,490
2	**HFB_MI_m108_2094**	**454**	**22,444**	20	HFB_MI_m114_2085	270	9,164
3	HFB_GF_m110_2052	386	26,109	21	HFB_MP_m114_2070	270	10,040
4	HFB_GF_M104_2072	373	22,677	22	HFB_MI_m113_2099	269	15,824
5	HFB_MR_m102_2062	356	13,851	23	HFB_GF_m110_2066	266	8,427
6	HFB_HA_m102_2065	345	17,975	24	HFB_MI_m115_2063	259	11,200
7	HFB_CC_m114_2085	331	11,826	25	HFB_MI_m102_2060	258	11,165
8	HFB_MI_m103_2103	325	18,572	26	HFB_GF_m108_2052	256	21,827
9	HFB_MI_m106_2059	315	16,510	27	HFB_HA_m115_2103	255	10,215
10	HFB_MP_m101_2067	311	10,992	28	HFB_GF_m111_2109	254	10,453
11	HFB_MI_m106_2083	305	13,615	29	HFB_MI_m113_2110	248	7,320
12	HFB_CC_m107_2084	304	10,537	30	HFB_GF_m112_2102	244	15,470
13	HFB_HA_m102_2067	301	12,774	31	HFB_MR_m102_2074	242	8,743
14	HFB_MR_m105_2091	300	8,990	32	HFB_MI_m101_2083	241	11,567
15	HFB_GF_m112_2053	296	16,196	33	HFB_HA_m104_2082	239	12,582
16	HFB_HA_m102_2105	288	13,427	34	HFB_HA_m101_2066	238	9,386
17	HFB_MR_m111_2066	287	12,171	35	HFB_HA_m105_2083	236	12,911
18	HFB_MI_m107_2060	279	14,309	36	HFB_CC_m110_2051	234	8,548

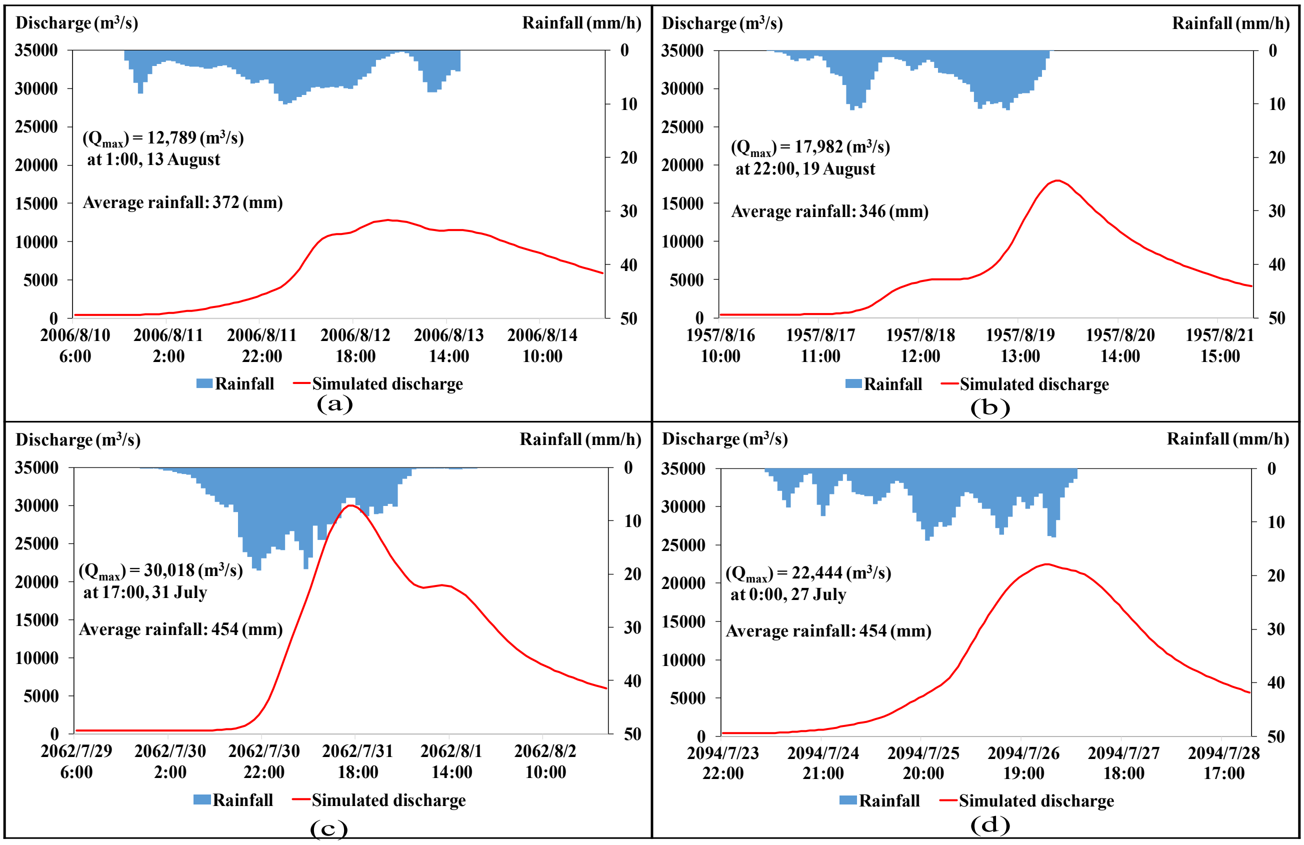


Figure 5. Discharge hydrographs for (a) the maximum rainfall event under the historical simulation (HPB_m043_2006), (b) the greatest discharge event under the historical simulation (HPB_m004_1957), (c) the maximum rainfall and the greatest discharge event under the future simulation (HFB_MP_m112_2062), and (d) the maximum rainfall event under the future simulation (HFB_MI_m108_2094)

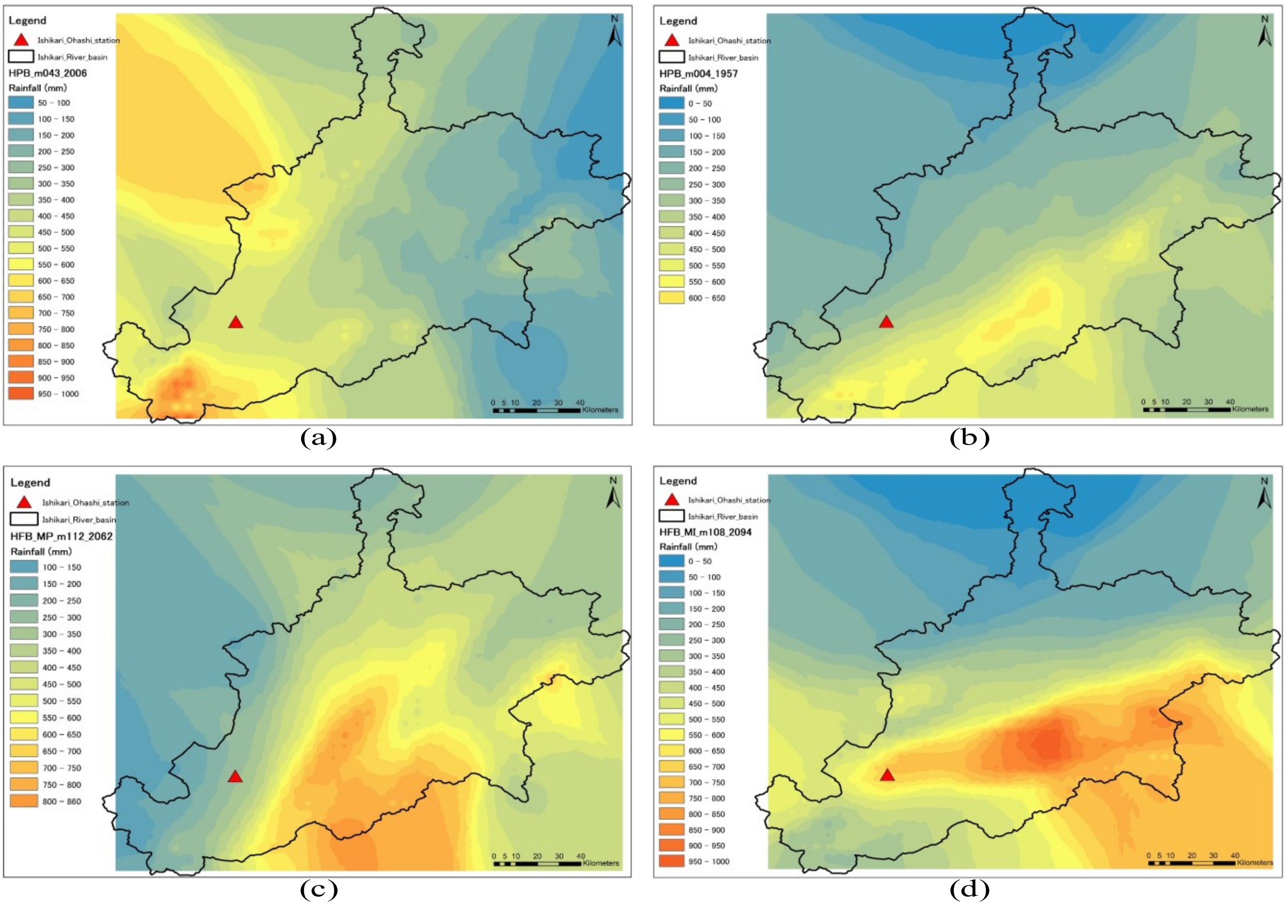


Figure 6. Rainfall distribution for (a) the maximum rainfall event under the historical simulation (HPB_m043_2006), (b) the greatest discharge event under the historical simulation (HPB_m004_1957), (c) the maximum rainfall and the greatest discharge event under the future simulation (HFB_MP_m112_2062), and (d) the maximum rainfall event under the future simulation (HFB_MI_m108_2094)

4. CONCLUSIONS

In this study, the following results were found:

- The IFAS model after validation can provide reasonable simulations of river discharge in the Ishikari River basin.
- The flood risk caused by extreme rainfall is expected to increase significantly in the target basin. Additionally, the ranking of rainfall for a certain event did not necessarily agree with the peak discharge ranking for the historical and future simulations. This difference can be explained by the distribution of annual maximum rainfall (mm/72h) over the basin. These results of this study will be helpful in developing flood disaster prevention plans in the target basin.
- In future studies, we will consider the influence of spatial and temporal rainfall distribution on flood risk under the historical and future simulations, and we will focus on two components: the exposure and vulnerability in the Ishikari River basin.

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