Research article

Impact Evaluation of Climate Change on Disaster Risk of Forested Watershed Rivers in Snowy Regions using SWAT+

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Abstract In this study, we analyzed the reduction in snowfall and snowmelt under climate change scenarios in a cold snowy region. Also, we clarified the causal relationship between deforestation and disaster risk in watershed management in Mishima Town, Fukushima Prefecture. We used SWAT+ to conduct simulations; the SWAT+ model of Mishima town was built in a previous study, and its reproducibility was verified by NSE and RMSE by correcting parameters and using auto-calibration. The latest set of models from the CMIP6, also used in the 6th Impact Assessment Report of the IPCC and statistically downscaled scenarios in Japan developed by the Center for Climate Change Adaptation, National Institute for Environmental Studies, was adapted to simulate climate change scenarios. The Emission Scenarios are based on RCP8.5, which has been used in future climate change discussions (i.e., the assumption that greenhouse gases will continue to increase without any global warming countermeasures). We simulated the end of the 21st century situation. As the result of the simulation, the RCP8.5 scenario showed a significant decrease in snowfall and snowmelt, with only one day of snowfall of RCP8.5 from January to March. The potential for early spring snowmelt water availability of RCP8.5 at the end of the 21st century could have been much higher. Additionally, we conducted a simulation of deforestation. We assumed that 5% of the forested area became agricultural land due to deforestation. Simulation results indicated that the surface flow under deforestation conditions was 145.1 mm, a 7% increase over the surface flow of the original forest prior to deforestation (135.1 mm). Heavy and long-lasting rainfall showed no difference in water storage function between the two cases, but 5% deforestation was shown to increase river discharge at the beginning of a rainfall event.

Keywords SWAT+, climate change, snowmelt, runoff, prediction

INTRODUCTION

Climate change significantly impacts the increase in average annual temperatures and fluctuations in rainfall and snowfall, resulting in more frequent natural disasters worldwide. The IPCC Sixth Assessment Report (2021) states that a 2°C rise in temperature would lead to a 14% intensification of rainfall intensity. On the other hand, land use change due to deforestation is known to increase runoff and affect flood risk, with 5.2 million hectares deforested each year (2000-2010), mostly in developing countries in Africa, Latin America, and Southeast Asia, where agricultural activities account for about 80% of the loss (Synthesis Report for REDD+ Policymakers, 2012). The impacts of climate change are also significant in Japan, where mountain disasters and floods are becoming more frequent and severe, and the importance of the water source recharge and flood mitigation functions of forests is increasing (Gunma Prefecture Basic Plan for Forest and Forestry 2021- 2030). Since an increase in average temperature due to climate change is expected to significantly impact the amount of snowfall and snowmelt and affect the availability of water for agriculture in early spring in snowy and cold regions, future predictions based on climate change scenarios are essential. Still, the assessment of the impact of climate change on water resources at the small watershed level has not been sufficiently verified.

In addition, although previous studies have examined the relationship between land use change due to urban development and other factors and disaster risk (Qingmu et al., 2017) and the flood control effects of agricultural land (Yoshikawa et al., 2009), there are few studies on the relationship between deforestation and additional agricultural land.

OBJECTIVE

In this study, we analyzed the effects of climate change on snowfall and snowmelt and the impact of deforestation on making agricultural land in the Hashigo River in Mishima town, Fukushima prefecture, a forested area with a cold and snowy climate.

We used SWAT+ to conduct simulations, the SWAT+ model of Mishima town was built in a previous study (Kikuchi et al., 2022), and its reproducibility was verified by NSE and RMSE by correcting parameters and using auto-calibration.

METHODOLOGY

Study Site

The study site is the Hashigo River watershed in Mishima Town in Fukushima Prefecture (Fig.1). The Hashigo River is a tributary of the Tadami River. The watershed is located at latitude 37.50 °-37.47 °, longitude 139.62 ° -139.63 °, and range of altitude 350-370 m. The watershed area is 2.85 km^2, covered mainly by mountain forests (Table 1). 0.4 % of paddy fields are located along the main river. The annual mean daily temperature, the minimum, and maximum daily temperatures are 10.6°C and 6.9°C, snowfall is from December to February, and snowmelt is from March to April. Rainfall is relatively heavy during the rainy season from June to July, and typhoons are more frequent from September to October. Annual precipitation was 1,340 mm in 2020.

Table 1 Land-use of the target watershed

Watershed area	Land-use (%)			River length
(km^2)	Forest	Grassland	Paddy field	(km)
2.85	98.4	1.2	0.4	2.5

Fig. 1 Location of target watershed (Hashigo River)

SWAT+

Utilizing a hydrological model for analyzing the hydrological cycle throughout a river basin is an effective method to assess the impacts of climate change on water resource management, flood control, and agriculture. SWAT (Soil and Water Assessment Tool) developed by USDA-ARS is a hydrological cycle model used worldwide for over 20 years (Williams et al., 2008). To face present and future challenges in SWAT code has undergone significant modifications over the past few years, resulting in SWAT+, a completely revised version of the model (Katrin et al., 2016). SWAT+ is a model that analyzes water movement by subdividing the target watershed into subwatersheds called HRUs (hydrologic runoff units) and can predict river discharge and water quality for an unspecified watershed with few input parameters. The data collection is shown in Table 2, and data sets of SWAT+ are shown in Table 3. The time interval for the calculations in this study was set to days. The warm-up period was set from 1st February 2019 to 31st December 2019, and the simulation period was set from 1st January 2020 to 31st December 2020. Some parameters were adjusted and entered from actual measurements.

Table 2 Data collection

Data	Source	Note
Elevation data	Geospatial Information Authority of Japan (GSI)	Raster data (10 m mesh)（Fig. 1 A）
Land use	The Japan Aerospace Exploration Agency (JAXA) and Earth Observation Research Center (EORC)	10m mesh <Land use: 12 categories>. Land use was confirmed by foot survey, and some obviously different land uses were corrected（Fig. 1 B）
Soil map	The National Institute of Agrobiological Sciences (NIAS)'s basic land classification survey data (Shapefile, 1:200,000)	Shapefile (polygon)
Soil component	Field survey data (17/Dec/2021)	Soil moisture content, EC, pH, specific gravity, permeability coefficient, particle size distribution
Weather data	National Institute for Environmental Studies of Japan (NIES)	10 min Data: River discharge (m^3/s) Daily data: rainfall, temperature (max., min., avg.), relative humidity, solar radiation, wind speed

Table 3 Data set of SWAT+ model

Item	Contents
Version	- SWAT+ Editor 2.0.4
Period	- Warm-up：2019/2/1-2019/12/31 Simulation：2020/1/1-2020/12/31
Time interval	- Daily data
Input parameters	- The following parameters are adjusted and input from actual measured values Permeability (soil k), maximum water capacity (awc), clay, silt, sand, rock, EC, clay, silt, sand, rock. - Snowfall temperature: 2.51°C, Melting snow temperature: 2.71°C
Calculation method	- Evapotranspiration calculation: Penman-Monteith method - Calculation of surface flow: Curve Number method

Climate Change Scenario

In this study, we generated a hypothetical dataset for the year 2090 by adjusting the data of 2020 using the variability parameters (e.g., temperature increases) from published climate change scenarios. As the publish methods, We adopted the latest set of models from the CMIP6 (Coupled Model Intercomparison Project 6th), which is also used in the 6th Impact Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and adapted statistically downscaled scenarios NIES2020 in Japan developed by the center for climate change adaptation, National Institute for Environmental Studies (NIES)（Ishizaki, 2021）. The Emission scenarios use the Representative Concentration Pathway (RCP) scenarios, introduced as part of the IPCC's Special Report on Emissions Scenarios (SRES). There are several RCP scenarios, but in this study, RCP8.5, which assumes no action on global warming and continued greenhouse gas emissions, was selected. The hypothetical dataset as input for the SWAT+ model to simulate how climate change will impact various factors: snowfall, snowmelt, and flow, comparing conditions between 2020 and 2090.

Table 4 Basic information on climate change scenario

Name of climate scenario	NIES2020
Climate model	MIROC6
Climate parameters	Max. and mini. temperature, precipitation, total solar radiation, relative humidity
Emission scenarios	RCP8.5
Forecast period	2090

Table 5 Data prediction of RCP 8.5 for 2090 and 2020 in Fukushima

SSP585-MIROC6-NIES2020 for Fukushima	2090			2020		
	Jan.	Feb.	Mar.	Jan.	Feb.	Mar.
Max temperature	6.2	7.5	11.4	3.0	3.5	8.1
Min temperature	-2.2	-2.1	1.2	-4.9	-5.1	-1.7
Relative humidity	70.3	67.1	70.1	73.6	72.2	71.8
Solar radiation	6.8	9.5	13.1	7.1	9.7	12.7
Precipitation	103.3	77.1	129.0	90.3	73.2	107.7

Deforestation Situation

In Mishima Town, a renewable energy project using woody biomass resources is being considered with the establishment of the Regional Recycling and Symbiosis Promotion Council. On the other hand, flood risk from deforestation needs to be adequately assessed. According to studies by the National Institute for Environmental (Ooba et al., 2017), the upper limit of forest use is estimated to be 1/50 (2%) due to the limitation of age class composition. In this study, the upper limit of forest use, 2%, was exceeded, and a case was assumed in which 5% of the forest area became agricultural land due to logging. From the standpoint of convenience in transporting timber, the area of deforestation was assumed to be two downstream watersheds (Fig. 1 Watershed 3 and 4).

RESULTS AND DISCUSSION

Climate Change Scenario

The simulation results based on the observed data for 2020 (Original) and the 2090 climate change scenario (RCP8.5) are shown in Fig. 2. The river discharge of January is more significant for RCP8.5 because precipitation is more considerable for RCP8.5. On the other hand, after mid-February, the original data tends to have more significant river discharge.

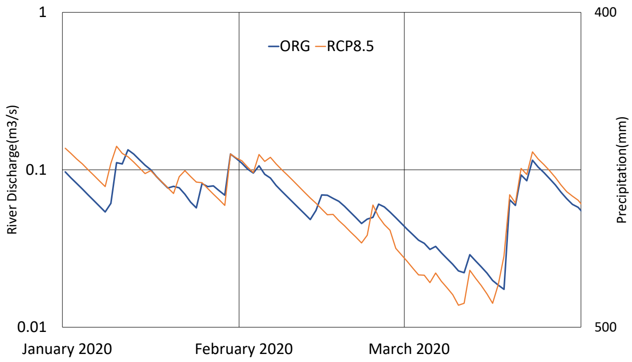

Fig. 2 River discharge of original (2020) and RCP8.5 (2090)

The results of average river discharge, snowmelt, snowfall, evapotranspiration, days of snowfall, and days of snowmelt from January to March are shown in Table. 6. River discharges of RCP 8.5 are higher than the originals, except in March. After mid-February, the river discharge of RCP8.5 temporarily decreased a little, but there is no significant difference between RCP8.5 and the original in terms of monthly river discharge. On the other hand, the original from January to March had 78.8 mm of snowfall and 93.4 mm of snowmelt, while RCP 8.5 had 5.7 mm of both snowfall and snowmelt. In addition, RCP 8.5 has only 6-7% of the original snowfall and snowmelt, and RCP 8.5 has only one snowfall and snowmelt day. The above results indicate a significant decrease in snowfall and snowmelt in RCP 8.5 in 2090. The evapotranspiration of RCP 8.5 during January-March is 19.48 mm, which is about 1.37 times higher than the original (14.19 mm). The impact of climate change on the flow rate indicates that there is no significant difference between RCP8.5 and the original (2020) due to increased rainfall. The results indicate that while changes in river discharge may not be immediately apparent due to increased rainfall in the RCP 8.5 scenario, the alarming decrease in snowfall and snowmelt could have far-reaching consequences for water resources management and the ecosystem.

Table 6 Simulation results of the original (2020) and RCP8.5 (2090)

	Original				RCP 8.5			
	Jan.	Feb.	Mar.	Total	Jan.	Feb.	Mar.	Total
Average River discharge (m^3/s)	0.086	0.067	0.050	0.068	0.098	0.069	0.049	0.075
Snowmelt (mm)	52.80	32.80	7.80	93.40	0.00	5.70	0.00	5.70
Snowfall (mm)	38.30	32.70	7.80	78.80	0.00	5.70	0.00	5.70
Evapotranspiration (ET) (mm)	0.65	1.80	11.74	14.19	1.13	3.17	15.18	19.48
Snowfall days	7	6	5	18	0	1	0	1
Snowmelt days	10	10	4	24	0	1	0	1

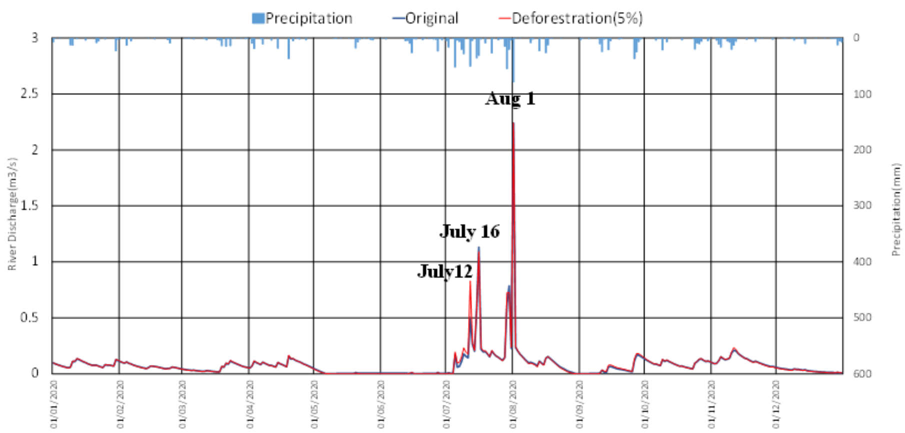

Fig. 3 River discharge of the simulation of deforestation

Deforestation Situation

In the one-year river discharge data for 2020 (Fig. 3), days with particularly high daily river discharge (July 12th, July 16th, and August 1st) were extracted and compared between the original and deforestation. there were no significant differences for July 16th and August 1st, but July 12th increased the daily river discharge by a factor of 1.66. Heavy and long-lasting rainfall showed no difference in water storage function between the two cases, but 5% deforestation was shown to increase river discharge at the beginning of a rainfall event. The result of the deforestation situation is shown in Table 7. Surface flow of deforestration was 145.1 mm, 7% increase over surface flow of the t original (135.1 mm). The ET of deforestration was 395.9 mm, 0.3% increase over ET of the original (394.7 mm). The result of surface flow also indicates that the water storage function of the watershed is declining due to the decrease in forest area. This effect was particularly pronounced at the beginning of precipitation events, indicating that the presence of forests role which moderate early-stage discharge.

Table 7 Simulation results of the original (2020) and deforestation 5%

	Surface flow	Evapotranspiration (ET)	River discharge			
			Annual average	July 12th	July 16th	Aug. 1st
Original	135.1 mm/y	394.7 mm/y	0.083 $m^3/s/y$	0.50	1.13	2.24
Deforestation 5%	145.1 mm/y	395.9 mm/y	0.084 $m^3/s/y$	0.83	1.09	2.24

CONCLUSION

Herein, we analyzed the effects of snowfall and snowmelt (from January to March) in a small watershed in Mishima, Fukushima Prefecture. The results of the climate change simulations indicate a significant reduction in snowfall and snowmelt in RCP8.5 (2090) within CMIP6 when compared to the original simulation results for 2020. If climate change were the RCP8.5 scenario, agricultural use of spring snowmelt would be problematic by the end of the 21st century. However, there would be no significant difference in river discharge because of increased precipitation. However, climate change mitigation measures need to take into account that the water storage function of forests through snowfall and snowmelt will disappear. In addition, it may not show significant changes in the short term, but the loss of snowfall and snowmelt and the associated changes in forest water storage functions by snow raise concerns about the long-term sustainability of water resources and ecosystems.

The results of the deforestation simulation showed a 7% increase in annual surface runoff and a reduction in water storage function during the first rainy season. It is crucial to consider the need for the water storage function of forests in combination with the effects of climate change and deforestation. Both climate change scenarios and land use change simulations are few in small watershed studies. However, local governments need to update their water resource management based on climate change scenarios, and in small watersheds, water balance simulations based on climate change scenarios should be more necessary. Although only runoff analysis was conducted in this study, inundation analysis based on calculated river flow data would provide a more accurate assessment of disaster risk.

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