Research article

Estimation of Long-term River Discharge in Forested Watershed in Snowy Region by SWAT

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Abstract 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. Although there are various hydrological models developed, in this study, Soil and Water Assessment Tool plus (SWAT+) is used as it is widely used and predicts the impacts of land use management in watershed management. SWAT+ is a complex quasi−physically based water quality model relying on numerous input files and parameters, thus this poses a great challenge when attempting to set up the model manually, and there is a lack of information regarding the validation of SWAT+'s of performance for snow accumulation and melting processes. The objective of this study is to estimate long-term streamflow in forested watershed in snowy region using SWAT+, and to verify the accuracy of the estimation and to confirm the improvement of the accuracy by adjusting parameters. In order to improve the accuracy of simulation, "the saturated hydraulic conductivity of soil layer" and "the available water capacity of soil layer" were adjusted for parameter of soil moisture content, moreover, we adjusted parameter of temperature of "snowfall" and "snowmelt". Finally, "the time of lateral flow travel" which is difficult to measure was calibrated using the auto-calibration of SWAT+. As the results, it was difficult to achieve high accuracy in predicting river discharge with the default parameters of SWAT+, but some months (May-Oct) could be accurately predicted after adjusting parameters using measured data and conducting the auto-calibration. On the other hand, simulations during snowfall and snowmelt term (Dec-Mar) were less accurate and need to set more detailed conditions.

Keywords SWAT, long-term river discharge, snowmelt, runoff, prediction,

INTRODUCTION

With rising temperatures by climate change will threatens to disturb this balance by altering the fraction of precipitation falling as snow and the timing of snowmelt, which may have profound effects on food production (Qin et al., 2020). 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 that has been used worldwide for more than 20 years (Williams et al., 2008). In order to face present and future challenges in SWAT code has undergone major modifications over the past few years, resulting in SWAT+, a completely revised version of the model (Bieger et al., 2016).

SWAT+ is a complex quasi–physically based water quality model relying on numerous input files and parameters to represent hydrologic, climatic, water quality, management, plant, and soil processes within a watershed, thus this poses a challenge when attempting to set up the model manually (Qi and Grunwald, 2005). Moreover, although snowmelt hydrology is an important subcomponent and prediction of snow accumulation and melting processes are one of the great challenges for SWAT+ (Qi and Grunwald, 2005), but there is a lack of information regarding the validation of SWAT+'s snowmelt season performance (Wang and Melesse, 2005), especially studies of SWAT+ in forested watershed in snowy region are currently lacking.

OBJECTIVE

The objective of this study is to estimate long-term streamflow in forested watershed in snowy region using SWAT+, and to verify the accuracy of the estimation and to confirm the improvement of the accuracy by adjusting parameters. For this, in this study, SWAT+ was used to simulate the daily flow in the Hashigo River in Mishima town, Fukushima Prefecture which is a forested area with a cold and snowy climate. The several parameters were adjusted based on measured data, and the SWAT+ automatic parameter calibration method was conducted to improve the accuracy of model. The calculated river discharge was verified by comparing with the observed.

METHODOLOGY

General Description of Study Site

The study site is the Hashigo River watershed in Mishima Town in Fukushima Prefecture (Fig.1). Hashigo River is a tributary of the Tadami River. The watershed locates at latitude 37.50^o - 37.47^o, longitude 139.62^o-139.63^o and range of altitude 350-370 m. Watershed area is 2.85 km^2, mostly covered by mountainous forest (Table 1). The watershed has 0.4% of paddy field which is located along the main river. Annual mean daily temperature, minimum and maximum daily temperature is 10.6°C, 6.9°C and 15.3°C. The snowfall period is from December to February, and the snowmelt period 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 (2019-2020) was 1,632 mm in 2019 and 1,340 mm in 2020.

Table 1 Land-use of the target watershed

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

Data Analysis Using SWAT+

SWAT creates objects called Hydrologic Response Units (HRUs), which are lumped areas within a subbasin with a combination of land use, soil type, and slope, etc., for simulating all hydrologic processes occurring in the landscape (Bieger et al.,2016). SWAT+ also introduces Landscape Units (LSUs), which allow for the separation of lowland (wetland) processes from upland processes. The use of LSUs allows for a more detailed classification of HRUs compared to SWAT and increases the number of HRUs. (Kakarndee et al., 2020).

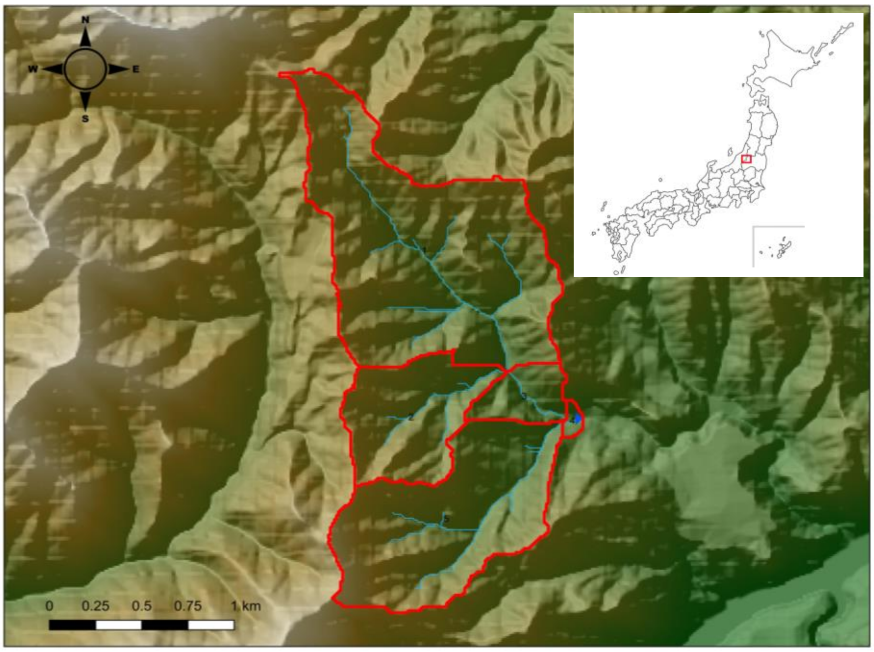

Fig. 1 Location of target watershed (Hashigo River)

The modeling process adopts the water balance method, which is expressed as follows (1).

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{serf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day (mm), t is the time (day), R_{day} is the amount of precipitation on day (mm), Q_{surf} is the amount of surface runoff on day (mm), E_a is the amount of evapotranspiration on day (mm), W_{seep} is the amount of water entering the unsaturated zone from the soil profile on day (mm), Q_{gw} is the amount of return flow on day (mm).

The subdivision of the watershed enables the model to reflect differences in evapo-transpiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance (Neitsch et al., 2009). The surface runoff is estimated using the NRCS Curve Number (CN) method (2).

$$Qsurf = \frac{(R_{day} - I_a)^2}{R_{day} - I_a - S} \qquad \because \quad R_{day} > I_a \quad (2)$$

Where Q_{surf} is the surface runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstraction (surface storage, interception, and infiltration prior to runoff) (mm), S is the retention parameter (mm).

The retention parameter depends on topography (slope), soil, land-use, management practices, and changes with the time due to soil water content (3).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

Where *CN* is the NRCS curve number corresponding to antecedent water content, soil infiltration, land-use and land management conditions (Kakarndee et al., 2020).

Evaluation of the Simulated Data

The Root Mean Squared Error (RMSE) is used to indicate the degree of fit between the simulation and observed values (4).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} EV}{n}} \quad (4)$$

Where *EV* is error variance (squared of observation value minus simulation value) and *n* is number of observation days.

The Nash-Sutcliffe Efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - Q_{ave})^2} \quad (5)$$

Where Q_{sim} is the simulated value (m^3/s), Q_{obs} is the observed value (m^3/s), and Q_{ave} is the average of observed value for the term of simulation (m^3/s).

Q_{sim} and Q_{obs} are respectively the simulated and observed streamflow at time step (m^3/s), *P* and *Q* are the corresponding means of the simulated and observed streamflow over the entire period (m^3/s), and *n* is the total number of streamflow data points.

Description of Spatial Data

The spatial data used in SWAT+ are Digital Elevation Model (DEM), soil and land-use data. 10 meters resolution elevation data obtained from the Geospatial Information Authority of Japan (GSI) was used for DEM. Soil maps were obtained from the National Institute of Agrobiological Sciences (NIAS)'s basic land classification survey data (Shapefile, 1:200,000). The default parameters in SWAT+ database was used for soil parameters. The High-Resolution Land Use and Land Cover Map of Japan (10 m grid size) prepared by the Japan Aerospace Exploration Agency (JAXA) and Earth Observation Research Center (EORC) was used for the land-use data. A 5% threshold area was used to define HRUs applying a 5% threshold means that land-uses, soils and slope ranges whose areas are less than 5% of the subbasin area are eliminated from HRU formation within each subbasin. A total of 123 HRUs were created using these spatial data, 45 of which were defined as actual HURs.

Description of Temporal Data

Daily data for discharge of river (measured at 10-minute intervals) and rainfall, maximum and minimum temperature, relative humidity, solar radiation, and wind speed were measured automatically by networked weather station. The meteorological data are for the years February 2019 to December 2020. In this study, Penman-Monteith was used as the calculation method for evapotranspiration (Okazawa and Takeuchi, 2016).

RESULTS AND DISCUSSION

Simulation of Daily River Discharge

The SWAT+ model was built from the above data. In the first calculation, the default parameters of SWAT database were used for the parameters, and the calculation period was set from February

2019 to December 2020. The calculation results are shown in Fig. 2. The peak river discharge during the rainfall event is higher than Observed value. In addition, the river discharge during snowmelt events (From February to April in 2019 and 2020) is lower than observed data, and the snowmelt rate is not properly reproduced.

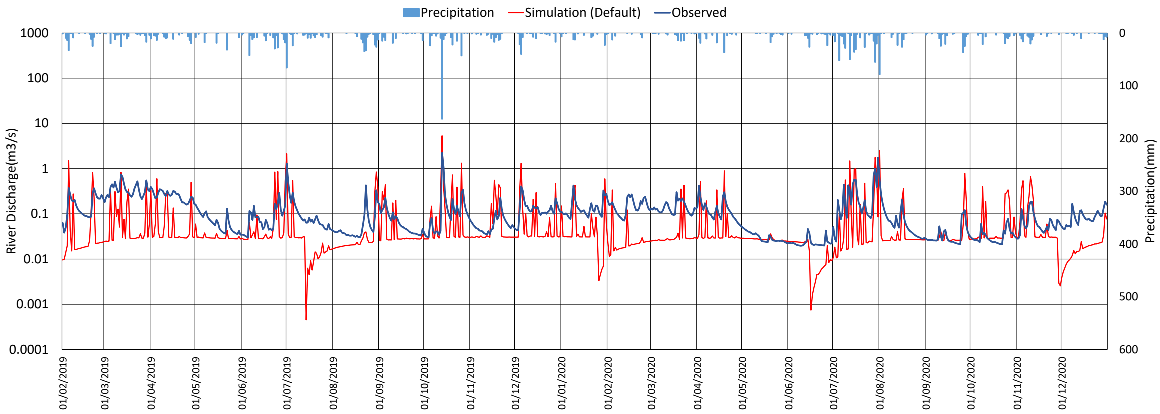

Fig. 2 River discharge of the first simulation results

Simulation after Adjusting Parameters

Comparing the first simulation and observed value, most of the data between December and March was rainfall, and snowfall and snowmelt were not properly reproduced, thus the parameter of snowmelt and snowfall temperature needed to be adjusted. Using the meteorological data which was maximum temperature, average temperature, and snow depth collected at 10-minute intervals by a networked weather station, the snowfall temperature (fall_tmp) and snowmelt (melt_tmp) were calculated to replace the default parameters (fall_tmp: 1.0°C, melt_tmp: 0.5°C). The snowfall temperature was set to the average temperature (2.51°C) on days when there was snowfall (November and March within 2019-2020). The snowmelt temperature was set to the maximum temperature (2.71°C) on days when there was no rain (during December-February 2019-2020) and the snow depth decreased by at least 1 cm.

The peak river discharge of surface runoff in the first simulation was higher than observed data, and it was assumed that parameter of infiltration was not properly recognized in default settings. Therefore, the default parameter which were the saturated hydraulic conductivity of soil layer (soil_k) and the available water capacity of soil layer (awc) were adjusted using the soil data surveyed by the National Institute of Agrobiological Sciences of Japan. The data was input for the first layer (soil_k: 159.84 mm/hr, awc: 0.70 mm/mm) and the second layer (soil_k: 25.20 mm/hr, awc: 0.67 mm/mm).

Simulation After Auto Calibration

In addition to the adjustment of the above parameters, a calibration was conducted using the SWAT+ auto-calibration. The auto-calibration uses the observed value to correct the parameters and improves the value of NSE, RMSE and MSE by repeating the simulation. The auto-calibration can be selected from NSE, RMSE and MSE. In this study, NSE was selected for the auto-calibration. The parameters calibrated for the auto-calibration are those that are difficult to measure and input. In this study, the time of lateral flow travel (lat_time) was calibrated because the time lag between rainfall and groundwater retention time or direct runoff is difficult to measure. The results of adjusting the parameters and the results of automatic calibration of lat_time are shown in Fig. 3.

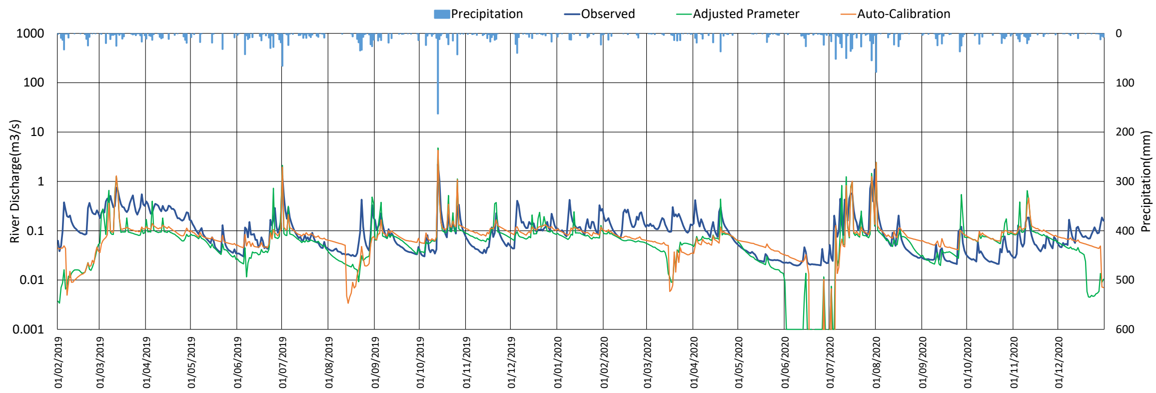

Fig. 3 River discharge of the simulation after calibration of parameters

The river discharge after the calibration within February to April was closer than the first simulation to the observed data. The calibration slowed the decrease in the river discharge after the peak of flow and increased the correlation between simulated and observed values

Accuracy of the Obtained Result

The NSE for each month were calculated from the simulation results of the default parameter, adjusted parameter, and auto-calibration. The results are shown in Fig. 4, where the NSE is an evaluation index that takes into account the variability, and the closer the value is to 1, the highest accuracy. Within Snowfall season (Dec-Feb) and snowmelt season (Mar-Apr), the value of NSE is low, indicating low accuracy. The accuracy of the adjusted parameter and auto-calibration were shown to be improved over the default parameter in NSE. The accuracy is relatively good during the season when there was not much rainfall, while the accuracy tends to decrease from the snowfall season to the snowmelt season (Apr-Dec). The results of calculating the NSE for whole period are -0.70 for default parameter, -0.02 for adjusted parameter, and 0.27 for auto-calibration. The RMSE for each month were calculated from the simulation results of the default parameter, adjusted parameter, and auto-calibration.

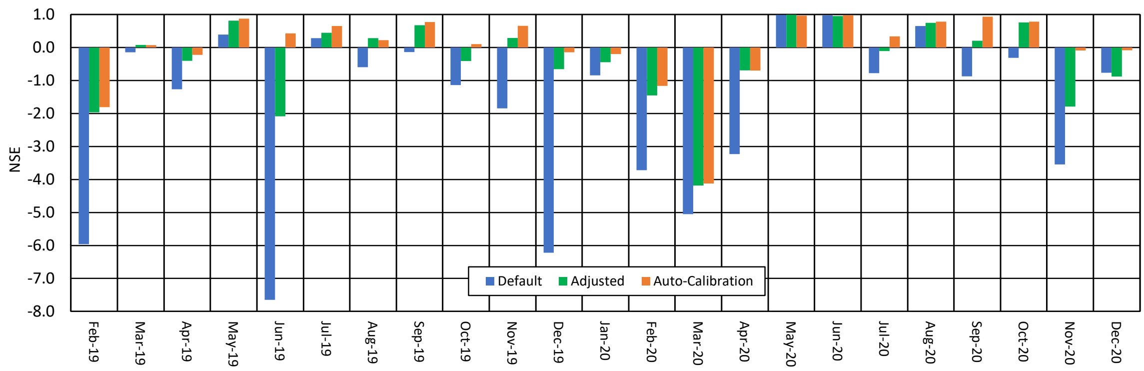

Fig. 4 The monthly NSE of river discharge for each simulation

The results are shown in Fig. 5. The best value of RMSE is 0, which is an evaluation index that emphasizes the difference between the actual value and the observed value. During rainfall events, the value of RMSE is high and the accuracy is evaluated to be low. During low rainfall events, the river discharge is low and the accuracy is better because the difference between observed and predicted values become smaller. The RMSE of auto-calibration has lower values overall and is rated at higher accuracy compared to the other simulations. The RMSE for the whole period was calculated to be 0.21 for the Default parameter, 0.16 for the adjusted parameter, and

0.14 for the auto-calibration.

In the simulation with default parameters, NSE is negative in most months. On the other hand, by adjusting parameters and conducting auto-calibration, some months showed NSE are more than 0.5. RMSE was improved even when auto-calibration was conducted based on NSE. NSE during snowfall and snowmelt (Dec-Mar) is lower than other term, even with parameter adjustments and auto-calibration. It was shown that except for the snowfall and snowmelt season, reproducibility of the river discharge can be secured.

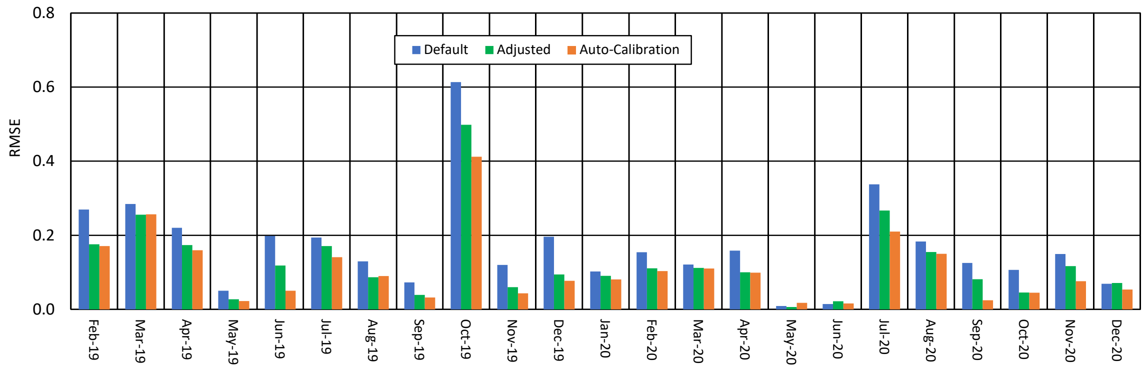

Fig. 5 The monthly RMSE of river discharge for each simulation

CONCLUSION

The accuracy of SWAT+ in forested snowfall areas was verified by simulating river discharge in the Hashigo river in Mishima town, Fukushima prefecture. According to the results, although it was difficult to secure high reproducibility in simulations using default parameters, the accuracy of simulations could be improved by adjusting parameters and conducting auto-calibration. In this study, soil data could not be measured, thus the accuracy of the simulation would be improved by using the actual measured soil data. RMSE was improved even when auto-calibration was performed based on NSE in this study, on the other hand, it is necessary to select the auto-calibration criteria among NSE, RMSE, and MSE according to the purpose because each calibration criteria have different characteristic. It is quite difficult to ensure reproducibility of simulations during the snowfall and snowmelt season compared to other because of the complexity of conditions such as different elevations and slopes, thus to ensure reproducibility of snowfall and snowmelt, setting more detailed conditions are needed for prediction using SWAT+. Although the simulation period was from February 2019 through December 2020, weather and flow data will continue to be measured to verify the accuracy of the simulation.

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