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Article

Development of SWAT-Paddy for simulating lowland paddy fields

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Abstract: Recent increase in global consumption of rice led to increased demand for sustainable water management in paddy cultivation. In this study, we propose an enhanced paddy simulation module in the SWAT model to evaluate sustainability of paddy cultivation. Enhancements added to SWAT are: 1) to modify water balance calculation for impounded fields, 2) to add an irrigation management option for paddy fields, which is characterized by flood irrigation with target water depth, and 3) to add puddling operation that influences water quality and infiltration rate of top soil layer. In a case study, the enhanced model, entitled SWAT-Paddy, was applied to an agricultural watershed in Japan. Results showed that the SWAT-Paddy successfully represents paddy cultivation, water management, and discharge processes. Simulated daily discharge rates with SWAT-PADDY (R^2=0.8) were superior to SWAT2012 result (R^2=0.002). SWAT-Paddy allows simulating paddy management processes realistically and thus, can enhance model accuracy in paddy-dominant agricultural watersheds.

Keywords: SWAT, water quality, paddy fields, irrigation, rice, watershed

1. Introduction

Rice is the staple food of more than half of the world's population and supplies more dietary energy than many other grain crops [1]. Consumption of rice is increasing because of population growth in many African as well as South, Southeast and East Asia countries [2, 3]. Increasing demand for rice requires land productivity of paddy fields to increase by 0.6 ton/ha globally, during the next 10 years [4]. To increase land productivity, several methods are generally used: increasing the number of rice cultivations per year, improving crop yield potential with genetic modification, or applying more agrochemicals, fertilizers, and irrigation. In addition, improving soil fertility is important to sustainable crop production. [5]. Paddy fields are cultivated under inundation of irrigated water as these consume and discharge a large volume of water. Therefore, paddy cultivation often affects local water resource sustainability by consuming a large amount of water and discharging pollutants into downstream water bodies [6-8]. To mitigate impact on water quality in watersheds containing paddy fields, a management plan for land use, irrigation, and drainage should be employed. In order to assess the sustainability of natural resources such as land and surface or ground water, several hydrological models have been used including MIKE Système Hydrologique Européen (MIKE SHE) [9, 10], Hydrological Simulation Program-FORTRAN (HSPF) [11, 12], and others [13, 14]. Soil and Water Assessment Tool (SWAT) is one of the hydrological models used to assess sustainability of land and water resources, considering agricultural production at the watershed scale [15, 16]. SWAT has been globally applied to address water quantity and associated challenges [17-19], including irrigation management [20, 21] and land management plan [22, 23], and effects of climate change on hydrological cycle [24, 25]. Because several kinds of software tools are available to prepare input data (ArcSWAT and QSWAT, http://swat.tamu.edu/software/), check errors in a simulation (SWAT-Check, http://swat.tamu.edu/software/swat-check/), and calibrate parameters (SWAT-CUP, http://swat.tamu.edu/software/swat-cup/) of a SWAT model simulation, the users of SWAT can easily apply a model. Therefore, SWAT model has a significant potential to help administrators make sustainable management plans for watersheds with paddy fields.

However, SWAT is not designed to model wetting condition with water inundation commonly practiced in paddy fields [26, 27]. To mimic water impoundment in paddy fields in SWAT simulation, the pothole module, which is available in SWAT, was used in several studies [28, 29]. However, the pothole module was originally developed to model the hydrologic characteristic of pothole landscapes that are common in the Corn Belt and Great Lakes in US. Sakaguchi et al. [30] pointed out the unsuitability of pothole module to simulate paddy water balances. To date, a handful of studies have been published regarding paddy modeling with the SWAT model. Xie and Cui [31] modified the existing pothole algorithm to simulate hydrological processes in paddy fields. Boulange et al. [32] developed PCPF-1@SWAT by combining a field scale model for estimating pesticide concentration in paddy water and surface soil (Pesticide Concentration in Paddy Field-1; PCPF-1 [33]) with the modified pothole model to evaluate the impact of pesticides in paddy fields. In the water balance computation, lateral seepage through embankment was considered in this model. Sakaguchi et al. [30] developed a paddy model based on the modified pothole. In this model, a new parameter representing the potential percolation rate of paddy fields was proposed. This parameter was defined as a hydraulic property that represents lateral seepage and vertical percolation from paddy impoundment in one term. Therefore, an advantage of Sakaguchi's model compared to PCPF-1@SWAT, which requires users to define two parameters to represent water loss from impoundment through paddy soil, is lesser number of fitting parameters for paddy simulation. Sofiyuddin et al. [34] analyzed the performance and structure of Sakaguchi's model by comparing it to the original SWAT model, and concluded that the proposed model structure improved the model performance. Though those models showed acceptable simulation results in their research, the structures of those models are still based on the concept of pothole module. The characteristics of potholes are conceptually different from paddy fields in the aspects of hydrology and agricultural management. Depth of impoundment in a paddy field is controlled by a farmer every day, considering the growth of paddy crop and climatic conditions. In addition, a difference exists between soil water conditions in paddy fields and potholes. Soil in the pothole region is completely drained with tile drainage when a field is used for crop production [35]. However, soil is kept wet under paddy impoundment to stabilize water supply to paddy plants, to control dynamics of organic matter, to supply inorganic mineral salts contained in irrigated water, to control weeds, to prevent damages by blight and harmful animals, insects, and other living things, and to maintain temperature [36]. Furthermore, agricultural management practices in paddy fields are unique and distinctive, and have sophisticated effects on hydrology and crop growth. To keep paddy field impounded, puddling, which means mixing soil and impounded

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water before transplanting, is usually carried out by farmers. Puddling decreases infiltration rate of soil and it allows a paddy field to be impounded. Besides, puddling makes water muddy by mixing surface soil and impounded water and thus, discharge water from paddy fields shortly after puddling often contains more sediment and pollutants than usual. However, in the SWAT modifications used in the previous studies, puddling was not taken into account. In addition, previous studies revealed that paddy fields sometimes discharge nutrient with a large amount of water [6, 37].On the other hand, polluted irrigation water is purified in paddy fields because of plant uptake, biodegradation, denitrification, and cyclic water use in paddy field districts [38, 39]. Therefore, agricultural management in paddy fields should be taken into account when environmental conservation practice is planned in watersheds containing them [40]. Furthermore, paddy fields should be modeled based on their own unique hydrological process and agricultural managements.

The goal of this study was to enhance paddy simulation by improving accuracy in watershed modeling using the SWAT model. As an objective in this research, to simulate paddy fields water management, SWAT2012 was modified, 1) to equip with a new water balance model including water impoundments in paddy fields, 2) to add an irrigation management option for paddy fields, which is characterized by flood irrigation with target ponding depths managed on a daily basis, 3) to consider that puddling influences discharge water quality and infiltration rate during growing periods. The modified model was named SWAT-Paddy. To examine the model performance, SWAT-Paddy was applied to an actual watershed containing paddy fields in Japan.

2. Materials and Methods

2.1 Overview of SWAT model simulation

SWAT is a semi-distributed and process-oriented eco-hydrological model that computes water, nutrients, and pesticide discharge from a watershed on a daily time step [15]. Water and mass balance, plant growth, and management practices are simulated in each hydrological response unit (HRU), which is generated by overlying maps of land use, soil, and slope. Then, outputs from HRUs are aggregated at subbasin level and routed downstream through a channel network. This enables the model to represent hydrological characteristics of watershed efficiently, with reasonable approximation. For the simulation, SWAT requires input data of weather, maps, and schedule of management practices. Detailed description of the model is available in SWAT2012 theoretical documentation [29].

2.2 Development of SWAT-Paddy

In previous studies, the pothole module was often used to model impoundment in paddy fields [30-32]. However, computational algorithm of the pothole model is not targeted on the hydrological process in paddy fields (Figure 1) and a paddy field and a pothole have conceptually different hydrological characteristics. Therefore, the pothole module is not appropriate to simulate paddies to aid decision making or agricultural policy development. In this study, we propose a scheme to simulate paddy fields based on their physical hydrological processes, which can be the basis of further modification and application of SWAT in paddy field districts. A terrestrial process was modified, as shown in Figure 2, for this purpose. Besides, agricultural management practices in paddy fields are different from the other farmlands assumed in SWAT. Thus, new paddy management options are added to the scheduled management scheme in SWAT.

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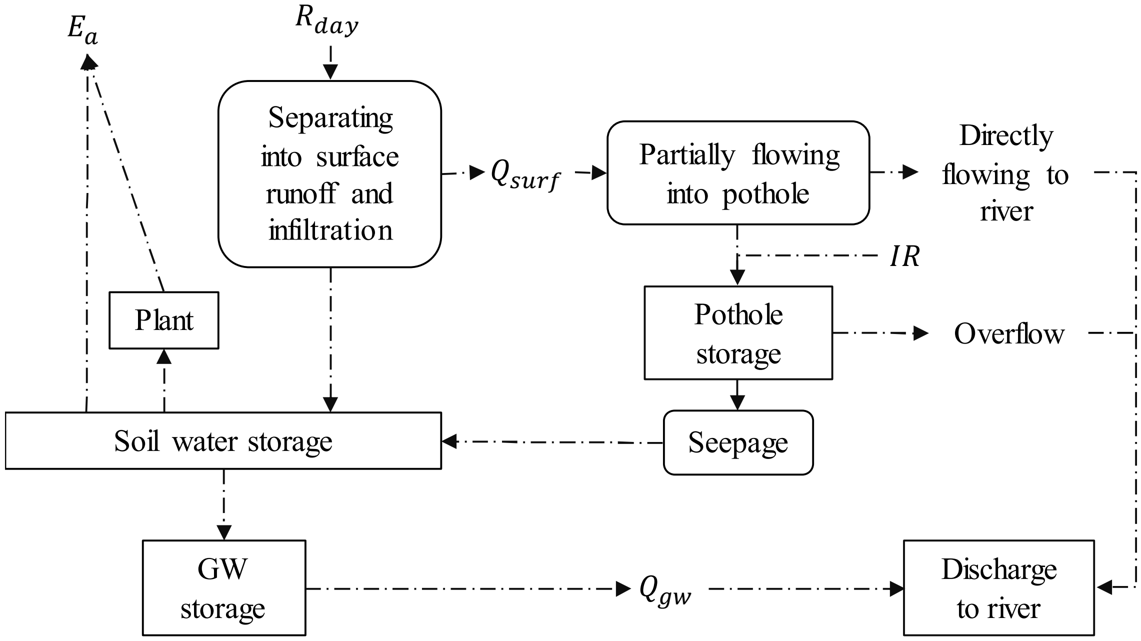

Figure 1. Schematic chart of pothole procedure in SWAT2012

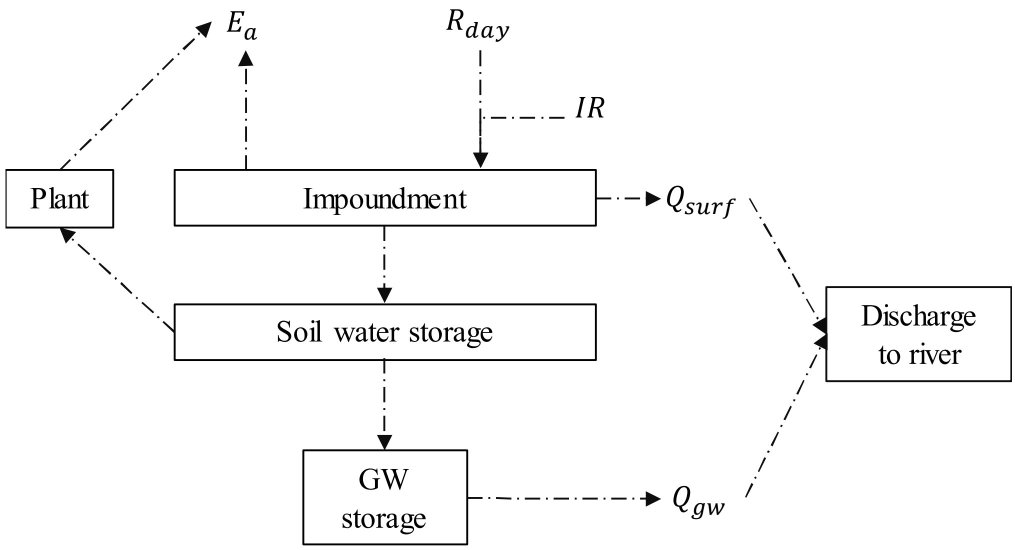

Figure 2. Schematic chart of the paddy model developed in SWAT-Paddy

2.2.1 Development of paddy impoundment module

Hydrological processes in paddy fields are different from processes in other land uses because water from rainfall and irrigation is stored in the ground as an impoundment during growth seasons [36]. To represent paddy impoundment in SWAT, new module for impoundment was developed [30]. Water balance was calculated using:

$$\Delta DEP_{impnd} = IR + R_{day} - Q_{surf} - EV_{impnd} - PERC_{day}, \quad (1)$$

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Where, ΔDEP_{impnd} is daily change of impounded depth (mm H_2O), IR is daily irrigated water depth (mm H_2O), R_{day} is daily precipitation (mm H_2O), Q_{surf} is daily surface discharge (i.e. overflow from outlet weir) from paddy fields (mm H_2O), EV_{impnd} is daily evaporation from water surface (mm H_2O), and $PERC_{day}$ is daily water percolation to soil surface layer (mm H_2O). Q_{surf}, EV_{impnd}, and $PERC_{day}$ were determined in newly developed subroutine for paddy field simulation, which is named paddy subroutine. One of the major improvements is that water balance of impoundment is calculated in depth, whereas the pothole module calculates water balance in volume, which is not appropriate for paddy fields. Evaporation from water surface was calculated using equations (2) and (3).

$$\text{If } LAI < LAI_{ev},\ EV_{impnd} = \eta\, E_0\,(1 - LAI / LAI_{ev}), \tag{2}$$

$$\text{If } LAI \geq LAI_{ev},\ EV_{impnd} = 0, \tag{3}$$

Where, η is the evaporation coefficient, E_0 is potential evapotranspiration for a given day (PET; mm H_2O), LAI is leaf area index of a crop grown in flooding, LAI_{ev} is the leaf area index when evaporation from water surface does not occur. For the parameters of η and LAI_{ev}, the values of 0.6 and 4.0 were adopted, respectively, based on previous reports [30]. Computation techniques for Q_{surf} and IR are described in the following sections.

In SWAT-Paddy, the method to compute percolation of water from impoundment to soil that was used in the original or modified pothole [28, 31] was not adopted, because soil water content and saturated hydraulic conductivity of surface soil layers are only elements in determining the percolation rate and these lead to underestimation of percolation in paddy fields [27]. In actual paddy fields, there is a constant water loss by seepage through the bund of paddy field and vertical percolation even though surface soils are saturated and hydraulic conductivity is very low because of puddling. Thus, potential percolation rate ($PERC_0$) from impoundment to soil layers is defined as a constant value after puddling as modeled in the previous research [30].

2.2.2 Modification of the operation scheme of irrigation and drainage for paddy fields district

In paddy fields, impounded water depth is controlled by farmers based on growth stage of paddy and climatic conditions. Controlling impounded water depth is quite important for rice production [41]. In SWAT-Paddy, the water depth control method used in the previous study [31] was adopted. Three critical water depths, namely: maximum flooding depth for surface discharge computation (DEP_{max}), irrigation trigger depth ($DEP_{trigger}$), and irrigation target depth (DEP_{target}), were introduced in this method. The new command was added to schedule management subroutine and it changes values of the critical water depths on each day. Surface discharge was calculated using equation (4) and (5) in paddy subroutine.

$$\text{If } DEP_{impnd} > DEP_{max},\ Q_{surf} = DEP_{impnd} - DEP_{max}, \tag{4}$$

$$\text{If } DEP_{impnd} \leq DEP_{max},\ Q_{surf} = 0, \tag{5}$$

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Where, DEP_{impnd} is depth of impoundment on a given day (mm H_2O), and DEP_{max} is maximum depth of impoundment (mm H_2O). Demanded irrigation depth on a given day (IR_{demand}, mm H_2O) was calculated using equation (6) and (7).

$$\text{If } DEP_{impnd} < DEP_{trigger},\ IR_{demand} = DEP_{target} - DEP_{impnd}, \tag{6}$$

$$\text{If } DEP_{impnd} \geq DEP_{trigger},\ IR_{demand} = 0, \tag{7}$$

During rice cultivation, the value of IR_{demand} increases and one water resource is sometimes insufficient to satisfy the water demand. Therefore, multiple water resources, including river aquifer, and irrigation pond, are designed to be used in paddy irrigation system when the amount of available water from a resource is estimated to be insufficient [8, 42]. In a paddy field district with well-developed irrigation system, including water withdrawal facilities and irrigation canals, a ratio of irrigated water amount from each resource can be assumed to be the same as the area of paddy fields and the ratio does not fluctuate. Therefore, we introduced a parameter of the main resource ratio (r_{main}), assuming doubled water resource requirement for one district as shown in equation (8) and (9).

$$IR_{demand,main} = r_{main} \times IR_{demand}, \tag{8}$$

$$IR_{demand,sub} = (1 - r_{main}) \times IR_{demand}, \tag{9}$$

Where, $IR_{demand,main}$ is irrigation demand for main water resource (mm H_2O), and $IR_{demand,sub}$ is irrigation water demand for sub water resource (mm H_2O). Equations 6 – 9 were added to a subroutine of auto-application of irrigation.

2.2.3 Puddling as a scheduled management

To keep water above land surface, farmers maintain a low hydraulic conductivity of paddy soil. Puddling, which means mixing soil and impounded water before transplanting, is carried out for this purpose [43-45]. In puddling, farmers break soil aggregations by rotary tillage and fill cracks in plow sole made by tractor's compaction with small soil particles, and this leads to low conductivity of plow sole. Therefore, hydraulic conductivity of surface soil in a paddy field is low in rice growing season. In addition, this makes surface soil saturated with water, and leads to reduced condition in paddy soil. Reduced soil environment promotes denitrification, which is related to nitrogen loss in paddy soil. In this sense, modeling puddling in SWAT is important when the model is used in a paddy field watershed. Therefore, the operation command "puddling" and "break puddle" were added to scheduled management subroutine in SWAT-Paddy. Equation (10), originally from the previous work in APEX modification for paddy fields [46], is computed when puddling is operated.

$$K_{sat,wet} = coeff_{pudd} \times K_{sat,dry} \tag{10}$$

Where, $K_{sat,wet}$ is saturated hydraulic conductivity after puddling (mm/h), $coeff_{pudd}$ is puddling coefficient less than 1, and $K_{sat,dry}$ is an original value of hydraulic conductivity (mm/h). Users can set the depth of plow sole and this equation is applied to the layer including plow sole and the overlying layers. After completion of paddy cultivation, users can operate break puddle to return the value of hydraulic conductivity to the original ($K_{sat,dry}$). In addition to changing physical property of soil, puddling often causes water pollution when farmers drain water, which contains high concentrations of sediments and nutrients resuspended by mixing surface soil and impounded water, just after the management is operated. To represent this, the resuspension after puddling was also modeled in this puddling scheme based on the tillage algorithm existing in SWAT2012. The basic idea of this is conceptually the same as the modification in APEX [46].

2.3 Study area for evaluation

SWAT-Paddy was evaluated in a case study in the Upper Kashima River watershed in the Imbanuma Lake basin, Chiba Prefecture that is located in the central region of Japan. The area of the study watershed is 117 km^2. The watershed is covered mainly by andosol soil, which is made from volcanic ash and is highly permeable [47]. In this area, small valleys and hills make a complex landscape, called “yatsu”; however, there is no significant difference in their elevation. Therefore, surface runoff is insignificant in this area and river flow is dominated by groundwater discharge. In this watershed, lowland areas are used for paddy fields, which occupy 9% of the watershed. Water is pumped up from the river and deep aquifer to irrigated paddy fields through small open canals and is drained through channels to Kashima River. Irrigation pumps and the gate between a drainage channel and the river, which is usually closed in irrigation period, are controlled mainly by farmers. Farmlands, excluding paddy fields, constitute the largest land use in this watershed; it is located on the hilly area (Figure 3). The areal portion of paddy fields is not so high, but it has a significant impact on the watershed hydrology because paddy fields are located along the river. In addition, 2000–3000 mm of water is withdrawn from the river and deep aquifer using pump facilities for the irrigated rice fields. This value is much larger than average annual precipitation (approximately 1400 mm) and the main source of irrigation, which accounts

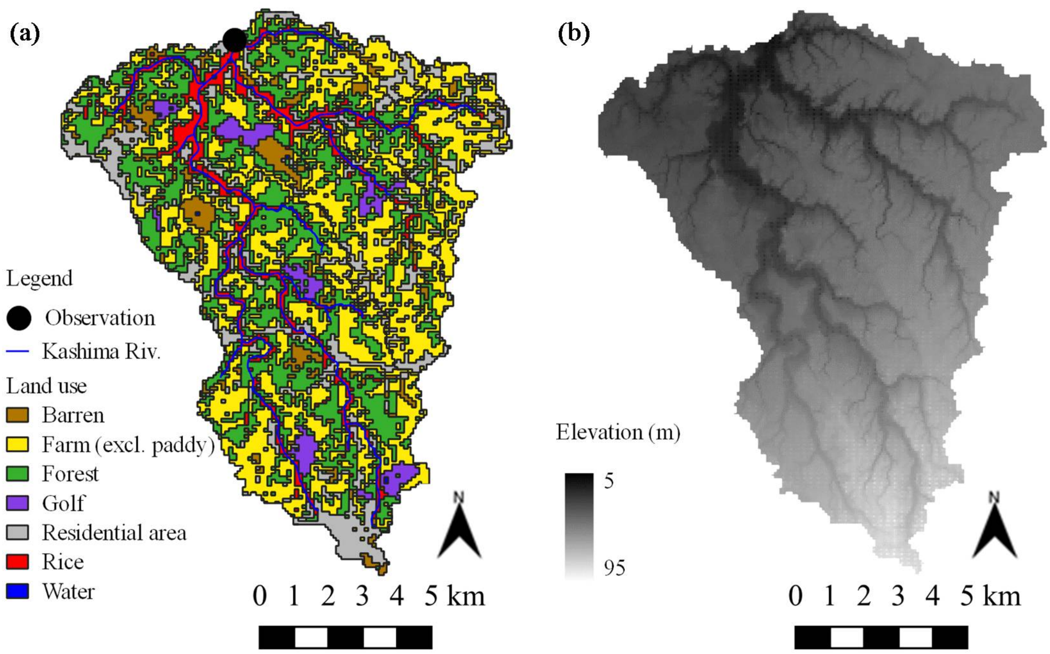

Figure 3. Maps of (a) land use distribution in the watershed and (b) topography of the watershed

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Table 1. Land classification in the study area

Land use	Land use code for SWAT	Area (%)
Paddy	RICE	8.98
Farm (excl. paddy)*	AGRL	38.08
Forest	FRST	28.61
Barren	BARR	5.79
Residential area	URMD	15.24
Others	BARR	0.09
Water surface	WATR	0.16
Golf	RNGB	3.05

* Major crops for "farm" are peanut, carrot, and sweet potato in this watershed.

for 80 % of total irrigation water use, is Kashima River itself. Therefore, paddy irrigation has an impact on water environment through both irrigation and drainage practices. Thus, considering paddy fields in hydrological simulation is important for the management of this watershed. We set a hydrologic investigation point in the middle of Kashima River and observed river flow rate in the period of 2012–2014 though we stopped monitoring from January–March because paddy fields are not cultivated in that period. In addition, data were not recorded during October–December 2013 because of damage in sensors by a big typhoon that happened on October 13th, 2013. Edge-of-field paddy discharge was monitored for irrigation volume and discharge rate in the period of April 26th–August 4th in 2016. Actual evapotranspiration (ET) was estimated using FAO56 method [48], which is well validated in similar environments [49]. Using this observation data, the water balance of target paddy fields was estimated.

2.4 The application and calibration of SWAT2012

Model input files were generated using ArcSWAT 2012 with following data:

1. Digital Elevation Model (10 m mesh, [50])
2. Land use (100 m mesh [51])
3. Soil map by Japan Soil Association [52] with vertical data from SolphyJ [53]
4. Weather data obtained at the weather station in Sakura (precipitation, temperature, and wind velocity), Chiba (precipitation, temperature, wind velocity, and relative humidity), and Tsukuba (solar radiation) [54]

With this data, 227 HRUs were defined in 11 subbasins. The simulation period was 2012–2014 and a warm-up simulation was conducted for five years (2008-2011) prior to the main simulation. Management schedule in paddy fields was determined based on the local standard of fertilizing [55], local guideline for paddy management [56], and field monitoring conducted in 2016 at a paddy field located near the outlet of watershed. In addition, both river and deep aquifer sources are used for irrigation in this region. However, SWAT2012 allows only one irrigation source per HRU. In the aspect of water balance, water withdrawal from deep aquifer is an

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Table 2. Inputted schedule of paddy management and assigned operation type in SWAT2012

Date	Management	Operation type in SWAT
Apr. 25^{th}	Start impoundment	Auto irrigation initialization / outlet weir control (new)
Apr. 28^{th}	Puddling	Puddling (new)
May 1^{st}	Transplanting	Plant (initially, LAI=0.1 and biomass = 20 kg/ha[27])
Jun. 9^{th}	Mid-summer Drainage	Auto irrigation initialization /outlet weir control (new) (Setting three critical values = 0)
Jun. 23^{rd}	Finish mid-summer drainage	Auto irrigation initialization / outlet weir control (new)
Jul. 31^{st}	Intermittent Irrigation	Auto irrigation initialization / outlet weir control (new)
Aug. 25^{th}	Draining	Auto irrigation initialization / outlet weir control (new) (Setting three critical values = 0)
Sep. 10^{th}	Harvest	Harvest and kill operation / Break puddle (new)

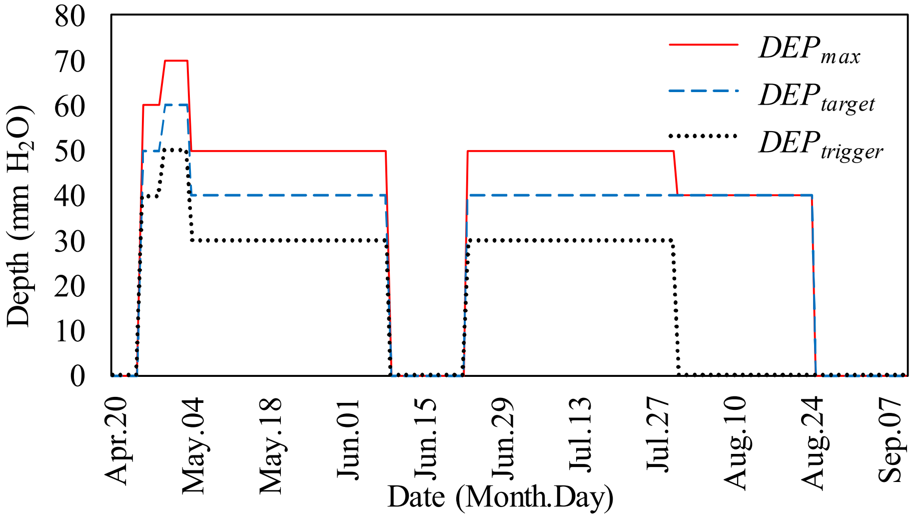

Figure 4. Water depth management schedule used in the simulation

additional water resource in a river watershed scale because deep groundwater flows directly to the sea and does not affect river flow in this watershed. On the other hand, river water use within this watershed is cyclic due to use of small pumps locating along the river. Therefore, groundwater was chosen as the irrigation source in the calibration of SWAT2012. To widen the model capability globally, SWAT allows users to choose several methods to compute each hydrological process. In this study, we chose plant-evapotranspiration-related estimation method for soil moisture-retention parameter used in surface runoff computation [57] and Priestley-Taylor method [58] to compute potential ET for representing hydrological characteristics of the watershed. Though Penman-Monteith method [59] is widely used in SWAT application, Priestley-Taylor method can also be used when the model is applied in wet condition, as seen in rice-cultivated regions, and it requires less climatic data input [29]. Thus, the latter method is more suitable than the former when considering SWAT-Paddy application to the southeast and south Asian countries, where data availability is relatively poor and demand for hydrological models is currently increasing rapidly. To evaluate performance of the model, the hydrological parameters were calibrated in watershed scale by SWAT-CUP with the original SWAT2012 at first and then, SWAT-Paddy was applied with the parameters gained in calibration.

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Table 3. The list of calibrated parameters and sensitivity

Parameters	Type	Original	Range min.	Range max.	Best	Rank	P-Value
CN2.mgt	R	36 ~ 86	1.04	1.07	38.12 ~ 91.05	2	0.17
SOL_AWC.sol	R	0.09 ~ 0.25	1.35	1.43	0.13 ~ 0.35	7	0.55
ALPHA_BF.gw	V	0.005	0.00	0.02	0.08×10^{-2}	1	0.00
GW_DELAY.gw	V	5	36.83	39.39	38.22	10	0.91
ESCO.hru	V	0.95	0.98	1.00	1.00	6	0.29
EPCO.hru	V	1.00	0.71	0.76	0.73	8	0.74
SURLAG.bsn	V	4	14.77	16.75	16.67	5	0.23
RCHRG_DP.gw	V	0.02	0.10	0.12	0.11	9	0.88
ALPHA_BF_D.gw	V	0.9	0.12	0.19	0.15	4	0.22
CNCOEF.bsn	V	0.5	0.52	0.55	0.52	3	0.19

Further information about each parameter can be found in the theoretical documentation [29]. The column "Type" shows whether the value was replaced (V) or multiplied (R) by the original value. The values tabulated in the column "Range min. (max.)" were replaced or multiplied by the values tabulated in "Original". The column "Best" shows the best parameter set used in the model evaluation described in the following part. The column "Rank" shows rank of parameter sensitivity.

2.5 The setting and evaluation of SWAT-Paddy

In SWAT-Paddy application, water depth and agricultural management were defined as shown in Figure 4 and Table 2, respectively. The schedules (Table 2 and Figure 4) were determined based on agriculture guideline of the Chiba Prefecture local government [60]. The value of $PERC_0$ was set to 10 (mm H_2O) as recommended and observed in the same region [61, 62]. To examine the performance of puddling model introduced in SWAT-Paddy, five values were inputted to the parameter, $coeff_{pudd}$: 1, 0.1, 0.01, 0.001, and 0.0001. For the evaluation, we chose a HRU, which is defined as a paddy field, with gleysol soil, which is used for paddy cultivation in this region, and gentle slope towards the lowest subbasin. The simulated values of surface runoff using SWAT and SWAT-Paddy were compared with each other. Subsequently, performances of the two models were compared by the simulation result of river flow and water balance in the paddy HRU.

3. Results

3.1 Calibration of SWAT2012

The parameters required to compute hydrologic cycle in this watershed were calibrated using daily river flow data, which was observed in the period between 2012 and 2014, by SUFI-2 [63] method in SWAT-CUP. After seven iterations (one iteration equals 1500 times simulations), we got the best parameter set. Table 3 shows the calibrated values of hydrological parameters and the rank of sensitivity. In SUFI-2 method, parameter sensitivity is determined by computing multiple regression systems [64]. In this process, we got the rank of parameter sensitivity in the final iteration (Table 3). The P-value of each parameter obtained from t-test, shows that the sensitivity of ALPHA_BF is considerably significant. This means that groundwater process in this watershed has a large impact on river flow compared to other processes. In addition, the value of ALPHA_BF is calibrated to a significantly low value to represent much stable base flow in

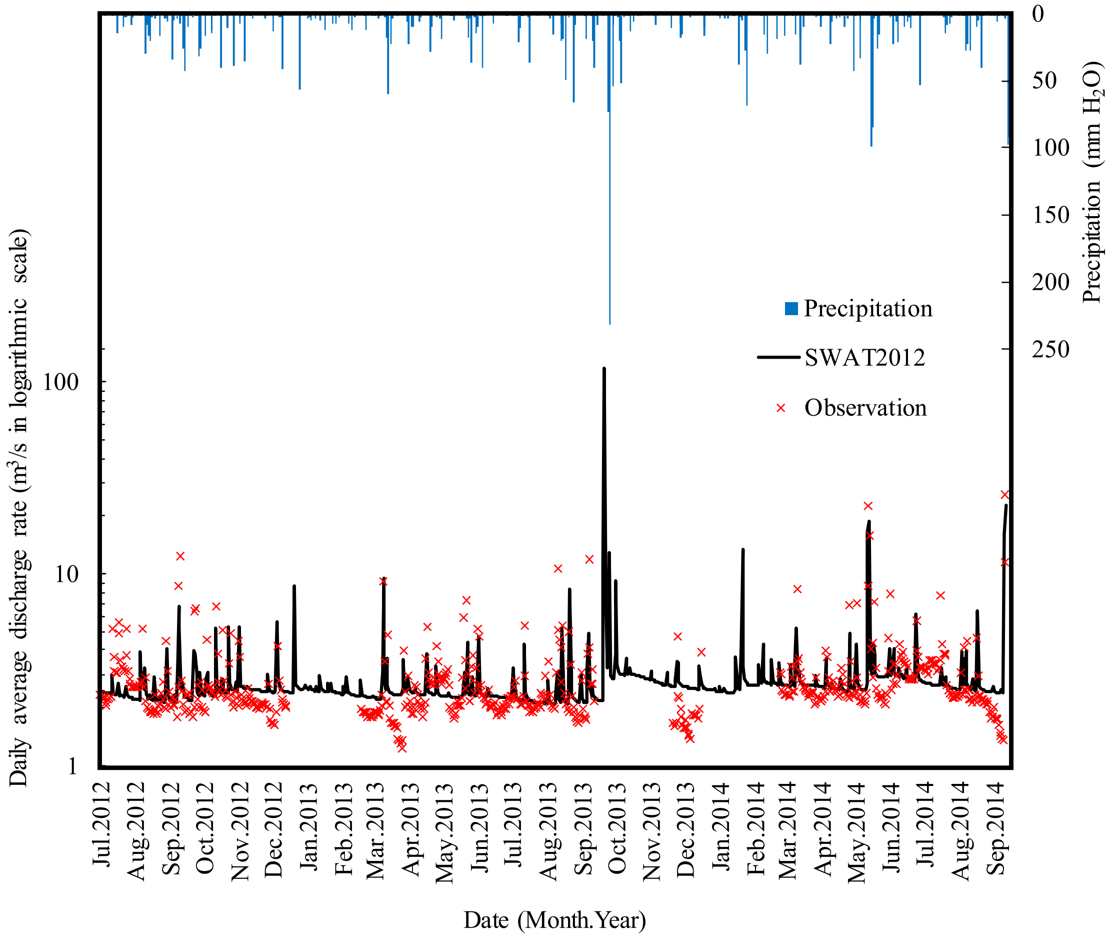

Figure 5. Daily hydrograph simulated with SWAT2012 model compared with the observed river flow

308 Kashima River. Based on the result of calibration, the watershed was characterized to be very flat, and groundwater discharge takes a very long time to reach river flow. With the best parameter set gained in calibration process, Nash Sutcliffe model efficiency (NSE) [65] of the daily river flow simulation (Figure 5) was measured to be 0.63, which indicates that the hydrological simulation is "satisfactory" [66]. Therefore, this parameter set was chosen to be used for the test of SWAT-Paddy.

3.2 Test of soil moisture simulation with puddling operation

In order to represent a saturated soil condition in paddy fields, puddling management was added to SWAT-Paddy. To check the model performance and to identify the value of $coeff_{pudd}$, different values were inputted to the model. Literature [67] shows that the effect of puddling in terms of $coeff_{pudd}$ is in the range between 5×10^{-10} and 1×10^{-4} for paddies in Japan. Among the values of original hydraulic conductivity, the highest value was 85.41 mm/h for the second layer (10–294 mm) and the lowest value was 6.46 mm/h in the layers deeper than 466 mm. Figure 6 shows the soil water content simulated with each coefficient value. Soil water content in irrigation periods was observed to increase with a decrease in coefficient and no significant difference was observed between the simulation results with $coeff_{pudd}$ = 0.001 and $coeff_{pudd}$ = 0.0001. Therefore, the value of 0.0001 was considered extraordinarily low for the model and the value of 0.001 was used in the case study. Figure 7 shows the fluctuation of degree of saturation in each layer of soil in

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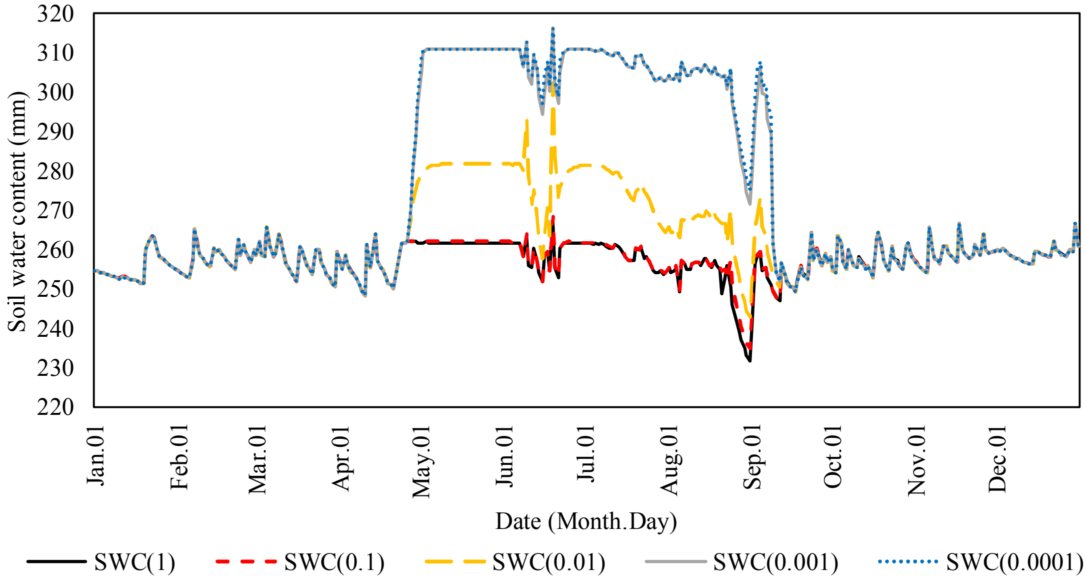

Figure 6. Daily soil water content (SWC) in a paddy field HRU, simulated with different $coeff_{pudd}$ values in 2012

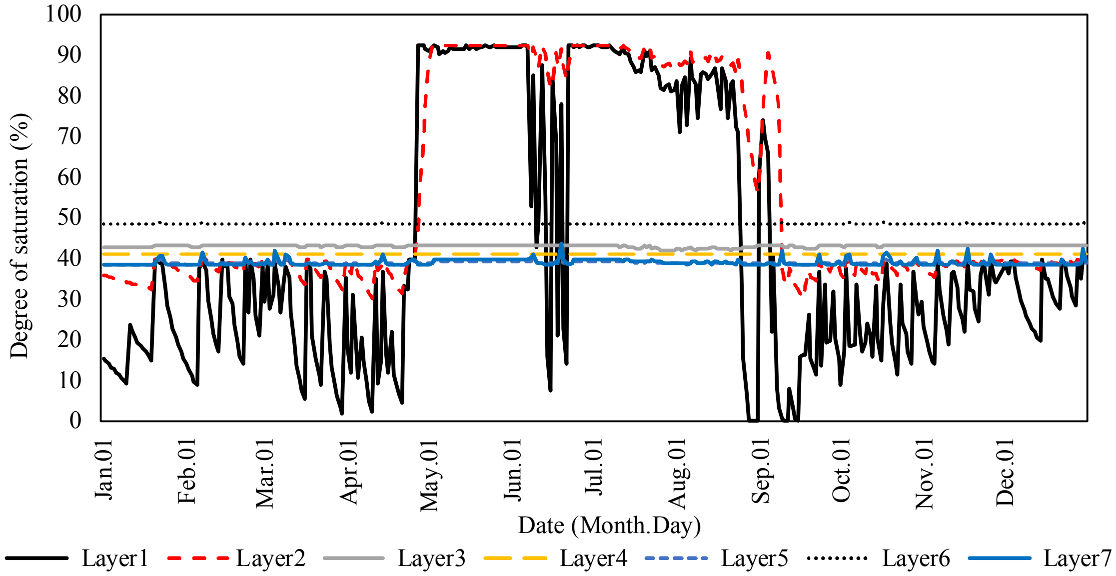

Figure 7. Daily fluctuation in degree of saturation of soil layers in a paddy HRU, in 2012, simulated with SWAT-Paddy

the paddy HRU with $coeff_{pudd}$ = 0.001. In this study, plow sole was set in the second layer. Thus, the first and second layers became saturated after puddling. This graph suggested the puddling was operated successfully in SWAT-Paddy.

3.3 Evaluation of water balance simulated by SWAT-Paddy

3.3.1 Rainfall-runoff simulation

SWAT-Paddy showed a better simulation of surface discharge at rainfall events than SWAT2012 did (Figure 8). Compared to the observed surface discharge, the R^2 value for SWAT-Paddy simulation was 0.8, while that of SWAT2012 was 0.002, indicating a poor performance. As

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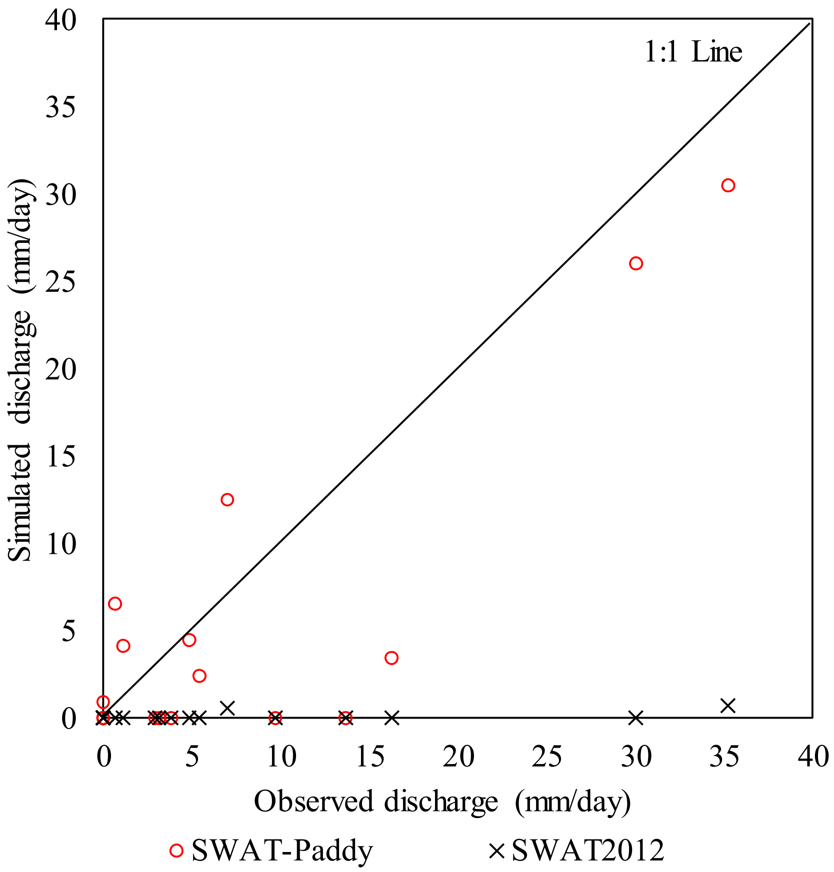

Figure 8. The values of surface discharge on rainfall events simulated by SWAT-Paddy and SWAT2012 plotted against those of the observation

depicted in Figure 8, the curve number method used for simulating surface runoff from the lowland paddy field districts predicted a very low surface discharge, while the SWAT-Paddy output estimated rainfall-surface discharge better. Thus, the alternative simulation scheme in SWAT-Paddy model discharges process better than the curve number method in simulating the water balance of paddy fields.

3.3.2 Evaluation of simulation for impoundment water

The water balance of surface impoundment layer above soil surface of paddy fields simulated with SWAT-Paddy is shown in figure 9. The paddy field was kept impounded for the most part of the growing season of 2016. Surface discharge occurred during or after storm events. Daily evaporation from ponding water reduced to negligible amounts after a canopy was fully established in mid-July. These trends are reasonable for paddy fields in Japan.

The observed and simulated water balance in the Upper Kashima River Basin is summarized in Table 4. Simulated ponding water depth and water yield with both SWAT-Paddy and SWAT2012 were much lower than observed amounts because the observed data contains excessive irrigation, which directly flowed to drainage ditch on the same day of irrigation. In addition, errors in irrigation and ET were due to input uncertainty regarding the definition of management schedule and crop parameterization. However, when comparing the ratio of discharged water quantity (Q) to irrigation water quantity (IRR) (hereafter, referred to as drainage ratio=Q/IRR), the values of observation (= 0.54) and SWAT-Paddy (= 0.47) showed more

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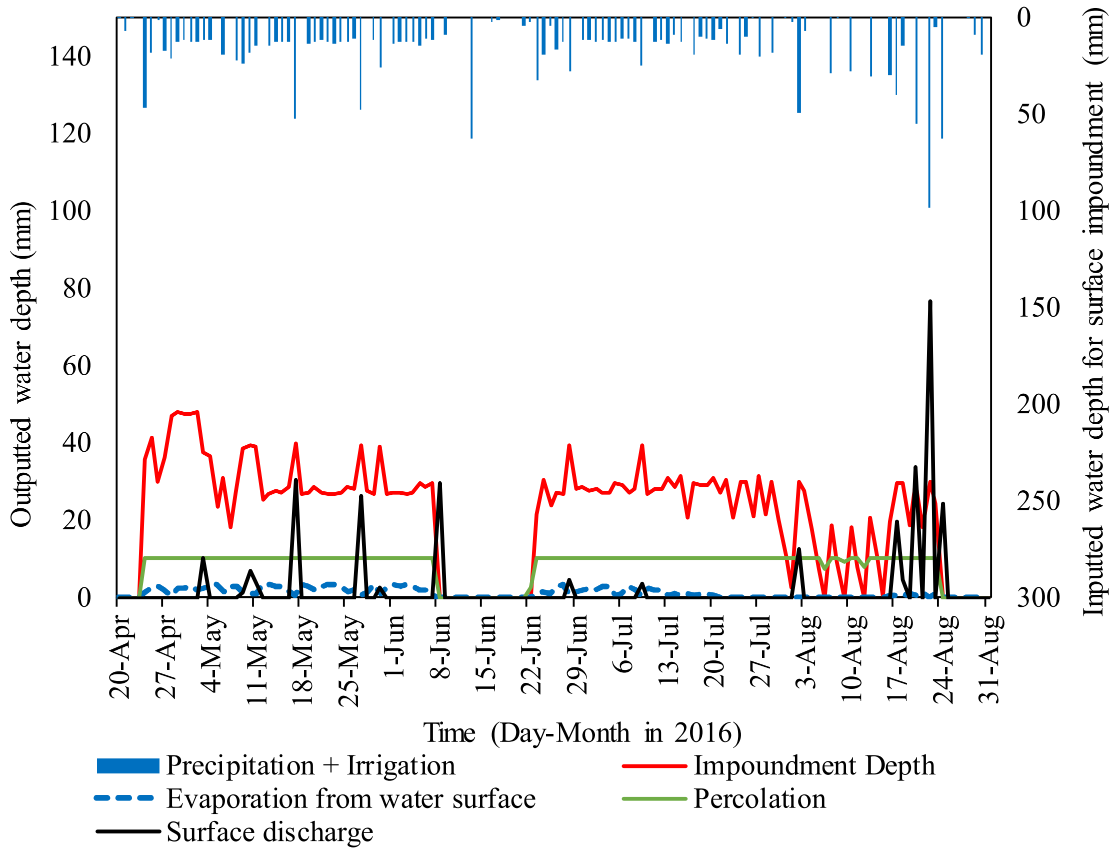

Figure 9. Daily water balance of surface impoundment layer above soil surface in paddy fields in 2016 simulated with SWAT-PADDY

Table 4. Water balance of paddy fields in irrigation period (Apr. 26th to Oct. 4th) observed and simulated by SWAT-Paddy and SWAT2012

	Observation	SWAT-Paddy	SWAT 2012
Precipitation (a)	3.7	3.7	3.7
Irrigation (b)	17.7	8.1	4.5
ET	4.6	2.9	2.3
Water yield (discharged water amount in drainage channel in observation) (c)	11.6	5.5	2.2
Outlet/Inlet ratio (drainage ratio) [c/(a+b)]	0.54	0.47	0.27

353 similarity with each other than with SWAT2012 (= 0.27). Thus, SWAT-Paddy succeeded in
354 modeling paddy field discharge process better than the original method.

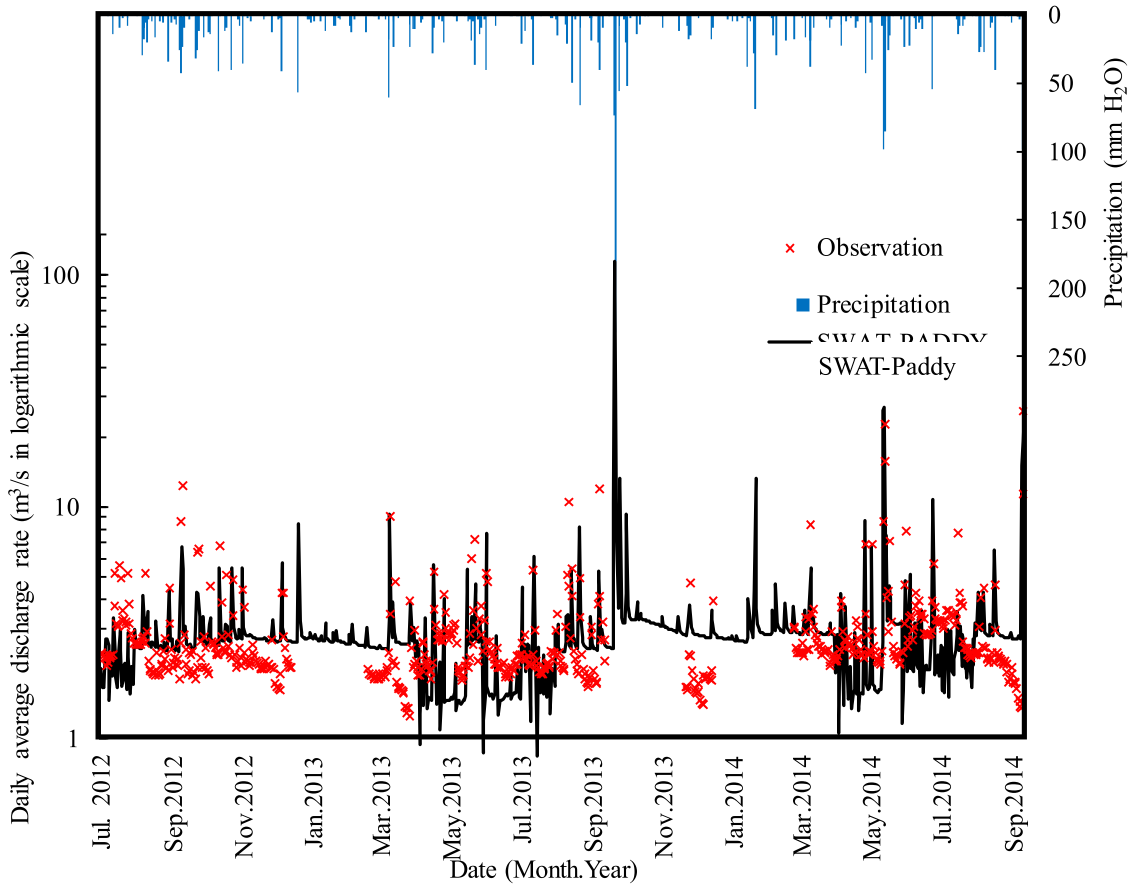

Figure 10. Daily hydrograph simulated with SWAT-Paddy

3.4 Comparison of river flow simulated with SWAT-Paddy and the observation

The hydrograph simulated with SWAT-Paddy, compared with the observed river flow is shown in Figure 10. The accuracy of river flow simulation by SWAT-Paddy (NSE=0.40 and R^2=0.51) was lower than that of the original model (NSE=0.63 and R^2=0.63). The comparison of Figure 5 and Figure 10 shows that the base flow largely decreased once irrigation period starts, which is not occurred in the observation. The comparison about correlations of SWAT2012 and SWAT-Paddy against the observation also shows the poor model accuracy in baseflow simulation of SWAT-Paddy (Figure 11). Percent biases (PBIAS) calculated in irrigation period (May to August) and non-irrigation period (Table 5) showed the trend

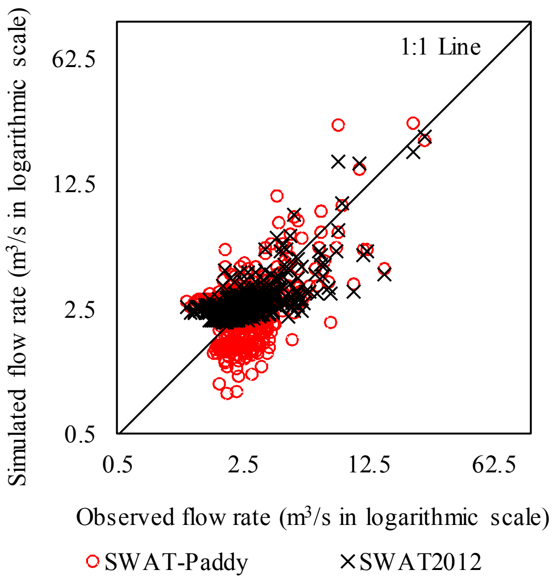

Figure 11. The values of daily average discharge rate estimated by SWAT-Paddy and SWAT2012 plotted against those of the observation

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that SWAT-Paddy underestimate the river flow in irrigation period, overestimate that in non-irrigation period more than SWAT2012 estimates and the magnitude of bias was almost doubled in SWAT-Paddy. Those results suggest that SWAT-Paddy has the problem of poor base flow estimation in this watershed, characterized as lowland paddy field watershed.

Figure 5. The comparison of PBIAS in irrigation period (May to August) and non-irrigation period of the simulations by SWAT2012 and SWAT-Paddy

	SWAT 2012	SWAT-Paddy
Irrigation period	8.8	16.3
Non-irrigation period	-5.7	-13.6

4. Discussion

4.1 Water balance model for paddy impoundment

By introducing paddy module, SWAT was enabled to represent water balance in paddy fields. As Figure 10 shows, the water balance of impounded water above the ground was estimated reasonably in SWAT-Paddy, by calculating water storage over ground, surface discharge, evaporation from water surface, constant percolation from water impoundment to soil layers, and irrigation water supply to impoundment in depth, which were calculated in volume in the previous pothole-based models. Especially, SWAT-Paddy succeeded in modeling surface discharge from paddy fields with much higher accuracy (R^2=0.8) than the original SWAT (R^2=0.002). The original model calibrated with the observed river flow tended to estimate a very low surface discharge, representing the groundwater-dominant hydrology in the lowland watershed. However, even in lowland watershed, surface discharge is observed in paddy fields by farmers' water management. This process was modeled to improve the accuracy of SWAT-Paddy.

4.2 Management operation for paddy cultivation

In SWAT-Paddy, two important enhancements were made in SWAT for simulating rice cultivation in paddies: 1) irrigation scheme was modified to model water management of paddy and 2) puddling was added to the options of agricultural management. Modified irrigation function enables the model to simulate irrigated water use more accurately than the original SWAT. Puddling operation reduces the hydraulic conductivity of paddy soil and allows the model to simulate water ponding in paddy HRUs that in turn allows modeling nutrient dynamics in saturated soils and fertilizer mass balance in the ponding water as well as in soils. This is very important when SWAT-Paddy is used to evaluate water pollution in the watershed including irrigated paddy field districts because nitrate in irrigated water decreases through denitrification in reduced conditions [39]. However, there still exist challenges regarding simulating paddy-associated processes in SWAT, to be addressed in future studies. Firstly, effect of simplifying irrigation scheduling on simulated irrigation water depth and water balance calculation, was unclear in the current case study due to the lack of detailed management data. Secondly, irrigation schedules for individual paddies are not the same within the watershed, in which there may exist hundreds of paddy HRUs. Thus, an approximation method that diversifies irrigation schedule among paddy HRUs, needs to be developed.

4.3 Further improvement of SWAT-Paddy

Though SWAT-Paddy showed good performance for a field-scale water balance simulation, the simulation accuracy of river flow was less in SWAT-Paddy, especially in base flow simulation. This is related to the large amount of water uptake for irrigation. Irrigated water is partially consumed in paddy fields and flows back to river through well organized drainage channel network in modernized paddy fields, called irrigation return flow. However, in the simulation of lowland watershed, irrigation return flow is mostly estimated as groundwater discharge, which is hydrologically characterized as "very slow" to represent stable flow rate in this watershed. However, paddy drainage system increases water discharge through lateral flow process and seepage through the ridge of paddy fields, and quickly transfers discharged water to river [43]. Thus, baseflow underestimation in irrigation period and overestimation in non-irrigation period are caused by less estimation of irrigation return flow. Therefore, modeling drainage system in paddy field districts is important to improve the baseflow estimation accuracy and enhance model applicability of SWAT-Paddy.

4.4 Contribution of SWAT-Paddy to sustainable water use in paddy cultivation

Irrigation is one of the most important factors for paddy cultivation as water scarcity affects the production of rice largely. Farmers irrigate more water than actual requirement for growing paddy because it takes much labor to manage water depth strictly by starting or stopping water intake, or changing height of outlet weir many times. This leads to excess water use and sometimes causes water scarcity in paddy field region. In addition, irrigation requires energy input in lowland area where large scale paddy fields are located. Therefore, to increase rice productivity at the regional scale while saving water and energy consumption, irrigation management should be planned, considering various aspects of crop production and water balances, such as, productivity, lower input, and sustainability of water resources and environment. SWAT-Paddy will help decision makers develop policies on agricultural irrigation, based on hydrological condition of their region and to clearly explain the effect of management practices to farmers.

5. Conclusions

In this study, discharge processes and management practices in paddy HRUs were newly developed in SWAT-Paddy. As demonstrated in a case study, SWAT-Paddy successfully simulated paddy water balance and watershed hydrology compared to SWAT2012. The R^2 value for surface discharge increased substantially with SWAT-Paddy. Thus, the proposed model succeeded in representing the hydrological characteristics of an irrigated and impounded paddy field. However, the improved accuracy in simulating paddy water balance did not result in significant improvement in river flow simulation at the watershed scale SWAT-Paddy. We speculate that, in part, the small areal portion (8%) of paddy fields in the watershed may have acted to diffuse the paddy-level improvement in hydrologic simulation at the watershed scale. Especially, base flow was underestimated in irrigation period and overestimated in non-irrigation period by SWAT-Paddy. This is because the model was not configured to simulate quick return flow process through drainage system. Further improvement in ability to configure drainage ditches in paddy fields SWAT-Paddy may improve model performance.

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