Agricultural Water Management 137 (2014) 116–122

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Development and evaluation of a paddy module for improving hydrological simulation in SWAT

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ARTICLE INFO

Article history:
Received 12 February 2013
Accepted 12 January 2014
Available online 4 February 2014

Keywords:
SWAT
Model development
Paddy field
Irrigation
Pothole

ABSTRACT

The soil and water assessment tool (SWAT) is becoming a popular tool for modeling watershed-scale hydrological and chemical transport in Asia, where paddy rice is cultivated in typical agricultural management systems. In this study, a paddy module was developed by modifying an algorithm designed for pothole landscapes in SWAT. To simulate the percolation processes in paddy fields, a new parameter, the 'potential percolation rate of the paddy field,' was introduced which determines the upper limit of the rate of percolation into the subsoil. The potential percolation rate was calibrated to fit the observed flow rate of a stream. In addition, the ponding-releasing process was varied to simulate a winter paddy field. Moreover, the irrigation process was modified to avoid overflows from paddy fields during irrigation management. Furthermore, the evaporation process was modified in accordance with the evaporation rate observed at a paddy field. The developed paddy module was tested by applying it to a 3 km^2 watershed in which paddy fields comprise 18% of the total area. It was concluded that the water balance in the irrigated paddy fields was reasonably modeled by the modified SWAT with the developed paddy module and that the modified SWAT is effective for watershed-scale modeling for watersheds containing paddy fields.

1. Introduction

The soil and water assessment tool (SWAT) is a physically based continuous time-step hydrological model. This tool was designed to predict the effects of land management practices on water, sediment, and agricultural chemical yields in basins containing various soil types, land uses, and management conditions (Arnold et al., 1998). SWAT has been widely used in the U.S. and Europe (Gassman et al., 2007). In addition, SWAT is increasingly used in Asia because of its versatility. In Japan, 54% of farmlands are irrigated paddy fields (Ministry of Agriculture, Forestry and Fisheries (MAFF), 2013), and two-thirds of total domestic water use occurs in the agricultural production sector, mainly for the irrigation of paddy fields.

Researchers in Asia (Xie and Cui, 2011) have applied SWAT to watersheds containing paddy fields using a pothole module, which was originally designed for pothole landscapes in the Corn Belt area of the Midwestern United States (Du et al., 2005), and the use of the pothole module for paddy field simulation is recommended in the theoretical documentation for SWAT (Neitsch et al., 2002). This module in SWAT allows for ponding in hydrological response units (HRUs), which occurs in paddy fields. In SWAT, HRUs are areas that consist of homogeneous land use, with land management and soil characteristics in sub-watersheds. In another study, Kang et al. (2006) added their original paddy module to SWAT to develop a total maximum daily load program. In their SWAT paddy module, the daily percolation rates of paddy fields under saturated conditions were fixed depending on the soil types of each paddy field rather than by applying soil moisture routing.

The purpose of this study was to develop a paddy module and incorporate this new module into the SWAT model. The modified SWAT model with the developed paddy module was applied to a 3 km^2 watershed with paddy fields comprising 18% of the total area, and the water balance in the paddy HRU and the watershed-scale model efficiency were examined.

2. Study area

The study area, the Arata River watershed, is located in central Japan. The area comprises approximately 3 km^2, of which 56.4% is upland fields and 18.0% is paddy fields (Fig. 1). This watershed extends from a minimum elevation of 35 m above sea level (asl) in the north to a maximum of 75 m asl in the south. At this site,

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http://dx.doi.org/10.1016/j.agwat.2014.01.009

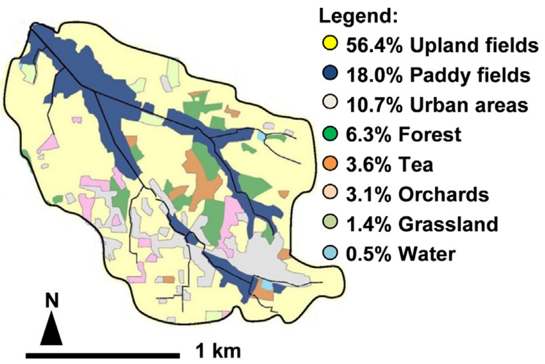

Fig. 1. Land use in the study watershed.

the annual mean precipitation is 1809.1 mm y^{-1}, the annual mean maximum air temperature is 20.5 °C, the annual mean minimum air temperature is 12.8 °C, the annual mean relative humidity is 76%, the annual mean wind speed is 3.4 m s^{-1}, and the annual mean solar radiation is 13.5 MJ m^{-2} d^{-1}. The Toyokawa irrigation canal flows into the Arata watershed, and supplies irrigation water to all the paddy fields.

Because a detailed water balance of the paddy fields was not measured in the Arata River watershed, the paddy module was applied to a paddy field in another watershed to validate the calculation of the surface runoff and the evapotranspiration (ET). The paddy field is located in the city of Tsukuba, Japan (elevation, 11 m asl; annual mean precipitation, 1282.9 mm y^{-1}; annual mean maximum air temperature, 19.1 °C; annual mean minimum air temperature, 8.8 °C; annual mean relative humidity, 75%; annual mean wind speed, 2.4 m s^{-1}; and annual mean solar radiation, 13.1 MJ m^{-2} d^{-1}).

3. Methodology

3.1. Overview of the developed module

The paddy module was developed by modifying the pothole module in SWAT 2009 rev. 488. Schematic diagrams of the water balance of an actual paddy field, the pothole module, and the paddy module are shown in Fig. 2. Five features of the pothole module were modified: the percolation algorithm, the shape of the impoundment, the irrigation algorithm, the release algorithm, and the evaporation algorithm. These details are described below. The water balance of the developed paddy module was validated by applying the module to a paddy field in central Japan.

3.2. Shape of the impoundment

The impoundment in the pothole module is shaped as a cone, in which the surface area of the water body decreases as drawdown occurs and the water volume decreases. However, paddy fields are shaped similar to a cuboid tank, in which the surface area of the water body remains constant with variations in the water level. Therefore, the formula for the surface area (SA) was modified as follows:

$$\mathrm{SA} = \mathrm{area}_{\mathrm{hru}} \tag{1}$$

where $\mathrm{area}_{\mathrm{hru}}$ is the area of the HRU (ha).

3.3. Percolation algorithm

In the algorithm of the pothole module (Eqs. (2)–(4)) which is described in the theoretical documentation for SWAT (Neitsch et al., 2002), the seepage process that calculates the amount of percolation from a water body to the soil profile stops when the soil water content reaches the field capacity (Eq. (4)). On the other hand, the percolation process from upper to lower soil layers in the algorithm of the soil water routine (Eqs. (5) and (6), which is also described in the theoretical documentation for SWAT) does not proceed unless the water contents of the soil layer go above the field capacity (Eq. (6)). As a result, the water contents of the soil layer remain at field capacity, although some water may be removed through the transpiration processes. This interdependence between algorithms of the seepage process and the percolation process at the field capacity leads to deadlock situation. The seepage process cannot proceed because the percolation process does not reduce the soil water contents, and the percolation process cannot proceed because the seepage process does not increase the soil water contents.

$$V_{\mathrm{seep}} = 240 K_S\, \mathrm{SA} \quad \text{if}\ \mathrm{SW} < 0.5\,\mathrm{FC} \tag{2}$$

$$V_{\mathrm{seep}} = 240 \left(\frac{1 - \mathrm{SW}}{\mathrm{FC}} \right) K_S \mathrm{SA} \quad \text{if} \quad 0.5\mathrm{FC} \le \mathrm{SW} < \mathrm{FC} \tag{3}$$

$$V_{\mathrm{seep}} = 0 \quad \text{if}\ \mathrm{SW} \ge \mathrm{FC} \tag{4}$$

where V_{seep} is the volume of water lost from the water body via seepage in a day (m^3); 240 is the unit conversion factor; K_S is the effective saturated hydraulic conductivity of the first layer in the profile (mm h^{-1}); SA is the surface area of the water body (ha); SW is the soil water content of the soil profile on a given day (mm); and FC is the soil water content at field capacity (mm).

$$\mathrm{SW}_{\mathrm{ly,excess}} = \mathrm{SW}_{\mathrm{ly}} - \mathrm{FC}_{\mathrm{ly}} \quad \text{if} \quad \mathrm{SW}_{\mathrm{ly}} > \mathrm{FC}_{\mathrm{ly}} \tag{5}$$

$$\mathrm{SW}_{\mathrm{ly,excess}} = 0 \quad \text{if}\ \mathrm{SW}_{\mathrm{ly}} \le \mathrm{FC}_{\mathrm{ly}} \tag{6}$$

where $\mathrm{SW}_{\mathrm{ly,excess}}$ is the drainable (available for percolation) volume of water in the soil layer on a given day (mm); $\mathrm{SW}_{\mathrm{ly}}$ is the water content of the soil layer on a given day (mm); and $\mathrm{FC}_{\mathrm{ly}}$ is the water content of the soil layer at field capacity (mm).

Therefore, impounded water in the pothole hardly percolates under saturated condition. However in actual paddy field, the impounded water percolated below soil surface even if the soil profile is saturated. To integrate this saturated flow under ponded conditions into the simulations, a new parameter, the potential percolation rate of paddy fields, was introduced into SWAT. This rate is a fitting parameter used to approximate the water balance of a paddy field, and its value is estimated using a calibration process. Using this new parameter, the seepage process of the pothole module was modified as follows:

$$V_{\mathrm{seep}} = 10 P_P\, \mathrm{SA} \quad \text{if}\, V_{\mathrm{stored}} > 10 P_P \mathrm{SA} \tag{7}$$

$$V_{\mathrm{seep}} = V_{\mathrm{stored}} \quad \text{if}\, V_{\mathrm{stored}} \le 10 P_P \mathrm{SA} \tag{8}$$

where P_P is the daily rate of potential percolation of a paddy field during ponded conditions (mm), and V_{stored} is the daily volume of water stored in the water body at the beginning of the day (m^3).

To estimate the potential percolation rate of the paddy fields in a watershed, seven scenarios consisting of seven different potential percolation rates between 0 and 30 mm d^{-1} was assumed. Then a sensitivity analysis and an autocalibration process (described in Section 3.11) was performed to fit the observed flow rate at a stream for each scenario. Because the stream flow includes all discharges from every type of land use, including paddy fields, it was assumed that the scenario in which the autocalibration process resulted in the highest NSE value had the most suitable potential percolation rate value. This potential percolation in paddy fields includes the vertical percolation that penetrates the low-permeable hardpan layer of a paddy, the subsoil lateral flow above the hardpan layer, and the leakage through the ridge, as shown in Fig. 3. These percolations occur as saturated flows on ponded days. However, they change to unsaturated flows for several days during periods of