# Simulation of rice paddy systems in SWAT: A review of previous applications and proposed SWAT+ rice paddy module

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**Abstract:** The Soil and Water Assessment Tool (SWAT) is an ecohydrological watershed-scale model which was initially developed in the early 1990s to simulate the impacts of land use, management systems, and climate on hydrology and/or water quality. First adopted in the U.S., the use of the model then spread to Europe and then later to Asia and other regions. The range of applications that SWAT has been applied to have also expanded dramatically, which influenced ongoing model development which has been virtually continuous over the past two decades. A key component of many SWAT applications in Asia is accounting for rice paddy production that is common in some subregions within the continent. However, most of these studies do not provide explicit details of how rice production was simulated in SWAT. Other research has revealed that significant problems occur when trying to represent rice paddy systems in standard versions of SWAT, due to limitations in algorithms based on the runoff curve number approach or the pothole option. In response, key modifications have been made to SWAT in recent studies that have resulted in a more accurate representation of rice paddy systems. These developments point to the need for the incorporation of an enhanced rice paddy module within SWAT to better capture rice paddy hydrological and pollutant dynamics, which would support improved use of the model in Asia and other rice production regions. Subtopics related to simulating rice production in SWAT are discussed as follows: 1) an overview of global rice production; 2) history of SWAT development; 3) typical approaches for simulating rice production; 4) problems associated with the typical approaches; 5) recent code modifications to address deficiencies in replicating rice paddy systems; 6) recommendations for developing a standard rice paddy module for future SWAT codes.

**Keywords:** SWAT, rice paddies, potholes, hydrology, pollutants, modified SWAT models
**DOI:** 10.25165/j.ijabe.20221501.7147

**Citation:** Gassman P W, Jeong J, Boulange J, Narasimhan B, Kato T, Somura H, et al. Simulation of rice paddy systems in SWAT: A review of previous applications and proposed SWAT+ rice paddy module. Int J Agric & Biol Eng, 2022; 15(1): 1–24.

## 1 Introduction

Rice is a staple food for almost 50% of the global population, with nearly 90% of Asia's population reliant on rice[1,2]. Rice production has risen steadily from the early 1960s[3], reaching a total global level of 760 million t in 2017[4]. Rice production

**Received date:** 2021-10-26 **Accepted date:** 2022-01-14
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levels are expected to increase in several countries during 2018/2019 including Bangladesh, Myanmar, Cambodia, Indonesia, Madagascar, Philippines, Sri Lanka, Tanzania, Thailand, United States and Vietnam[5]. Rice global demand is projected to reach 800 million t by 2025[6]. Global reserve stocks of rice were expected to reach a level of 173 tonnes by the end of the 2018/2019 marketing year[4], providing a strong reserve at present. However, the anticipated increasing population in Asia coupled with potential adverse impacts of climate change and environmental problems pose significant future challenges for maintaining an adequate supply of rice food stock in the future[6].

Multiple environmental problems have been linked to modern rice production practices, including water pollution due to over-applied and improper use of fertilizers and pesticides, elimination of beneficial insects and wildlife, excessive salt build-up, and overuse of groundwater[2,7]. Water quality monitoring has confirmed elevated in-stream pesticide levels due to rice production in Japan[8,9], Vietnam[10,11], Philippines[12], Thailand[13], and several European countries[14]. Excess nitrogen and phosphorus losses have been linked to over-fertilization and other rice production practices in several regions including rice production areas in South Korea[15,16], China[17-19], and Japan[20] (however, reduced nitrogen exports from rice paddies can also occur due to retention in the paddy and denitrification resulting from anoxic conditions[21]). Suspended sediment generated during puddling procedures can also be exported from rice paddies[20]. Rice production systems have been implicated as significant sources of agricultural methane ($CH_4$) emissions, due primarily to rice grown in flooded paddies which results in favorable conditions for methane-producing bacteria[22]. Techniques focused on reducing or interrupting irrigation, including alternate wetting and drying, can help mitigate $CH_4$ emissions[22] but may exacerbate $N_2O$ emissions[17]. Other environmental problems attributed to rice production include paddies functioning as sinks for heavy metal contamination due to agricultural chemical, wastewater irrigation, sewage sludge, and other inputs[23] and elevated levels of erosion due to excessive tillage in upland rice fields, which are commonly located in fragile ecosystems with vulnerable soils in mountainous or other sensitive areas[2,24,25].

Numerous models have been developed to simulate different aspects of growth, water management, and/or environmental impacts of rice production. Some of these models focus primarily on simulating rice crop growth and yield, taking into account various aspects of rice water, nutrient, and cultivation management practices[26-29]. Other models have been designed to simulate the hydrologic balance, pesticide fate, transport dynamics, and/or cycling and transport of other pollutants, which have been applied primarily for single rice paddies[30-34] or for a few small watershed areas[14,30,35].

The Soil and Water Assessment Tool (SWAT) is a watershed-scale ecohydrological model[36-40] which has been used worldwide to simulate an extensive range of watershed/river basin scales, environmental conditions, and climatic, management, land use, and other scenarios[41-47]. The use of SWAT has expanded greatly in Asia and elsewhere during the past decade, reflecting the increasing demand for effective and flexible tools that can be used to evaluate options for solving challenging water resource problems that are occurring across the continent. These SWAT applications have included dozens of studies that incorporated some level of rice production in the overall mix of land use simulated in the model[48-57]. Many of these studies report satisfactory to strong model testing results for the watershed systems that were simulated in the respective analysis. However, the majority of these studies report no or only limited details of how rice production was accounted for in SWAT. Furthermore, several studies strongly suggest that typical simulation methods used in SWAT do not adequately represent the characteristics of hydrological processes and pollutant transport that occur in rice paddy systems, including conditions where it appears that the overall watershed hydrology appears to be reasonably well simulated[15,58-64].

The previous research performed with SWAT underscores the critical need to develop a comprehensive and flexible module within SWAT that can be used to simulate rice paddy systems more realistically. The ability to account for differences in cultural practices, water dynamics, and pollutant cycling/transport between major types of rice production systems is an important attribute of such an enhanced SWAT rice paddy module. It is envisioned here that the development of this module would build on the foundation of existing key studies[58-64] and recent modifications made to the Agricultural Policy/Environmental eXtender (APEX) ecohydrological model[38,65,66], resulting in the APEX-Paddy model that supports enhanced simulation of rice paddy conditions[67]. Thus, the specific objectives of this study are to provide: 1) an overview of major rice production systems used in Asia and other regions; 2) a review of typical applications of SWAT that incorporate rice production including inherent weaknesses in standard simulation approaches; 3) a description of key modifications performed in recent SWAT applications that have resulted in more realistic representation of rice paddy systems; 4) a summary of the improvements and results that have been obtained with APEX-Paddy; 5) a conceptual structure for the proposed SWAT rice paddy module.

## 2 Rice production systems

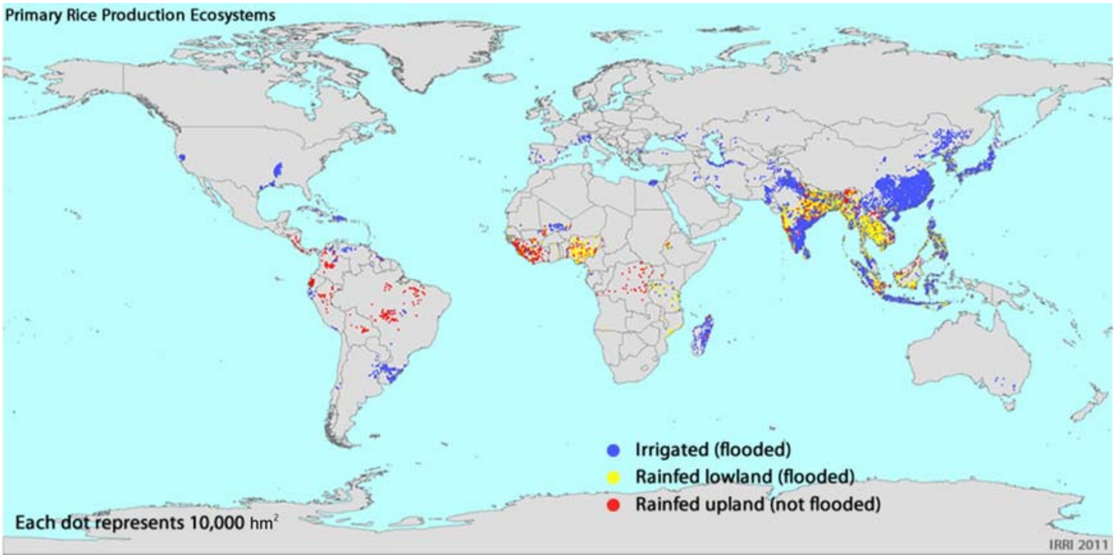
The vast majority of rice grown globally can be categorized as either irrigated lowland or rainfed lowland, with considerably smaller production areas managed as rainfed upland or flood-prone systems (Table 1)[2,24]. Supplemental irrigation may be beneficial for some rainfed lowland production systems such as has been shown for production areas in Nigeria[68] and Cambodia[69]. Table 1 lists key characteristics of each of these rice production systems including global production statistics, field management schemes, and average annual yields. Irrigated lowland rice is by far the dominant production system, resulting in 75% of the overall global rice production on about 54% of the total global production area. Irrigated lowland rice systems are also the most intensively managed, relying on irrigated water to maintain continuous flooding of rice paddies and higher chemical inputs on average of any of the rice production systems. Rainfed lowland systems comprise 19% of the remaining total global rice production while rainfed upland and flood-prone systems represent just 4% and 2% of the overall global rice production, respectively. Flood-prone production areas[2] are characterized by at least one of the following conditions: 1) covered with deep levels of water that exceed 100 cm for 10 d to a few months; 2) subjected to flash floods for 10 d or longer; 3) coastal landscapes where vegetation experiences tidal submergence on a daily basis, and/or 4) locations with marginal soils where problems can develop due to excess water.

The global distribution of the irrigated lowland, rainfed lowland, and rainfed upland production areas is shown in Figure 1. Irrigated lowland systems are clearly the dominant production approach in China, northern and southern India, the Indonesian islands of Java and Sumatra, South Korea, Japan, southern Brazil, the Malay Peninsula, and the Philippines, Madagascar, and other smaller areas in Africa, Asia, Europe, and the United States. Rainfed lowland rice production is the primary system used in Nigeria and in an arc that extends across the center of the Indian subcontinent and into much of Southeast Asia and is also an important component of rice production in subareas of Indonesia, Philippines, South Korea, and Africa. Production of rainfed upland rice is the most prominent system in the western horn of Africa, the Democratic Republic of the Congo, and parts of Central America and South America, and also occurs in relatively small areas of the Indian subcontinent, Southeast Asia, and the Indonesian and Philippine archipelagos.

**Table 1 Characteristics of the three primary global rice production systems**

| Rice production characteristic | Irrigated lowland | Rainfed lowland | Rainfed upland | Flood prone |
|---|---|---|---|---|
| Global production area/million·hm$^{-2}$ | 93 | 52 | 15 | 11 |
| Global production area/% | 54.4 | 30.4 | 8.8 | 6.4 |
| Total global production/% | 75 | 19 | 4 | 2 |
| Primary water source | Irrigation | Rain | Rain | Rain/flooding |
| Field type | Bunded | Bunded | Non-bunded | Non-bunded |
| Extent of flooded conditions | Continuous | Partial | Rarely | Partial |
| Level of chemical inputs | High | Medium/low | Low | Low |
| Potential total annual rice crops | 2-3 | 1-2 | 1 | 1 |
| Average yields/t·hm$^{-1}$ | 5.3 | 2.3 | 1.0 | 1.5 |

Source: International Rice Research Institute (IRRI)[2].




Note: Each dot represents 10 000 hm$^2$.

Figure 1 Global distribution of three primary forms of rice production[70]

### 2.1 Issues regarding rice paddy hydrology and pollutant transport dynamics

A wide range of rice production schemes exists within the three main rice production systems described above. Examples of different rainfed or irrigated rice production systems are shown in Figures 2-7, which are grown under differing conditions including upland areas, lowland or valley areas, and terraced systems. Collectively, these images underscore the diverse types of hydrologic conditions that rice is grown across the globe. Commonly, paddy fields retain runoff water resulting in reduced soil erosion and sediment yield, and alleviation of downstream flooding. They also release water slowly into the ground and recharge groundwater. However, rice production is further impacted by differing management schemes including the amount of irrigation or rain water inputs, puddling (wet tillage) or other types of tillage, the amount of pesticide and nutrient inputs, and

a. Rice terraces of Madagascar

b. Rainfed lowland rice paddies located in Laos

Figure 2 Examples of rice production: (a) rice terraces of Madagascar, where rice is grown under different ecological conditions, from uplands at the top of the slope, to more favorable rainfed and irrigated areas midway, to flood-prone areas at the bottom of the slope (farmers normally grow different varieties based on adaptation to each condition)[25] and (b) rainfed lowland rice paddies located in Laos[71]

a. Irrigated valley lowland rice paddies in South Korea b. Irrigated rice fields in Rio Grande do Sul (RS) in southern Brazil

Figure 3 Examples of rice production: (a) Irrigated valley lowland rice paddies in South Korea (Jeong J. Personal communication. Temple, Texas: Blacklands Research and Extension Center), and (b) irrigated rice fields in Rio Grande do Sul (RS) in southern Brazil (Tornquist C. Personal communication. Porto Alegre, RS, Brazil: Federal University of Rio Grande do Sul, Soil Science Department)

a. Irrigated lowland rice paddies in the Aizu Region b. Terraced rice paddies near the town of Misaki in Okayama Prefecture

Figure 4 Rice production in Japan: (a) irrigated lowland rice paddies in the Aizu Region[72], and (b) terraced rice paddies near the town of Misaki in Okayama Prefecture (Somura H. Personal communication. Okayama, Japan: Graduate School of Environmental and Life Science, Faculty of Engineering, Okayama University)

a. Rainfed rice in Laos b. Terraced rice in Vietnam

Figure 5 Examples of upland rice production: (a) rainfed rice in Laos[71], and (b) terraced rice in Vietnam[73]

a. Near Fanjing Shan, Tongren District, Guizhou Province, China b. Yanting County, Sichuan Province, China

Figure 6 Examples of lowland rice production in China: (a) near Fanjing Shan, Tongren District, Guizhou Province, China (Crosby M. Personal communication. Cambridge, United Kingdom: BirdLife International), and (b) Yanting County, Sichuan Province, China[74].

Figure 7 Examples of Longli (Longsheng) terraced rice production[75] located in Longsheng Various Nationalities Autonomous County, Guangxi Province, China (Cheng Z, Personal communication. Yulin City, Guangxi Province, China)

rotation and transplanting of rice seedlings versus broadcast or other seeding methods. Thus, the specific management regimes used within a given rice paddy or field have direct implications regarding the water quality impacts of stream systems that drain the respective rice production area.

2.1.1 Taihu Lake region (China) example

Rice paddy fields occasionally release large amounts of nitrogen and phosphorous to neighboring water bodies, mainly due to the excessive use of fertilizers. For example, 75% of the 36 500 $km^2$ total drainage area to Taihu Lake in the Yangtze River delta is dominated by rice production, which is one of the five major rice production regions in China. Rice has been grown in rotation with wheat for thousands of years in this area, resulting in one of the most fertilized regions in the world and increasing concern regarding environmental impacts due to high nitrogen loads including serious eutrophic conditions[18]. Rice and wheat seasons follow a distinct water regime within current standard farming methods in the previously described Lake Taihu region. Flooding the field alternating with frequent draining (e.g., for midseason aerations and harvest) is a common practice during the rice production periods. Contrarily, rainwater is the only source of soil moisture during wheat production seasons and rainfall levels are typically lower during wheat seasons relative to the rice seasons. However, rainfall amounts are often still excessive for the normal growth of wheat plants due to the subtropical monsoon climate, which usually results in the need for drainage ditches to protect the wheat plants from waterlogging injury. These distinct water schemes can influence the transformation and migration of N, and cause great variations in runoff and leaching N losses between rice and wheat seasons. One lysimeter study reported that N runoff and leaching are actually greater in wheat season than in rice season[19], indicating that improved nutrient management is needed for the overall rice-wheat rotational production system to successfully mitigate the Lake Taihu eutrophic conditions.

2.1.2 General schematics of rice paddy water allocation

A general schematic of possible hydrologic sources for rice paddy and subsequent discharge to potential downstream receiving water bodies is presented in Figure 8. A paddy field can be irrigated from a single source or multiple sources during the growing season. These irrigation sources can be reaches, aquifers, ponds, reservoirs, paddy fields, or other sources. Similarly, water in the paddy may discharge to channels, ponds, reservoirs, or another paddy field via a weir. Percolation from the paddy field recharges the shallow aquifer underneath the paddy field. The exact configuration of the hydrologic dynamics for a given rice paddy system will have further implications on water quality impacts such as the one described for the Taihu Lake region example. However, the focus in this sub-section is on the hydrologic interactions in various types of rice paddy systems.

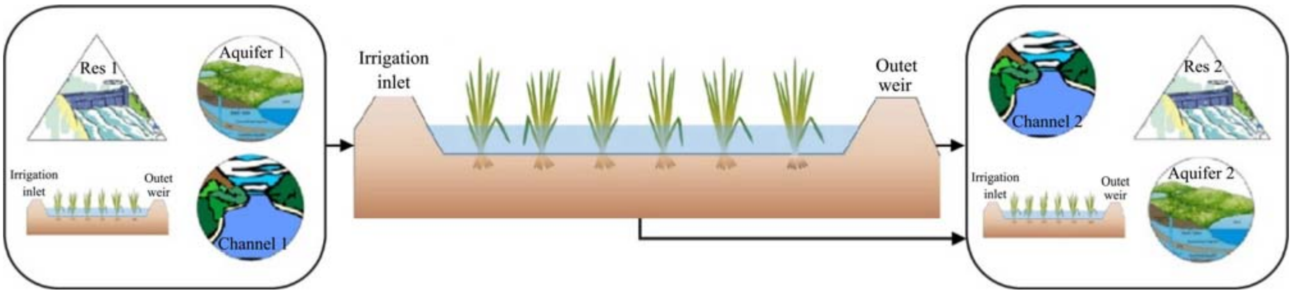



Figure 8 Example types of paddy irrigation sources and hydraulic connections to downstream flow

Paddy Example 1: This example represents a typical lowland paddy field (Figure 9). The paddy field is in part irrigated from a shallow well (Aquifer 1) and it also receives irrigation water from a reservoir (Res 1). The paddy drains into Channel 1.

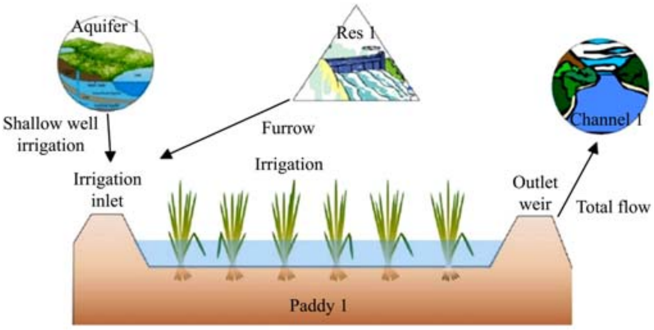



Figure 9 Graphical schematic of a paddy field having multiple sources of irrigation

A common version of the system portrayed in Figure 9 involves two channels: one that conveys irrigation water and a second that routes drainage water. In Japan, after land consolidation of paddy fields, the separation of irrigation and drainage canals is typically installed, especially for lowland and large paddy field areas. However, rice paddy systems also exist in Japan that rely on the same channel for obtaining irrigation water as well as receiving drainage water from the paddies. Dual-purpose canals for irrigation and drainage are installed for small-scale paddy field areas before land consolidation.

Similarly, Choi et al.[67] describe two lowland paddy sites in South Korea that rely on irrigation water from irrigation canals. The water that is discharged from the paddies is routed to a drainage canal, which is a different channel than the irrigation source channel. These types of lowland rice paddy systems are very common throughout South Korea.

Paddy Example 2: Paddy fields are often developed in a terrace system in steep valley areas following natural contours of the land (Figure 10). Irrigation systems in these paddies allow water to flow from the top floors of paddy down to lower level paddies through weirs and drainage conduits. In this example, Paddy 1 in the upper level is irrigated from Channel 1. Weir discharge from Paddy 1 drains to Paddy 2, the immediate lower level paddy. Paddy 2 drains into Channel 2.

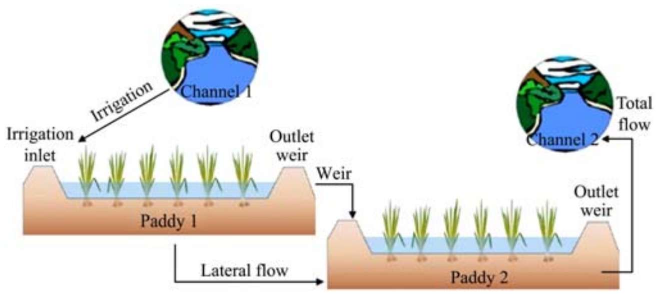



Figure 10 Graphical schematic of a cascading paddy system

A variant of this system is common in India without the terraces. In these systems, water is routed between two or more rice paddies but there is no cascading of flow between terraces because the paddies are located in lowland locations. Small ponds are often used as water sources for flooding rice paddies in India. However, drainage to a second aquifer (Figure 8) usually does not occur.

## 3 Comparisons of rice production and water quality models

As noted previously, a number of models have been developed for either simulation of rice production or accounting of water quality impacts for single rice paddy. Production models are commonly used to evaluate various managements, cultivars, or climate change effects on rice production at the field scale. These models are considered inadequate for simulating downstream water yield, water quality, or surface-subsurface hydrologic interactions. In addition, essentially none of the rice water quality models can simulate watershed-scale water quantity/quality impacts. Several of the key rice production and water quality models are discussed here in the context of comparisons with the SWAT and APEX-Paddy ecohydrological models, which can simulate both rice production and water quality impacts at a watershed scale (although with limitations). A more in-depth description of the use of SWAT and APEX-Paddy for simulating rice production systems is provided in the following sections.

### 3.1 Rice production models

Efforts on simulating rice (*Oryza sativa* L.) have been focused on estimating the growth and production of rice with conventional field-scale models. ORYZA (v3)[26] is the third-generation rice simulation model developed by the International Rice Research Institute (IRRI) which can simulate the growth and development of the rice based on water, carbon, and nitrogen availability in upland and lowland rice fields under potential production, and water-limited and nitrogen-limited conditions. This model simulates the growth of rice in five phenological stages including emergence, panicle initiation, flowering, and maturity. CERES-RICE[28] is part of the Crop-Environment Resources Synthesis (CERES) family of crop models. CERES-RICE simulates rice growth in nine phenological stages based on thermal time (or growing degree days) using eight generic parameters. Aquacrop v. 6.1[29] simulates rice growth based on the proportionality between relative yield decline and relative reduction in evapotranspiration occurring in the soil root zone. Grain yield is calculated by multiplying harvest index (HI) to biomass. During growing seasons, HI linearly increases from the flowing stage until maturity is obtained.

The SWAT and APEX ecohydrological models feature crop growth submodels that originated in the Environmental Policy Integrated Climate (EPIC) field-scale environmental model[38,66,76]. These submodels calculate potential daily biomass growth based on solar radiation and heat units, then actual growth is estimated based on stresses caused by limited water, temperature, nutrient, salinity, root aeration, and soil pH which provide less than ideal growth environment. These models use multiple sinusoidal curve relationships for estimating crop growth and development. Phenological stages are not considered in these submodels. Even though a number of studies found that these models predict grain (or biomass) yield accurately[68,76], these models are less sensitive to stressful growth conditions during sensitive phenological periods; e.g. water stresses during the grain-filling period which would reduce HI.

### 3.2 Rice water quality models

Several models have been developed to analyze water quality dynamics for a single rice paddy, most of which focus on pesticide fate and transport. Applications of multiple versions of the PADDY[77] and Pesticide Concentration in Paddy Field (PCPF)[78,79] models were described for pesticide movement in Japanese rice paddy conditions[23}. The authors also discuss the use of the Rice Water Quality (RICEWQ) model[14] for European rice paddy pesticide fate and transport assessments. Further comparisons of RICEWQ[14], PCPF-1, and an additional model are described for a rice paddy production area in northern Italy[80]. Two other studies describe the simulation of pesticide transport for one or more rice paddies in Vietnam[32] and California[33]. In contrast, the PADDIMOD model was used in two studies that report simulated nutrient transport output versus measured data collected for a rice paddy field site southeast of Seoul, Republic of Korea[34,81]. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model for rice paddies (CREAMS-PADDY) was also used to assess nutrient movement in rice paddies in South Korea[82]. None of these models are applicable at the watershed scale. At least three modeling systems have been developed[62] that are designed to simulate the hydrologic and pesticide transport impacts of rice production at the watershed scale including a modified version of the PADDY model called PADDY-Large[23,28]. However, these modeling systems are limited by either a focus on just rice production areas in a given watershed, and thus other land use is ignored, or by a constraint that the transport of only rice pesticides can be simulated (and thus other pollutants cannot be accounted for)[62].

The SWAT model has been used extensively to simulate water quantity and/or quality impacts for watersheds in Asia and elsewhere that are at least partially characterized by rice production as key agricultural land use. And SWAT is able to account for all land uses in a given watershed. However, the level of detail used to represent rice systems varies greatly across these simulations with some providing virtually no information on how rice was represented. Problems have been encountered when efforts were made to simulate rice paddy hydrological dynamics using the structure available in standard SWAT codes[58,59]. The structural limitations pertaining to simulating rice paddies in standard SWAT codes have resulted in several research efforts to modify the model to better represent various aspects of rice paddy production[15,60-64,83-85]. For example, the first attempt to introduce simulation of rice paddy water balance in irrigated paddy blocks in a modified version of SWAT is described in an application performed in South Korea[15]. The ability of APEX-Paddy to represent rice paddy hydrological and water quality dynamics has also been greatly enhanced by recent modifications[69]. These issues and advancements are discussed in more depth below, including the methodology envisioned to develop a standard rice paddy simulation module in SWAT.

## 4 SWAT model description and standard configurations for simulating rice

The current SWAT model represents over three decades of model development at the co-located U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) and Texas A&M University laboratories at Temple, Texas[38,39]. The initial version of SWAT was created via a fusion of the Simulator for Water Resources in Rural Basins (SWRRB) water quality model[86] with the Routing of Outputs to the Outlet (ROTO) model[87], which included components from other models such as the EPIC crop growth submodel[38,66,76]. Expansion and improvement of the SWAT code have been virtually continuous since that time, resulting in the incorporation of new algorithms to better represent specific management practices (e.g., subsurface tile drainage, filter strips, irrigation options), routing and depressional features (e.g., alternative sediment routing routines, wetlands, potholes), pollutant sources (e.g., septic tanks, point sources) and other components.

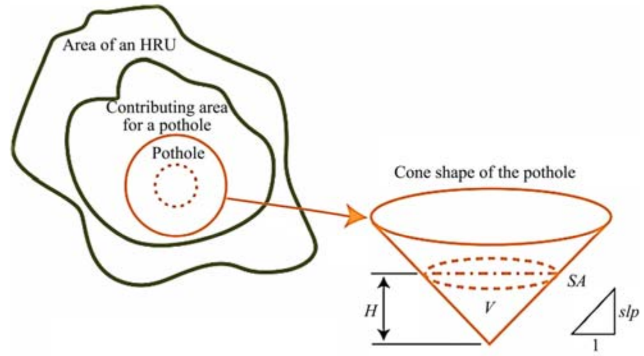
SWAT is usually executed on a daily time step although sub-daily options are also available[88,89]. A SWAT simulation is typically configured by subdividing a watershed into multiple subwatersheds and then further delineating the subwatersheds into hydrologic response units (HRUs), which are smaller land parcels consisting of homogeneous land use, soil, topographic and management characteristics that represent a percentage of a land area within a subwatershed (i.e., HRUs are not spatially identified within subwatersheds). Runoff and pollutant losses generated via surface and subsurface pathways at the HRU level are input to the stream network at the respective subwatershed outlet and then routed through the stream system to the watershed outlet. A variety of hydrologic and pollutant indicators can be output from SWAT at the HRU, subwatershed and/or overall watershed outlet.

Extensive SWAT theoretical and user guidance documentation is available online[90-96]. SWAT options related to rice production are the only aspects of the model that are discussed further here.

### 4.1 Simulation of rice production in SWAT

The SWAT structure and documentation guidance are relatively limited for simulating rice production. Rice crop parameters used in the SWAT crop growth component can be traced to the predecessor EPIC model, including testing of EPIC-predicted rice yields versus measured rice yields[76]. Additional work on the development of rice crop parameters was reported later for four varieties grown in the southern U.S.[97] Rice can be selected by users building SWAT simulations within standard SWAT Geographic Information System (GIS) preprocessing interfaces[98,99] or by other methods. Users can simulate water inputs for rice production as a function of precipitation and/or irrigation, and can also simulate other management practices such as tillage passes, nutrient applications, and pesticide applications. However, direct simulation of puddling (wet tillage) is presently not an option in standard versions of SWAT.

Explicit simulation of artificially impounded rice paddies is also not currently possible in SWAT. Documentation for SWAT version 2000 (SWAT2000)[90-91] and later major releases[92-96] state that rice paddies are hydrologically similar to potholes, which are closed depressional areas that frequently occur in regions characterized by low relief and/or young geologic development where the drainage network may be poorly developed[100]. Several studies report using the SWAT pothole algorithm for watersheds characterized by closed depressional areas including applications in the north-central U.S.[101-106], northern Germany[107] and Canadian Prairie Provinces[108-109]. A schematic of a SWAT pothole configuration[60] is depicted in Figure 11 which shows: (1) a pothole has to be identified within a specific HRU, (2) the portion of the HRU that contributes runoff to the pothole has to be defined, and (3) runoff generated from the contributing areas drains to the lowest point of the pothole which is assumed to be conical in shape. Only one HRU per subwatershed could be defined as containing a pothole up through SWAT2009; this restriction was later relaxed in SWAT2012[62,101]. The SWAT leaf area index parameter EVLAI, which defines the threshold when evaporation will no longer occur from the water surface for rice and other plants grown in ponded conditions, is an additional input related to the use of the pothole routine in the model.




Note: *SA* is the surface area of the water, $hm^2$; *V* is the volume of the water, $m^2$; *H* is the depth of the water, m; *slp* is the average slope of a specified HRU. HRU: Hydrological Response Unit.

Figure 11 Schematic of pothole configuration in a SWAT simulation; adapted from previously reported schematic[60]

### 4.2 Typical SWAT rice applications reported in the literature

The first known peer-reviewed SWAT study that included rice production was reported for an application that among other objectives investigated the streamflow impacts of producing irrigated versus rainfed rice for a watershed in southern Texas[110]. Numerous studies have since reported simulation of rice within respective SWAT applications, especially in India and China (Table 2), with some studies using just the term "paddy" to indicate rice production[50,111-114] while some other studies use a mix of the terms rice and paddy[115-117].

Several distinct application subthemes are represented within the example studies listed in Table 2 including: (1) investigation of the impacts of land use change[50,53,54,56,112,120-123,151], climate change[119,136,139,142,144,159] or combined land use change and climate change[111,155] scenarios, (2) analyses of primarily rainfed upland and/or lowland rice production among other simulated land use for relatively small watersheds located in northeast India[48,114,116,125,129-131,134], (3) the use of the SWAT pothole routine to represent rice paddy water dynamics[21,133,163], (4) relatively detailed reporting of management practices for a subset of the studies[21,48,113,163], and (5) SWAT rice-related studies in India or Pakistan[48,51,117,125,133,136-138] that incorporate accounting of crops grown during the kharif (monsoon or rainy) season, which typically occurs from June/July to October/November (versus crops grown in the Rabi (winter) season, which normally occurs from October/November to March/April[164,165]). Many of these studies (Table 2) simply state that rice was simulated, note the type of rice that was depicted in the study (Table 1 and Figure 1) and/or the amount of area that was represented by rice production[50,52,53,55-57,111,113,135,140,142,143,146-149,154-160,166]. Another subset of studies provides minimal details regarding how rice was simulated in SWAT. Examples include: (1) accounting for "paddy soils"[118,119,130,132,150], associated USDA Runoff Curve Number[167] (RCN) values[50,128,169] and/or USDA Universal Soil Loss Equation[168] (USLE) parameters[169,170], (2) noting that certain practices such as irrigation and fertilization were simulated but providing no specific details about the operation[113,120,123,129,134,137,144,152,170], or (3) mainly providing just specific dates or general time periods when selected planting and/or other operations were performed[121,122,125,130,134,136,141,171].

**Table 2 Examples of typical SWAT studies that report simulation of rice production for Asian and other conditions**

| Reference | Country or region | Watershed river name (size in $km^2$) | Rice-related simulation notes |
|---|---|---|---|
| [163] | Benin | 3 small inland valleys (≤5) | Lowland rice intensification systems; growing season=120 d; traditional unbunded rice versus bunded rice (both rainfed and direct seeded); bunded rice simulated with pothole routine; ponding is initiated two weeks after sowing (maximum water level=10 cm); water is released before fertilization and two weeks before harvest; fertilizer rates are reported. |
| [169] | Brazil | Camboriú (195) | Irrigated rice fields account for 5.7% of land use; RCN[a], USLE C[b], and USLE P[b] rice values reported. |
| [172] | Cambodia | Prek Te (4372) | Transplanting paddy rice requires 210 mm/d of water; percolation rate of 2.5 mm/d; growing season length, start/end days, and area for four types of wet or dry season rice (transplanted or direct seeded). |
| [50, 52, 55-57] | China | Upper Huaihe (10 190)[50,56]; NA[c][57]; DJKR[d] (85 500)[55]; TGRR[d] (58 000)[52] | Rice was a simulated crop. |
| [54, 118, 119] | China | Qinhuai (2631)[54]; Jinjiang (5629)[118]; Lake Dianchi (2920)[119] | Paddy soil included in simulation; note choice of RCN[a] for paddy soil[54]; included submerged paddy soil and water-logged paddy soil[119]. |
| [120-124, 173] | China | NA[a,e][120,121] Changjiang subbasin (6260)[122]; Fuhe (778)[123]; first-order river basins[f][124]; Abujiao[e] (143)[173] | Tillage for rice accounted for[120]; list dates for planting and fertilizer applications[121]; one rice crop irrigated in May and harvested in August[122]; irrigation performed with large amounts of water[123]; irrigation inputs to rice accounted for[124]; rice was the dominant land use[173]. |
| [21] | China | Fengyu (219) | Rice paddies were located in the lower parts of landscapes; rice comprised 11.8% of the land area; rice grown from May to September; rotated with broad bean or rapeseed; manure and fertilizer application rates reported for three dates; paddies were simulated with the SWAT pothole routine. |
| [174] | Ethiopia | Baro Akobo (75 906) | Irrigated rice is one of the agricultural crops. |
| [48, 117] | India | Nagwan (95.67) | Upland & lowland primarily rainfed rice grown in Kharif[g] season; six SWAT rice crop inputs modified; tillage, irrigation, planting, harvesting, and fertilizer application dates (and related data) reported. |
| [114, 125-129] | India | Nagwan (90.23[114,125,128], 92.46[126,127], 94.43[129]) | Upland and lowland primarily rainfed rice grown in Kharif[g] season[125]; rice production areas and associated RCN[a] values, plus fertilizer rates and tillage practices reported[128]; conventional tillage[129]. |
| [130-132] | India | Banha (16.95) | Rainfed lowland paddy rice; rice management based on local ploughing, puddling, planting, fertilizer and harvest practices[130]; Paddy Soils (Classes I and III) were used[130,132]. |
| [133] | India | Gomti (30,437) | Irrigated rice (kharif[g]) rotated with wheat (rabi[g]); rice (kharif[g]) rotated with pulses (rabi[g]); rotations occupy > 90% of land area; rice represented as transplanted crop; automatic fertilizer routine was used; paddies simulated with pothole routine (impounded before planting with release 5 d before harvest); simulated yields compared to measured yields. |
| [134] | India | Kapgari (9.73) | Rice is the major crop; usually cultivated during the rainy[g] season; high-yielding rice varieties require high levels of nitrogen application. |
| [116, 135] | India | Banikdih (89.50) | Primarily rainfed rice (62% of landuse); both lowland and upland rice part of watershed. |
| [136, 137] | India | Chaliyar (2530)[136]; Cauvery (81 155)[137] | Rice grown in both the kharif[g] and rabi[g] seasons; rice is the major crop (78% of land use), grown on 0 to 3% slopes and primarily irrigated[137]; annual watershed-level average simulated rice yields compared with measured yields over 39-year period[137]. |
| [51, 138, 139] | India | Mula and Mutha (2036) | Rice grown in rotation with spring wheat; rice in kharif[g] season and wheat in rabi[g] season[138]; auto-irrigation and auto-fertilization used[138]; rainfed during monsoon[g] season[51]; irrigation during dry season[51] |
| [140-143] | India | Palleru (NA[c])[140]; Upper Bhima (45 678)[141]; Upper Sind (3806)[142]; Malaprabha (2564)[143] | Rice mentioned as a major crop[140]; rainfed rice grown in monsoon[g] season[141]; rice was a simulated crop[142,143]. |
| [113, 115] | Indonesia | Bedog (155.3)[113]; Cisadane (4486)[115] | Rice covers 24.5%[113] or 27%[115] of the respective watershed; rice was irrigated[113]. |
| [175] | Iran | Tajan (4000) | Rice occupies 25% of land area; fertilizer, tillage, net irrigation, planting and harvesting periods, adjusted crop parameters and crop yields reported in tabulated form; irrigation sources and schedules accounted for. |
| [111, 112] | Japan | Teshio (2098) | Rice covers 4% of the land area; fertilizer application=71.8 kg·N/$hm^2$[112]; rice fertilizer inputs were based on government data[112]. |
| [44, 144] | Japan | Hii (920) | Rice covers 10.5% of the land area[144]; irrigation and fertilizer inputs for rice were based on local rice production data[144]; simulated versus measured rice yields compared at subwatershed level in 2003[144]. |
| [145, 146] | Japan | Lake Shinji (1194)[145]; Abashiri (1100)[146] | Rice was the dominant agricultural crop[145]; rice was a simulated crop[146]. |
| [170] | Japan | Takaya (121.9) | Rice paddy covers 18% of the land area; fertilizer amount and timing are subject to the prefectural cultivation standard; simulated with hourly precipitation data; USLE C[b] for rice paddy=0.03. |
| [147-150, 176] | South Korea | Gyeongan (262.3)[147]; Nakdong (NA[c])[148]; Bocheung (70.2)[149]; Haean (62.7)[150]; Yeongsan (724)[176] | Rice covers 7.3%[147], 15.48%[148], 15.6%[149], 13.6%[150] and 24%[176] of the land area; accounted for rice paddy soils[150]; BMPs simulated for paddies[176]. |
| [151] | South Korea | Gapcheon subbasin (597) | Report rice production areas for six different years between 1975 and 2000. |
| [171] | Pakistan | Lower Chenab Canal (NA[a]) | Rice-wheat rotation covered 12% of the land area; two major crop seasons: rabi[g] and kharif[g]. |
| [152, 153] | South Korea | Chungju multipurpose dam (6,642) | Rice covers 1.2% of the land area[153]; rice-growing season is April 1 to September 30[152]; irrigation applied based on requirements calculated for rice paddy field areas[152]. |

| Reference | Country or region | Watershed river name (size in km$^2$) | Rice-related simulation notes |
|---|---|---|---|
| [53, 154, 155] | Thailand | Chi (49 476)[53]; Lam Takong (3518)[154]; Lamtakhong (3403)[155] | Rice simulated in all three studies; rice covered 43.5%[53], 20%[154] and 17.8%[155] of the land area. |
| [156-160] | Vietnam | Upper Ca[h] (22 800)[156]; Huong (2830)[157]; Vu Gia (10 350)[158]; Song Cau (2941)[159] Bo (140.5)[160] | Rice simulated in all five studies; rice covered 4.1%[162] and 9.1%[157] of the land area. |
| [161[i], 162[i], 166] | Southeast Asia | Lower Mekong River Basin (629 520)[161]; (NA[c])[162]; (NA[c])[166] | Increasing rice production using multiple irrigation techniques[161]; 2.5 million hm$^2$ of rice produced in Mekong Delta region[161]; rainfed rice dominant due to high wet season rainfall[162]; rice productivity is relatively low in Thailand, Laos, and Cambodia but considerably higher in delta region[162]; rice was grown on 26% of the land area[166]. |

Note: [a]NA = not applicable; i.e., watershed names and/or watershed area were not provided; [b]USLE C and USLE P refer to USDA Universal Soil Loss Equation cropping and conservation practice factors[168]; [c]RCN refers to USDA Runoff Curve Number method which is described in detail in on-line documentation[167]; [d]DJKR and TGRR stand for Danjiangkou Reservoir and Three Gorges Reservoir Region, respectively; [e]The unnamed watershed for references 98 and 99 appears to be the same watershed as Abujiao in reference 156; [f]The first order basins refer to the seven major "breadbasket" (agricultural production areas) river basins in China: SongLiao, Hai, Huang (Yellow), Huai, Chang (Yangtze), Dongnan (Southeast) and Zhu (Pearl); [g]The kharif (monsoon or rainy) season typically spans June/July to October/November versus crops grown in the Rabi (winter) season that are normally grown from October/November to March/April)[164,165]; [h]The Upper Ca River watershed originates in Lao PDR; [i]A SWAT model developed by the Mekong River Commission[177] for the LMRB was used in both studies.

Some of the most complete descriptions of rice-related management simulation assumptions used in SWAT were reported for two studies conducted for the 95 km$^2$ Nagwan watershed in northeast India[48,117]. The authors describe the need to modify six SWAT rice crop parameters based on regional varieties and account for rice production in the context of typical crop rotations grown in the region. They also provide tabulated information listing the dates when key management operations were performed, the amounts of irrigation water and fertilizer that were applied to the rice crops and other pertinent rice-related simulation details. Another study conducted for the 16.95 km$^2$ Banha River watershed in northeast India[130] states that the rice ploughing, puddling, planting, fertilizer application and harvest practices simulated in SWAT were based on typical cultivation practices although explicit details are not provided regarding how ploughing and puddling were simulated in SWAT (and direct simulation of puddling is presently not possible in SWAT).

Explicit details regarding the use of the SWAT pothole routine to simulate rice paddy water management were reported in three studies conducted for three small watersheds (≤5 km$^2$) in Benin[163], the 219 km$^2$ Fengyu River watershed in China[21] and the 30 437 km$^2$ Gomti River watershed in northern India[133]. Detailed nutrient application rate data is also reported for the studies conducted in Benin[163] and China[21]. Satisfactory or better streamflow calibration/validation results were reported for all three studies. The study conducted in China also reported satisfactory total nitrogen loads while simulated rice grain yields generally replicated measured mean annual regional-level rice grain yields in the India study[133].

Comparisons of simulated versus measured mean annual regional-level rice grain yields were also reported across a 39-year period (1970 to 2008) for the 81 155 km$^2$ Cauvery River watershed in southern India[137] and in 2003 for the four main subbasins that comprise the 920 km$^2$ Hii River watershed in southwest Japan[144]. The mean simulated rice yields accurately replicated the measured yields in most years for both the southern India study as well as for the four subbasins reported in the Japan analysis. These rice grain yield validations coupled with strong streamflow calibration and validation results reported for the Cauvery River watershed[137] and Hii River watershed[144] studies resulted in some of the most robust overall testing results of any of the studies shown in Table 2, and provided a relatively strong basis for conducting scenario analyses in the two respective study regions. However, neither study attempted to replicate rice paddy impoundment characteristics in the respective study regions which have implications for the predicted hydrological results.

Many of the other studies compiled in Table 2 also report successful baseline streamflow testing results for the respective study watersheds[21,50,53-55,116,118,122,123,126,130,133,134,136,146-148,155,157,161,170] and some of the studies also report comparisons of predicted pollutant losses versus corresponding measured values[21,50,55,116,126,130,134,147,157,170]. The hydrologic testing reported in these studies further represents an extensive spectrum of watershed conditions and sizes, ranging from the ≤5 km$^2$ drainage area in Benin[163] to the 629 500 km$^2$ Lower Mekong River Basin (LMRB)[161]. Thus the overall testing of SWAT in these studies indicates that the model has performed well for Asian and other applications that incorporate rice production. However, it is virtually certain that hydrologic weaknesses due to misrepresentation of impounded rice paddies are occurring in most if not all of these applications and similar studies, even though watershed-scale statistical and graphical results imply successful replication of streamflow. This is clearly less of an issue for watershed systems characterized by relatively small areas of rice production[111,147,152,157]. However, there is likely major implications for systems with large areas of rice production, in the context of both baseline and scenario conditions[50,53,54,56,113,116,123,135,137,140, 148,155,157,161,170]. This is confirmed by the results of other studies that are reviewed in subsequent sections.

### 4.3 Problems encountered in simulating rice paddies in SWAT

Two studies conducted in Japan underscore the problems that can be encountered when attempting to simulate rice paddies in standard versions of SWAT[58,59]. The first study was performed for the 13.4 km$^2$ Yamada River watershed which is located in the drainage area to Lake Kasumigaura in the east-central part of Honshu, the main Japanese island[58]. The authors relied on the RCN approach[167] to simulate rice paddy hydrological dynamics and further distinguished between rice paddy non-irrigated and irrigated periods by using two different values of soil available water content (AWC). The simulated runoff generally replicated measured values well when the two different AWC values were used. However, predicted nutrient losses did not track corresponding measured levels well due in part to very limited measured nutrient data available at the time of the study. The authors stressed the need to develop actual rice paddy algorithms for SWAT rather than using the ad hoc parameter fitting approach they had to adopt for their application. They also pointed to the need to obtain better estimates of RCNs for Japanese soils and to categorize Japanese soils according to soil hydrologic groups (again per the use of the RCN method in SWAT).

The second study was performed for the 3 $km^2$ Arata River watershed which is located in the drainage area to Mikawa Bay, a semi-closed bay in the west-central part of the island of Honshu in Japan[59]. The authors compared the RCN method with the pothole approach[59] to simulate the rice paddy hydrology at the field scale as well as at the watershed scale. The study revealed that the pothole approach largely underestimated the percolation, surface runoff, and evapotranspiration at the field scale; as a consequence, the model efficiency was very low for simulating the river flow rate. On the contrary, the RCN method appeared reasonable for simulating the field and watershed-scale hydrology. However, this method in principle cannot simulate the ponded water conditions in rice paddies. Therefore, the authors concluded that neither of these two approaches is suitable for simulating rice paddy hydrology and underscored the need for developing a new rice paddy module in SWAT.

## 5 Overview of recently modified SWAT approaches

The structural limitations pertaining to simulating rice paddies in standard SWAT codes described above have resulted in several research efforts to modify the model to better represent rice paddy water balance dynamics[15,60-64,190], irrigation systems used to support rice production[60,61,63,64,83-85], or pesticide transport[61,62,189] or nutrient transport[181,191,192] in paddy systems. Some of the modified models feature adaptations of the original pothole routine in order to simulate rice paddy hydrology similar to that depicted in Figure 12[60-62,64,181,190-192]. Other efforts feature entire new rice paddy modules rather than adapting the pothole routine[65,67]. Improvements in the standard SWAT pothole algorithms have been described for the more recent SWAT2012 code[62], including more accurate accounting of soil water levels, shallow soil water table fluctuations, and leaf area index (LAI). These improvements likely mitigate some of the problems that were encountered in earlier research described above[59]. However, it is clear from the composite set of modified SWAT models and APEX-Paddy that relying on the current standard SWAT pothole routine is not sufficient to represent rice paddy hydrology and pollutant transport. Thus other attempts to use the pothole routine to represent rice paddies most likely introduced problems that may not have been transparent to the authors at the time they conducted their respective studies[21,133,163].

### 5.1 Typical depiction of rice paddies in modified SWAT models and APEX-Paddy

Figure 12 shows a schematic of a typical representation of rice paddy water dynamics that have been reported in the literature for several modified SWAT models and for APEX-Paddy[15,60-64,67,83-85,180,181,190,191,192]. The exact flow pathways included for the rice paddy hydrology characterization vary some between these studies and it is noted that the source of irrigation water and the outlet for drainage water may be different from the canals shown in Figure 12 (e.g., see Figure 8). It has been universally recognized in these studies that rice paddies are not shaped like conical depressional areas, as is represented for potholes in SWAT (Figure 11), but are rather cuboid in shape such as depicted in Figure 12. Thus the surface area of a rice paddy has been represented with the simple equation as follows in some studies[60,61,64]:

$$SA = A_{HRU} \tag{1}$$

where, SA is the surface area of the rice paddy ($hm^2$) and $A_{HRU}$ is the surface area of the HRU that the rice paddy is located in. This results in a relatively constant surface area to be represented for the simulated rice paddy, which is more realistic than the surface area represented by the conical depressions which can fluctuate considerably throughout a SWAT simulation[60].

The overall rice paddy water balance as shown in Figure 12 can be represented with the following relationship:

$$WD_i = WD_{i-1} + P_i + IR_i - DR_i - ET_i - PC_i - RF_i - SP_i \tag{2}$$

where, $WD_i$ is the water depth in the rice paddy on day $i$, mm; $WD_{i-1}$ is the water depth for the previous day, mm; $P_i$ is the precipitation that occurs on day $i$, mm; $IR_i$ is the irrigation depth on day $i$, mm; $DR_i$ is the drainage depth on day $i$, mm; $ET_i$ is the evapotranspiration on day $i$, mm; $PC_i$ is the percolation on day $i$, mm; $RF_i$ is the return (lateral) flow on day $i$, mm; $SP_i$ is the horizontal seepage on day $i$, mm. Variants of this water balance equation include exclusion of the $RF_i$ term[60], referring to the $SP_i$ and $RF_i$ terms as percolation and seepage, respectively[61], and referring to the $SP_i$ term as vertical percolation and accounting for two flow pathways that comprise an overall $RF_i$ impact: lateral flow and seepage through the berm that contains the outlet weir[64]. The concept of three critical depths (Figure 12) among these studies was first introduced by Xie and Cui[60]. The nomenclature of $DEP_{trigger}$ (irrigation trigger depth), $DEP_{target}$ (target depth for irrigation input) and $DEP_{max}$ (maximum depth that results in discharge from the rice paddy) for the three critical depths in Figure 12 are adopted from the more recent Tsuchiya et al. study[63].

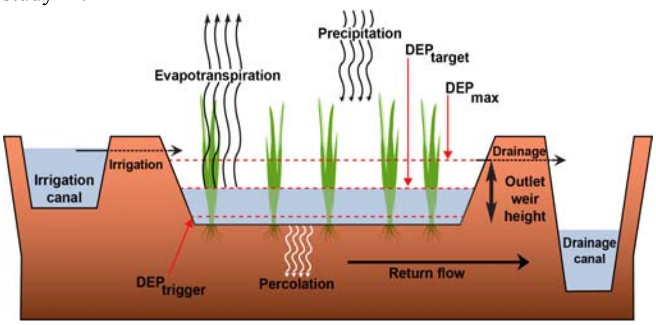



Figure 12 Depiction of typical rice paddy dynamics in modified SWAT and APEX models[15,60-64,67] (The dashed lines indicate irrigation and drainage flows via weirs in the paddy berms)

#### 5.1.1 Rice paddy irrigation methods introduced in modified SWAT models in China

Xie and Cui[60] describe in-depth modifications of SWAT to represent rice paddy irrigation inputs and related hydrologic dynamics for the Zhanghe Irrigation District in southern China, which greatly extended previous modifications performed in SWAT to represent rice paddy irrigation in South Korea[15]. Their modifications included the three critical depths shown in Figure 12, as well as accounting for irrigation requirements as a function of rice growth stage, the effects of paddy field conditions on ET and introducing ponds as an irrigation source. Six subsequent studies conducted in China built directly on the initial Zhanghe Irrigation District study[83-85,180,186,211], which further expanded the representation of rice paddy irrigation systems in modified versions of SWAT. Liu et al.[83] incorporated the previous developments[60] along with new canal seepage, rice canopy interception, and vertical seepage modules in an application of SWAT for a canal-well irrigation district in the lower Yellow River Basin in Northeast China. Additional research focused on the Zhanghe Irrigation District[84,85,180,186] also utilized the original improvements[60] in combination with several other new modifications representing enhanced canal seepage, rice ET, lateral subsurface flow, and other processes. The ability to account for multiple irrigation sources for a given subwatershed, including rivers, ponds, reservoirs, aquifers and/or outsides sources, has also been introduced[85,180] which overcomes a key limitation of standard SWAT code structures. Further modifications are reported to the SWAT code to represent return flows from rice paddies[180,186], which occur due to rainfall or irrigation inputs and can be reused for subsequent irrigation to downstream rice paddies. Fang et al.[211] modified SWAT based on the work of Xie et al.[60] and Sakaguchi et al.[64]. They introduced irrigation algorithms that set the daily rice paddy irrigation needed equal to the flow in the irrigation canal and also account for unused water by ensuring that irrigation water does not overflow a paddy impoundment. The primary modifications introduced in seven studies are shown in Table 3.

**Table 3 Primary modifications introduced to SWAT to support simulation of rice paddy irrigation strategies for irrigation districts or polder areas in China[60,83-85,178,180,186,211]**

| Reference | Modification description |
|---|---|
| [60, 83-85, 180, 186] | Incorporated three critical depths for management of water in rice paddies (Figure 12) |
| [60, 84, 85, 180, 186] | Ponds can be simulated as real-time irrigation sources (reservoirs simulated like ponds) |
| [60, 8-85, 180, 186] | Irrigation simulated as a function of seven different rice growth stages |
| [60, 83-85, 180, 186] | ET calculations account for whether paddy fields are in a wet or dry condition |
| [60, 84, 85, 180, 186] | Revised the land phase structure within the hydrologic cycle |
| [83] | Plow layer accounted for in vertical seepage calculations |
| [83] | Rice canopy interception module added |
| [83] | Dry crop module added to simulate LAI and actual transpiration for winter wheat |
| [83-85, 180] | Canal seepage module added; seepage calculated on the basis of water use efficiency |
| [83-85, 180] | Maximum irrigation amount was allowed to exceed soil field capacity levels |
| [84, 85, 180] | Rising capillary water accounted for; enters root zone and surface water cycle processes |
| [84, 85, 180] | Lateral seepage within paddy fields simulated when soil water exceeds field capacity |
| [84, 85, 180] | Rice ET estimated via a crop coefficient ($K_c$) and reference crop ET[b] ($ET_0$) methods |
| [84, 85, 180] | Fraction of subwatershed area that drains into ponds accounted for ($Pnd_{fr}$ = 0.3) |
| [84, 85, 180] | Average vertical daily percolation rate ($SP_i$; Equation 2) was set at a constant value (e.g., 2 mm ) |
| [60, 84, 85, 180, 186] | Stewart model was used to calculated rice yield based on ET |
| [85] | Crop coefficient ($K_c$) used in adjusting rice irrigation inputs as a function of growth stage |
| [84, 85] | Potential plant transpiration ($EP_{max}$) allowed exceeding reference crop ET ($ET_0$)[c] |
| [85, 180] | Multiple irrigation sources supported (rivers, ponds, reservoirs, aquifers, outside sources) |
| [85, 180] | Irrigation sources can vary between HRUs within a given subwatershed |
| [85, 180] | Simulates overall irrigation needs from one or more types of irrigations sources |
| [180] | Accounts for return flows from rice paddies due to precipitation and/or irrigation inputs |
| [186] | New method for calculating IE[d] and WSP[d] as a function of the reuse of irrigation return flow |
| [211] | Ensure that irrigation water does not overflow paddy impoundments |
| [178] | Hydrologically isolated polder areas accounted for in model structure |
| [178] | Accounts for storage and/or drainage from precipitation events in polders |
| [178] | Polder pumping systems represented; drain excess water or import irrigation water |
| [178] | Rice paddy irrigation simulated as a function of growth stages to supplement irrigation |
| [178] | Drainage of excess precipitation water estimated on basis of irrigation schedules |
| [178] | Crossed or looped channels are converted to dendritic patterns per SWAT requirements |

Note: [a]SWAT versions used in respective studies: three studies[60,83,84] used modified versions of SWAT2000[90,91]; Rice Irrigation System (RIS)-SWAT, a modification of ArcView SWAT (AVSWAT)[99] also introduced[84]; Wu et.al[85,180,186] used a modified version of SWAT2012[96]; SWATpld, a modified version of SWAT2012[96], Rev. 615[178]; [b]Four studies[83,84,85,180] cite a FAO method[179] for the reference crop ET; [c]Wu et al.[85] state that ET and $EP_{max}$ for rice can exceed $ET_0$, based on information provided in the FAO method[179], which was not properly accounted for in the original SWAT code; [d]IE: Irrigation efficiency; WSP: Water-saving potential.

One additional study performed in China describes modifications of SWAT that focused on unique polder production systems in the Taihu Lake region in Southeast China[178]. The polders are low lying land areas protected from flooding that are built along rivers or lakeshores, typically range in size from 0.1 to 10.0 km$^2$, and consist of rice paddies, other cropland, residences, ponds, inner rivers, canals, field ditches, dikes and pumping systems[178]. The polders are completely isolated from surrounding hydrologic systems, require manual drainage and irrigation management during flood season and the rice growing season, and interface external hydrologic systems only via pumping systems that can export excess drainage water or import required irrigation water[178]. The authors describe a modified SWAT called SWATpld[178], which supports the representation of polder systems via several code modifications including those listed in Table 3.

5.1.2 Modified SWAT models developed in Japan and India

Introduction of modified irrigation scheduling and other rice paddy hydrologic dynamics are reported in various levels of detail for six other modified models developed in Japan[61-64,189] or India[190]. Specific variants of the original SWAT model name that were adopted for five of these studies are as follows (and the original SWAT version and revision the revised models were based on): PCPF-1@SWAT[61] (SWAT2009, Rev. 466), PCPF-1@SWAT2012[62] (SWAT2012, Rev. 637), SWAT-RP[189] (SWAT2012, Rev. 637) and SWAT-Paddy[63] (SWAT2012, Rev. 629). The modified model reported by Sakaguchi et al.[61] was based on SWAT 2009, Rev. 488. The PCPF-1@SWAT and PCPF-1@SWAT2012 models are primarily described in Section 5.1.3, and SWAT-RP is primarily discussed in Section 5.1.4 along with two other modified SWAT models[181,191,192] and APEX-Paddy[67].

The research performed with the modified SWAT2009 codes[61,64] drew directly from the previous modifications reported by Xie and Cui[60], particularly in the use of the three rice paddy critical depths for a cuboid-shaped rice paddy (Figure 12). Sakaguchi et al.[64] found that a "comprehensive percolation rate" of 20 mm/d best-represented conditions for a 3 km$^2$ watershed they simulated in Japan, which represented the combined $SP_i$ flow and their previously described overall $RF_i$ term flows (combined lateral flow and leakage through the berm). They[64] further modified

HRU algorithms to overcome problems related to pothole hydrology dynamics, to allow for simulation of surface runoff and ET processes during periods that rice paddies were drained. Additional ET-related modifications were performed that included: (1) more accurate accounting of evaporation when paddies are impounded with water, (2) the introduction of an evaporation coefficient (set at 0.6) in the pothole evaporation equation to convert potential ET to actual evaporation, for improved representation of evaporation from paddies, and (3) setting the rice LAI when no evaporation occurs from the water surface to 4.0, which results in 90% of the ET occurring from transpiration when the rice LAI is in the range of 3.5 to 4.0.

The SWAT-Paddy model[63] features an independent rice paddy simulation module that was strongly influenced by several previous studies. As noted above, the authors again embraced the concept of three critical depths (Figure 12), which can be adjusted on a daily basis with a new command that was inserted in the management schedule routine[63]. The previously described comprehensive percolation rate and ET modifications reported by Sakaguchi et al.[64] were directly adopted in SWAT-Paddy[63]. Modifications to the auto-irrigation routine were also introduced in SWAT-Paddy that allow for accounting of irrigation demand from the main source and a secondary source[63]. An equation for puddling, based on methods used in APEX-Paddy[67], was further incorporated which represents tillage that occurs during shallow ponded water conditions[63,69]. The authors describe applying SWAT-Paddy to the 117 $km^2$ Upper Kashima River watershed that is located in the central part of Japan[63].

The modified SWAT-EP[190] model features an improved pothole-based approach for representing paddy hydrologic dynamics within the context of alternate wetting and drying (AWD) management. The enhanced pothole methodology includes the following components[190] (1) more realistic estimation of saturated hydraulic conductivity (versus Du et al.[104]), which is estimated as a function of soil texture and bulk density, (2) improved algorithms to represent deep percolation during the paddy ponding and drying phases, (3) Enhanced representation of evapotranspiration that accounts for the effects of soil evaporation, crop transpiration, and impounded water evaporation, as opposed to just crop LAI in the standard pothole method[104], and (4) incorporation of return flow from paddies to channels or streams based on methods previously developed by Wu et al.[180]. The authors report[180] that SWAT-EP was found to outperform SWAT-CN (original SWAT), SWAT-P (SWAT-pothole) and SWAT-PS (SWAT-PS is based on the method reported by Sakaguchi et al.[64]) as further discussed in Section 5.1.5.

5.1.3 Pesticide transport simulations performed with PCPF-1@SWAT and PCPF-1@SWAT2012

The influence of typical Japanese rice production growth stages on irrigation demand was accounted for in the development of PCPF-1@SWAT[61] for the 345 $km^2$ Sakura River watershed. The authors[61] also report setting $SP_i$ to 10 mm/d, a typical value for Japan, and that the most accurate $RF_i$ value was 12 mm/d based on the results of a calibration process. No irrigation strategy details are reported for the applications of PCPF-1@SWAT2012 reported in Tu et al. (2018)[62] and Tu (2020)[189]. However, both studies were a direct continuation of the previous PCPF-1@SWAT[61] research and thus incorporate the irrigation methods that were described in that earlier investigation.

The PCPF-1@SWAT[61] and PCPF-1@SWAT2012[62,189] models feature the integration of the PCPF-1 rice paddy pesticide fate model[78,79] with the respective SWAT codes used for the two modified models. This interface replaced the original equations used in SWAT that were derived from the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model[185] and provided the ability to more realistically simulate pesticide fate and transport in rice paddies[61]. Adaptions incorporated in PCPF-1@SWAT[61] included the ability to: (1) account for multiple pesticide applications for each simulated rice paddy, and (2) simulate the fraction of pesticide sorbed in sediment in rice paddy water, based on the pesticide's partition coefficient and the concentration of suspended solids that are present in a pothole. These improvements were adopted in PCPF-1@SWAT2012, along with the following additional enhancements[62,189]: (1) being able to represent rice paddies (potholes) at the HRU level rather than being constrained by being able to only represent a single rice paddy per subbasin (see Section 4.1), (2) improved pothole water balance representations including representation of lateral subsurface flow and both downward and upward percolation processes, and (3) more accurate representation of rice LAI during harvest and kill operations, which results in EVLAI > LAI during those phases and reduced levels of evaporation being estimated from the water surfaces of the simulated rice paddies.

Pesticide simulation results were reported for the Sakura River watershed using both PCPF-1@SWAT[61] and PCPF-1@SWAT2012[62,189]. Factors that influenced the simulation of the pesticide mefenacet using PCPF-1@SWAT[61] included the treated area, application rate and timing, the maximum ponding depth and related excess water storage depth, a regulatory 7-day water holding period before water can be discharged from a rice paddy treated with a pesticide and the $RF_i$ rate. The development of the SWAT Rice Pollutant (SWAT-RP) model followed the testing of PCPF-1@SWAT2012, which features further improvements in the paddy water balance and pesticide cycling and transport algorithms, and the incorporation of nitrogen cycling and transport algorithms as described below[189].

5.1.4 Nutrient cycling dynamics: SWAT-RP, SWAT-$N_2O$ coupler, SWAT-P, and APEX-Paddy

The SWAT-RP model represents nitrogen cycling dynamics in two distinct paddy zones[189]: (1) paddy water in combination with the first 10 mm of paddy soil, and (2) the remaining paddy soil zone to a depth of 300 mm. Key nitrogen transformation or transport processes depicted in the upper zone include hydrolysis, ammonia volatilization, nitrification, denitrification, irrigation water loading, discharge in runoff and leaching into the deeper paddy soil zone. Corresponding nitrogen processes accounted for in the lower zone are mineralization, nitrification, denitrification, immobilization, vertical movement in the soil profile and uptake via rice roots.

Gao et al.[181] describe the SWAT-$N_2O$ coupler, which is a modified version of SWAT2012 that integrates the rice paddy adaptations introduced by Xie and Cui[60] (Figure 11 and Table 3) with $N_2O_{soil}$ and $N_2O_{paddy}$ modules, to simulate $N_2O$ emissions from upland cropland areas and rice paddies, respectively. The previously described rice growth and irrigation stages (Table 3) are accounted for in SWAT-$N_2O$ coupler, which results in the $N_2O_{paddy}$ module being used during paddy ponded conditions versus the $N_2O_{soil}$ module, which is invoked when there is no ponded water in the paddies.

The SWAT-P model[191,192] is a modified version of SWAT2012 (Rev 635) that uses a restructured pothole module to more realistically represent paddy hydrology and pollutant dynamics, which is a further adaptation of the SWAT-$N_2O$ coupler[181] (SWAT-P is referred to as SWAT-Paddy in the title of the study reported by Ouyang et al. (2019)[191]). The ability of SWAT-P to replicate total P movement for rice production systems was further confirmed for the 121.4 km$^2$ Fushui River Watershed (Table 4), which is located in Hubei Province in East-central China[192]. Optimal drainage management was further evaluated using SWAT-P in the context of two primary options: (1) source reduction, which is focused on reducing surface runoff and pollutant losses from rice paddies, and (2) process interception, which relies on enhanced drainage ditch (or canal) and pond characteristics that result in greater amounts of captured pollutants prior to entering streams. The results of paddy scenarios are described in the study[192] that focused on modifying the $DEP_{max}$, $DEP_{trigger}$ and/or $DEP_{target}$ as shown in Figure 12.

**Table 4 Summary of statistics, that provide evaluation of simulated versus observed hydrologic and/or pollutant indicators, that were reported for the SWAT or APEX models that were modified to more accurately replicate rice paddy hydrologic and pollutant transport dynamics**

| Reference | Watershed/country·km$^{-2}$ | Indicator (time periods)[a] | Modified and/or original model | Calibration | | Validation | |
|---|---|---|---|---|---|---|---|
| | | | | NSE | $R^2$ | NSE | $R^2$ |
| [60] | Zhanghe Irrigation District subbasin (China/1,128.9) | Daily flow (Cal[b]:2005[c]; Val[b]:2006[c]) | Modified SWAT[d] | 0.68 | 0.79 | 0.83 | 0.90 |
| [61] | Sakura River (Japan/345) | Daily flow (Cal:2007; Val:2008) | PCPF-1@SWAT[d] | 0.71 | 0.74 | 0.74 | 0.74 |
| | | Mefenacet[e] (Val:2008[c]) | PCPF-1@SWAT[d] | | | 0.65[f] | 0.61[f] |
| [62,189] | Sakura River (Japan/345) | Daily flow (Val:2008[b]) | PCPF-1@SWAT2012[d] | | | 0.77 | 0.78[h] |
| | | | PCPF-1@SWAT[d,g] | | | 0.74[g] | 0.74[h] |
| | | Mefenacet[e] (Val:2008[b]) | PCPF-1@SWAT2012[d] | | | 0.71 | 0.89[h] |
| | | | PCPF-1@SWAT[d,g] | | | 0.65[g] | 0.61[h] |
| | | Daily flow (Cal:2007; Val:2008-2009) | PCPF-1@SWAT2012[d] | 0.48 | 0.60[h] | 0.73 | 0.76[h] |
| | | Mefenacet[e] (Cal:2007[c]; Val:2008-2009[c]) | PCPF-1@SWAT2012[d] | 0.91 | 0.94[h] | 0.69 | 0.85[h] |
| | | Pretilachlor[e] (Cal:2007[c]; Val:2008-2009[c]) | PCPF-1@SWAT2012[d] | 0.52 | 0.94[h] | 0.86 | 0.90[h] |
| | | Bensul-methyl[e] (Cal:2007[c]; Val:2008-2009[c]) | PCPF-1@SWAT2012[d] | 0.73 | 0.86[h] | 0.46 | 0.64[h] |
| | | Imazosulfuron[e] (Cal:2007[c]; Val:2008-2009[c]) | PCPF-1@SWAT2012[d] | 0.70 | 0.79[h] | 0.64 | 0.85[h] |
| [63] | Upper Kashima River (Japan/117) | Daily rice paddy flow[i] (Cal:2016[c]) | SWAT-Paddy[d,j] | | 0.80 | | |
| | | | Original SWAT[d,j] | | 0.002 | | |
| | | Daily flow (Cal:2012-2014[c]) | SWAT-Paddy[d,j] | 0.40 | 0.51 | | |
| | | | Original SWAT[d,j] | 0.63 | 0.63 | | |
| [64][g] | Arata River (Japan/3) | Daily flow (Cal:2005-2006[c]; Val:2004-2005[c]) | Modified SWAT[d,k] | 0.73 | 0.74 | 0.56 | 0.66 |
| [67] | Incheon rice paddy site (South Korea/0.15) | Daily rice paddy flow[h] (Cal:2002[c]; Val:2003[c]) | APEX-Paddy[d] | 0.87 | 0.88 | 0.65 | 0.80 |
| | | | Original APEX[d] | −1.91 | 0.57 | | |
| | | Daily nitrogen load (Cal:2002[c]; Val:2003[c]) | APEX-Paddy[d] | 0.63/0.68 | 0.66 | 0.43 | 0.64 |
| | | | Original APEX[d] | −14.4 | 0.02 | | |
| | Gimje rice paddy site (South Korea/0.05) | Daily rice paddy flow[h] (Cal:2014[c]) | APEX-Paddy[d] | 0.70 | 0.77 | | |
| [83] | Liuyuankou Irrigation District (China/407) | Monthly flow (Cal:1991-1999; Val:2001-2007) | Modified SWAT[d] | 0.75 | 0.88 | 0.77 | 0.95 |
| | | | Original SWAT[d] | 0.54 | 0.74 | 0.62 | 0.80 |
| [85] | Yangshudang River (China/43) | Daily flow (Cal:2005-2007[c]; Val:2008-2009[c]) | Modified SWAT[d] | 0.80 | 0.82 | 0.84 | 0.85 |
| | | | Original SWAT[d] | 0.48 | 0.65 | 0.68 | 0.79 |
| [178] | Shang polder, Lake Taihu Basin (China/0.047) | Monthly flow (Cal:2012-2014; Val:2010-2011) | SWATpld[d,l] | 0.61 | 0.61 | 0.55 | 0.64 |
| | | | Original SWAT[d,l] | 0.61 | 0.68 | 0.35 | 0.63 |
| [181] | Naoli River (China/2, 205) | Soil temperature (Cal:2015-2016) | SWAT-$N_2O$ coupler | 0.89 | 0.95 | | |
| | | Soil water content (Cal:2015-2016) | SWAT-$N_2O$ coupler | 0.74 | 0.79 | | |
| | | $N_2O$ submodel[m] (not reported) | SWAT-$N_2O$ coupler | 0.59 | 0.59 | 0.54 | 0.52 |
| | | $N_2O$ soil submodel[m] (not reported) | SWAT-$N_2O$ coupler | 0.77 | 0.78 | | |
| [189] | Kose River (Japan/84.7) | Daily flow (Cal:2008; Val:2009) | SWAT-RP[d] | 0.87 | 0.90 | 0.83 | 0.88 |
| | | Pretilachlor[e] (Cal:2009) | SWAT-RP[d] | 0.78-0.90 | 0.75-0.99 | | |
| [189] | Rice paddy; Sakura River Watershed (Japan) | Daily flow (Cal:2007[c]; Val:2007-2009[c]) | SWAT-RP[d] | 0.72 | 0.73 | 0.63 | 0.63 |
| | | Mefenacet[e] (Cal:2007[c]; Val:2007-2009[c]) | SWAT-RP[d] | 0.93 | 9.94 | 0.73 | 0.89 |
| | | Mefenacet[e] (Cal:2007[c]; Val:2007-2009[c]) | PCPF-1@SWAT2012[d] | 0.91 | 0.94 | 0.69 | 0.85 |
| | Lysimeter; Tokyo Univ. of Agric. and Tech. (Japan) | Daily Ammonium (Cal: April 14-22, 2002) | SWAT-RP[d] | 0.88 | 0.93 | | |
| | | Daily nitrate (Cal: April 14-22, 2002) | SWAT-RP[d] | 0.31 | 0.47 | | |
| [190] | Kangsabati River (India/12, 014.7) | Daily flow R[n] (Cal:1999-2003; Val:2004-2006) | SWAT-CN[d] | 0.66 | 0.66[h] | 0.65 | 0.64[h] |
| | | Daily flow S[n] (Cal:1999-2003; Val:2004-2006) | SWAT-CN[d] | 0.41 | 0.44[h] | 0.46 | 0.52[h] |
| | | Daily flow R[n] (Cal:1999-2003; Val:2004-2006) | SWAT-P[d] | 0.59 | 0.61[h] | 0.65 | 0.66[h] |
| | | Daily flow S[n] (Cal:1999-2003; Val:2004-2006) | SWAT-P[d] | 0.49 | 0.53[h] | 0.49 | 0.50[h] |
| | | Daily flow R[n] (Cal:1999-2003; Val:2004-2006) | SWAT-PS[d] | 0.64 | 0.62[h] | 0.67 | 0.53[h] |
| | | Daily flow S[n] (Cal:1999-2003; Val:2004-2006) | SWAT-PS[d] | 0.71 | 0.74[h] | 0.51 | 0.53[h] |
| | | Daily flow R[n] (Cal:1999-2003; Val:2004-2006) | SWAT-EP[d] | 0.77 | 0.77[h] | 0.84 | 0.85[h] |
| | | Daily flow S[n] (Cal:1999-2003; Val:2004-2006) | SWAT-EP[d] | 0.87 | 0.90[h] | 0.89 | 0.90[h] |

| Reference | Watershed/country·km$^{-2}$ | Indicator (time periods)[a] | Modified and/or original model | Calibration | | Validation | |
|---|---|---|---|---|---|---|---|
| | | | | NSE | $R^2$ | NSE | $R^2$ |
| [191] | Abujiao River (China/142.9) | Daily flow (Cal:2005-2007c; Val:2008-2009c) | SWAT-P[d] | 0.80 | 0.82 | 0.84 | 0.85 |
| | | | Original SWAT[d] | 0.48 | 0.65 | 0.68 | 0.79 |
| | | Nitrate (Val:2016c) | SWAT-P[d] | | 0.63 | | |
| | | | Original SWAT[d] | | 0.51 | | |
| [192] | Fushui River (China/121.4) | Total P (Cal:2017-2018c; Val:2019c) | SWAT-P[o] | 0.61 | 0.50 | 0.66 | 0.52 |
| [211] | Qinhuai River (China /2,631) | Monthly flow (Cal:1990-1994; Val:1995-1999) | Original SWAT | −3.28 | | −8.42 | |
| | | Monthly flow (Cal:1990-1994; Val:1995-1999) | Modified SWAT | 0.86 | 0.88 | 0.65 | 0.71 |
| | | Evapotranspirtation (May-November 2007) | Original SWAT | | | | 0.49 |
| | | Evapotranspirtation (May-November 2007) | Modified SWAT | | | | 0.75 |

Note: [a]Flow reported here also represents similar hydrologic terms reported in some studies such as discharge or runoff; [b]Cal: Calibration, Val: Validation; [c]These studies actually report time periods of several months that were fewer than a full year or years; e.g., May to September of each year[60,85]; [d]SWAT versions used in respective studies: SWAT versions are reported for five of the studies[60,83,85,178] in Table 3 footnote a; PCPF-1@SWAT[61] developed from SWAT2009[94,95] (Rev466); PCPF-1@SWAT2012[62,189] developed from SWAT2012[96]; SWAT-Paddy[63] was developed from SWAT2012[96] (SWAT2012=original SWAT); APEX-Paddy[67] was developed from APEX1501 (APEX1501=original APEX); SWAT-$N_2O$ coupler based on SWAT2012 (inferred from study)[181]; SWAT-RP[189] based on SWAT2012[96] (Rev 637); SWAT-CN, SWAT-P, SWAT-PS, SWAT-EP[190] all based on SWAT2012[96] (Rev 637) (SWAT-CN=original SWAT, SWAT-P (SWAT-pothole)=pothole method, SWAT-PS based on method reported by Sakaguchi et al.[64], SWAT-EP = new modified version); SWAT-P[191,192] = SWAT-Paddy, based on SWAT2012 (Rev 635) (Original SWAT = SWAT2012 (Rev 635)); [e]Mefenacet, pretilachlor, bensulfuron-methyl, imazosulfuron and pretilachlor are pesticides; comparisons with measured data were on a daily basis; [f]Statistics based on calibrated $RF_i$ value of 12 mm/d; weaker results reported for two other $RF_i$ values included in the calibration process. [g]These PCPF-1@SWAT statistics[61] are repeated (and based on the time period that Mefenacet was reported for) from the previous study[60]; [h]Tu L H, Personal communication, Agric. and Environ. Engineering, United Graduated School of Agric. Science, Tokyo Univ. of Agric. and Tech., Tokyo, Japan; [i]Statistics determined for daily flow comparisons at the outlet of simulated rice paddies rather than overall stream flow; [j]A composite $SP_i$ and $RF_i$ rate of 10 mm/d was used for the SWAT-Paddy and original SWAT simulations[62]; [k]A calibrated composite $SP_i$ and $RF_i$ rate of 20 mm/d was used; weaker results occurred in simulations using six other composite rates[63]; [l]Additional statistics are reported for individual years; [m]$R^2$ values of 0.61, 0.64 and 0.61 were also reported[181] for varying irrigation conditions for the $N_2O$ paddy submodel, based on previous study results. [n]$R$ is the inflow into the Kangsabati Reservoir; $S$ is the streamflow at the Mohanpur gauging station at the outlet of the watershed; [o]Modified SWAT-P model described in the previous study reported by Ouyang et al.[191]; [p]Irrigation and non-irrigation periods each year were from May to September and from October to April, respectively.

APEX-Paddy is an adaptation of the standard APEX model (version 1501) that features an enhanced rice paddy module, which was applied to the 15 hm$^2$ Icheon and 0.5 hm$^2$ Gimje research sites located in South Korea[67]. The rice paddy module can simulate water pounding for subareas designated as rice paddies, with appropriate diking and discharge controls. Rice paddy management practices including puddling, irrigation, transplanting, and fertilizer applications can also be simulated. The possibility of actual ET (AET) exceeding potential ET (PET) during ponded conditions is accounted for, similar to the adaption reported by Wu et al. (2019)[85] as noted in Table 3. The ET algorithms used in APEX-Paddy are partially based on the approach reported by Sakaguchi et al.[64] Default subarea modules that simulate upland non-ponding land processes are used during periods when the rice paddies are not ponded or outside of the rice-growing season.

5.1.5 Statistical Results Reported for Modified SWAT Models and APEX-Paddy

Hydrologic- and/or pollutant-related statistical results have been reported for most of the modified SWAT models described in the literature listed in Table 4. This includes: 1) five of the studies described in Section 5.1.1[60,83,85,178,211]; 2) three studies that investigated rice paddy hydrologic dynamics in Japan and India[63,64,190] (Section 5.1.2); 3) three studies that reported both hydrologic and pesticide loss results in Japan[61,62,189] (Section 5.1.3); 4) four studies that report hydrologic and/or nitrogen cycling results in China[181,191,192] and Japan[189] (Section 5.1.4). Six of these studies provided comparisons between original SWAT and modified SWAT results[63,83,85,178,191,211], and a seventh study[190] provides comparisons between the modified SWAT model (SWAT-EP), two versions of the standard SWAT model (SWAT-CN and SWAT-P) and the modified SWAT-PS code (all four models[190] are further described in Section 5.1.2 and the Table 4 footnotes). Statistical results are also listed in Table 4 for hydrologic and nitrogen loads comparisons between the original.

A range of statistics was reported across the studies reviewed here to evaluate simulated versus observed hydrologic or pollutant indicators. However, the statistics listed in Table 4 were limited to the Nash-Sutcliffe efficiency (NSE)[182] and coefficient of determination ($R^2$)[182], which were two of the most commonly reported statistics among the modified models reviewed in this study and are also consistent with summaries of statistics reported in previous SWAT review studies[41-45,47]. The statistical results of these studies can be assessed according to the criteria suggested by Moriasi et al.[183], which supersedes earlier suggested criteria reported by Moriasi et al.[184] The suggested NSE/$R^2$ criteria[183] were>0.50/>0.60 and >0.70/>0.75, for satisfactory and good or better flow results; less stringent criteria are proposed for simulated sediment and nutrient pollution results. The majority of flow statistics met the satisfactory criteria and many of the statistics could be classified as good or better (Table 4).

The modified SWAT or APEX models usually outperformed the corresponding original models for the eight studies that reported both sets of results[63,67,83,85,178,190,191,211]. However, the opposite occurred for the watershed-level daily flow results reported for the SWAT-Paddy model application in Japan[63] and the calibration results of the SWATpld model[178]. These outcomes and other study results reveal that some weaknesses in replicating observed streamflows continued to manifest in various ways for the revised codes[e.g.,60,63,85,178].

Satisfactory results were obtained for the mefenacet simulations performed with the $RF_i$ rate of 1.2 mm/d, based on proposed pollutant NSE and $R^2$ criteria[183] (intended for sediment and nutrients but extended to pesticides here). Slightly improved mefenacet simulation results were reported using PCPF-1@SWAT2012[62], versus the previous results[61], due primarily to a more accurate accounting of the portion of the watershed that was represented by rice paddies. Satisfactory or better NSE and $R^2$ calibration and validation results were also reported for three other pesticides that were simulated with PCPF-1@SWAT2012[62].

The authors[181] report results of testing the SWAT-$N_2O$ coupler system for Naoli River watershed of 2205 $km^2$, which is located in the Sanjiang Plain region in Northeast China. Satisfactory to very good statistical results (Table 4) were obtained for simulated versus observed comparisons for soil moisture, soil temperature, $N_2O$ emissions from upland cropland areas, and $N_2O$ emissions from rice paddies per the same statistical criteria cited above[183]. SWAT-P simulated soil water levels more accurately than the original SWAT model for non-frozen soil conditions, which was evidenced both by graphical and root mean square error (RMSE) statistical results[191]. SWAT-P also simulated nitrogen and phosphorus cycling more accurately than the original SWAT model, in terms of timing (e.g., the freeze-thaw period in March and April), magnitude, constituent form (inorganic versus organic), and flow pathways[191]. The revised algorithms incorporated in SWAT-P were further validated by improved overall simulation of nitrate relative to the standard SWAT2012 code (Table 4), for the 142.9 $km^2$ Abujiao River Watershed located in far Northeast China.

Satisfactory or better NSE and $R^2$ nitrogen yield statistics (Table 4) per suggested criteria[183] were further found with APEX-Paddy for nitrogen exported from the simulated rice paddy at the Icheon site in South Korea (Table 4). The APEX-Paddy nitrogen yield results were also greatly superior as compared to the standard APEX model results (Table 4); the latter was considered very unsatisfactory[183].

## 6 Proposed paddy module in SWAT+

The historical applications of SWAT across Asia and in other regions described above underscore the need for the development of a module that can more realistically replicate rice paddy dynamics and rice production in general. This module will be incorporated into future releases of SWAT+[40,187,210} which features a more flexible code structure as well as a greater ability to more accurately represent cropped landscapes, various water bodies such as ponds and reservoirs, irrigation systems, and other aspects of watershed management relevant to rice production. The proposed module will draw on advancements reported in the previously discussed modified SWAT models[15,60-64,67,83-85,180,190-192], APEX-Paddy[67], and new components developed in consultation with cooperating institutions in South Korea, Japan, China, India, and elsewhere. The core component of this module will be structured to represent the rice paddy dynamics depicted in Figure 12 and will allow an accurate representation of rice paddy configurations. This approach will eliminate the constraints encountered in adapting the pothole module or other impoundment options. Components of the new rice paddy module will include: (1) a better water balance calculation with realistic irrigation scheduling and water budget simulation; (2) improved timing and magnitude of predicted outflow in response to variable storm events at the daily scale; (3) improved correlation of water quality output to storm events; (4) the ability to adequately design different conservation practices for paddies.

### 6.1 Rice paddy hydrologic dynamics

Critical hydrologic elements that will be incorporated in the new paddy module include: (1) various sources of irrigation and different discharge outlets, which will be enabled by the flexible connectivity of spatial objects; (2) the ability to simulate non-growing season conditions when the paddy field remains dry as well as growing seasons when the paddy field is inundated; (3) new methods for calculating daily evapotranspiration from paddy fields; (4) improved crop growth submodel and parameters to estimate the growth of paddy rice accurately; (5) the ability to simulate rice in rotation with corn, soybean, wheat and other crops; (6) irrigation methods to replicate standard practices in paddy fields such as target depth irrigation; (7) vertical and lateral seepage rates to manage irrigation and outflow; (8) management practices specific to paddy rice cultivation. In addition, storage volume and depth relationships have been refined in SWAT+[188] and thus provide a more realistic relationship than the previous pothole storage algorithm. Many of these components have already been developed and tested in APEX-Paddy and modified SWAT applications, which can be incorporated into SWAT+.

### 6.2 SWAT+ object-oriented structure

SWAT+ is an advanced version of previous SWAT codes that features object-oriented programming techniques[40]. Basic plant growth, water, and nutrient process algorithms are unchanged except for various model improvements and refinements to those routines. However, the structure of SWAT+ differs in many ways from preceding standard SWAT versions (see SWAT version list reported in Gassman and Wang[193]). Several standard structural elements can be defined as spatial objects in SWAT+ (Table 5), including HRUs, routing units (RU), aquifers (AQU), channels (CHA), reservoirs (RES), canals (CAN), pumps (PUM) and outlets (OUT).

Other spatial objects are provided that represent new simulation capabilities such as HRU-LTE, which is designed to depict less complex landscape processes. A MODFLOW grid (MOD) has also been incorporated to facilitate interfaces between SWAT+ and the MODFLOW groundwater model[194,195]. In addition, an interface between a modified version of SWAT+ with an alternative groundwater submodel (gwflow module) has been developed[222]. Both the MODFLOW and gwflow approaches provide the foundation for developing improved interactions between surface, soil water and groundwater for paddy conditions, especially for lowland conditions with shallow groundwater tables. Allocable outflow variables have also been configured in SWAT+ (Table 5).

**Table 5 Connectivity options for the HRU spatial objects available in the HRU.CON file of SWAT+**

| Spatial objects available for connection | | Allocatable outflow variables | |
|---|---|---|---|
| Name | Description | Name | Description |
| HRU | Hydrologic response unit | TOT | Total flow |
| HLT | HRU-lte | RHG | Aquifer recharge |
| RU | Routing unit | SUR | Surface runoff |
| MFL | MODFLOW grid | LAT | Lateral flow |
| AQU | Aquifer | TIL | Tile flow |
| CHA | Channel | | |
| RES | Reservoir | | |
| REC | Recall | | |
| EXC | Export coefficients | | |
| DR | Delivery ratio | | |
| CAN | Canal | | |
| PUM | Pump | | |
| OUT | Outlet | | |
| SDC | SWAT-DEG channel | | |

This object-oriented structure supports hydrologic connections between HRUs, aquifers, reservoirs, reaches, and other features across the landscape. The modular structure allows flexible connections of each spatial object via connection files (*.con). This structure can allow an HRU in SWAT to be defined as a paddy field. However, this approach can be somewhat ambiguous for some applications because HRUs are often comprised of many small random patches of land within a subbasin. Thus, representing paddy field HRUs as self-contained spatial objects will provide a more direct method of accounting for paddies in landscapes dominated by rice production. This provides the capability to transfer water between individual rice paddies, connect paddy outflow to any other spatial object (e.g., reservoirs, ponds, other paddies), and simulate individual canal segments and their connections.

SWAT+ also has the capacity to support sub-daily time step simulations based on algorithms inserted in the predecessor SWAT codes[88,89]. This option can be utilized for rice paddy applications that require analyses of processes that occur at a faster rate than 1 d.

6.2.1 Depiction of management practices in SWAT+

Another new capability of SWAT+ relevant to rice paddy processes is decision tables[187]. Decision tables are a compact way to model complex rule sets and their corresponding actions, and are used in SWAT+ for agricultural management operations, reservoir release, land use change, and scenario analysis. Rice paddy irrigation source, timing, and amounts can be conditioned on rice growth stage, time of year, reservoir and aquifer levels, streamflow, and ponding depths. The release of water from the paddies can be simulated based on the same variables and numerous other state variables[187]. The depiction of a rice paddy as a spatial object in SWAT+ will result in the elimination of natural surface water drainage when a discharge weir is constructed. If the amount of irrigation or rainfall exceeds a paddy soil's infiltration rate, the field becomes submerged, and the water stage increases up to the height of the outlet weir.

The planned rice paddy module will aim for simulating paddy practices as scheduled field management operations during distinct cropping periods. This approach can take into account the scheduling of practices as a function of rice growth stage and the three critical paddy depths (Figure 12) as described for previous modified SWAT applications[60,85]. The primary paddy practices that will be introduced in the rice paddy module include discharge controls, puddling, transplanting, irrigation, fertilization, pesticide applications, and harvesting (Table 6).

**Table 6 Key rice paddy management processes that will be represented in the rice paddy module**

| Practice | Description |
|---|---|
| Discharge controls | Outlet weir height/width is set for runoff control. This management operation triggers a placeholder for ponding water and its constituents in the source code |
| Puddling | Tillage operation while the paddy field is submerged. Sediment and organic/inorganic nutrient (N/P/K) are resuspended. Constituents in the ponding water and the soils with tillage depth are well mixed after puddling. |
| Transplanting | Transplanting seedlings with initial weight and LAI. Transplanting operation ensures that crop growth continues immediately without a lead-time on the S-curve based on the given leaf area index of the seedling. |
| Irrigation | New irrigation scheme uses target depth of ponding water. Daily irrigation amount is determined based on the difference between a target ponding depth and the current water depth. Flexible maximum, target and trigger depths (Figure 12) will be easily accommodated. |
| Fertilization | Fertilizer (N/P/K) is applied to ponded water in paddies to provide nutrient inputs to support crop growth and yield. |
| Pesticide application | Pesticide is applied to ponded water in paddies to support crop growth by controlling weeds and other pests. |
| Harvesting | Harvesting of rice crop at appropriate time of maturity. |

Puddling is a unique rice production tillage operation that is performed with rotary tillers when a paddy field is submerged during field preparation. Transplanting of rice seedlings to paddies facilitates a uniform crop stand and improved growth versus weed competition[196,197]. The transplanted rice must currently be represented by a fixed plant population (plant density) in APEX-paddy and SWAT+, which along with seedling age at transplanting, nitrogen availability, temperature, and other factors affect rice yield at the end of the growing season[198,199]. The module will also be able to account for distinct irrigation and drying periods during the growing season.

6.2.2 SWAT+ crop growth submodel

Rice growth and yield have been represented in SWAT using rice crop parameters developed in previous research[76,97]. It is likely that revised rice crop parameters representing a wider spectrum of rice varieties and genetics will need to be developed for the SWAT+ rice paddy module. It is also anticipated that further modifications of the SWAT+ crop growth submodel will be required to support more accurate depiction of rice production. For example, the incorporation of an option to switch from standard ET methods to a custom ET method when a rice paddy is inundated to allow ET>PET under special conditions, as can be currently simulated in APEX-Paddy[67]. There are other ET methods reported in previous modifications of SWAT for simulating rice paddy dynamics as listed in Table 3 or described in specific studies[e.g.,190,191] that could also be considered. The option to simulate the relationship between plant population and LAI has been introduced in SWAT+, which potentially can replicate more accurate accounting of transplanted rice populations in a given paddy. However, this relationship requires further testing before it can be implemented more widely among the user community.

6.2.2 Irrigation source and transfer options

The SWAT+ rice paddy module will provide the ability to simulate irrigation from multiple sources including rivers, ponds, reservoirs, aquifers, and other water sources, as documented for previous modified SWAT models[85,180]. The algorithms will be structured such that sources can be located within the same subbasin where paddy is located or in other subbasins that border the subbasin of a paddy location. Similarly, paddy discharge will be possible to different surface water and/or groundwater repositories within the downstream flow path. Allocation and transfer of water in irrigation canals can also be conditioned on irrigation demand from individual paddies or a defined set of paddies. This includes simulation of cascading flow between two or more paddies which will be strongly facilitated by representing paddies as spatial objects as previously described. This gives SWAT+ the capabilities to simulate all of the rice paddy water allocation types described in Section 2.1.2. Other enhancements listed in Table 3 will also be accounted for in the overall module structure.

An example of cascading paddy flow is "plot-to-plot irrigated systems", where water drained from upper paddies is used to irrigate paddies connected below within hillslope or terraced configurations in mountainous areas in Asia such as Indonesia, Japan, Korea, and the Philippines. Representation of these types of plot-to-plot systems in the SWAT+ rice paddy module will be possible including accounting for continuous flows during irrigation periods using a static irrigation rate. Depiction of paddy polder systems, such as those described for the Taihu Lake region in Southeast China[178], will also be possible by accounting for recycled water used within the polder paddy areas. Simulation of recycled water discharge from the isolated polder systems using pumps would only occur when there is a need to avoid inundation from large rainfall events.

### 6.3 Vertical percolation and horizontal paddy percolation rates

Movement of ponded water in rice paddies commonly occurs both vertically via percolation through the semi-impermeable hardpan paddy layer, and through horizontal seepage that occurs either above the hardpan layer and or by leakage through the paddy ridge[64] (Figure 12). Different vertical percolation and horizontal seepage rates have been reported in the literature (Table 7). The SWAT+ rice paddy module will be designed to account for these and other percolation/seepage rates that may be appropriate for specific simulated conditions. Algorithms will also be incorporated in the module to account for a decrease in hydraulic conductivity following puddling operations, which will correspondingly result in reduced vertical percolation rates. This may be similar to the scaling factor approach currently available in APEX-Paddy which allows users to automatically reduce the hydraulic conductivity (and vertical percolation rate) immediately after the following puddling.

**Table 7 Reported vertical percolation and horizontal seepage rates at various paddy field sites in Asia and Europe**

| Type | Reference | Percolation or seepage rates /mm·d$^{-1}$ | Soil type | Location |
|---|---|---|---|---|
| Vertical percolation | [79] | 2.0 | Sandy clay | 1998 Field monitoring at Tsukuba, Ibaraki, Japan |
| Vertical percolation | [80] | 7.0-23.0 | Sandy loam | 2001-2002 field monitoring in Po Valley, Italy |
| Vertical percolation | [200] | 11.0-22.0 | Light clay | 2001 field monitoring at Fuchu, Tokyo, Japan |
| Vertical percolation | [201] | 10.0 | Light clay | 2003 field monitoring at Fuchu, Tokyo, Japan |
| Vertical percolation | [202] | 14.0 | Light clay | 2004 field monitoring at Fuchu, Tokyo, Japan |
| Vertical percolation | [203] | 1.1 | Heavy clay | 2003 Field monitoring at Tsukuba, Ibaraki, Japan |
| Vertical percolation | [204] | 9.7 | Light clay | 2003 field monitoring at Fuchu, Tokyo, Japan |
| Horizontal seepage | [203] | 2.1 | Heavy clay | 2003 Field monitoring at Tsukuba, Ibaraki, Japan |
| Horizontal seepage | [205] | 2.0-20.0 | Coarse silt | 2009 to 2012, Vercelli Plain, northern Italy |
| Horizontal seepage | [206] | 10.0-14.0 | Sandy loam | 1986, Ludhiana, Punjab, India |
| Horizontal seepage | [207] | 3.5-13.0 | Silt | 1997 to 1998, Ten-Chung, Chung-Hwa County, Taiwan |
| Horizontal seepage | [208] | 1.6-280.0 | Quaternary red clay | Ecological Experimental Station of Red Soil, Liu Jia Zhan Township, Jiangxi Province, China |
| Horizontal seepage | [209] | 5.4-6.8 | Silty clay loam & loam | 2010 to 2011, Zhanghe Irrigation District, Tuanlin, Hubei Province, China |

### 6.4 Pollutant cycling and transport processes in rice paddies

As noted in the Introduction, rice paddies can be sources of sediment[2,20,24,25], nutrients[15-20,218-220], pesticides[7-14] and greenhouse gas (GHG) emissions[17,22], and also exacerbate other environmental problems[17,22]. However, rice paddies may also provide ecosystem services similar to wetlands during inundation periods, such as supporting ecosystems and biodiversity, groundwater recharge or water purification, and reduced N exports[21,212,213]. The configuration of rice paddies in SWAT+ as spatial HRUs will allow for simulating many of these critical water quality and environmental processes such as nutrient cycling and transport in paddy fields using existing HRU modules. The adaptation of SWAT+ HRUs for simulating inundated rice paddies will also allow for utilizing existing computational modules to estimate soil and water quality at the HRU scale. The ability to account for differences in pollutant processes in cultivation versus non-cultivation periods is a further important component of the rice paddy module.

#### 6.4.1 Sediment deposition and transport

Puddling is a significant cultivation operation influencing water quality and topsoil properties. A puddling operation involves mixing ponding water and top soils to make the topsoil muddy and soft, which is suitable for transplantation of rice seedlings. According to the Rural Development Administration of South Korea (RDA)'s unpublished measurements at a research paddy field, sediment concentration in the ponding water increased substantially after a puddling operation. Multiple samples collected at the same plot showed wide variability in sediment concentration between 5000 mg/L to 20 000 mg/L. Sediment concentration is highly correlated with soil type and management practices such as water depth, drainage height, and pudding duration, thus an option will be provided to input the sediment concentration for specific case studies. Sediment settling rates after puddling operations will be accounted for by using the modified Stokes Law equation that is currently used in APEX-Paddy[67].

Puddling operations usually result in a low-permeability layer at the bottom of the plow layer. In Japan, transplanting of rice seedlings is typically conducted one week after completion of the puddling procedure to allow for thorough settling of suspended soil particles (the transplanting delay is based on guidelines to reduce the discharge of muddy water). In addition, the irrigation flood water depth after puddling is often too high to transplant the rice seedlings so the floodwater should be discharged one day before transplanting to obtain an appropriate water depth. These operations are the major reason for the fact that most of the pollutant discharge from paddy fields during cropping season occurs during the puddling and rice transplanting period in Japan and likely for many other reasons. These processes can also trigger unusually high spikes in sediment and nutrient yields to rivers in many rice production regions if they coincide with a significant storm event. The SWAT+ rice paddy module will be designed to capture these and other puddling-related pollutant dynamics.

#### 6.4.2 Nutrient cycling, transformation, and transport

Unlike sediment, nutrients, pesticides, and metals are assumed conservative in ponding water in SWAT+ and estimated based on daily mass balance. For computational purposes, an inundated paddy HRU is set to have two compartments: ponding water and soils. These compartments have a one-way transaction of water and nutrients from the water compartment to the boundary of the soil compartment as a function of percolation or seepage processes (Figure 12). Further vertical percolation into the soil profile facilitates the percolation of nutrients into saturated soils and aquifers. Nutrient yield at the paddy outlet is the product of nutrient concentration and discharge water volume. Any nutrient in irrigation water or applied fertilizer is added to the nutrient concentration of the ponding water.

Fertilizer can be applied prior to paddy flooding, in slow-release forms to rice seedlings growing in nursery boxes (prior to transplanting) or post-transplanting to inundated paddies in either liquid or granular forms. Application of nitrogen to an inundated paddy will dissolve in the ponded water instantly or over time and can ultimately seep into soils via infiltration, be captured in discharge to downstream water bodies, or released atmospherically via denitrification and other processes[218-220]. Nitrogen fertilizer applied prior to inundation or via transplanted seedlings can also be lost through those pathways, although those application methods are likely less vulnerable. Soil nitrogen dynamics in the SWAT+ code include nitrogen partitioning among root uptake, denitrification, aquifer recharge, and return flow. Soil nutrient dynamics in rice paddies are significantly influenced by plant root uptake and soil water conditions.

Regarding nitrogen, rice plants prefer uptake of ammonium ($NH_4^+$) to nitrate ($NO_3$) resulting in increased application of ammonium-based fertilizer for rice production during the past couple of decades[189]. However, the $NH_4^+$ can be converted to $NO_3$ in the oxidized paddy surface layer; at the same time, denitrification occurs in the saturated (reduction) zone beneath the oxidized layer where $NO_3$ is converted $N_2O$ or $N_2$ gas. Very unique redox conditions occur in submerged paddy soils which are characterized by: 1) very oxic conditions in the uppermost surface layer due to very active oxygen production by blue-green algae, and 2) very anoxic conditions that start only a few centimeters below the soil surface where the soil is rich in labile organic carbon, due to very active oxygen consumption by heterogeneous microorganisms.

These complex interactions point to the need for further improvement of nitrogen cycling and transformation algorithms within the forthcoming SWAT+ rice paddy module. The adoption of the methods used in developing $N_2O$ fluxes and underlying transformation processes in the SWAT-$N_2O$ coupler model[181] is a possible starting point for introducing these processes in the SWAT+. Other nitrogen-related modifications reported for SWAT-RP[189] and APEX-Paddy[67] could also be potentially ported to the SWAT+ code. Depiction of $CH_4$ gas emissions from rice paddies in SWAT+ may also require porting of algorithms from an existing model such as reported by Fumoto et al.[217]

Simulation of phosphorus cycling and transport in rice paddy environments in SWAT+ currently follows standard theoretical methods as described in previous documentation[94]. This includes the depiction of phosphorus sorption, which can be estimated by either the nonlinear Langmuir function[214] or a linear function described by Jones et al.[215] To date, the only study reviewed here that reported assessments of rice paddy phosphorus export is the application of the SWAT-P model in Northeast China by Ouyang et al.[191] They report some minor modifications of the SWAT code that resulted in improved representation of phosphorus transport. Further research is needed to improve the SWAT+ phosphorus cycling and transport algorithms for rice paddy conditions.

6.4.3 Pesticide fate and transport

The current SWAT+ pesticide fate and transport algorithms are described in detail in the SWAT theoretical documentation[94] and have since been subsequently briefly summarized[61]. Core attributes accounted for in current SWAT+ algorithms include partitioning of pesticides between soluble and sediment-sorbed forms (governed by a pesticide equilibrium soil partitioning coefficient), and transport of pesticides as a function of solubility, degradation half-life, and soil carbon adsorption coefficient. However, pesticide fate and transport processes in rice paddies also manifest dissolution, degradation, and sorption-desorption processes in contrast to other crops grown in upland fields, which were accounted for in the PCPF-1@SWAT, PCPF-1@SWAT2012, and SWAT=RP models[61,62,189]. Some insecticides (such as imidacloprid) are also applied directly to rice seedlings or nursery box soils, which allows rice plants to absorb the insecticide. These and other relevant pesticide-related processes can again be ported from previously modified SWAT models or introduced as new algorithms in the SWAT+ rice paddy module.

6.4.4 Additional watershed-scale pollutant transport issues

Development of algorithms will be required in the SWAT+ rice paddy module to address several other issues associated with rice production at various watershed scales. This is illustrated with two other examples that have been encountered in previous research in Japan. These phenomena observed in Japan may not be universal across all rice production regions located across the globe. Either way, accounting for these and other watershed-scale processes accurately is an additional goal of the forthcoming SWAT+ rice paddy module.

A previous summary of research studies in Japan[216] revealed that N, P, and COD effluent loads from rice paddies were higher during the non-cropping season (generally October-April) versus the five-month cropping season of May to September. This is due to the following factors: 1) restriction of surface water discharge from the paddies during the rice cropping season by artificially controlling the height of the outlet weir and irrigation water input; 2) During the non-cropping season, the outlet weir and tile drainage outlets are fully open, allowing unrestricted drainage of any surface runoff from the paddy fields; 3) the permeability of the upper paddy soil layer increases due to an increase in shrinkage cracks caused by soil drying in the non-cropping season, resulting in possible movement of pollutants to subsurface flow pathways. It is important to introduce the ability to simulate these conditions within the context of rice production systems across a watershed.

In Japan, pesticide application timing depends on multiple factors including the type of pesticide; i.e., herbicide, insecticide, or fungicide. For example, herbicides are usually applied during or after rice transplanting while insecticides and fungicides are often applied when pests are clearly attacking a rice crop in one or more paddies. Data regarding pesticide application timing and mass are usually not available for rice produced across a watershed. Thus, Iwasaki et al.[221] describe using a log-normal distribution to estimate application of herbicide across the Sakura River watershed in Japan for a simulation study based on the PADDY-Large model. This log-normal distribution was also introduced in the applications of PCPF-1@SWAT and PCPF-1@SWAT2012 to describe the timing and amount of pesticide applications across different rice paddies in the respective simulated Japanese watersheds[61,62]. The previously described decision tables can be used to help address this simulation problem by supporting random applications of pesticides or fertilizers to different HRUs (including rice paddies) over a specified time period, such that the applications would take place over several days.

## 7 Conclusions

The SWAT ecohydrological model has been used extensively for applications incorporating rice production in Asia and other regions. These applications have generally been reported as being successful based on comparisons between simulated and measured hydrographs (or other data), using graphical, statistical, and other evaluation methods, typically at an overall watershed level. However, explicit simulation of rice paddy dynamics has been ignored in the majority of relevant SWAT studies published in the literature to date.

A limited subset of studies report attempts to directly simulate rice paddy hydrology and/or pollutant transport in SWAT. Some of these studies describe attempts to simulate rice paddy dynamics using the pothole routine as recommended in user manuals and other SWAT documentation[90-96]. However, research over the past decade has revealed that adaptation of the pothole method and/or other options in SWAT have generally not worked well for replicating rice paddy dynamics in SWAT. Several studies[15,59-62,64,84,85,181,190,192] report the incorporation of modified algorithms in SWAT that allowed a more realistic representation of hydrologic and pollutant cycling within simulated rice paddies. The results of this subset of studies underscore the need to insert a specific module within the current SWAT+ codes that can support direct simulation of rice paddy dynamics.

The SWAT+ framework described in this study will provide the basis for developing a flexible module for simulating rice paddy hydrology, and pollutant cycling and transport. The object-oriented code used in SWAT+ will allow the direct representation of rice paddies, irrigation, and discharge canals, multiple irrigation sources (e.g., streams, ponds, aquifers), and other components of rice production systems that are used in Asia and elsewhere. The module will support direct simulation of rice paddy irrigation management including timing between irrigation and dry periods, and accounting for irrigation trigger, target, and maximum depths. Other key management practices will also be supported including transplanting, puddling, fertilization, nutrient and pesticide applications, and harvesting. It is anticipated that the development of the rice paddy module will provide greatly enhanced SWAT+ applications for users across the globe who desire to accurately simulate complex rice production systems. However, the rice paddy module will likely need to be developed in multiple phases that will require testing in key rice production regions to ensure that all pertinent processes are being correctly simulated.

## Acknowledgements

The work was partially supported by the Rural Development Administration of the Republic of Korea (Grant No. M2100296). Appreciation is also again expressed to the following people and organizations who granted permission to use one or more of the rice paddy photos shown in Figures 2-7: 1) Figures 2b and 5a: United States Department of Agriculture (USDA), Foreign Agricultural Service (FAS), Washington, DC (USDA-FAS staff photos; 2) Figure 3a: Dr. Jaehak Jeong, Blackland Research and Extension Center, Texas A&M AgriLife, Temple, TX; 3) Figure 3b: Dr. Carlos Tornquist, Soil Science Department, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brazil; 4) Figure 4a: Wikipedia: http://en.wikipedia.org/wiki/Rice_production_in_Japan (Mr. Brian Adler, public domain, rice paddies in Aizu, Japan.JPG (file), created 25 August 2007; 5) Figure 4b: Dr. Hiroaki Somura, Graduate School of Environmental and Life Science, Faculty of Engineering, Okayama University, Okayama, Japan; 6) Figure 5b©: Vietnam Academy of Agricultural Sciences (VAAS), Ministry of Agriculture and Rural Development (MARD), Vinh Quynh, Thanh Tri, Ha Noi, Vietnam (https://vaas.vn/en); 7) Figure 6a: Mr. Michael Crosby, BirdLife International, Cambridge, United Kingdom; 8) Figure 6b: Institute of Mountain Hazards and Environment, Yanting Agro-ecological Experimental Station of Purple Soil, Chinese Academy of Sciences, Chengdu, China; 9) Figure 7: Zhi Cheng, Yulin, Guangxi Province, China.

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