Application of the SWAT Hydrologic Model in Malaysia: Recent Research

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Abstract

Hydrologic models are particularly useful tools for investigating the many practical issues that arise during the planning, design, operation, and management of water resource systems. In Malaysia, several commercial hydrologic models have been used to model river basin dynamics, at both small and larger watershed scales. These include empirical, physical, stochastic, and distributed models such as InfoWorks River Simulation (IWRS), InfoWorks Collection System (IWCS), MIKE-SHE, and Stormwater Management Model (XP-SWMM). Open-source watershed models have also been used to model river basin dynamics in Malaysia. These models include the Soil Water Assessment Tool (SWAT), Hydrologic Engineering Centre – The Hydrologic Modeling System (HEC-HMS), Kinematic Runoff and Erosion Model (KINEROS) software, and the Long-Term Hydrologic Impact Analysis (L-THIA) program. Among these models, SWAT is a well-established, physically based distributed model used for analyzing the impacts of land management practices on the water in large complex watersheds. Here we provide an overview of the application of hydrological modeling in Malaysia, highlighting application of the SWAT model in the country in terms of model performance and coverage of several river basins, with details of the analyses. Finally, we highlight the current activities of the SWAT Network of Malaysia, including workshops and conferences, as well as the future plans of the network.

Keywords: hydrologic models, river basin, SWAT model, SWAT Network of Malaysia.

1. Introduction

Hydrology, which deals with all phases of the Earth's water, is a subject of great importance to humans and the environment (Chow et al., 1988). This discipline has many practical uses, such as in the design and operation of hydraulic structures; planning for water supply, wastewater, and irrigation; flood control; erosion and sediment control; pollution abatement; and recreational

uses (McCuen, 1988; Shaw et al., 2010). Hydrological modeling considers the relationships among water, climate, land use, and soil. During the development of hydrological models, scientists try to capture various characteristics of catchments (Alam et al., 2011), and this has yielded numerous mathematical models for watershed simulation used in the evaluation of surface and groundwater flow modeling. These models vary from empirical to physical, stochastic, and distributed models. The mathematical model includes a chronological set of relational, numerical, and logical steps that change numerical inputs to numerical outputs.

There are numerous types of mathematical models, including analytical, deterministic, dynamic, empirical, heuristic, interactive, linear and nonlinear, numerical, probabilistic (stochastic), semi-empirical, simulation, and theoretical (ASCE, 1982). However, most hydrological models contain four basic components, namely the simulation basis, spatial representation, temporal representation, and method of solution (Dingman, 2002). Each component can be further subdivided into more detailed subcategories. The simulation basis includes physically based (represent the physical processes observed in the real world), conceptual, empirical, or regression and stochastic time series. The spatial representation consists of lumped (simplifies the description of the behaviour of spatially distributed physical systems into a topology), distributed (simulation of the key decisions associated with a distribution channel to compute the optimal stream flow), and a coordinate system. Temporal representation comprises steady state, steady state seasonal, single event, and continuous representations. Finally, solutions are subdivided into four classes, namely dimensional, formal analytical, formal numerical, and hybrid solutions.

This paper provides an overview of the application of hydrological modeling in Malaysia. We describe the various hydrological models that have been used in the country in the second section. It is important for researchers to understand the range of hydrological modeling that is being practiced in the country. Next, we discuss the application of the SWAT model in the various river basins, particularly in Peninsular Malaysia. We then explain the current activities of the SWAT Network of Malaysia, with regard to SWAT model performance and coverage of the river basins, along with details of the analysis in this research. Finally, we highlight the current activities of the SWAT Network of Malaysia, including workshops and conferences, as well as the group's future plans.

2. Hydrological Models in Malaysia

Many hydrological models have been used for watershed modeling research in Malaysia. Studies using a stochastic model are common. The statistical concept (Suhaila and Jemian, 2008; Wan-Zin et al., 2009) and artificial neural network (Nor et al., 2007; Sulaiman et al., 2011) seem to be preferred over other stochastic models. Deterministic models are still relatively new in Malaysia, even though they have been used widely in other countries (Ab. Ghani et al., 2009). MIKE-SHE is one of the deterministic models used for Malaysian watersheds. The model simulates two-dimensional overland flow and one-dimensional flow in channels. The flow routing of the model uses a diffusive wave approximation. Rahim et al. (2012) used MIKE-SHE

to simulate the individual hydrological components of the Paya Indah Wetlands watershed and revealed that the overall total water balance is predominantly controlled by climate variables. Other MIKE models have also been applied to hydrodynamic modeling. For example, one study used MIKE-FLOOD coupled with MIKE-11 and MIKE-21 to simulate flood events in the Damansara River, Selangor (Lim and Cheok, 2009).

With regard to conceptual models, many studies have used the Hydrologic Engineering Centre – The Hydrologic Modeling System (HEC-HMS) software (Yusop et al., 2007; Supiah et al., 2010; Razi et al., 2010; Mustafa et al., 2011; Alaghmand et al., 2012). For example, HEC-HMS was used to determine runoff and for hydrograph-characteristic modeling of an oil palm plantation in the Skudai watershed (Yusop et al., 2007). The investigators reported good model performance, with calibrated and validated model efficiency indexes of 0.81 and 0.82, respectively. The study suggested that the model could be used to fill in runoff missing from rainfall data. HEC-HMS was successfully used at the Johor River to estimate flooding, and it has been recommended as a tool to estimate peak discharge (Razi et al., 2010). Supiah et al. (2010) performed an uncertainty analysis of HEC-HMS model parameters for southern Malaysia. Other researchers have integrated remote sensing, GIS, and the HEC-1 model to evaluate the hydrological impacts due to land-use modifications in the Upper Bernam River basin of Malaysia (Mustafa et al., 2011). The model performed well, and the objective functions of the mean absolute error, root mean square error, and coefficient of determination (R^2) were 0.14, 0.18, and 0.86, respectively. Another study prepared design flood hydrographs by using HEC-HMS in river flood modeling of the Sungai Kayu Ara River basin in Kuala Lumpur (Alaghmand et al., 2012). Hydraulic modeling was then performed by using MIKE-11 to define scenarios, and this was followed by GIS to visualize the results of the hydraulic model.

In Malaysia, the Stormwater Management Model (SWMM) and InfoWorks Collection System (IWCS) are among the software packages most widely used to model drainage systems (Liew and Selamat, 2011). Toriman et al. (2009) used XP-SWMM, a one-dimensional hydrodynamics model, to simulate flood waters of the Damansara River in Selangor, and they successfully produced a flood hazard map for urban areas. InfoWorks River Simulation (IWRS) and IWCS are commercial software packages commonly used in simulating hydrological processes. A study of the Damansara catchments for the years 2006, 2007, and 2008 applied IWRS to simulate flood events (Ali and Ariffin, 2011). The model was able to simulate and produce hydrographs and was useful in designing the retention ponds and flood walls, especially in low-lying areas. IWRS was also used to simulate the impact of runoff on the flood plain of the Sungai Sarawak basin (Mah et al., 2007) and in another study it was used to model the flood bypass channel in Kuching, Sarawak (Mah et al., 2010).

Singular models have also been used for hydrological research in Malaysia. Izham et al. (2010) applied the L-THIA model (Purdue University) to simulate runoff at the Pinang River in Pulau Pinang. The KINEROS2 model was applied to evaluate the impacts of land-use/cover changes on a developed basin at Hulu Langat (Memaria et al., 2012). The authors used three storm events of different intensities and durations for calibration and validation processes, and the model showed a good fit in the runoff simulation. However, the KINEROS2 model cannot be

operated in a continuous simulation and it cannot simulate non-releasing ponds in the basin. Finally, the TREX model was used to simulate the extreme monsoon rainstorms at three locations in Peninsular Malaysia (Abdullah, 2013). The model performance was excellent in the large watershed (Nash-Sutcliffe efficiency [NSE] coefficient of 0.8), but it was good in the midsize and small watersheds (NSE of 0.7 and 0.4, respectively). The L-THIA, KINEROS2, and TREX models are available as free unpatented commercial software, and the models are capable of hydrological modeling in tropical basins, although no technical support is given by the software providers.

3. SWAT Model in Malaysia

Soil Water Assessment Tool (SWAT), a public domain model, has been used successfully by scientists around the world for distributed hydrologic modeling and management of water resources in watersheds with various climates and terrain characteristics. The model provides continuous-time simulation to facilitate modeling real watershed responses over long simulation periods. In the river basins of Peninsular Malaysia, several researchers have used the SWAT model in studies of basin water resources and hydrologic behavior (Ayub et al., 2009; Lai and Arniza, 2011; Majid and Rusli, 2013; Ali et al., 2014; Rahman et al., 2014; Khalid et al., 2015; Mohd et al., 2015; Tan et al., 2015) . Many of the studies have focused on basin hydrological processes, including historical water discharge, sediment and nutrient dynamics, and the impact of land-use change on discharge and direct runoff and also the climate change impacts on sediment. Fig. 1 shows the river basins in Peninsular Malaysia that have been modeled by using the SWAT model. Sg in fig. 1 represent river in local attributes.

Majid and Rusli (Majid and Rusli, 2013) used the SWAT model to investigate the impact of land-use change from large rubber plantations to oil palm plantations on streamflow and flooding on the Muar River, Johor. They showed that the SWAT model was capable of modeling hydrological traits in a heavy-rainfall, tropical monoculture (rubber, oil palm) environment. The SWAT model has also been used in hydrological modeling of paddy agricultural areas of the Bernam River basin in Selangor (Lai and Arniza, 2011). According to that study, the SWAT model satisfactorily simulated the hydrologic response of a river basin and can be used for long-term river basin management. In a study applying SWAT to the hydrological assessment of the Langat River Basin, historical data for 1997, 2001, and 2003 were used for comparison with simulated results from the model (Ayub et al., 2009). Unfortunately, the 2 months of data used for the calibration period (June and July 1997) were not sufficient to describe the behavior of the streamflow of the river basin in terms of temporal changes using a daily time-step hydrological model. Most hydrological researchers recommend using at least 20 years of continuous daily historical data to describe the basin in the right manner.

Tan et al. (Tan et al., 2015) investigated the impacts of land-use and climate variability on hydrological components in the Johor River basin. They reported that the combined impacts caused the annual streamflow and evaporation to increase by 4.4% and 1.2%, respectively. Another study examined the effects of climate change on streamflow in the Kuantan River basin

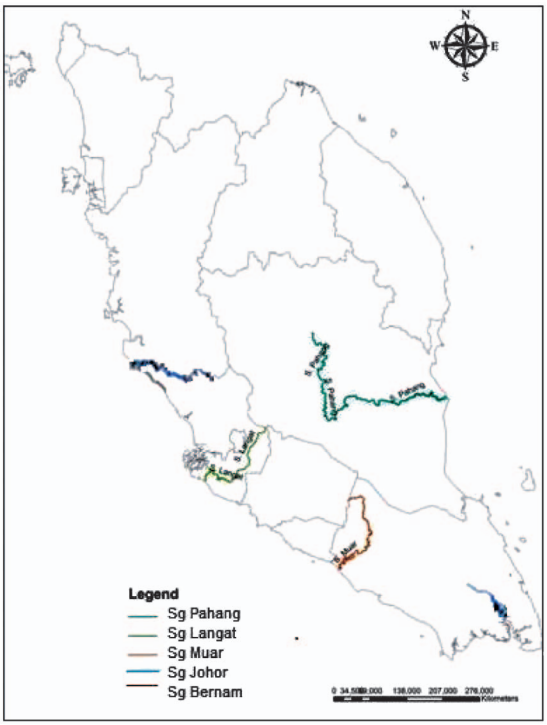

Fig. 1 Locations of the five river basins that have been modeled by using the SWAT model: Pahang River basin, Langat River basin, Muar River basin, Johor River basin, and Bernam river basin.

by coupling statistical climate downscaling tools with the SWAT model (Mohd et al., 2015). The future streamflow trend was projected to increase, especially toward the end of the 21st century, particularly in the months of August and September. The increment was estimated to be up to 100% under the Representative Concentration Pathways (RCP) 8.5 scenario and a 50% increase in the month of August during the middle-term period under both the RCP 8.5 and RCP 4.5 scenarios. In addition, no significant decreasing trend was found, except a minor one in November in the near-term period. The results showed that SWAT can be used and implemented for watershed planning and management purposes.

Rahman et al. (Rahman et al., 2014) highlighted a framework for integrated streamflow and sediment yield using the SWAT model, and they showed that SWAT could successfully model streamflow and sediment in the upper Langat River basin. Simulation results based on 30 years of rainfall records indicated that average water quantity would not be substantially affected by suspended sediment. Urban areas were found to be the main contributors to sedimentation. Another study coupled GIS with the SWAT model to predict river discharge in the same watershed (Ali et al., 2014). The simulation results for the period 1999 to 2010 represented fluctuation of discharge quite well, with both R^2 and Nash Sutcliffe Index (NSI) values above 0.6. The results indicated that the development of integrative GIS technology coupled with the SWAT model is an excellent tool for environmental technology development. Finally, Khalid et

al. (Khalid et al., 2015) attempted to provide a framework for hydrological assessment by using Malaysian soil data as soil input in the SWAT model. They found that the SWAT model could be applied for hydrological evaluation of the Langat River basin, Malaysia, where Soil Conservation Service (SCS) runoff curve number, base-flow alpha factor, and groundwater delay were found to be the most sensitive input parameters.

4. Current Activities of the SWAT Network of Malaysia

The SWAT Network of Malaysia was established on July 1, 2013, as a non-government organization. Its members are from universities, research centers, and government agencies. The number of members has been increasing since the network's establishment, and now about 20 active members are involved. The group's activities include conducting SWAT workshops, collaboration with the ASEAN SWAT Network, technical visits, and active involvement in academic publications.

Several workshops have been conducted. The SWAT School in Malaysia was the first program presented (November 21–23, 2013), and 35 people participated in the workshops. This event was jointly organized by the SWAT Network of Malaysia and the Malaysian Agricultural Research and Development Institute, with the aims of (a) ensuring early exposure to SWAT in Malaysia, (b) broadening the number of SWAT users in this country, (c) expanding the use of SWAT software among participants and other relevant agencies, and (d) strengthening collaboration among the researchers involved. Feedback from participants indicated the need for another workshop on preparing the SWAT input data. The next set of workshops was held from April 14–16, 2014, at Felda Residence Trolak, Perak. The aims were to establish a new environmental database in Malaysia to standardize the land-use categories and to train participants in how to prepare weather data to be employed as SWAT input data. A third workshop was conducted on November 23 and 24, 2015; it focused on coupling open-source GIS with the SWAT model in watershed modeling.

The Malaysia SWAT Network has participated in the first regional discussion with the SWAT Network of Vietnam. The event was held on March 26, 2013, at Crystal Crown Hotel, Kepong, and was attended by four SWAT Malaysia members and three Vietnamese counterparts. In November 2013, SWAT Vietnam member Associate Professor Dr. Nguyen Kim Loi and his team served as trainers for the first SWAT School of Malaysia. The two networks decided to set up a committee of SWAT ASEAN delegates, who will serve as a conduit of SWAT regional information and activities. The meeting also agreed to send SWAT ASEAN representatives to the International SWAT-Asia Conference IV in Japan, held in October 2015. The first Malaysia-Vietnam delegates meeting – a technical visit – was conducted at Nong Lam University, Vietnam, in November 2014. The group agreed to participate in training, research projects, a joint effort to secure international research grants related to water resources, and promotion of the SWAT model to new users. The SWAT Network of Malaysia also conducted an exploratory meeting with the Faculty of Agriculture at Chiang Mai University, Chiang Mai, Thailand, on March 26 and 27, 2015.

Members of the SWAT Network of Malaysia are actively involved in presenting papers at many conferences and publishing research in various journals. The publications are related to application of the SWAT model and watershed modeling. Thus far, 11 journal articles have been published and cited within Scopus, another five were cited under Thompson Reuters, and one was cited within Engineering Village and Pro Quest. Four papers were presented at the 2014 Nationwide GIS Application Conference at Can Tho University, Vietnam, and another seven were presented at the International SWAT-Asia Conference IV in Tsukuba, Japan.

5. Conclusion

Engineers and researchers in many disciplines are increasingly using hydrological models to study the potential impacts of human development on water quantity and quality at the river basin scale. As shown by simulation results, SWAT has the potential to be a valuable tool for planning and managing Malaysian watersheds. The model can be operated in both long-term and short-term simulations, and it can be applied to different areas of the target basin. Future research directions of SWAT model application in Malaysia are to conduct nutrient, water quality, pesticide, and best management practices studies in the study area.

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