Automated procedure of real-time flood forecasting in Vu Gia – Thu Bon river basin, Vietnam by integrating SWAT and HEC-RAS models

Nguyen Kim Loi, Nguyen Duy Liem, Le Hoang Tu, Nguyen Thi Hong, Cao Duy Truong, Vo Ngoc Quynh Tram, Tran Thong Nhat, Tran Ngoc Anh and Jaehak Jeong

ABSTRACT

The precise and reliable simulation of hydrologic and hydraulic processes is important for efficient flood forecasting and warning. The study proposes a real-time flood forecasting system which integrates a coupled hydrological-hydraulic modeling system, weather station network, and stream gauges in a web-based visualization environment. An automated procedure was developed for linking dynamically terrestrial rainfall-runoff processes and river hydraulics by coupling the SWAT hydrological model and the HEC-RAS hydraulic model. The flood forecasting system was trialed in the Vu Gia – Thu Bon river basin, Quang Nam province, Vietnam. The results showed good statistical correlation between predicted and measured stream flow for a 10-year calibration period ($R^2 = 0.95$, $NSI = 0.95$, $PBIAS = -1.54$) and during the following 10-year validation period as well ($R^2 = 0.93$, $NSI = 0.93$, $PBIAS = 6.18$). A close-up analysis of individual storm events indicated that the magnitude and timing of peak floods were accurately predicted in 2015 ($R^2 = 0.88$, $NSI = 0.69$, $PBIAS = 4.50$) and 2016 ($R^2 = 0.80$, $NSI = 0.93$, $PBIAS = 6.18$). In addition, the automated procedure was demonstrated to be reliable with dependable computational efficiency of less than 5 minutes' processing time.

Key words | flood forecasting, flood warning system, HEC-RAS, SWAT, Vu Gia – Thu Bon river basin

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INTRODUCTION

Vietnam is evidently one of the most vulnerable countries to natural disasters (Mechler 2003). In recent years, variability in natural disasters has increased due to the changes in global climate and socio-economic development (World Bank 2010; Ranger & Lopez 2011; Shaw & Riha 2011; Arnell & Gosling 2016). Among various types of natural disasters, ones related to floods are listed at the top in incidence, severity and frequency of occurrence. Moreover, floods cause the most economic, social and environmental damage in Vietnam. In particular, the central region of the country is susceptible to extreme events of floods and droughts (Asian Development Bank 2009; Institute of Water Resources Planning 2011). According to Quang Nam Steering Committee for Storm & Flood Prevention & Control (2010), a 5-year statistic from 2003 to 2007 indicates the losses due to natural disasters in Quang Nam province are estimated to be up to 6.26% of GDP. In those years with excessive rains and floods, losses of human lives and damaged properties increased from 18% to 20% of GDP. The catastrophic damage due to natural disasters should be reduced with a systematic study to find out the causes and identify prevention measures. Although there have been studies on flooding (Ho *et al.* 2008; Dobler *et al.* 2012; Safaripour *et al.* 2012; Stefanidis & Stathis 2013; Lepelletier

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et al. 2014; Meraj et al. 2015), the limitations in applicability and locality of proposed frameworks still remain thoroughly unsolved.

The core component of the state-of-the-art flood warning systems is hydrologic and hydraulic models. These models rely on historical hydrometeorological data for conditioning the current state of a catchment and forecast input data (precipitation and the like) in order to calculate future flood flow and river stages (Divac et al. 2009). Compared to lumped hydrologic models, distributed hydrologic models such as SWAT can capture the heterogeneities in the river basin characteristics and hydrometeorological forcings. Therefore, distributed models better represent the physical mechanisms of floods (Nguyen et al. 2015). However, the weakness of distributed hydrologic models in flood modeling is water routing, because conceptual channel systems are often employed with watershed models without accounting for true physical characteristics of the rivers/channels (Nguyen et al. 2015). Hydraulic models such as HEC-RAS have better predictive capacity in simulating floods because one of the main advantages of river hydraulic models is that they can simulate flow based on the topography of the channel and floodplain, in accordance with continuity and momentum principles and minimal parameterization (Nguyen et al. 2015).

There has been a lot of effort to apply SWAT and HEC-RAS models for real-time flood modeling and forecasting purposes. Divac et al. (2009) proposed an approach to the operational use of a SWAT-based rainfall-runoff hydrological model, using an algorithm for rainfall distribution estimation based on data from few automated weather stations. Santillan et al. (2012) developed a near-real-time flood extent monitoring system for Marikina river basin in the Philippines using the HEC-RAS model. Siqueira et al. (2016) presented a real-time updating procedure for stream flow forecasting in the Lower Iguazu basin, Brazil which uses the HEC-RAS model and Shuffled Complex Evolution – University of Arizona optimization algorithm. Leon & Goodell (2016) developed a set of MATLAB scripts to write input files, read output files, make plots, execute parallel computations, and perform fully automated functions of HEC-RAS. Tiwary (2016) described a real-time flood forecasting and flood inundation mapping for the Bagmati river system of Bihar, India coupling SWAT and HEC-RAS models. Desalegn et al. (2016) proposed a meaningful model-based warning system using SWAT and LISFLOOD-FP models to forecast floodplain inundations following extreme storm events for a mid-size watershed in Ethiopia.

A great deal of work has been conducted to understand flooding in the Vu Gia – Thu Bon (VGTB) river basin, the largest basin in Quang Nam province, such as assessment of the importance of forests to flood control using the SWAT model (Khuong & Linh 2012); flood simulation based on HEC-HMS and HEC-RAS models (Son 2006, 2013; Tinh 2013); coupling MIKE11 and HEC-RAS models to flood modeling in A Vuong river (Thien 2011), Bung 4 river (Nga 2013); real-time flood forecasting by integrating WetSpa and HEC-RAS models (Mai 2009); integration of MIKE NAM, MIKE11, HEC-ResSim models and a weather forecast model for flood forecasting (An & Hoa 2013) (descriptions of all the variables in this paper are listed in Appendix 1, available with the online version of this paper). However, until now, there has been little effort made to integrate SWAT and HEC-RAS models for simulating real-time floods and predicting flood risks at the river basin scale.

The study developed a flood early-warning system integrating GIS, ICT, SWAT and HEC-RAS to support farmers in the downstream floodplain of VGTB river basin access to timely information of impending flood events, leading to minimizing flood damage. This paper presents an automated procedure of flood forecasting on a sub-daily basis in the VGTB river basin by coupling the SWAT hydrological model with the HEC-RAS hydraulic model based on a set of console scripts, USACE HECRASController (Goodell 2014) and mouse tracking. The procedure includes writing SWAT input files, executing the SWAT model, writing HEC-RAS input files from extracting output files of the SWAT model, executing the HEC-RAS model, and visualizing the online floodplain map.

MATERIALS AND METHODS

Study area

The VGTB river basin is the largest river system in the central region of Vietnam. With a catchment area of about 10,350 km², the basin covers a part of Kon Tum and Quang Ngai provinces, and almost the whole of Quang

Nam province, and Da Nang city (An & Hoa 2013). The basin is surrounded by Cu De basin and Huong basin to the north, Laos to the west, Se San basin to the south west, Tra Bong basin to the south east, and Tam Ky basin and the East Sea to the east (see Figure 1).

Over the past century, floods have occurred frequently in the VGTB river basin with historic floods recorded in 1964, 1996, 1998, 1999, 2007, 2009, 2011 and 2013. During the period from 1997 to 2009, floods in Quang Nam province left 589 dead, 33 missing, 1,550 injured, economic damage of 9,436.5 billion (10^9) VND (Quang Nam Steering Committee for Storm & Flood Prevention & Control 2010). The main factors which contribute to flooding in the VGTB river basin include: (1) mountainous terrain is predominant, resulting in a dense, short, steep river system and rapid flooding; (2) the coastal plain is narrow, the river mouth changes seasonally, leading to slow flood drainage; (3) effects of many forms of weather (typhoons, tropical low pressure, cold air, Northeast monsoon) cause heavy and long rains which are concentrated in the rainy season; (4) land use activities (riverine infrastructure construction, primary forest clearance, hydropower dam development, mineral exploitation) increase the incidence and severity of floods. Therefore, deployment of a flood warning system is very urgent to ensure the social-economic development sustainability of the VGTB river basin in the context of climate change.

Automated SWAT, HEC-RAS module for real-time flood forecasting

In order to ensure systematic, consistent flood forecasting, the automated SWAT, HEC-RAS program for real-time flood forecasting was developed (see Figure 2). There are five subroutines of the program including Model setup, Auto SWAT, Auto HEC-RAS, Auto RAS mapper and View online flood map.

In the first subroutine, Model setup, users declare initial parameters including start time, end time, time step and running mode. By default, the start time is on September 1,

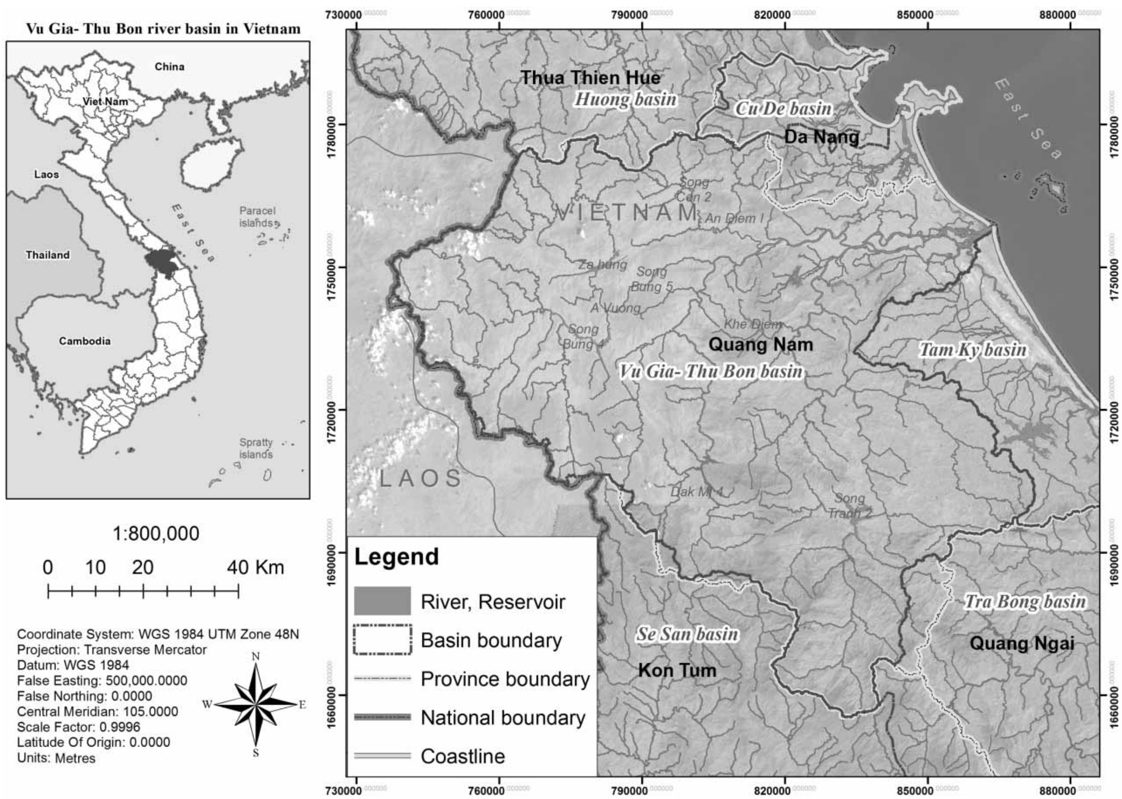

Figure 1 | Geographic location of the VGTB river basin.

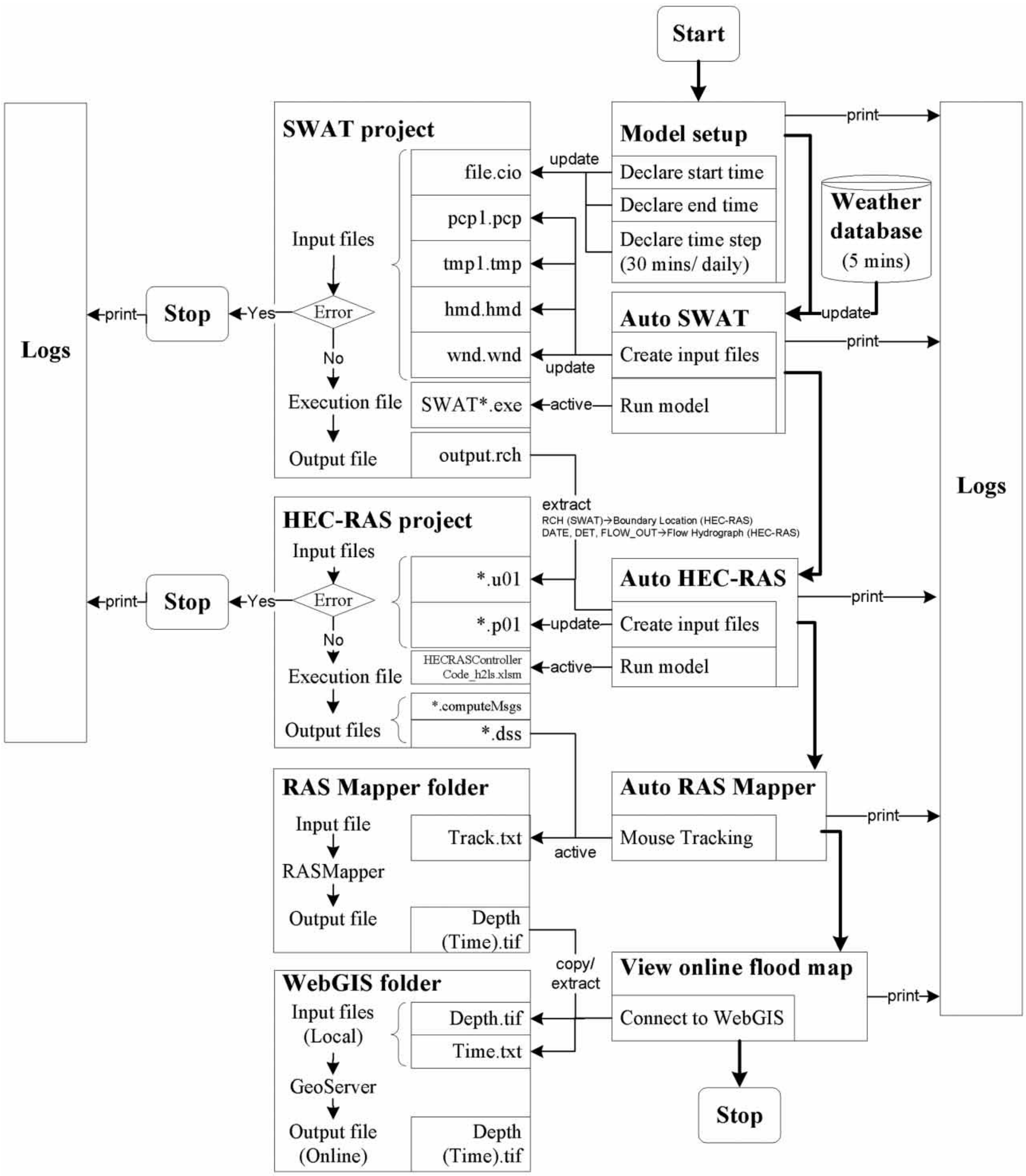

Figure 2 | The flowchart of automated SWAT, HEC-RAS program for real-time flood forecasting. Furthermore, a logs file which records not only step-by-step implementation but also error data is generated to support the user in easily tracking and troubleshooting the whole process.

2015 when automatic meteorological stations began to transmit real-time data fully and validly. The end time is assigned to the current time of the system. The two time-steps, 30 minutes and daily, are provided with seasonal flexibility, the wet and dry. The above three settings change simulation duration and print frequency of output files in the master river basin file of the SWAT project. In addition, the program is designed to operate in either automatic or manual running mode. In manual mode, users use the mouse and keyboard to perform the entire process.

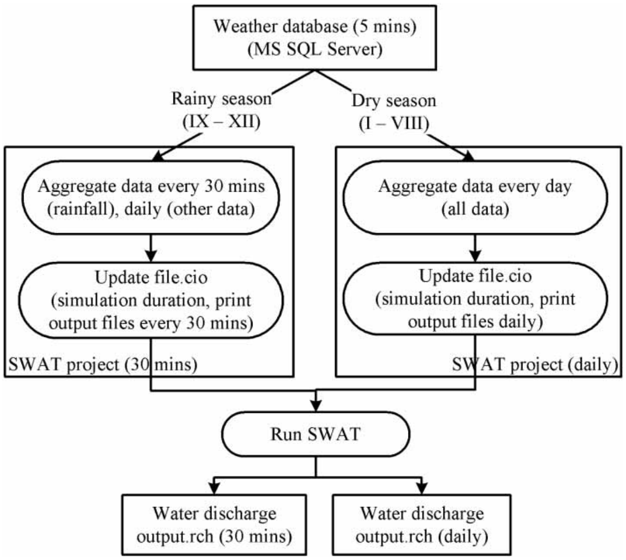

Figure 3 | Automated process of stream flow simulation in SWAT model.

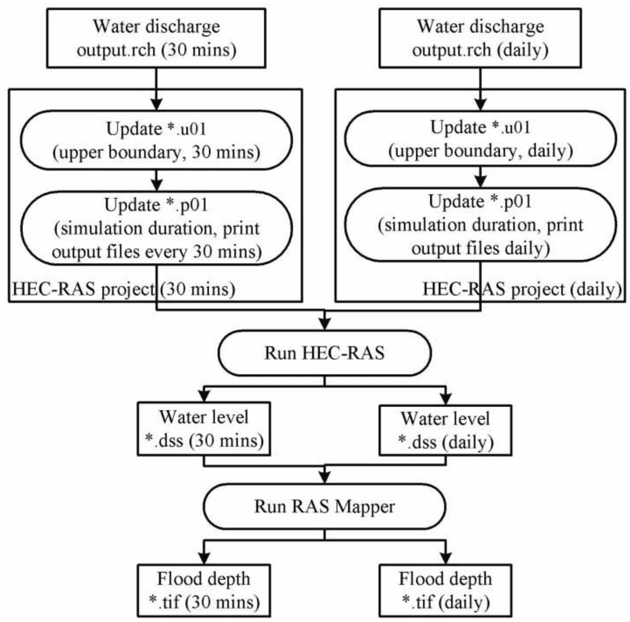

Figure 4 | Automated process of water level, flood depth simulation in HEC-RAS model.

Under the automatic mode, the whole process is done automatically and sequentially.

The second subroutine, Auto SWAT controls the process of stream flow simulation (see Figure 3). Specifically, based on the real-time weather data (every 5 minutes), the input files (precipitation, air temperature, relative air humidity, wind speed) are updated to match the declarations in the Model setup. If there is any error found in the updated data, the program stops immediately. In the opposite case, the SWAT execution file is activated to generate stream flow lasting to the end time of the weather data series. These simulated stream flow values in the main channel output file are then inputted to Auto HEC-RAS, Auto RAS Mapper subroutines to simulate water level and flood depth, respectively (see Figure 4).

Similar to Auto SWAT, the Auto HEC-RAS subroutine also starts with the preparation of input files and ends with the model run. For flood forecasting, two input files including the plan and unsteady flow are edited. The parameters of the plan file such as simulation date, computation interval and output interval are modified by the declarations in the Model setup. Meanwhile, reach number, Julian date and/or the ordinal number of 30 minutes, and stream flow of the main channel output file of the SWAT project are referenced to the boundary location and flow hydrograph of unsteady flow file. If there is no error found in the updated data, the HEC-RAS execution file is activated to generate water level lasting to the end time of the stream flow data series. These simulated water level values are stored in a DSS output file. At the same time, a results report of the running model is also created.

Auto RAS Mapper and View online flood map subroutines are used to produce and visualize a flood depth map. Based on simulated water level of HEC-RAS model and the given mouse event records, the Mouse Tracking technique is activated on the RAS Mapper application platform to zoning of flood depth at the end time of the water level data series. The flood depth file is stored in raster format with its name containing the flood time. Finally, the View online flood map routine copies the flood depth file in the RAS Mapper folder to the WebGIS directory and extracts the flood time in this file name to a separate file before displaying the flood depth map online by using GeoServer.

Automated procedure for SWAT model

The automated process of stream flow simulation in the SWAT model (see Figure 3) includes three steps. (1) Based on the real-time weather data (every 5 minutes) stored in the Microsoft Structured Query Language (MS SQL) Server database management system, aggregate data into weather input files in a given time step (every 30 minutes or day) depending on raining or dry season. (2) Update simulation duration (the ending day of simulation matches the last updated date of weather data), print frequency of output files (every 30 minutes or day) in master river basin file. (3) Run SWAT model to simulate stream flow stored in the main channel output file.

The SWAT model requires a large amount of input data such as topography, land use, soil, and weather in order to run. For flood warning, weather data needs to be monitored in real time due to its continuous change. Meanwhile, the other data can be updated periodically (yearly) due to its slow change. After completing the first SWAT scenario, the entire input and output files are stored in the TxtInOut folder in ASCII format. The user can easily interact with them by using simple scripts of reading or writing input files. Input files relevant to this study include master configuration file and weather data input files. The rainfall data at each station are stored for a given time: 30 minutes, or daily.

To run SWAT, the script System.Diagnostics.Process.Start () is used for active SWAT executable. The reach output file is one of the output files generated in every SWAT simulation. By using simple scripts of reading input files in the library System.IO.Files, the user can extract stream flow data from the reach output file to write HEC-RAS input files.

Automated procedure for HEC-RAS model

The automated process of water level, flood depth simulation in the HEC-RAS model (see Figure 4) includes four steps. (1) Update boundary and initial conditions of cross sections in the unsteady flow data file by extracting stream flow stored in the main channel output file of the SWAT model. (2) Update simulation duration (the ending day of simulation matches the last updated date of stream flow data), and print frequency of output files (every 30 minutes or day) in the plan file. (3) Run the HEC-RAS model to simulate water level stored in DSS format. (4) Run the RAS Mapper application for flood depth mapping stored in GeoTiff format. The file name matches the inundation time.

Similar to SWAT, the input files of HEC-RAS are also stored in ASCII format. The user can easily interact with them using simple scripts of reading or writing input files. For flood warning, the concerned input files include the plan file, and unsteady flow (boundary and initial conditions). Unlike SWAT, HEC-RAS runs in a Windows Form application which prevents script commands from directly accessing the HEC-RAS algorithm. To automatically execute HEC-RAS, we used the HEC-RAS Controller Code module that controls HEC-RAS through a set of macros written in VBA (Visual Basic for Applications). After creating the input data for HEC-RAS, the library Microsoft.Office.Interop.Excel is used to read the macros to activate the macro Compute_CurrentPlan and to execute HEC-RAS.

After calculating water levels at cross sections, a Mouse Tracking technique is used to collect users' mouse cursor positions when users perform inundation mapping in the RAS Mapper tool. The goal of this step is to automatically estimate flood depth and visualize the online floodplain map. The RAS Mapper application creates a raster layer showing flood depths in GeoTiff format. This file is then uploaded to WebGIS by using GeoTIFF module of GeoServer.

RESULTS AND DISCUSSION

Calibration and validation of SWAT and HEC-RAS models

The performance of the SWAT hydrologic model was evaluated using historical daily stream flow data over the 10-year period from 1995 to 2004 at Thanh My stream gauge. Overall, the performance of SWAT was excellent in estimating stream flow as demonstrated by the statistical measures including coefficient of determination (R^2) of 0.95 and Nash-Sutcliffe index (NSI) of 0.95. Percent BIAS ($PBIAS$) was -1.54%, which indicates a slight underestimation of the simulated values. The model performance was evaluated over the 10-year validation period (2005–2014) following the calibration. The statistical indices for the validation period showed that the model performance was as good as for the calibration period with $R^2 = 0.93$, $NSI = 0.93$, $PBIAS = 6.18$. It proved

Table 1 | Statistical indices of SWAT model at Thanh My stream gauge in the VGTB river basin

Period \ Index	R^2	*NSI*	*PBIAS*	*r*-factor	*p*-factor
Calibration (1995–2004)	0.95	0.95	−1.54	0.46	0.66
Validation (2005–2014)	0.93	0.93	6.18	0.48	0.81

the high reliability of the SWAT model after calibration (see Table 1, Figures 5 and 6).

The SWAT model comprises many sub-models for calculating hydrology, water quality, plant growth, and other watershed processes. This inevitably results in taking empirical model parameters into consideration. Improper decisions on parameter values may incur unexpected uncertainty in the model output. Two indices used to quantify model uncertainty in this study include the percentage of observations covered by the 95 Percent Prediction Uncertainty (95PPU) and relative width of 95% probability band (*r*-factor) (Abbaspour 2015). The *p*-factor depicts how well the model outputs replicate the temporal distribution of observed values and the *r*-factor indicates variability in model output within tested parameter spaces. There are

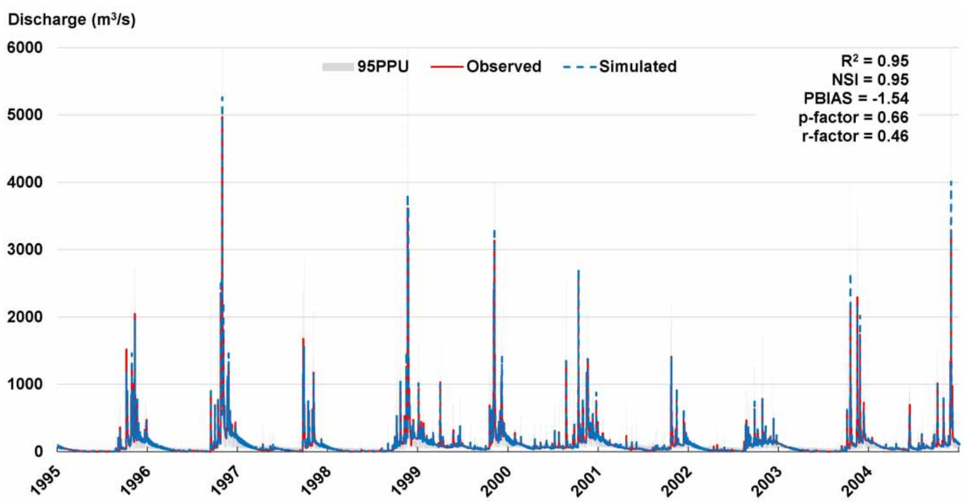

Figure 5 | Simulated and observed water discharge on daily timestep at Thanh My stream gauge in the calibration period (1995–2004).

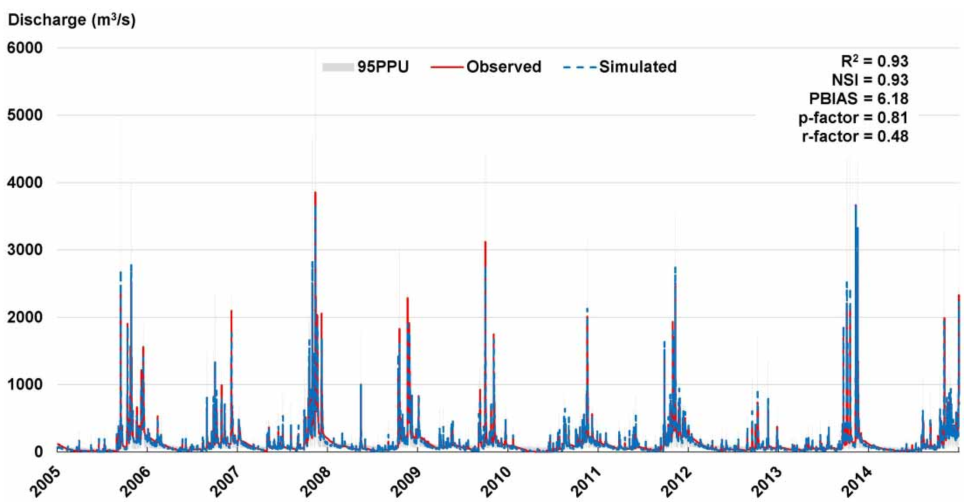

Figure 6 | Simulated and observed water discharge on daily timestep at Thanh My stream gauge in the validation period (2005–2014).

Table 2 | The calibrated Manning roughness coefficients of the reaches of the VGTB floodplain

No.	Reach	Manning roughness coefficient
1	Ai Nghia – Da Nang	0.030–0.100
2	Ba Ren – Hoi An	0.015–0.100
3	Cau Lau – Da Nang	0.015–0.040
4	Giao Thuy – Hoi An	0.013–0.060
5	Giao Thuy – Da Nang	0.015–0.040
6	Hoi An – Da Nang	0.015–0.100
7	Hoi Khach – Giao Thuy	0.015–0.100
8	Nong Son – Giao Thuy	0.015–0.100

Table 3 | Statistical indices of HEC-RAS model at Ai Nghia stream gauge in the VGTB river basin

Period \ Index	R^2	*NSI*	*PBIAS*
Calibration (September 13–20, 2015)	0.88	0.69	4.50
Validation (October 30–November 7, 2016)	0.80	0.93	6.18

no hard numbers for these indices to determine model uncertainty; however, a *p*-factor over 0.7 and *r*-factor around 1.0 are recommended (Abbaspour 2015). In this study, the estimated *p*-factor was 0.66 and *r*-factor was 0.46 for the calibration period. In the validation period, their values were 0.81 and 0.48, respectively. The result implies that the 95PPU of the calibrated SWAT exhibits lower variability in the output than usually allowed. Therefore, the model performance is less influenced by parameter uncertainty. Moreover, the *p*-factor indicates that the 95PPU sufficiently captures observed values during the validation period. On the contrary, the model uncertainty is less than satisfactory in the calibration period as the 95PPU captured only 66% of the observed stream flow.

The HEC-RAS hydraulic model was applied with an hourly time step using SWAT model results as the upstream boundary condition. The calibration and validation of the HEC-RAS model were performed sequentially using the observed water level at Ai Nghia stream gauge during the two flood events in 2015 (September 13–20) and 2016 (October 30–November 7). In order to evaluate the performance of the HEC-RAS model, the same criteria as for the SWAT model are used. Calibration of the HEC-RAS model was performed manually by adjusting the Manning roughness coefficient of the reaches of the VGTB floodplain as shown in Table 2. The results showed that flood peak and flood timing were well simulated in the flood events of 2015 and 2016 as shown in Table 3, Figures 7 and 8.

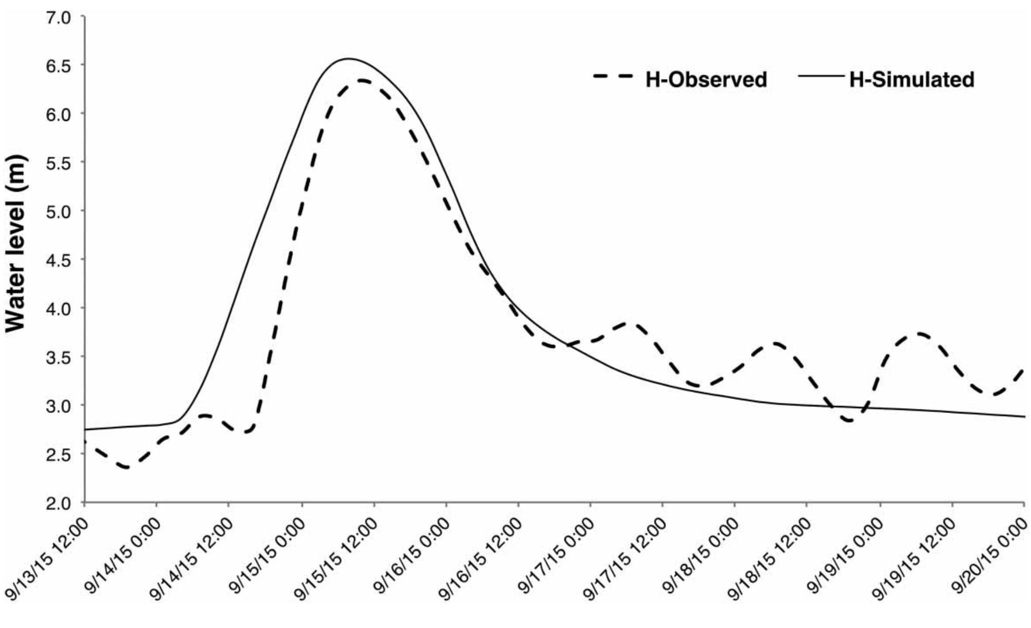

Figure 7 | Simulated and observed water level on hourly timestep at Ai Nghia stream gauge in the calibration period (September 13–20, 2015).

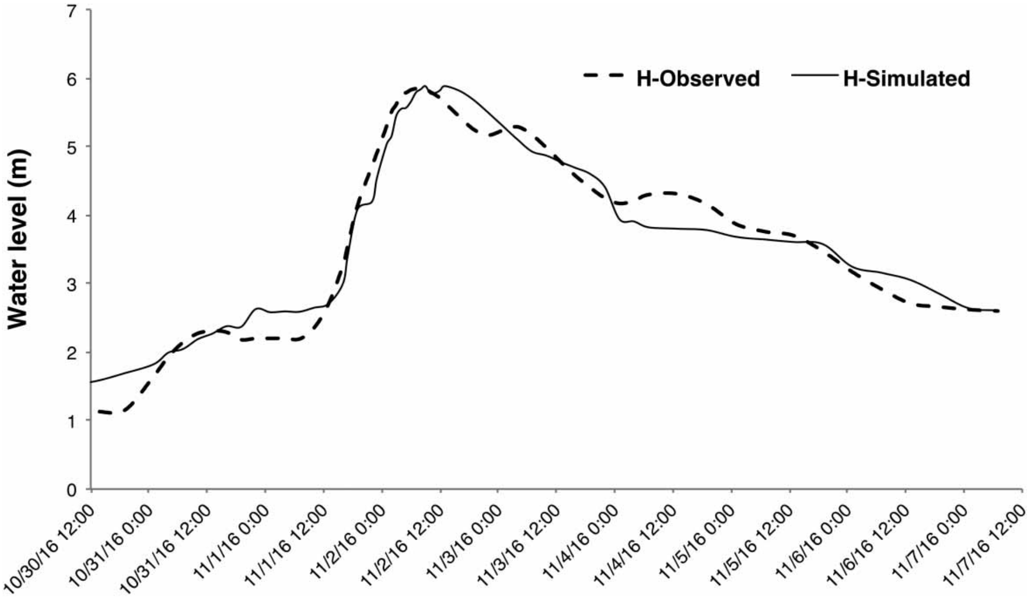

Figure 8 | Simulated and observed water level on hourly timestep at Ai Nghia stream gauge in the validation period (October 30–November 7, 2016).

Floodplain mapping in flood season of 2015, 2016

Based on time series analysis of 20 meteorological stations in the VGTB river basin (see Figure 9) since August 2015, the three largest rainfall events occurred on October 14,

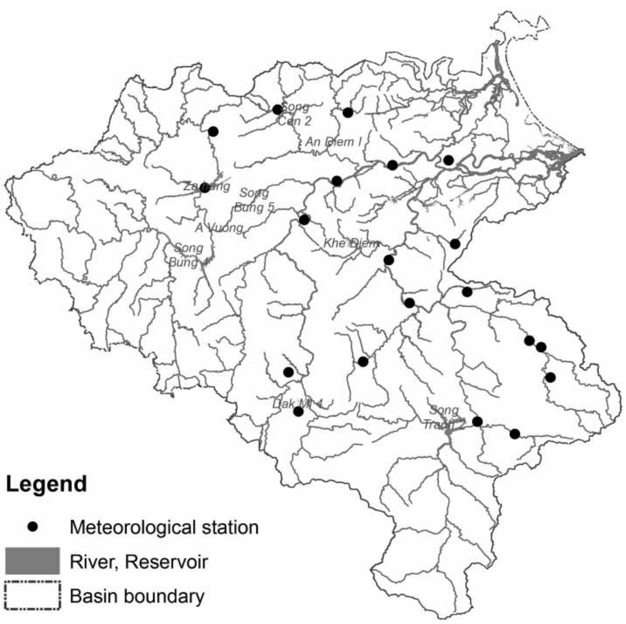

Figure 9 | Location of meteorological stations in VGTB river basin.

2015, November 1, 2016 and November 3, 2016. With the processing time of about 5 minutes, automated SWAT and the HEC-RAS program simulated a floodplain map of these events (see Figure 10). The water level predicted by the HEC-RAS model was compared with the precise Digital Terrain Model combined river channels and inundation areas to derive an inundation map showing the spatial extent of the flooding and the water depth at each location.

CONCLUSIONS

An automated procedure was developed for flood forecasting on a sub-daily basis using an integrated framework of SWAT and HEC-RAS for the VGTB river basin in Vietnam. The whole procedure, including writing SWAT input files, executing the SWAT model, writing HEC-RAS input files for extracting output files of the SWAT model, executing the HEC-RAS model, and visualizing the online floodplain map, were packaged in a single module and fully automated with strict constraints on the accuracy and processing time. The key procedure of dynamically integrating rainfall-runoff simulation and river hydraulics was demonstrated to be reliable in predicting downstream flooding events. The

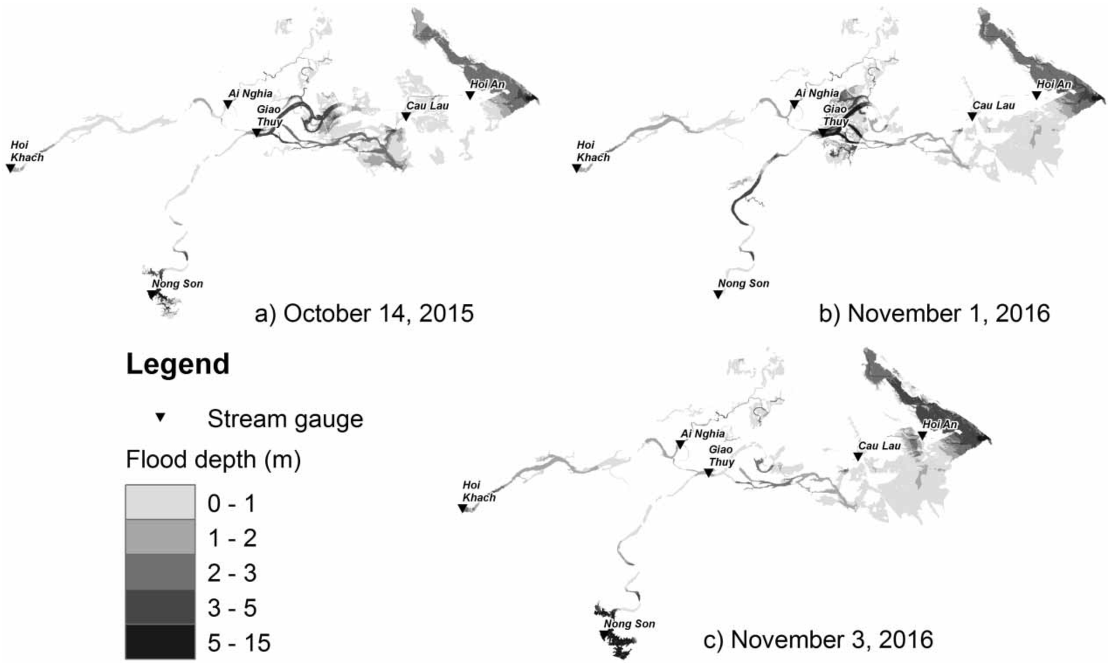

Figure 10 | Simulated floodplain map in the lower of VGTB river basin in 2015 and 2016.

integrated SWAT and HEC-RAS modeling system accurately predicted peak flow not only in a long-term assessment (2005–2014) but also in two specific flood events in 2015 and 2016. Therefore, the procedure proposed in this study can be implemented with minimum effort in many river systems where SWAT and HEC-RAS models are already available.

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CONFLICT OF INTEREST STATEMENT

Conflict of interest – none.

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