VIETNAM JOURNAL OF
HYDROMETEOROLOGY

Research Article

Global Land Surface Data Applications in Flood Hydrologic Modeling Using HEC–GeoHMS and HEC–HMS for Three Watersheds in Southeast Asia

Nguyen Thi Thuy Linh[1*], Hoang Thi Nguyet Minh[1]

[1] Hanoi University of Natural Resources and Environment; nttlinh.tnn@hunre.edu.vn; htnminh.tnn@hunre.edu.vn

*Corresponding author: nttlinh.tnn@hunre.edu.vn; Tel.: +84–945014398

Abstract: Flood is one of the most commonly occurring forms of natural disaster which damage to environment and society. Flood events have been increased both in their intensity and frequency associating with increasing average global temperature due to climate change. In order to contribute to the work of mitigating the effect of climate change as well as floods' damage, this study introduces a method to simulate discharge with respect to design storm through hydrological modeling system (HMS). This model is applied for three case studies the Upper Sunter river basin in Indonesia, the Vu Gia–Thu Bon river basin and the Nhat Le River basin in Vietnam in which there were several severe floods occurred, causing severe impacts on social development. Hydrologic simulations were performed using the software of Hydrologic Engineering Center's Hydrologic Modeling System (HEC–HMS). With three different precipitation input data, daily data in the Upper Sunter river basin, 6–hourly data in the Vu Gia–Thu Bon river basin and hourly data in the Nhat Le river basin were used to simulate. The HEC–HMS calibration and validation were conducted to assess the model performance, and the estimation of design floods with respect to design storm was also presented. NSE coefficients are higher than 0.70 in both calibration and validation process through the years which is acceptable for further simulation. With the validated model, seven return periods (2, 5, 10, 25, 50, 100 and 200 years) were used to design seven floods.

Keywords: HEC–HMS; Model; Rainfall–runoff; Simulation.

1. Introduction

Lack of database in many areas of the world is a serious obstacle for the hydrologic model. At the similar time, most of the generating databases on a local and global scale are also making a problem of model that causes an uncertainty source [1–2]. The unsimilar databases were applied for the one river basin making the unlike model results and, consequently, different estimates of water resources ecosystem variables [3–5]. In order to understand and support decisions regarding of water resources management, water pollution, and flood control, the consequences of anthropogenic and natural changes forecasting in the environment are crucial [6–8]. However, using a model to simulate the real river basin has made evidence to be challenging, because of many impossible sources, such as parameter estimation, model structure, forcing data, input data, and using goodness–of–fit criteria [9–11]. The spatial information was used for input data of distributed or semi–distributed hydrological models, such as topography (elevation), LULC (land use/land cover), soils, or (hydro–) geology [12–14]. These categories of data are often possible in different or same resolutions and can be collected from different sources, with the latter providing some different information [15–17].

Now a day, the technology of satellite and remote sensing is providing extraordinary data on land surface processes, which allow land surface hydrology modeling at large spatial scales, arranging from the river basin to regional, to continental [18–20]. Therefore, we can simulate or forecast some kinds of natural disasters such as typhoons, floods, droughts [21–22]. Due to climate change and the rising of global temperature, the flood tendency and intensity has been increased as well [23–25]. Therefore, in order to minimize the bad effect of climate change, it is needed to provide reliable models for simulating a flood.

Hydrological modeling system (HMS) was created in the nineteenth century when the software systems and technologies have been generally. HMS model was developed by the US Army Corps of Engineers [26]. A part of the major objectives of the model is to support engineers and hydrologists in provided the most reliable evaluation of annual floods [27–28]. The HEC–HMS was applied to simulate flood events and continuous hydrologic modeling [29–30]. This model was proved to perform flood events accurately through several studies. The rainfall–runoff is simulated by separating the river basin into three sub–catchment, and each sub–catchment is simulated with its parameters [31]. The hydrologic modeling article was used new version of HEC–HMS released in April 2006 by the US Army Corps of Engineers. This model contains of two parts: runoff scenarios using IDF curves and event–based hourly simulations. Infiltration loss and baseflow parameters of each sub–catchment is calibrated with hourly simulations [32–33]. Therefore, the simulated run–off results can be applied for flood damage estimation and flood control in another studies.

Simulating the rainfall–runoff by the HEC–HMS model from Probable Maximum Storm (PMS) – a most severe event that can occur in a particular region [34–35]. This simulation was to assess discharge hydrographs combined with the Probable Maximum Flood (PMF) at extraordinary locations in each river basin. These hydrographs were consequently applied for developing flood inundation maps of the study areas and characterizing phenomena of sediment transport in the streams with severe flooding conditions [36]. Moreover, at Tapi river India, HEC–HMS was used for simulation of rainfall–runoff [37]. The peak flow discharges and maximizing the Nash–Sutcliffe is fitted to this study. For better runoff estimation SCS unit hydrograph and Snyder Unit hydrograph methods are analyzed, and the best adapted method for the study area is chosen for the final simulation.

The flood frequency analysis (FFA) and hydrological modeling system (HMS) is used to estimate the peak discharges [38–39]. FFA method was carried out using two distribution functions, i.e., Gumbel’s extreme value distribution (Gumbel’s) and lognormal (LN) distribution, while HMS was performed using the Hydrologic Engineering Center’s Hydrologic Modeling System (HEC–HMS) model [40]. Calibrating and validating processes were using to analyze the applicability of HEC–HMS model to simulate the discharge of Sungai Rinching [38]. These results showed that the model performance is exceptional. Using FFA and HMS to estimate peak discharges for several average recurrence intervals (ARIs), i.e., 2, 5, 10, 20, 50, and 100 years estimated, were also compared.

This study mainly used ArcGIS 10.4 with Geospatial Hydrologic Modeling (HEC–GeoHMS) and HEC–HMS 4.2.1. The ArcGIS used to prepare the spatial datasets for the hydrological and hydraulic model, in HEC–HMS and HEC–RAS respectively. The HEC–GeoHMS extension component delineates and maps river networks for HEC–HMS manipulation [41]. In HEC–HMS, each component in the model performs different purpose of the precipitation–runoff process within a part of the catchment or basin known as a sub–catchment [42]. The result of the modeling process is the figuring of streamflow hydrographs at the catchment outlet or inlet to the reservoir. Finally, the discharge hydrographs with respect to the seven design storms are estimated and presented in the study.

2. Methodology

2.1. Study site

In this research, three different study areas will be selected to simulate the rainfall–runoff and design storm. In order to make the result comparisons, each study area will use different precipitation time steps: daily, 6–hour and hourly for simulation.

The Upper Sunter river basin will be select for daily data time step, as shown in Figure 1. The watershed includes two upstream rivers: Sunter River and Cipinang River that combine into a major river in the downstream area. The maximum watershed length is approximately 37 km; the river basin is calculated 330 km^2 with the annual average temperature is 26°C. Moreover, the average annual rainfall is estimated 1883 mm according to the Cipinang gauge station data from 2001 to 2007 [43]. The Cipinang Gauge roles the streamflow observation. Furthermore, the purpose of water is identifying for agricultural, urban business and hydroelectric power industry sectors [44]. Nevertheless, the stream role is only for domestic purposes nowadays.

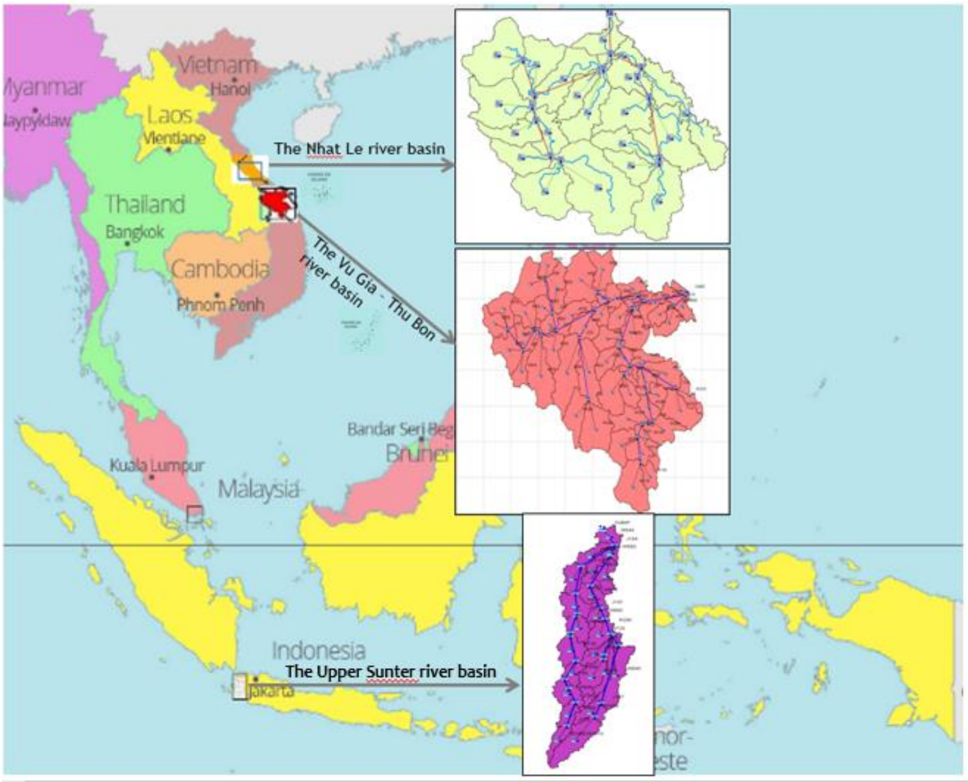

Figure 1. The three river basins in this study.

The Vu Gia–Thu Bon river basin will be used with 6hours data time step, which is the largest river basin in the Vietnam central region. The river basin area is approximately 10,350 km^2, the basin consists of a part of Kon Tum, Quang Ngai, Quang Nam province, and Da Nang city [45]. Over the past century, floods have appeared more frequently in the Vu Gia–Thu Bon river basin. The historic floods were in 1964, 1996, 1998, 1999, 2007, 2009, 2011 and 2013 [46]. During the period from 1997 to 2009, the floods in Quang Nam province leaded to 589 dead, 33 missing, 1,550 injured, the financial loss of 9,436.5 billion (109) VND [47].

The Nhat Le River basin will be used with hourly data time step, is located in the south Quang Binh Province, Vietnam, with its area of about 2,647 km^2. This basin is the second largest river system in Quang Binh, after the Gianh River system in the north area. Downstream of the river, there are densely populated areas, especially the coastal areas including Dong Hoi city, in which the population density is six times higher than that of the whole province. Along the banks of the river, the population is also more concentrated; therefore, people living here are strongly affected by severe floods. The topography of the area is mainly mountainous, narrow with short streams and steep slopes from West to East. This characteristic leads to water is rapidly gathered, and the floods quickly rise and flow down to the sea when heavy rains appear. However, unlike other river systems, the amount of water usually drains into the sea through several streams, the Nhat Le river system only has one outlet (Nhat Le estuary). Therefore, floods cannot be released directly to the sea. Moreover, there is a relatively high sand dune (30–40 m) making a natural dike running parallel to the shoreline that also contributes to preventing the floods flush out. Besides, in some areas, the terrain is lower than the sea level (0.8–1 m), so heavy rains combined with high tides cause these areas to flood in a long time and water escape to the sea in days [48].

2.2. Data collection

A proper understanding of the hydrological, topographical and climatic conditions of this study areas and considerable set of data defining them are most essential for analyzing and simulating the realistic hydrologic and hydraulic event. In addition, the exactly of input data for modeling has direct impact to the model results, so the data collection should be analyzed and processed before using them.

Watershed/ Sub–basin Characteristics

Topography in the form of a Digital Elevation Model (DEM) was extracted from an open–source, 1 arc–second (approximately 30 m) resolution, U.S. Geological Survey (USGS).

Land Cover data was downloaded from High–Resolution Land Use and Land Cover (LULC) Map of the Central Region of Vietnam – 1/3 arcsecond (approximately 10 m) resolution and Water Base of United Nations University global repository of data with 400 m resolution for Australia/ Pacific data.

Digital Soil Survey Data was collected from Global Hydrologic Soil Groups – 1/480 decimal degrees (approximately 250 m) resolution– Distributed Active Archive Center for Biogeochemical Dynamics (DAAC).

Climate data

Precipitation data: hourly–series data for five flood events in Nhat Le and Upper Sunter river basin and a six–hours period data for Vu Gia–Thu Bon river basin.

Design storm data: hourly–series data for 2, 5, 10, 25, 50, 100, and 200 years.

Flow data

Daily discharge data (Station No: Meteorology 745) are used for the calibration of the hydrological model in the Upper Sunter river basin, hourly discharge data of Kien Giang station for Nhat Le river basin and a six–hour period of Nong Son stations for Vu Gia–Thu Bon river basin.

2.3. Model development

The watershed and streams in the study area were first delineated from a 30–meter spatial resolution DEM using the HEC–GeoHMS tool. The HEC–GeoHMS permits users to visualize spatial data, perform spatial analysis, document watershed properties, delineate stream and sub–basins, and building inputs data for hydrologic models [49].

The next step in the model development is deriving input parameters for each sub–basin (Loss, transform and routing parameters). For those parameters, the dataset of LULC and soil map was used to calculate the CN grid. With the calculated CN grid, the losses and transformations in sub–basins can be estimated [49]. Precipitation that does not create to surface runoff is identified as losses. The total runoff volume of watershed was controlled by losses mainly, which influence to the magnitude of peak streamflow [50]. Soil infiltration and initial abstraction are the major losses components. Initial abstraction mentions to the total depression storage and vegetation interception that do not donate to runoff. The infiltration losses were measured by using the Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) curve number method (SCS–CN). The SCS–CN method calculates precipitation excess as a functioning of cumulative precipitation, soil group, and land use.

A hydrograph is showing the discharge against time. The unit hydrograph is the hydrodynamic flow that flows directly as a result of a unit of precipitation per unit time and is used to determine the theoretical shape of the hydrograph during precipitation period. Using the parameterization of this method, it is possible to estimate the time and intensity of peak flows generated in the catchment. The SCS Unit Hydrograph method was applied to the simulated watersheds [50]. For this method, the input to the HEC–HMS model is the river basin time lag. This parameter is a factor-adjusted estimate of the condensation time, which is the time required for direct runoff to travel from the furthest point in the river basin to the outlet. This time depends on the hydraulic length of the watershed, watershed slope and maximum retention in the watershed. For sub-basins receiving flows from the upstream catchment, channel routing is used to transmit discharge through the primary channel to the catchment outlet. Sub-basins that do not accept flows from the upstream sub-basin will not include routing elements. The routing component of the HEC–HMS controls the attenuation of the flow due to energy resistance and can therefore control the magnitude and duration of the peak flow. It does not influence the total amount of runoff volume developed in a river basin.

The schematic diagram shows steps that required for running the model, calibrating, validating and simulating the design floods.

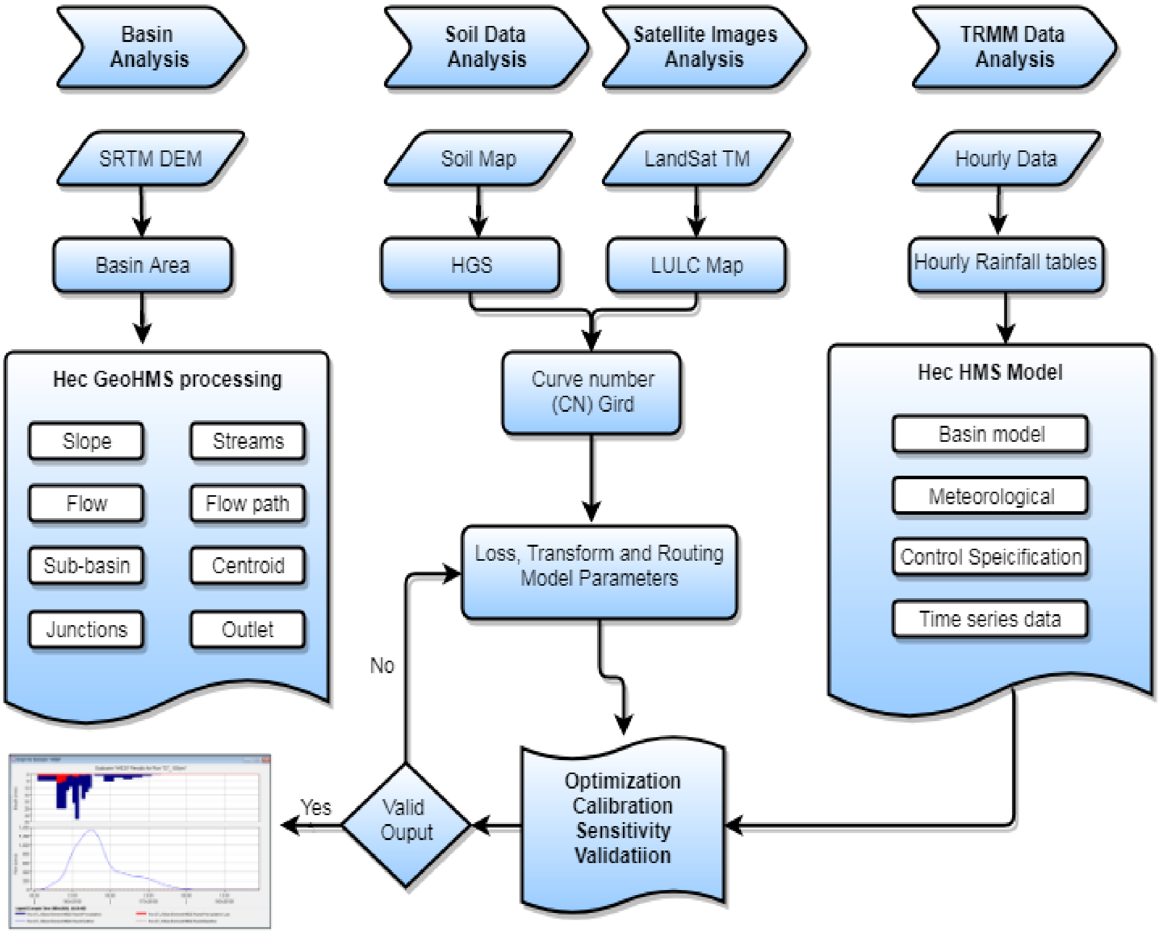

Figure 2. Flow chart of the study.

2.4. Model calibration and validation

The model was manually calibrated for daily and six–hours and hourly time–step for simulation with three different case study areas. The simulated runoff was compared with the measured runoff for the river basin. In order to get good calibration, this study will determine the key parameters and parameter accuracy required for calibration. Therefore, the calibration of the model is mainly carried out by changing model parameters including loss parameters (f_0 – Initial intensity and f_c – Stable permeability intensity); Parameters of the unit line (t_{lag} – transmission time and C_p – flood peak coefficient); Flood parameters (K – coefficient specific to infusion time and X – coefficient for river length). Statistical indicators were used to assess the model performance. Statistical indices were applied to evaluate the performance of the model, containing the coefficient determination (R^2), the root–mean–square error (RMSE), Nash–Sutcliffe model efficiency coefficient (NSE), the relative errors of peak discharge and runoff volume.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - F_i)^2} \qquad (1) \qquad\qquad \mathrm{Nash} = 1 - \frac{\sum_{i=1}^{n}(O_i - F_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \qquad (2)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O - \overline{O})*(P - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O - \overline{O})^2 * (P - \overline{P})^2}} \qquad (3) \qquad\qquad \mathrm{Re}\,Q_{max} = \frac{(F_{max} - O_{max})}{O_{max}}100 \qquad (4)$$

$$\mathrm{Re}\,W = \frac{(W_F - W_o)}{W_o}100 \qquad (5)$$

where O_i is observed discharge, $\overline{O}$ is average observed discharge, F_i is calculated discharge; F_{max} and O_{max} are maximum observed and calculated discharge; W_o and W_F are total observed and calculated volume.

After calibration, the models were validated using the same input parameters as determined by the calibration process but with different simulation time. Models for three study areas were calibrated for three years and validated for two years.

2.5. Model Application

In order to develop the implementation of the results, this study will design a storm for discharge calculation at the outlet with seven return periods (2, 5, 10, 25, 50, 100, 200 years). For the Vu Gia–Thu Bon river basin, in order to simulate the design storm, the study was used the design frequencies of 0.5%, 1%, 2%, 5% 10%, 20%, and 50%, and used flow data series largest from 1977 to 2005 to calculate the frequency of the largest flow rate at Nong Son hydrological station according to PIII distribution.

For the Upper Sunter river basin, seven flood scenarios were performed to gain the peak values of designed storm events. Fisher–Tippet Type I method can be used to calculates the extreme value distribution based on time series data. The extraction of the highest daily rainfall of each year was ranked from the maximum values. Then, the extreme rainfall value R_{24} is calculated for the specified return period Tr after the plotting position Fm. Two reduction factors also calculated for the data reduction factor ym and the reduction factor from return period yr, respectively. The rainfall depth proceeds in order to get the Depth Duration Curve as input for Frequency Storm Modelling in the HEC–HMS.

$$F_m = 1 - [(m-0.44)/(N_T+0.12)] \quad (6)$$

$$y_m = -\ln [-\ln (F_m)] \quad (7)$$

$$y_r = -\ln [-\ln (1 - 1/T_r)] \quad (8)$$

$$R_{24} = Ay_r + B \quad (9)$$

where NT is total data and m is data rank, R_{sm} is the maximum rainfall data for each year, and several parameter formula are $c_1 = \sum y_m 2$; $c_2 = \sum y_m$; $d_1 = \sum y_m$; $d_2 = NT$; $F_1 = \sum R_{sm} y_m$; $F_2 = \sum R_{sm}$; $Det = c_1 d_2 - c_2 d_1$; $A = (d_2 F_1 - d_1 F_2)/Det$; and $B = (c_1 F_2 - c_2 F_1)/Det$.

For the Nhat Le river basin, these design storms were gathered from the hydrological report of Quang Binh Irrigation and Drainage Management Company.

3. Result and Discussion

3.1. HEC–HMS

In this study, the Upper Sunter river basin with a total area is 330 km^2, dived into 18 sub–basins; the Vu Gia–Thu Bon river basin was contained 57 sub–basins with a total area is 10,350 km^2; and the Nhat Le river basin was separated to 20 sub–basins, with a total area is 2,647 km^2. For each basin the SCS–CN, initial abstraction, and percentage of the impervious area are differences.

3.2. Calibration and Calibration

Results of the HMS model for the selected rainfall duration have been calibrated using discharge observation data. To perform the calibration process, four parameters, such as Muskingum–K, Muskingum–X, lag time, and impervious, has been adjustment. This research operates 3 periods of precipitation events for each river basin calibration to gain the optimal value for the precipitation model. In order to get the optimal value for each simulation, the model efficiency was tested for each simulation using some objective value such as root means square error (RMSE), R^2, Nash–Sutcliffe (NS), and PBIAS. The following table was presented the optimal parameters for each calibration simulation.

The model performance output for each calibration case can be viewed in Table 1. It can be seen that the average acceptable value is shown from the result of second simulation. Hence, the parameter used in second simulation can used for validation simulation in the Upper Sunter river basin.

Table 1. The criteria for calibrating parameters in the HEC–HMS model.

River basin	Simulation	RMSE	R^2	NSE
Upper Sunter	11/03–19/33/2007	9.64	0.41	0.31
	12/08–18/08/2004	5.94	0.54	0.43
	08/02–16/02/2005	8.03	0.27	0.16
Vu Gia–Thu Bon	20/10–22/10/2001	109.1	0.81	0.83
	24/10–26/10/2002	215.4	0.86	0.83
	20/10–22/10/2003	245.8	0.75	0.76
Nhat Le	07/10–09/10/2005	201.81	0.86	0.83
	30/09–03/10/2006	131.14	0.78	0.72
	03/10–05/10/2007	92.96	0.92	0.90

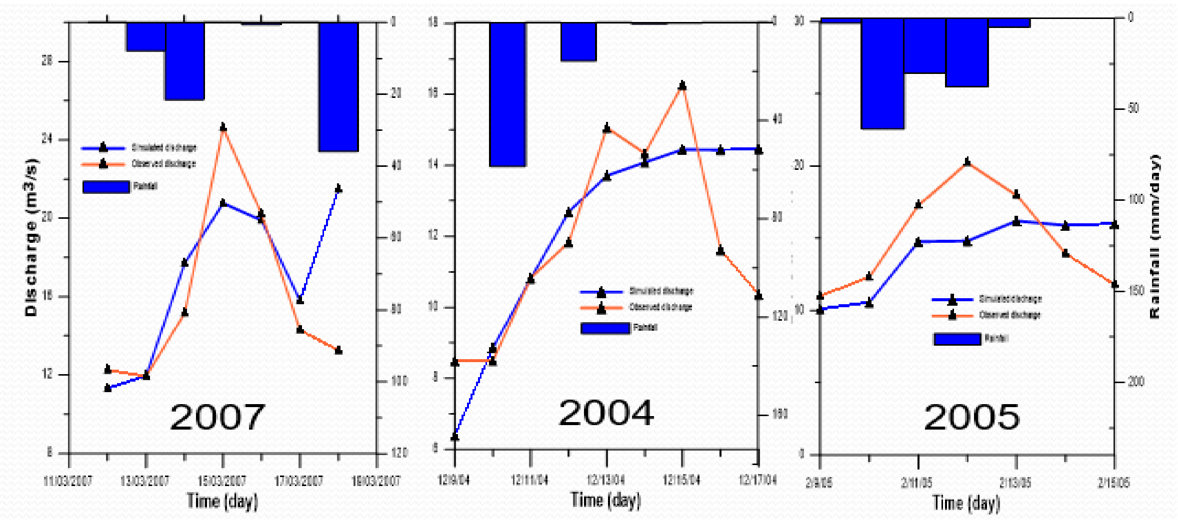

Figure 3. The model results of calibration simulation for the Upper Sunter river basin.

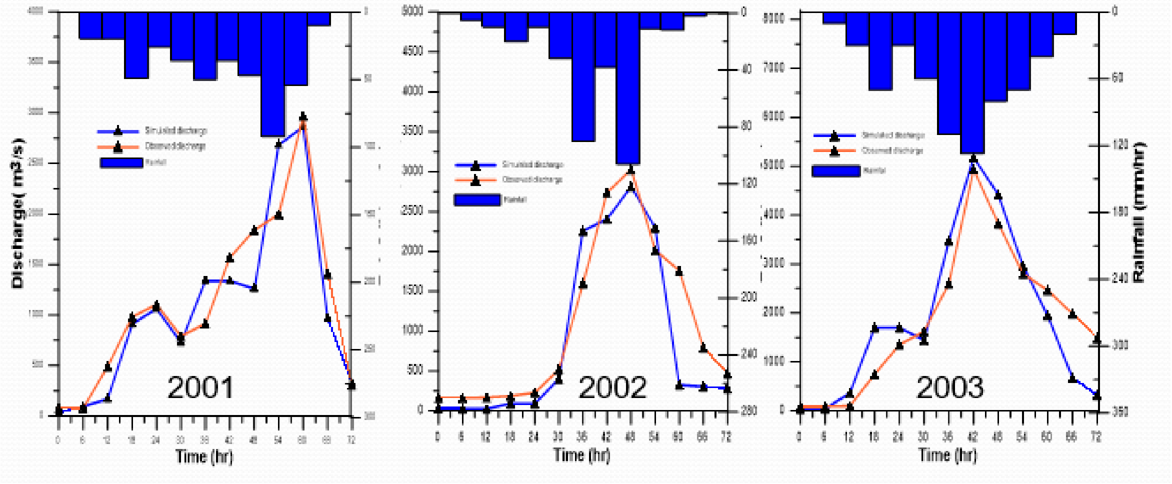

Figure 4. The model results of calibration simulation for the Vu Gia–Thu Bon river basin.

Calculation results of the hydrological simulation for the Vu Gia–Thu Bon river in typical floods of 2001, 2002, 2003 showed that the relative between calculation lines and actual measurement lines stick to each other in terms of oscillation phase and peak flood value. The difference in maximum flow between calculation and the actual measured value is negligible. Peak deviation errors at inspection stations are within the acceptable range. The results of the calculation of the NASH coefficient are relatively good, ranging from 0.75 to 0.83. It can be seen that the calculated discharge was consistent with the observed discharge. NSE coefficients are higher than 0.70 in both calculation and validation scenarios. Also, a high value of R^2 (above 0.78) presented the close correlation between simulated and observed curves. In terms of shape and peak time, the results of this model seem close to the real data presented in Figure 5.

Using the calibration parameters of the model HEC–HMS as described above, the project will be validated for 2 flood seasons in each river basin. The results of validation for the years are presented in table 2 and in Figures 6.

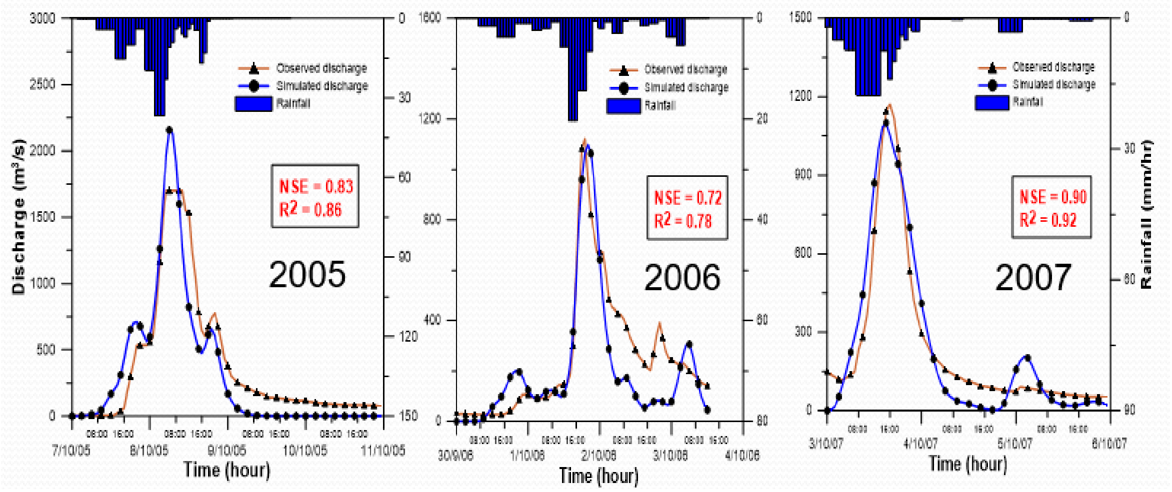

Figure 5. The calibration model result for the Nhat Le river basin.

Table 2. The statistical performance measures for validation.

River basin	Simulation	RMSE	R^2	NSE
Upper Sunter	23/2–04/03/2003	4.23	0.38	0.21
	02/02–13/02/2006	9.20	0.58	0.55
Vu Gia – Thu Bon	25/10– 7/10/2004	145.1	0.82	0.83
	22/10–24/10/2005	230.7	0.86	0.80
Nhat Le	02/10–05/10/2010	130.98	0.89	0.84
	15/10–17/10/2011	263.47	0.89	0.70

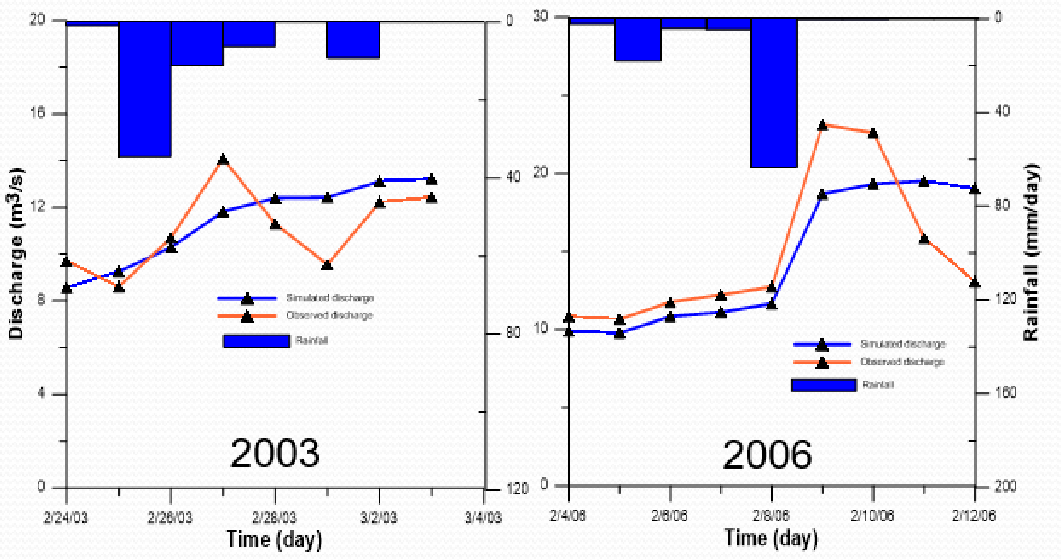

Figure 6. The validation model result for the Upper Sunter river basin.

Each model results of the optimum value were validated with 2 durations of precipitation for the daily hydrograph. Although the value of R^2 for simulation 1 is not too high, the effective output of the model for each validation case can be classified as acceptable. This shows that in the Upper Sunter river basin, the optimized parameters from calibration 2 can be used for flood modeling. The assumption of lower values of model efficiency comes from the limitation of hourly discharge data. In addition, the chosen optimized parameter with Muskingum K = 30; Muskingum x = 0.01; and Percent Impervious = 0; Initial Abstraction=0 and the number of routing = 1 can be performed to simulate the design storm.

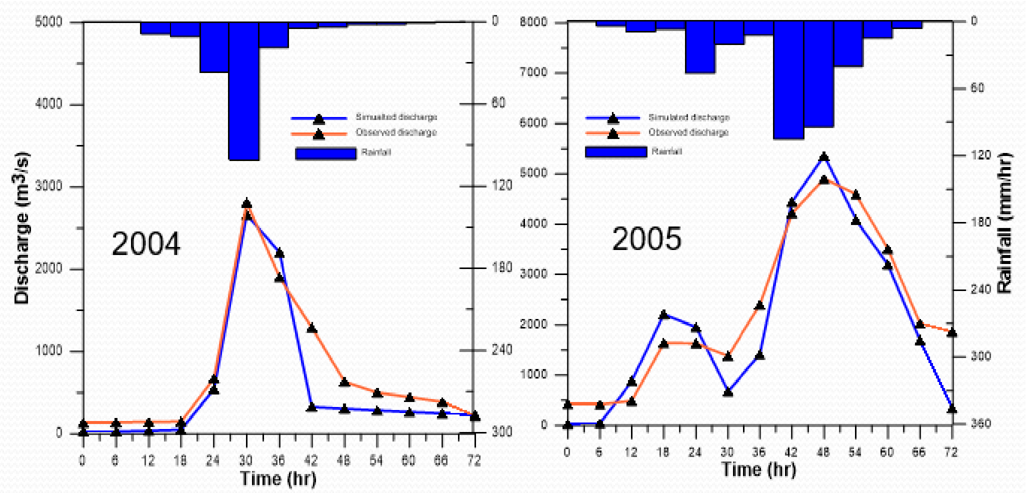

Figure 7. The validation model result for the Vu Gia–Thu Bon river basin.

The validation results with the floods in 2004 and 2005 assessed the accuracy of the hydraulic simulation. The calculation results and the real data measured at the Nong Son stations have shown relatively appropriate results. The calculation results are similar to the observed data. Evaluate results with the NASH coefficient for very good results in the range above 0.8. Thus, the selected optimized parameter with Muskingum K = 1.1, 3, 5, and 10; Muskingum x = 0.01 and 0.1; and Percent Impervious = 25; Initial Abstraction= 470 and the number of routing = 1 can be performed to simulate the design storm.

With the results as shown in figure 7 and the suitability of flood line at the Vu Gia–Thu Bon river basin, it shows that the set of parameters can be applied to the next steps of flood simulation with the design flood frequency and for future studies in the Vu Gia–Thu Bon river system.

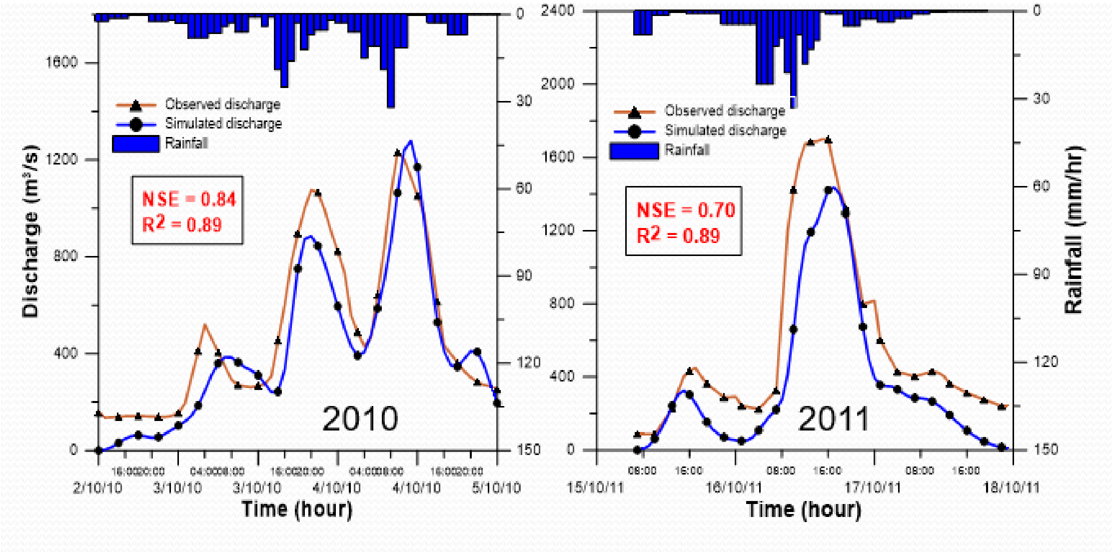

Figure 8. The validation model result for the Nhat Le river basin.

The results of this model seem to close to the real data which is shown in the results for validation. This means that the HMS model simulated well for flood events in the Nhat Le river basin. Therefore, the selected optimized parameter initial abstraction = 75 and 70, percentage of the impervious area = 75, Muskingum K = 1 and 2, and Muskingum X = 0.01. Consequently, this model is possible of estimating the peak discharges corresponding to the design storm for the Nhat Le river basin.

3.3. Design storm

This research simulates seven return periods from 2 years to 200 years. In the Upper Sunter river basin case study, design storm events were estimated by using Fisher Tippet I Distribution method. The calculation results are value of 24-hour of precipitation for the selected return period. Moreover, the analysis of storm events was performed using the Depth-Duration-Frequency (DDF) curves representing precipitation depth to time concentration. In the Vu Gia–Thu Bon case study, to calculate the 3–day rainfall designed for 7 future scenarios 2, 5, 10, 50, 100, 200 years, the project selected rainfall from October 20 to October 22, 2003, to calculate (the rainfall in 2003 is the largest rainfall in the computation period). Last but not least, design storms were obtained from the hydrological report of Quang Binh Irrigation and Drainage Management Company for the Nhat Le river basin.

The discharges hydrographs result with seven design storms (2, 5, 10, 25, 50, 100 and 200 years return period) for three river basins are presented in figure 13. It can be seen that the graph of each simulation shows a similar shape and grows higher as the return period is higher.

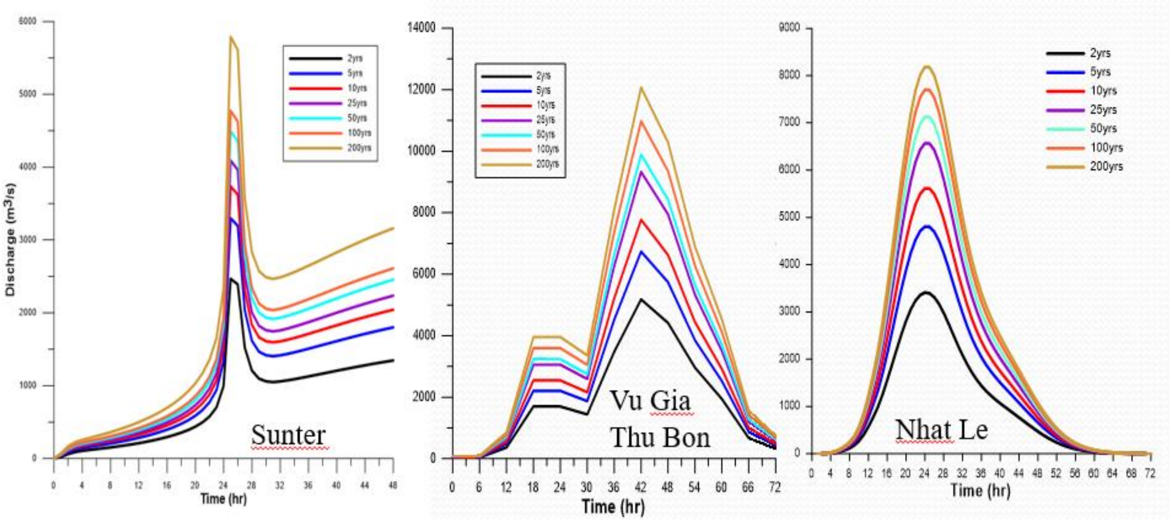

Figure 9. The hydrographs for design storm simulation.

Table 3. The peak discharges of design storm for three case study area.

	River basin		
Return period	**Upper Sunter**	**Vu Gia–Thu Bon**	**Nhat Le**
2 years	2329.4	5383.2	3409.4
5 years	3257.0	6736.6	4805.1
10 years	3871.1	7789.2	5612.6
25 years	4647.1	9327.6	6657.1
50 years	5222.9	9887.3	7127.6
100 years	5794.3	10974.9	7700.9
200 years	6363.6	12072.3	8183.3

Summarize the peak discharge data of each graph is presented in Table 3. The peak discharge simulated at the outlet is increasing with the increase of the return period. These results of hydrograph can be used as the input of the HEC–RAS model for making an inundation map or can be applied for practical tasks in projects related to design dams and waterworks.

4. Conclusions

This research shown that the HEC–HMS hydrological model is conformable to tropical climate conditions. The model is on the basis of topographical, hydrological, soil type and land use characteristics of the study area. The river basin features and initial values were analyzed using HEC–GeoHMS in ArcGIS in order to calibrate model. The rainfall-runoff models were performed using extreme precipitation events and initial results showed a difference between observed and simulated discharge and peak discharge in the research area. Therefore, model calibration was carried out to optimize the parameters. To know the most influential parameter in the simulation, a sensitivity analysis was performed and the results presented that the curves number is the most sensitive parameter come next the lag time.

This research developed successful three hydrological models to assess flooding behavior due to rainfall events in three study areas in Upper Sunter, Vu Gia–Thu Bon and Nhat Le river basins, which the result could be the baseline for the early warning hazard of flooding area. Based on the simulation result, we can see that the errors are the difference in each case study. With the detail input data and shortly time step, we will get more accuracy with observation data. The model calibration and validation result show an acceptable value of model efficiency. The overall performance of the HEC–HMS model is great in terms of relative error functions, Nash Sutcliffe efficiency and coefficient of determining consistent with the selected loss, transform and flow routing methods. Therefore, it can be suggested that the adjusted parameters can be further used for another river sub-basin within the river basin and adjacent river basin. The design floods for seven different return periods for the three study areas were determined. These results can be used in further studies in order to simulate inundation maps and also for water management purposes.

Lastly, the methodologies established in this study can also be applied to other ungauged river basins and regions with similar characteristics. We recommend further researches in these river basins to produce more detailed information for modeling work by considering the effectiveness of meteorological and hydrological measurements (poor in quantity and quality) to establish the optimum number of stations and their adequate distribution in the river basin.

Author contribution statement: Calculation; manuscript writing and editing: H.T.N.M.; methodology; results analysis and discussions: N.T.T.L., H.T.N.M.; data processing and analysis: N.T.T.L.

Competing interest statement: The authors declare no conflict of interest.

References

1. McMillan, H.; Krueger, T.; Freer, J. Benchmarking observational uncertainties for hydrology: Rainfall, river discharge and water quality. *Hydrol. Process.* **2012**, *26*, 4078–4111.
2. Yen, H.X.; Wang, D.; Fontane, R.; Harmel, M. Arabi. A framework for propagation of uncertainty contributed by parameterization, input data, model structure, and calibration/validation data in watershed modeling. *Environ. Model. Softw.* **2014**, *54*, 211–221.
3. Abbaspour, K.C. Modelling hydrology and water quality of the European Continent at a subbasin scale: calibration of a high–resolution large–scale SWAT model. *J. Hydrol*, **2015**, *524*, 733–752.
4. Abbaspour, K.C. Uncertainty in Estimation of Soil Hydraulic Parameters by Inverse Modeling: Example Lysimeter Experiments. *Soil Sci. Soc. Am. J.* **1999**, *63*, 501–509.

5. Rouholahnejad, E. A high resolution spatiotemporal distribution of water resources quantity and quality in the Black Sea Basin. *Water Resour. Res.* **2014**, *50*, 5866–5885.
6. Hall, J.; Arheimer, B. Understanding Flood Regime Changes in Europe: A state of the art assessment. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 2735–2772.
7. Barnett, T.; Pierce, D. Human–Induced Changes in the Hydrology of the Western United States. *Science* **2018**, *319*, 1080–1083.
8. Lin, S.; Jing, C. Evaluating DEM source and resolution uncertainties in the Soil and Water Assessment Tool. *Stoch. Environ. Res. Risk Assess*. **2013**, *27*, 209–221.
9. Beven, K.; Binley, A. The future of distributed models: Model calibration and uncertainty prediction. *Hydrol. Process*. **1992**, *6*, 279–298.
10. Legates, D.; McCabe, G. Evaluating the use of "goodness–of–fit" measures in hydrologic and hydroclimatic model validation. *Water Resour. Res*. **1999**, *35*, 233–241.
11. N. Ajami.; Q. Duan.; S. Sorooshian. An integrated hydrologic Bayesian multimodel combination framework: Confronting input, parameter, and model structural uncertainty in hydrologic prediction. *Water Resour. Res*., **2007**, *43*.
12. O. Wani.; A. Scheidegger. Parameter estimation of hydrologic models using a likelihood function for censored and binary observations. *Water Res.,* **2017**, 121, 290–301.
13. Sharma, A.; Tiwari, K. A comparative appraisal of hydrological behavior of SRTM DEM at catchment level. *J. Hydrol.* **2014**, *519*, 1394–1404.
14. Wang, H.; Wu, Z. A Comprehensive Study of the Effect of Input Data on Hydrology and non–point Source Pollution Modeling. *Water Resour. Manag.* **2015**, *29*, 1505–1521.
15. Bormann, H.; Breuer, L. Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) IV: Model sensitivity to data aggregation and spatial (re–) distribution. *Adv. Water Resour.* **2009**, *32*, 171–192.
16. Bastola, S.; Murphy, C. The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. *Adv. Water Resour.* **2011**, *34*, 562–576.
17. Najafi, M.; Moradkhani, H. Assessing the uncertainties of hydrologic model selection in climate change impact studies. *Hydrol. Process.* **2011**, *25*, 2814–2826.
18. Niehoff, D. Land–use impacts on storm–runoff generation: scenarios of land–use change and simulation of hydrological response in a meso–scale catchment in SW–Germany. *J. Hydrol.* **2002**, *267(1–2)*, 80–93.
19. Price, K. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. US Environmental Protection Agency, USA, **2011**, *35*, 465–492.
20. DeFries, R. Land–use change and hydrologic processes: a major focus. *Hydrol. Processes* **2004**, *18*, 2183–2186.
21. Yang, X.; Ren, L.; Singh, V.P.; Liu, X.; Yuan, F.; Jiang, S.; Yong, B. Impacts of land use and land cover changes on evapotranspiration and runoff at Shalamulun River watershed, China. *Hydrol. Res.* **2012**, *43(1–2)*, 23–37.
22. Horritt, M.S.; Bates, P.D. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *J. Hydrol.* **2002**, *268(1–4)*, 87–99.
23. Behbahani, R. The effect of base map scale on the accuracy of floodplain zoning using GIS. *J. Appl. Sci.* **2006**, *6(1)*, 20–26.
24. Bates, P.D. Remote sensing and flood inundation modeling. *Wiley Inter. Sci.* **2004**, *18(1–2)*, 2593–2597.

25. Borga, M. Accuracy of radar rainfall estimates for streamflow simulation. *J. Hydrol.* **2002**, *267(1–2)*, 26–39.
26. USACE. Engineers, Hydrologic Modeling System (HEC–HMS) Applications Guide: Version 3.1.0. Institute for Water Resources, Hydrologic Engineering Center, 2008.
27. Oleyiblo, J.O. Application of HEC–HMS for flood forecasting in Misai and Wan'an catchments in China. *Water Sci. Eng.* **2010**, *3*, 14–22.
28. Wahren, F.T.; Julich, S.; Nunes, J.P.; Gonzalez-Pelayo, O.; Hawtree, D.; Feger, K.H.; Keizer, J.J. Combining digital soil mapping and hydrological modeling in a data scarce watershed in north–central Portugal. *Geoderma* **2016**, *264*, 350–362.
29. Steinman, A. Event and Continuous Hydrologic Modeling with HEC–HMS. *IJETSR* **2009**, *135(1),* 119–124.
30. Feldman, A. Hydrologic Modeling System HEC–HMS, Technical Reference Manual, USA: U.S. Army Corps of Engineers. Hydrologic Engineering Center, 2009.
31. Yener, M.K. Modeling studies with HEC–HMS and runoff scenarios in Yuvacik Basin, Turkiye. International Congress on River Basin Management, 2009.
32. Knebl, M.R.; Yang, Z.L.; Hutchison, K.; Maidment, D.R. Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC–HMS: a case study for the San Antonio River Basin Summer 2002 storm event. *J. Environ. Manage.* **2004**, *75,* 325–336.
33. Enard, B.; Kavetski, D. Understanding predictive uncertainty in hydrologic modeling: The challenge of identifying input and structural errors. *Water Resour. Res.* **2010**, *46(5)*, W05521.
34. William, J. Hydrologic Modeling of a Probable Maximum Precipitation Event Using HEC–HMS and GIS Models – A Case Study of Two Watersheds in Southern Virginia. Thesis in Civil Engineering, Virginia Polytechnic Institute and State University, 2012, pp. 269.
35. Kalita, D. A study of basin response using HEC–HMS and subzone reports of CWC. Proceeding of 13th National Symposium on Hydrology, Roorkee, New Delhi, 2008.
36. Oudin, L.; Andréassian, V. Dynamic averaging of rainfall–runoff model simulations from complementary model parameterizations. *Water Resour. Res.* **2006**, *42(7),* W07410.
37. Rathod, P. Simulation of Rainfall–Runoff Process Using HEC–HMS – Case Study: Tapi River, India. Proceeding of 20th International Conference on Hydraulics, 2015.
38. Abdullah, J. Estimation of Peak Discharges Using Flood Frequency Analysis and Hydrological Modeling System. In International Symposium on Flood Research and Management, Singapore, 2015.
39. Muthukrishnan, E. Calibration of a simple rainfall–runoff model for long–term hydrological impact evaluation. *URISA J.* **2006**, *18(2)*, 33–40.
40. Tassew, B.; Belete, M.; Miegel, K. Application of HEC–HMS Model for Flow Simulation in the Lake Tana Basin: The Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia. *Hydrology* **2019**, *6(1)*, 21.
41. Merwade, V. Terrain Processing and HMS–Model Development using GeoHMs. School of Civil Engineering. Purdue University, USA, 2012.
42. World Bank. In Jakarta Tantangan Perkotaan Seiring Perubahan Iklim. The World Bank, Jakarta, Indonesia, 2017.
43. Emam, A.; Mishra, B.; Kumar, P.; Massago, Y.; Fukushi, K. Impact Assessment of Climate and Land–use Changes on Flooding Behavior in the Upper Ciliwung River, Jakarta, Indonesia. *Water* **2016**, *8(12)*, 559.

44. Nga, T.T. Establishing a flood simulation model for reservoir operation in the Vu Gia–Thu Bon River during the flood season. **2013**, *42*, 18–24.
45. Loi, N.K. Automated procedure of real–time flood forecasting in Vu Gia – Thu Bon river basin, Vietnam by integrating SWAT and HEC–RAS models. *J. Water Clim. Change* **2019**, *10(3)*, 535–545.
46. Son, N.H. Study on the application of flood forecasting model for Vu Gia – Thu Bon River. **2013**, *43*, 118–124.
47. Hau, N.X. Assessment of Climate Change Impact on Floods in the Nhat Le River Basin, Vietnam. *VNU J. Sci.: Nat. Sci. Technol.* **2015**, *31(3S)*, 125–138.
48. Halwatura, D.; Najim, M.M.M. Application of the HEC–HMS model for runoff simulation in a tropical catchment. *Environ. Modell. Softw.* **2013**, *46*, 155–162.
49. Sardoii, E.; Rostami, N. Calibration of loss estimation methods in HEC–HMS for simulation of surface runoff (Case Study: Amirkabir Dam Watershed, Iran). *Adv. Environ. Biol.* **2012**, *6*, 343–348.
50. Tewolde, M.; Smithers, J.C. Flood routing in ungauged catchments using Muskingum methods. *Water SA.* **2016**, *32*, 379–388.