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A Combined Hydrological and Hydraulic Model for Flood Prediction in Vietnam Applied to the Huong River Basin as a Test Case Study

Dang Thanh Mai [1] and Florimond De Smedt [2,*]

[1] National Hydro-Meteorological Service, National Center for Hydro-Meteorological Forecasting, 8 Phao Dai Lang Street, Dong Da District, Ha Noi 100000, Vietnam; dangthanhmai1973@gmail.com

[2] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Pleinlaan 2, Brussels 1050, Belgium

* Correspondence: fdesmedt@vub.ac.be; Tel.: +32-2629-3547

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Abstract: A combined hydrological and hydraulic model is presented for flood prediction in Vietnam. This model is applied to the Huong river basin as a test case study. Observed flood flows and water surface levels of the 2002–2005 flood seasons are used for model calibration, and those of the 2006–2007 flood seasons are used for validation of the model. The physically based distributed hydrologic model WetSpa is used for predicting the generation and propagation of flood flows in the mountainous upper sub-basins, and proves to predict flood flows accurately. The Hydrologic Engineering Center River Analysis System (HEC-RAS) hydraulic model is applied to simulate flood flows and inundation levels in the downstream floodplain, and also proves to predict water levels accurately. The predicted water profiles are used for mapping of inundations in the floodplain. The model may be useful in developing flood forecasting and early warning systems to mitigate losses due to flooding in Vietnam.

Keywords: flood prediction; inundation mapping; WetSpa; HEC-RAS; Huong River; Vietnam

1. Introduction

As a result of human intervention in the natural environment and the effects of global climate change, floods are occurring more frequently. Thus, prediction and control of floods are a major challenge. Of all natural disasters in Vietnam, flooding ranks first in terms of affected area, severity, frequency, and financial losses [1]. The most notable cases in the past include the great flood of the Red River in August 1971 (which may have caused as many as 100,000 deaths), and the severe flooding of the central coastal provinces of Vietnam in early November 1999, caused by a huge storm with a peak rainfall intensity of 120 mm/h, killing hundreds of people and causing huge economic losses [2,3]. There were also devastating floods in Northern and Central Vietnam in November 2007, killing dozens of people and causing severe damage to crops, housing, and infrastructure [4].

The evidence that floods have large social and economic impacts in Vietnam has led to the establishment of operational flood forecasting and warning systems to help mitigate losses. Efforts to set up real-time flood forecasting in Vietnam began in the 1970s through a combination of telemetry rainfall data acquisition and flood prediction by runoff modeling. However, accurate flood forecasting remains problematic due to a lack of expertise and up-to-date flood forecasting models.

Recent developments in flood forecasting are based on a combination of hydrological and hydraulic modeling concepts. The main advantages of such an approach are that spatially distributed characteristics of river basins can be taken into account and subjective concepts such as design hydrographs can be avoided. Some noteworthy examples are as follows. Lian et al. [5] linked the

Hydrological Simulation Program (HSPF) [6] with the hydraulic model UNET (Unsteady flow through a full NETwork of open channels) [7] to predict flows in the Illinois River basin, USA. Kamp and Savenije [8] used artificial neural networks to couple rainfall runoff and river channel routing models for the Alzette basin, Luxembourg. Gül et al. [9] combined the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) [10] and River Analysis System (HEC-RAS) [10] to examine the potential serviceability of a planned dam in the Bostanli basin, Turkey. Bonnifait et al. [11] coupled TOPMODEL (TOPography based hydrological MODEL) with a hydraulic model for reconstructing a catastrophic flood event in the Gard region, France. Biancamaria et al. [12] coupled the land surface scheme Interactions between Soil–Biosphere–Atmosphere (ISBA) with the flood inundation model LISFLOOD-FP [13] to model flow in the Ob River in Siberia. Kim et al. [14] coupled the Triangulated Irregular Network Real Time Integrated Basin Simulator (tRIBS) [15]) with the Overland Flow Model (OFM) for the Peacheater Creek watershed, OK, USA. Nam et al. [16] combined a lumped hydrological tank model with the Hydrologic Engineering Center River Analysis System (HEC-RAS) [17] for flood prediction in the Vu Gia-Bon River basin, Vietnam. Grimaldi et al. [18] presented a hydrologic–hydraulic modeling framework for flood mapping in the Torbido River in central Italy. Schumann et al. [19] coupled the Variable Infiltration Capacity (VIC) hydrologic model with hydrodynamic model LISFLOOD-FP [13] for flood forecasting in the Zambezi River. Nguyen et al. [20] coupled the Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM) with the hydraulic model BreZo for flash flood modeling in Baron Fork River, OK, USA.

The objective and novelty of this work is to combine the physically-based distributed hydrologic model WetSpa [21] with the hydraulic model HEC-RAS for flood prediction in Vietnam. This model is tested by simulation of flooding in the Huong River basin in Central Vietnam. The objective is achieved in three steps: (1) calibration and validation of the hydrological model components based on observations of recent flood events in the upper reaches of the basin; (2) calibration and validation of the hydraulic model based on observations of recent flood water surface levels in the floodplain; and (3) mapping of inundations in the floodplain.

2. Materials and Methods

2.1. Methodology

Flood simulation is achieved by combining a hydrological model to predict flood flows with a hydraulic model to predict inundation levels. The WetSpa hydrologic model [21] is used to simulate flood generation and propagation in the upper sub-basins. WetSpa is a distributed watershed model, suitable for flood prediction and water management on a catchment scale. The reliability of the model has been tested by model inter-comparison projects (e.g., [22–24]) and the model also proved its suitability for application in Vietnam [25]. The WetSpa model is physically based and simulates spatially and temporally varying hydrological processes such as rainfall interception, depression storage, evapotranspiration, infiltration, surface runoff routing, soil water percolation, and groundwater drainage. The model accounts for spatially distributed hydrological and geophysical characteristics of the catchment. The main components of the model are: (1) generation of surface runoff using a modified rational method with a runoff coefficient depending on slope angle, land use, and soil type, allowing variation with soil moisture content, rainfall intensity, and storm duration; and (2) overland flow and channel flow routing by a diffusive wave approximation of the Saint-Venant equations, which enables us to predict flood flows at any point and time in the catchment. The main inputs to the model are hydro-meteorological data (rainfall, potential evaporation, wind speed, and temperature) and distributed basin characteristics (topography, land use, and soil type), from which all relevant hydrological parameters are derived by means of a built-in database. Calibration of the model consists of finding appropriate values for some adjustable, but time and space-invariant model parameters, for example, base flow recession coefficient precipitation intension scaling factor, correction factor for potential evaporation, and starting values for soil wetness and groundwater storage [21]. These parameters depend on local conditions, and can thus only be determined by fitting model predictions with observations.

Prediction performance of the hydrological model is evaluated by comparing the observed and corresponding predicted stream flows. The first criterion evaluates the model bias (MB) as

$$MB = \sum_{i=1}^{n}(Qp_i - Qo_i)/\sum_{i=1}^{n}Qp_i \quad (1)$$

where Qp_i and Qo_i are predicted and observed stream flows (L^3/T) at time instance i, respectively, and n is the number of observations. The second criterion evaluates the ability of the model to reproduce the flow variability using the Nash-Sutcliffe efficiency (NS) [26],

$$NS = 1 - \sum_{i=1}^{n}(Qp_i - Qo_i)^2/\sum_{i=1}^{n}\left(Qp_i - \overline{Qo}\right)^2, \quad (2)$$

where $\overline{Qo} = \sum_{i=1}^{n} Qo_i/n$ is the mean observed stream flow over the simulation period. The third evaluation criterion is a modified Nash-Sutcliffe (MNS) efficiency emphasizing the ability of the model to accurately reproduce high flows [27]:

$$MNS = 1 - \sum_{i=1}^{n}\left(Qo_i + \overline{Qo}\right)(Qp_i - Qo_i)^2/\sum_{i=1}^{n}\left(Qo_i + \overline{Qo}\right)\left(Qp_i - \overline{Qo}\right)^2, \quad (3)$$

The ideal criterion values are MB = 0, NS = 1, and MNS = 1, in the case of a perfect fit between predictions and observations.

Flood propagation and inundation levels in the flood plain are simulated with the well-known and free public domain HEC-RAS model developed by the Hydrologic Engineering Center of the US Army Corps of Engineers (USACE). This hydraulic model solves the full dynamic Saint-Venant equations for unsteady flow through single, dendritic or looped systems of natural and constructed open channels, including overbank/floodplain areas, levee failures, spillways, and overflow structures, and so forth. Upstream boundary conditions are required at the upstream end of all river reaches not connected to other reaches or storage areas in the form of hydrographs (graph of discharge versus time). In the case of subcritical flow downstream, boundary conditions need to be specified at the downstream end of all reaches not connected to other reaches or storage areas, which can be in the form of a normal or critical water depth, a rating curve, or known or observed stage hydrographs (graph of water surface levels versus time). A full description of the model and its computational schemes is given by USACE [17]. Calibration of the model is usually achieved by adapting the Manning coefficients (resistance to flow) of the river reaches to reduce the difference between observed and simulated water levels.

The prediction performance of the HEC-RAS model can be evaluated by comparing observed and corresponding predicted water surface levels, using Nash-Sutcliffe efficiency (NS) and modified Nash-Sutcliffe efficiency (MNS) criteria similar to those given by Equations (2) and (3), but in this case using predicted and observed water surface levels instead of flows.

2.2. Test Case Study Area

The combined hydrological and hydraulic flood prediction model is tested and validated by simulating flood flows and inundations levels in the Huong River basin, located in the Thua Thien–Hue Province in central Vietnam (Figure 1). The Huong River basin (~2830 km^2) consists of a complex downstream floodplain (~445 km^2) and three upstream tributaries: Ta Trach (729 km^2), Huu Trach (718 km^2), and Bo (938 km^2). The floodplain is a pan-shaped valley with elevations between 1.5 m and 8 m, and a dense river network with series of lagoons affected by tides. The exact boundary of the floodplain is uncertain due to the flat topography and tidal effects. Situated along the bank of the Huong River in the floodplain is the city of Hue, which is well known for its historical United Nations Educational, Scientific, and Cultural Organization (UNESCO) world heritage sites. The upstream mountainous sub-catchments have a hilly topography with elevations ranging from 5 m to 1760 m and very steep slopes, that is, ~30% on average. The basin is located in a tropical monsoon zone, which receives the largest precipitation in Vietnam, with an annual rainfall of 2500 mm in the floodplain, and up to 3500 mm in the upper mountainous parts of the basin. Tropical storms occur regularly in the rainy season from September to December and generally lead to flash floods in the upper reaches and inundations in the floodplain.

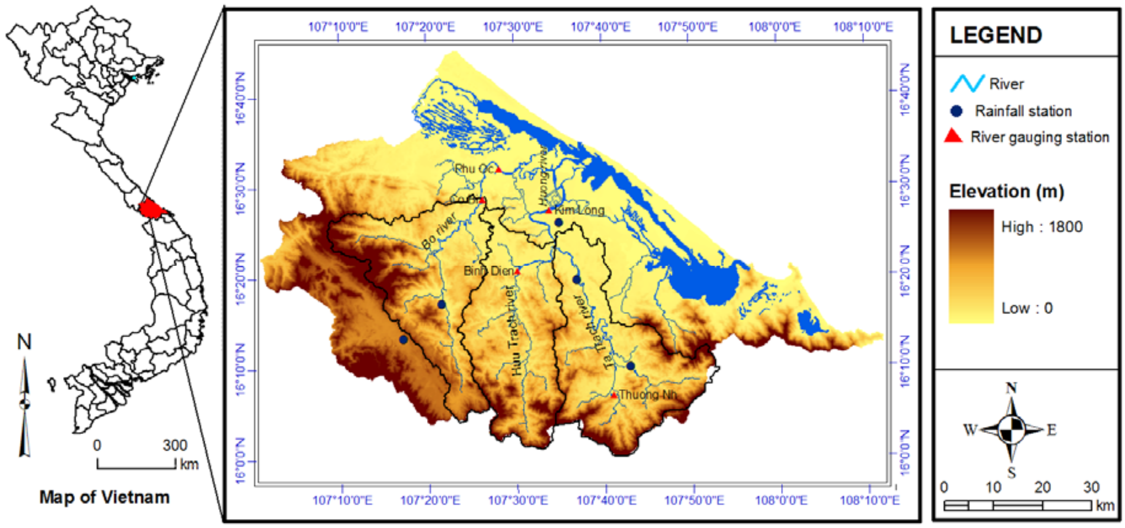

Figure 1. Map of Thua–Thien Hue province showing the location of the Huong River basin, consisting of a floodplain and three upstream mountainous sub-catchments (Ta Trach, Huu Trach and Bo). The topography, river courses, coastal lagoons and the location of the hydro-meteorological stations are also shown.

Five meteorological stations are located in the Thua Thien Hue province, four in the Huong basin, and one close to the Bo River border (Figure 1), where rainfall, potential evaporation, temperature, and wind speed have been recorded with 6-h intervals on a regular basis since 1980. There are also five river gauging stations located in the Huong basin (Figure 1). Two gauging stations are located in the floodplain in Phu Oc and Kim Long, where water surface levels are recorded at 6-h intervals each year during the flood season from 1 September to 15 November, but not discharges because the flow in the floodplain river reaches is affected by tides. Three gauging stations are located in the upstream sub-catchments: the Binh Dien station at the Huu Trach River, the Thuong Nhat station at the Ta Trach River, and the Co Bi station at the Bo River. Discharge observations are recorded at Binh Dien and Thuong Nat stations every six hours during the flood season. For this study, use is made of observations from these stations from 2002 to 2007. For the Co Bi station at the Bo River there are only historical records available with respect to daily discharge observations from 1979 to 1985.

Digital maps of topography, soil type, and land use of the three upstream sub-catchments were prepared for flood modeling with the WetSpa model. Elevations (Figure 1) were digitized from a topographic map, at a scale of 1:50,000, produced in 2002 by the Cartographic Publishing House, Ministry of Natural Resources and Environment, Vietnam. Land use and soil maps at a scale of 1:50,000, produced in 2001 by the Research Institute of Geology and Mineral Resources of Vietnam, were digitized and converted to 50-m grid size raster maps. Land cover was regrouped into 14 classes (Figure 2) and the soil map was reclassified into 12 USDA (U.S. Department of Agriculture) soil texture classes (Figure 3). The major land use classes are the evergreen broad tree (34.4%), evergreen shrub (20.5%), and deciduous broad tree (15.2%); the major soil types are clay (37.3%), loamy sand (17.6%), and sandy loam (15.5%). The combination of steep slopes and clayey shallow soils in the upper sub-catchments promote the occurrence of flash flows in the case of prolonged and heavy rainfall, whereas forest cover has a very minor impact [28].

The river network in the floodplain consists of eleven reaches, five junctions, three upstream end sections with inflow from the upstream sub-catchments, and four downstream end sections with outflow to coastal lagoons. The input data needed for hydraulic modelling with HEC-RAS of this river network are location, geometry, and hydraulic characteristics of all river reaches including overbanks and possible inundation areas, which in this application extend over the entire floodplain. The geometry of the river channels and overbanks was obtained from 121 surveyed cross sections of the stream bed, while for the inundation areas a digital terrain model (DTM) with a grid size of 10 m was derived by digitizing topography maps of the floodplain at a scale of 1:5000 with elevation contours at 2-m intervals, produced in 2004 by the Institute of Water Resources Planning of Vietnam. Elevations of the streambed sections were exported to a 10-m resolution raster map and combined with the DTM of the floodplain to obtain a precise elevation map for inundation mapping. The layout of the hydraulic model is presented in Figure S1.

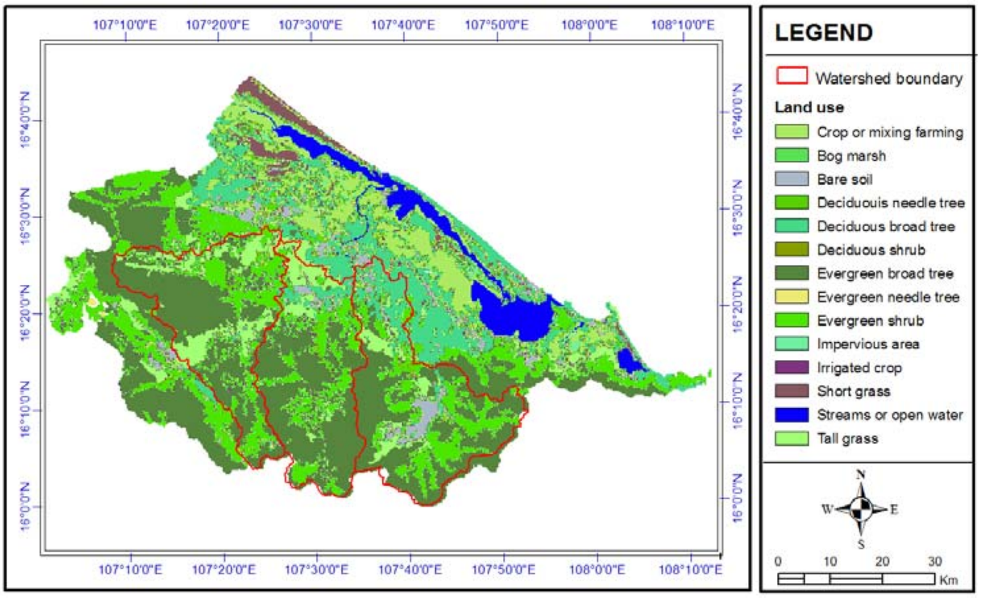

Figure 2. Land cover map of Thua Thien Hue province showing 14 land use classes. The major land use classes are the evergreen broad tree (34.4%), evergreen shrub (20.5%), and deciduous broad tree (15.2%).

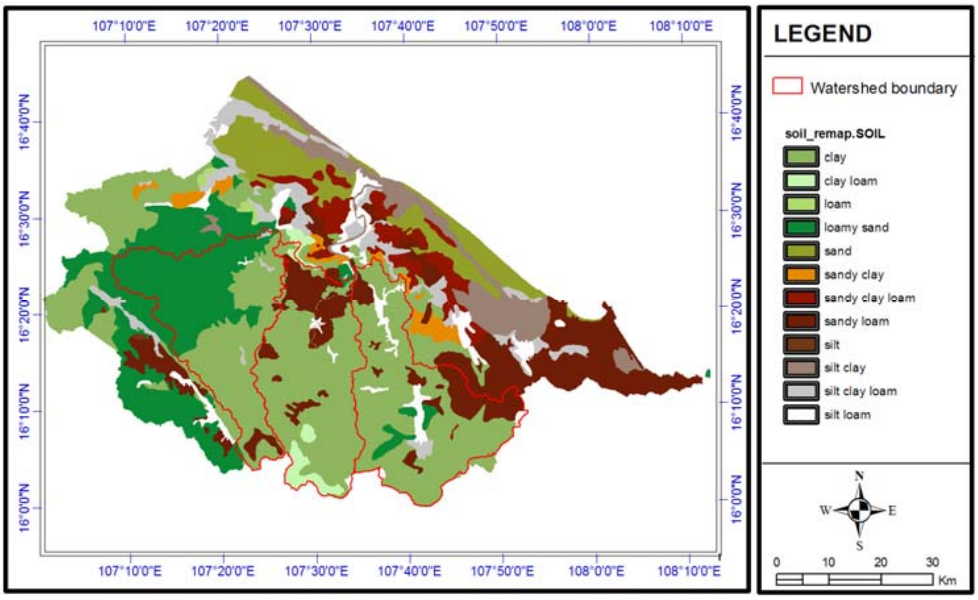

Figure 3. Soil types map of Thua Thien Hue province showing 12 soil type classes. The major soil types are major soil types are clay (37.3%), loamy sand (17.6%), and sandy loam (15.5%).

3. Results

Flood generation and flow routing in the three upper reaches of the Huong River basin are simulated with the WetSpa model with a spatial resolution of 50 m and a 6-h time step. Discharge time series for the 2002–2005 flood seasons observed at Thuong Nhat station on Huu Trach River, and for the 2003–2005 flood seasons observed at Binh Dien station on Ta Trach River are used for calibration of the WetSpa model, while observed discharge time series for the 2006 and 2007 flood seasons are used for model validation. Because there are no recent discharge observations available for the Co Bi station at the Bo River, the WetSpa model is only calibrated for the Bo sub-catchment using the historical data set of 1979–1985. Calibration of the WetSpa model is performed automatically using the PEST (Parameter ESTimation model) non-linear optimization procedure [29]. Calibrated parameters of the WetSpa model with 95% confidence intervals for the three upstream sub-catchments of the Huong River are presented in Table S1. Table 1 shows the performance criteria (Equations (1)–(3)) for each flood season of the calibration and validation periods. The model bias criterion (MB) ranges from −0.12 to 0.15, the Nash-Sutcliffe efficiency (NS) from 0.54 to 0.92, and the modified Nash-Sutcliffe efficiency (MNS) from 0.58 to 0.97.

Table 1. Performance criteria of the hydrological WetSpa flood prediction model for the three upstream sub-catchments of the Houng River; MB: model bias (Equation (1)); NS: Nash-Sutcliffe efficiency (Equation (2)); MNS: modified Nash-Sutcliffe efficiency for high flows (Equation (3)).

Station	Period	MB	NS	MNS
Thuong Nhat	1 September–15 November 2002 [a]	−0.02	0.68	0.76
	1 September–15 November 2003 [a]	−0.04	0.58	0.64
	1 September–15 November 2004 [a]	−0.03	0.92	0.97
	1 September–15 November 2005 [a]	−0.09	0.70	0.83
	1 September–15 November 2006 [b]	−0.09	0.81	0.88
	1 September–15 November 2007 [b]	−0.12	0.78	0.83
Binh Dien	1 September–15 November 2003 [a]	−0.04	0.82	0.88
	1 September–15 November 2004 [a]	0.04	0.81	0.83
	1 September–15 November 2005 [a]	0.12	0.86	0.90
	1 September–15 November 2006 [b]	0.06	0.89	0.92
	1 September–15 November 2007 [b]	0.01	0.90	0.92
Co Bi	1 January 1979–31 December 1985 [a]	0.15	0.54	0.58

[a] Calibration, [b] Validation.

Comparison between simulated and observed flow at the Thuong Nhat and Binh Dien gauging stations for the 2006 and 2007 flood seasons are presented in Figures S2–S5. The most relevant result is presented in Figure 4, showing a graphical comparison between simulated and observed flows at the Binh Dien gauging station at the Huu Trach River for the 2007 flood season. This gauging station is most interesting because it is located much further downstream than the Thuong Nhat station at the Ta Trach River. The 2007 flood season is also interesting because there were five major flood events, whereas there was only one flood event in 2006. Moreover, the last storm (11–13 November 2007) was the largest storm observed in the Huong basin, which resulted in inundation of large parts of the floodplain, especially in and around Hue. On November 12, the river flow reached a peak of about 3300 m^3/s at the Binh Dien gauging station at the Huu Trach River, which is about one hundred times the mean discharge.

The hydraulic model HEC-RAS is applied with an hourly time step using WetSpa model results as upstream boundary condition and tidal water levels in the coastal lagoons as a downstream boundary condition. Tidal fluctuations have been derived by correlating a set of tidal observations from 7 to 17 May 2000, in a coastal lagoon with continuous sea level recordings made in Da Nang, about 50 km to the southeast. The tidal amplitude is about 0.2 m. Calibration of the HEC-RAS model is performed using observed water surface levels at Kim Long and Phu Oc gauging stations for the 2002–2005 flood seasons, and the model prediction accuracy is subsequently validated using the observations of the 2006 and 2007 flood seasons.

In order to evaluate the performance of the HEC-RAS model, the same criteria as for the hydrological model are used (MB, NS and MNS, Equations (1)–(3), respectively), but expressing differences between measured and simulated water levels at the Kim Long and Phu Oc stations. Calibration of the HEC-RAS model was performed manually by adjusting the Manning coefficients of the river reaches. Starting with Manning coefficients equal to 0.03 for the river channel sections and 0.12 for the riverbanks and inundations areas. Values were adjusted first with intervals of 0.005 to obtain a better fit with the observations, and secondly with intervals of 0.001 to obtain an optimal fit. The calibrated Manning coefficients for the 11 reaches of the Huong floodplain are given in Table S2. Table 2 lists obtained results for the model for each flood season of the calibration and validation periods using the performance criteria given by Equations (2) and (3). The Nash-Sutcliffe efficiency (NS) ranges from 0.79 to 0.94, and the modified Nash-Sutcliffe efficiency (MNS) from 0.87 to 0.94.

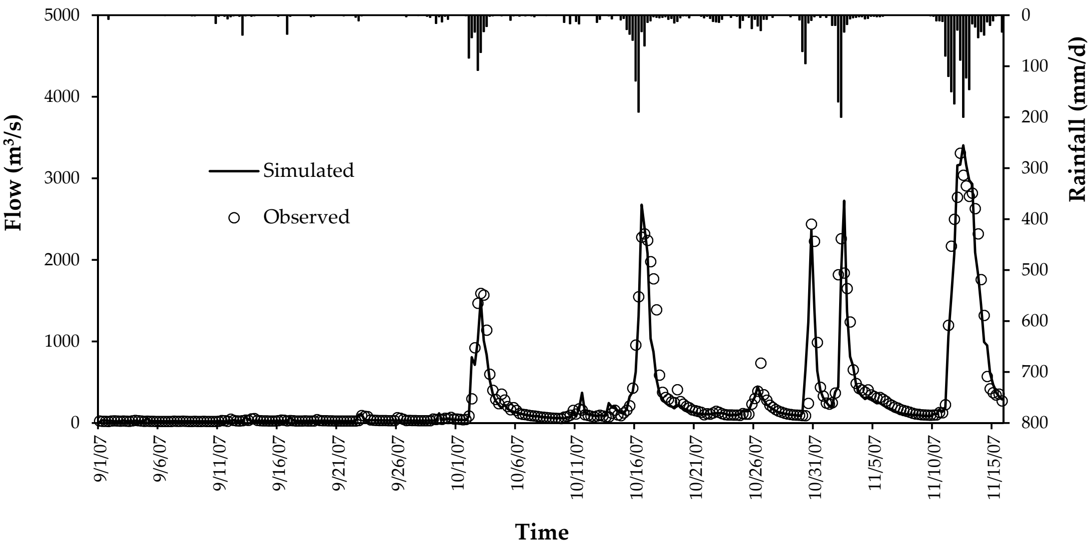

Figure 4. Comparison between simulated and observed flow for the 2007 flood season at the Binh Dien gauging station at the Huu Trach River.

Table 2. Performance criteria of the hydraulic Hydrologic Engineering Center River Analysis System (HEC-RAS) flood prediction model for the two gauging stations in the Huong floodplain. NS: Nash-Sutcliffe efficiency for water levels; MNS: modified Nash-Sutcliffe efficiency for high water levels.

Station	Period	NS	MNS
Phu Oc	1 September–15 November 2002 ^{a}	0.92	0.93
	1 September–15 November 2003 ^{a}	0.92	0.92
	1 September–15 November 2004 ^{a}	0.86	0.89
	1 September–15 November 2005 ^{a}	0.93	0.93
	1 September–15 November 2006 ^{b}	0.87	0.90
	1 September–15 November 2007 ^{b}	0.94	0.93
Kim Long	1 September–15 November 2002 ^{a}	0.84	0.89
	1 September–15 November 2003 ^{a}	0.79	0.87
	1 September–15 November 2004 ^{a}	0.79	0.88
	1 September–15 November 2005 ^{a}	0.85	0.88
	1 September–15 November 2006 ^{b}	0.81	0.90
	1 September–15 November 2007 ^{b}	0.92	0.94

^{a} Calibration, ^{b} Validation.

Comparison between simulated and observed water surface levels at the Phu Oc and Kim Long gauging stations for the 2006 and 2007 flood seasons are presented in Figures S6–S9. The most relevant results is given in Figure 5, showing a graphical comparison between simulated and observed water surface levels at the Phu Oc gauging station located for the 2007 flood season. The water level in Huong floodplain is normally close to zero and the alarm level for inundation near Hue is 3 m, which was exceeded four times for all the storms observed in the 2007 flood season, with peak water level rising to nearly 5 m above sea level.

The water surface elevations predicted by the HEC-RAS model were exported to raster format with a resolution of 10 m and compared with the precise DTM of combined river channels and inundation areas to derive an inundation map showing the areal extend of the flooding and the resulting water depth at each location. As an example, Figure 6 shows the inundation map at 13:00 h on 12 November 2007.

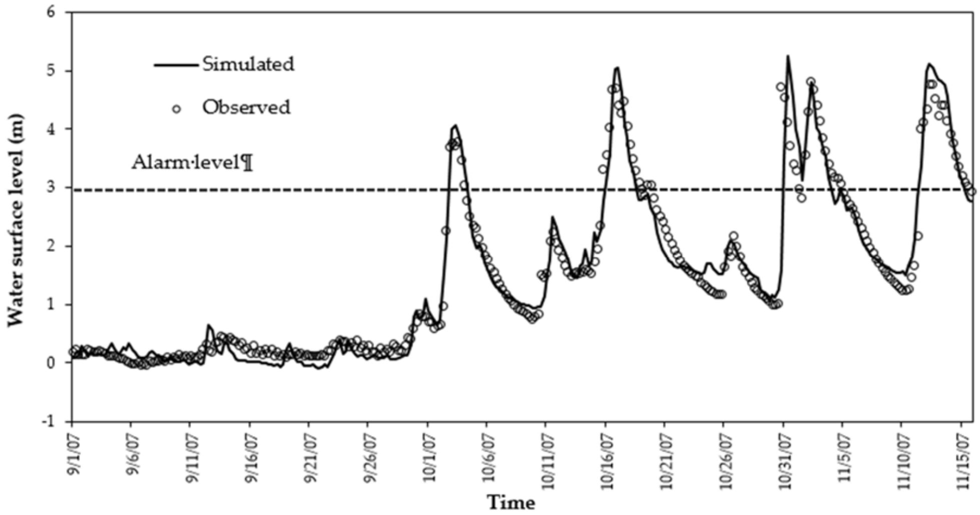

Figure 5. Comparison between simulated and observed water surface levels for the 2007 flood season at the Phu Oc gauging station located in the Huong floodplain.

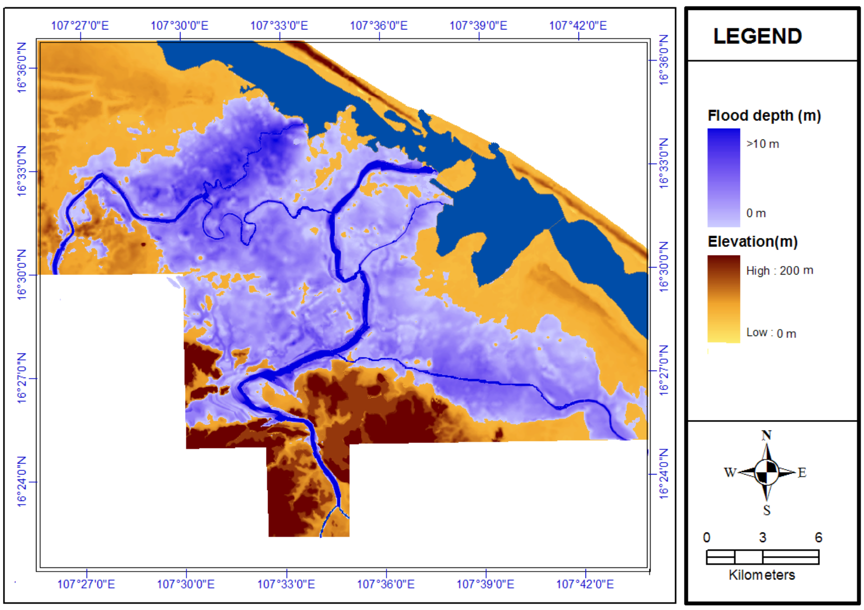

Figure 6. Predicted inundation map at 13:00 h on 12 November 2007, showing the extent of the inundation and resulting water depth (only the inundated part of the floodplain is shown).

4. Discussion

It is important to stress that validation of the model has been performed by splitting the observation data into a calibration period and an independent validation period. The calibration period consists of the 2002–2005 floods seasons in which some storms occurred but none which led to an important inundation of the floodplain. For the validation period consisting of the 2006–2007 floods seasons there were six major storms, one in 2006 and five in 2007, most of which were larger than any of the storms that occurred in the calibration period. The last storm (11–13 November 2007) was the largest storm recorded and resulted in severe inundation of the floodplain around Hue at the mount of the Huong River. Therefore, this test case mimics a real flood warning event, whereby after a large period of increasing but not catastrophic storms the effect of a sudden large critical storm needs to be forecasted accurately. The results shown in Figures 4–6 show that the combined hydrologic and hydraulic model performs well as it accurately reproduces all observed flows at the Binh Dien gauging station at the Huu Trach River and all water surface levels observed at the Phu Oc gauging station in the Huong floodplain for the 2007 flood season. In particular, the flash flood flows and water surface levels resulting from the largest storm (11–13 November 2007) are well predicted. Furthermore, the model enables prediction of the areal extent of the inundation and the resulting water depth in the floodplain as shown in Figure 6.

The validation criteria for the flows listed in Table 1 are fair, indicating that the hydrological model is capable of reproducing accurately flows in the upper sub-basins of the Huong River basin. The model bias criterion for Binh Dien station indicates that predicted flows for the 2007 flood season are on average one percent larger than the observations. However, this is not systematically so for peak flows. The second and fourth peak flow in Figure 4 are somewhat overestimated, whereas the other peak flows are accurately reproduced. Hence, the WetSpa model does not systematically underestimate peak flash flood flows, as is often the case with hydrological simulation models. The model bias can also be interpreted as a validation of the mass balance, because the model predicts how much rainfall is reduced after interception, retention, evaporation, and infiltration, and eventually results in runoff. Present results show that the model can simulate these processes accurately and produce runoff volumes within a reasonable error.

The values obtained for the Nash–Sutcliffe efficiency indicate that the model can reproduce about 70–90% of the variability observed in the hydrographs, which is also clearly noticeable in Figure 4 because all observed flows are closely matched by the model predictions. The Nash-Sutcliffe efficiency can also be statistically interpreted as the goodness of fit, R^2, which is the proportion of the variance of the observations that can be predicted by the model, so 1–NS is the lack of fit or proportion of the variance that is unexplained by the model, which relates to the variance of the residuals (simulation errors). The present results show that the model errors constitute only 10–30% of the overall variation observed in the data, which is an encouraging result. When examining predicted and observed data depicted in Figure 4, there is no particular period or occasion where flows are reproduced less accurately than in other periods, indicating that the model is robust and performs well for all circumstances. More important is the fact that for all stations and flood seasons, the modified Nash-Sutcliffe efficiency always appears to be greater than the ordinary Nash-Sutcliffe efficiency, implying that the model predicts large (peak) flows more accurately than other flows. This is a very encouraging property, especially for a model intended for use in forecasting of flood flows.

The validation criterions for predicted water surface levels listed in Table 2 are close to one, indicating that the hydraulic model reproduces water surface levels in the floodplain of the Huong River basin with high accuracy. The comparison between simulated and observed water levels depicted in Figure 5 shows that all observed water levels, low or high, are well reproduced. Also, the time instance at which a particular level is reached, in particular the alarm level of 3 m and the occurrence of peak levels, is accurately predicted by the model. Values obtained for the Nash-Sutcliffe efficiency indicate that the model can reproduce about 80–90% of the variability observed in the water levels. Also in this case, the modified Nash–Sutcliffe efficiency always appears to be greater than the ordinary

Nash-Sutcliffe efficiency, implying that the model predicts peak water levels on average more accurately than other water levels, which is of utmost importance for flood forecasting.

In the flood visualization map of the Huong River flood, shown in Figure 6, darker tones represent water depths up to 10 m, which evidently occur only in the river channels of the floodplain, while the lighter tones indicate water depths between 0 and 5 m, which occur in the inundation areas. The map clearly indicates that the inundation areas are mainly located along the main watercourses of the Huong River and Bo River around Hue. However, because there is no precise and detailed information available about the extent of the actual flooding and the resulting water depths in the floodplain, the predicted flood map cannot be verified in a qualitative way. Nevertheless, such flood visualization maps are important tools for portraying to community members and government agencies what can be expected in case of huge storms that lead to inundation in a floodplain. Moreover, such models can become essential parts of real-time flood forecasting systems to set off alarms in times of emergency and to reduce loss of lives and properties. However, real-time flood forecasting systems also require weather forecasts. Hence, operational rainfall forecasting models have to be developed in combination with flood forecasting systems to accurately transmit real-time information about flash flows and floods.

It is also well known that changes in land use and climate can have important effects on the generation of flash flows and floods. However, such effects were not considered in this study. Therefore, for future work an important part of research should be devoted to developing flood forecasting models that can deal with the complexities and interactions of climate and land use changes.

5. Conclusions

The spatial distributed hydrological model WetSpa was coupled with the hydraulic HEC-RAS model for simulation of inundation in the Huong River basin, located in central Vietnam. The WetSpa model predicted flood flows and was applied, calibrated, and validated for three upstream mountainous watersheds, for which topography, land use, and soil data are available in raster form. HEC-RAS model was applied in the downstream floodplain of the Huong River basin using discharge series predicted by the WetSpa model as the upstream boundary condition and tidal water levels as the downstream boundary condition, and the model was calibrated and verified with observed stage hydrographs in the floodplain by adjusting the Manning coefficients of the river reaches. The following conclusions can be drawn:

(1) Hydrographs were accurately predicted, with Nash-Sutcliffe efficiencies larger than 0.8. In particular, time of concentration and flow volumes of peak flows were well predicted.
(2) Simulation results show that water level predictions were generally in good agreement, with Nash-Sutcliffe efficiencies larger than 0.8. Peak flood levels and time of occurrence were well predicted.
(3) Inundation of the floodplain, visualized by three-dimensional (3D) graphical representation, shows that the model is suitable for predicting inundation and assessing flood risks.
(4) Coupling of hydrological and hydraulic models can form an important tool for the management of flood control and for real-time simulation of inundation in Vietnam to prevent or reduce damage in terms of lives, property, and infrastructure.
(5) The modeling approach can easily be applied in practice as only common basin characteristics that can be handled easily by standard GIS (Geographical Information System) tools are needed, so that effects of topography, soil type, and land use on flooding can be predicted.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/9/11/879/s1, Table S1: Calibrated parameters of the WetSpa model with 95% confidence intervals for the three upstream sub-catchments of the Huong River (for details about the WetSpa parameters, see [21]), Table S2: Calibrated Manning coefficients of the HEC-RAS model for the 11 river reaches of the Huong floodplain (for the location of the river reaches see Figure S1), Figure S1: Layout of the hydraulic model in the Huong floodplain, showing the eleven river reaches, three upstream end sections with inflow from the upstream sub-catchments, four downstream end sections with outflow to coastal lagoons, and location of the surveyed cross sections, Figure S2: Comparison between simulated and observed flow for the 2006 flood season at the Thuong Nhat gauging station at the Ta Trach river: (a) observed and simulated 6-hourly flow versus time; (b) scatter plot of observed versus simulated flow; (c) ranked observed and simulated flow, Figure S3: Comparison between simulated and observed flow for the 2007 flood season at the Thuong Nhat gauging station at the Ta Trach river: (a) observed and simulated 6-hourly flow versus time; (b) scatter plot of observed versus simulated flow; (c) ranked observed and simulated flow, Figure S4: Comparison between simulated and observed flow for the 2006 flood season at the Binh Dien gauging station at the Huu Trach River: (a) observed and simulated 6-hourly flow versus time; (b) scatter plot of observed versus simulated flow; (c) ranked observed and simulated flow, Figure S5: Comparison between simulated and observed flow for the 2007 flood season at the Binh Dien gauging station at the Huu Trach River: (a) observed and simulated 6-hourly flow versus time; (b) scatter plot of observed versus simulated flow; (c) ranked observed and simulated flow, Figure S6: Comparison between simulated and observed water surface level for the 2006 flood season at the Phu Oc gauging station at the Bo River: (a) observed and simulated 6-hourly water level versus time; (b) scatter plot of observed versus simulated water level; (c) ranked observed and simulated water level, Figure S7: Comparison between simulated and observed water surface level for the 2007 flood season at the Phu Oc gauging station at the Bo River: (a) observed and simulated 6-hourly water level versus time; (b) scatter plot of observed versus simulated water level; (c) ranked observed and simulated water level, Figure S8: Comparison between simulated and observed water surface level for the 2006 flood season at the Kim Long gauging station at the Huong River: (a) observed and simulated 6-hourly water level versus time; (b) scatter plot of observed versus simulated water level; (c) ranked observed and simulated water level, Figure S9: Comparison between simulated and observed water surface level for the 2007 flood season at the Kim Long gauging station at the Huong River: (a) observed and simulated 6-hourly water level versus time; (b) scatter plot of observed versus simulated water level; (c) ranked observed and simulated water level.

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