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Research Paper

Application of a two-dimensional model for flooding and floodplain simulation: Case study in Tra Khuc-Song Ve river in Vietnam

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ABSTRACT

In this paper, a GIS-integrated two-dimensional (2D) model namely Telemac-2D was used to construct floodplain maps of the study area. Firstly, the NAM model based on characteristics of the watershed, rainfall and evaporation data were used to provide initial boundary conditions for the Telemac-2D model along with other parameters. In turn, this Telemac-2D was integrated with Digital Elevation Map (DEM) in ArcGIS for floodplain mapping. The calibration and validation results for water level showed a high conformity about the phase and water amplitude between calculated and observed data in the years 2007, 2009 and 2013. A comparison between floodplain mapping and information from surveys showed relative consistency in 2009 and 2013 with a low error. The evaluation criteria of NSE, PBIAS, and RSR had a goodness-of-fit between the simulated and the observed values. Finally, this paper has given us an opportunity to understand the application capabilities of the Telemac-2D model and GIS in floodplain and flood inundation mapping and in the study area.

1. Introduction

Throughout the world, there has been increasing interest in river flood analysis and modeling due to extreme flood events in the last decades (Aronica et al., 2002; Nachtnebel, 2003; Van der Sande et al., 2003). Floodplain extent is considered as a major natural hazard worldwide and its estimation and forecasting are significant tasks for planners, environmental managers, and the insurance industry. River hydraulic models used for flood and floodplain simulation can be classified as the one-dimensional (1D) models (MIKE 11 (Doan et al., 2014; Doan and Quach, 2016), HEC-RAS (HEC, 2001)). Many studies on floodplain mapping have been conducted using 1D or 2D hydrodynamic models (Bates et al., 1997; Sinnakaudan et al., 2002) or the two-dimensional (2D) models (Telemac-2D (Catherine and Hervouet, 2006), RMA-2 (Donnell, 2001), TRIM2RD (USGS, 2003), LISFLOOD-FP (Bates and De Roo, 2000; Horritt and Bates, 2001), Delft-FLS (Klijn et al., 2007) and MIKE 21 (Doan et al., 2013, 2015). The 1D models accurately simulate the main river channels, however, they are not good at overbank flows especially for wave propagation modeling when river waters spread onto the floodplain. The 2D hydraulic models are the state of the art for the flood modeling in the rivers (Mason et al., 2002). However, the disadvantages of 2D models are time-consuming to set-up the model, requirements of large amount of data and computational facilities.

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The major river systems in Quang Ngai Province are Tra Khuc and Song Ve Rivers. The province is frequently affected by natural disasters such as heavy rain events, tropical depressions and typhoons, and floods. Normally, typhoons, tropical depressions, cold air and the combination of these phenomena cause heavy rain events and flooding in the river basins. As a consequence, they lead to huge loss of human life and widespread property damage. Quality of forecasting, flood and inundation warning currently have been improved in many river systems. However, forecasting surface water, surface elevation and inundation depths has always been a challenging problem for technical staff and hydrological forecasters. In this study, the Telemac-2D model was used to calculate, simulate and map floodplains and inundation risk in the study area. The input data for upstream and downstream boundaries was chosen for the years 2007, 2009 and 2013.

The objectives of this study are: (1) to calculate the flow processes by a hydrological model - NAM; (2) to simulate the hydro-dynamic regimes in the rivers by the Telemac 2D model; (3) to establish floodplains and inundation risk in the study area. A flowchart of the study procedure is presented in **Fig. 1**.

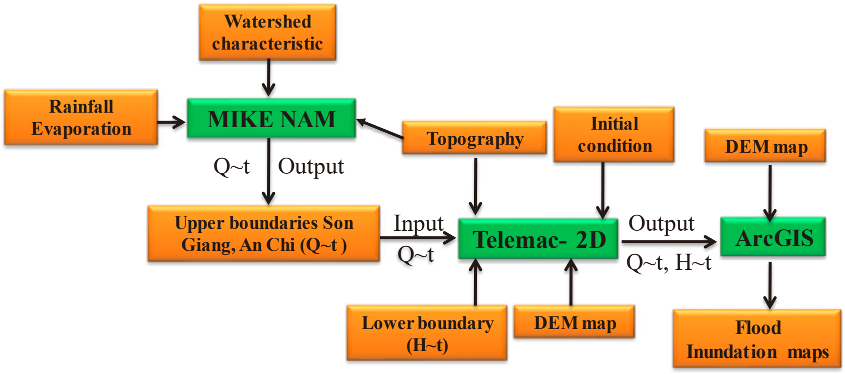

Fig. 1. Flowchart of study procedures.

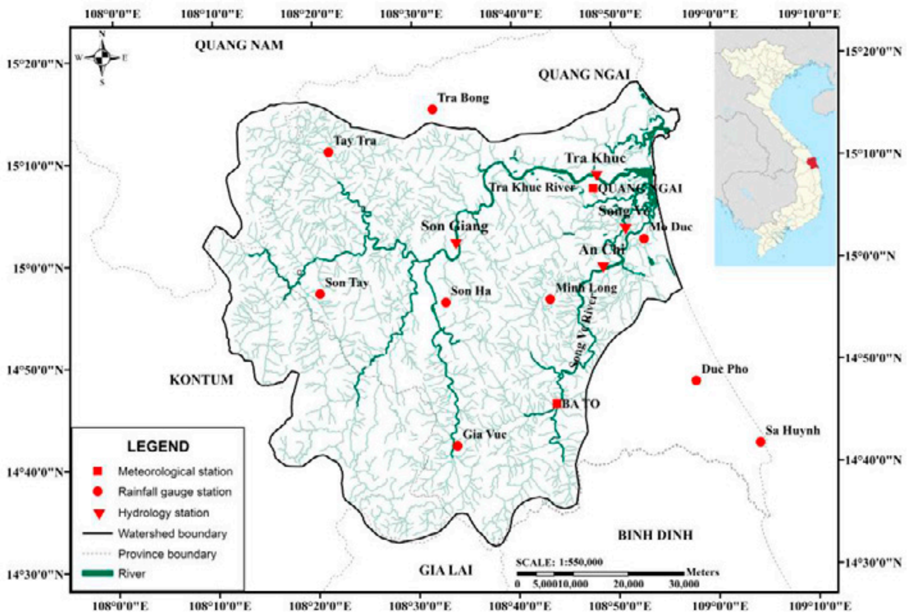

Fig. 2. Location of the study area.

2. Materials and methods

2.1 Description of study site

Tra Khuc River is one of the largest rivers in Quang Ngai Province with a catchment area of 3,240 km^2 (**Fig. 2**). The river has a steep terrain with a length of 135 km, of which the high mountains with an elevation of 200 - 1000 meters have been found in about one third of its length. About 1 million people live in the river basin, 87% of them are in rural areas. The annual flow of 70 l/s.km^2 is produced from heavy rainfall events in the upstream and it is shown that it is high in Vietnam (Nguyen, 2006). The 91 km-length of Ve River flows from the southwest to the northeast of the province, in which 2/3 of its length flows through a high mountain of 100-1000 m. The river network density in Ve River is 0.79 km/km^2 in a catchment area of 1,260 km^2 and an average elevation of 170 m. The characteristics of flood events in the main rivers are the short time of concentration, the floodwaters which rise rapidly, widespread flooding, that often cause difficulties in the response measures during flood events (Luong, 2011).

2.2 Data collection

In this study, the observed data in 2007, 2009 and 2013 were collected from meteorological stations at Tra Khuc-Song Ve catchment to calibrate and validate the rainfall-runoff process using conceptual NAM model. The meteorological stations provided 6-hourly rainfall and hourly evapotranspiration. Two hydrological stations namely Son Giang and An Chi in the upstream were applied in the calibration and validation. The output of NAM (water discharge at Son Giang and An Chi stations) were used as input data in Telemac-2D model. The flood event recorded in Tra Khuc and Song Ve hydrological stations in the period of November 2 to 11, 2007 were used for the calibration, whereas the flood events from September 28 to October 4, 2009 and November 15 to 18, 2013 were used for validation. The topographic map of Quang Ngai Province with the scale of 1:10000 and the DEM with the size 30x30 m was also collected to simulate and floodplains and inundation risk in this study.

2.3 Rainfall-runoff hydrological model

The NAM model is a part of the 1D river modeling system to simulate the rainfall-runoff process in sub-catchments (Havnø et al., 1995). This model has been applied to a number of catchments with different hydrological regimes and climatic conditions around the world. Arcelus (2001), Kjelstrom and Moffat (1981), Kjelstrom (1998), Fleming (1975), Shamsudin and Hashim (2002) and many other researchers have carried out rainfall-runoff modeling using the NAM model. It represents the various components of the rainfall-runoff process by continuously accounting for the water content in four different mutually interrelated storages where each storage represents different physical elements of the catchment. The nine most important parameters of the NAM model (shown in **Table 1**) are determined by the calibration process. An optimization algorithm was applied for the parameter calibration in NAM model.

Table 1. The nine most important parameters of the NAM model.

No.	Parameter	Unit	Description	Parameter range	Effects
1	U_{max} (mm)	Mm	Maximum water content in surface storage	5.76-20	Overland flow, infiltration, evapotranspiration, interflow
2	L_{max} (mm)	Mm	Maximum water content in lower zone/root storage	100-300	Overland flow, infiltration, evapotranspiration, base flow
3	C_{QOF}		Overland flow coefficient	0.1-1	Volume of overland flow and infiltration
4	T_{OF}		Interflow drainage constant	0-0.99	Drainage of surface storage as interflow
5	T_{IF}		Overland flow threshold	0-0.99	Soil moisture demand that must be satisfied for overland flow to occur
6	TG		Interflow threshold	0-0.99	Soil moisture demand that must be satisfied for groundwater recharge to occur
7	C_{KIF} (hours)	hours	Groundwater recharge threshold	200-1000	Routing overland flow along catchment slopes and channels
8	C_{K1K2} (hours)	hours	Time constant for overland flow and interflow routing	10-50	Routing interflow along catchment slopes
9	C_{KBF} (hours)	hours	Time constant for base flow	500-10000	Routing recharge through linear groundwater recharge

2.4 Description of Telemac-2D model

Telemac-2D is an ideal modeling framework for the rivers due to its finite element grids which allow graded mesh resolution (Hervouet, 2007). The 2D program solves the Saint-Venant or shallow water equations on triangular or quadrilateral elements, through the application of both conservations of mass and momentum equations. The main results give the water depth and the average vertical velocity at each point of the resolution mesh (Villaret and Hervouet, 2006). In many problems of the hydrodynamic simulation of the rivers, the flow varies slightly in the vertical direction and it can be realized that the equations in two dimensions can be considered to solve the problems. In fact, from Navier-Stokes (3D) to Saint-Venant (2D) it is assumed that vertical velocities are almost zero and the variables can be integrated vertically (Roche et al., 2012). The hydrodynamic models based on the full set of 2D Saint-Venant equations are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (h\nu)}{\partial y}=0 \quad (1)$$

$$\frac{\partial (hu)}{\partial t}+\frac{\partial \left(hu^2\right)}{\partial x}+\frac{\partial (hu\nu)}{\partial y}=-hg\frac{\partial Z_S}{\partial x}+\frac{\tau_{xx}}{\rho}+F_x \quad (2)$$

$$\frac{\partial (h\nu)}{\partial t}+\frac{\partial (hu\nu)}{\partial x}+\frac{\partial \left(h\nu^2\right)}{\partial y}=-gh\frac{\partial Z_S}{\partial y}+\frac{\tau_{yy}}{\rho}+F_y \quad (3)$$

3. Results and discussion

3.1 Rainfall-runoff hydrological model

3.1.1. Input data

The input data of the NAM model is hydro-meteorological data such as rainfall, evatranspiration and water discharge, which are also used for the calculation, calibration, and validation of the model. The data requirements for this model are 1-hour precipitation, 3-hour precipitatation, 6-hour precipitation or 12-hour precipitation at Son Tay, Son Giang, Tra Khuc, Song Ve, An Chi, Minh Long, Ba To and Gia Vuc stations (their locations are shown in Fig. 2); and average-6-hour evapotranspiration at the stations. The hourly flow data at Son Giang and An Chi stations were applied to calibrate and validate the model. The hydro-meteorological data used to calibrate the model was extracted from November 02 to 11, 2007, and was extracted from September 27 to October 04, 2009 and November 15 to 18, 2013 to validate the model.

3.1.2. Model evaluation statistics

In this study, model evaluation was used several quantitative statistics such as Nash-Sutcliffe efficiency (NSE), Percent bias (PBIAS) and RMSE-observations standard deviation ratio (RSR) in order to calculate and compare the observed and simulated water levels and stream-flows. The model evaluation performance ratings for each quantitative statistic are presented in Table 2. The model performance can be evaluated as “satisfactory” if NSE > 0.5 and RSR ≤ 0.7 and, for observed data of typical uncertainty, if PBIAS ± 25% for stream-flow. The recommended values for adequate model calibration are within the “good” and “very good” performance ratings presented in Table 2.

Table 2. Evaluation criteria for the quality indicators (Moriasii et al., 2007).

Performance Rating	RSR	NSE	PBIAS (%) Streamflow
Very good	0 ≤ RSR ≤ 0.5	0.75 < NSE ≤ 1	PBIAS < ± 10
Good	0.5 ≤ RSR ≤ 0.6	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15
Satisfactory	0.6 ≤ RSR ≤ 0.7	0.5 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25
Unsatisfactory	RSR > 0.7	NSE ≤ 0.5	PBIAS ≥ ±25

NSE, PBIAS and RSR are computed as shown in equation 4, 5, 6 as follows:

$$NSE = \frac{\sum_{i=1}^{n}\left(Q_i^{sim} - Q_i^{obs}\right)^2}{\sum_{i-1}^{n}\left(Q_i^{obs} - \overline{Q}\right)^2} \qquad (4)$$

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)x100}{\sum_{i=1}^{n}\left(Q_i^{obs}\right)} \qquad (5)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Q_i^{obs} - \overline{Q}\right)^2}} \qquad (6)$$

3.1.3. Calibration and validation of the hydrological model

The calibration results for two flood events show an agreement about the phase and vibration amplitude in 2007 at Son Giang and An Chi stations: Even though to achieve fitting among multiple peaks are relatively difficult, in this study the simulated values of two peak floods during November 02-11, 2007 show a good consistent with their measured ones (**Fig. 3**). For example, at An Chi station in 2007 the simulated peak discharge value is 14.1m^3/s smaller than the observed value with a maximum error of 1% and at Son Giang station in 2007; the simulated peak discharge value is 116m^3/s smaller than the observed with a maximum error 1.7% (**Table 3**). It is clear that in calibration process in both stations, the calculated and observed peak discharge error is smaller than 2%.

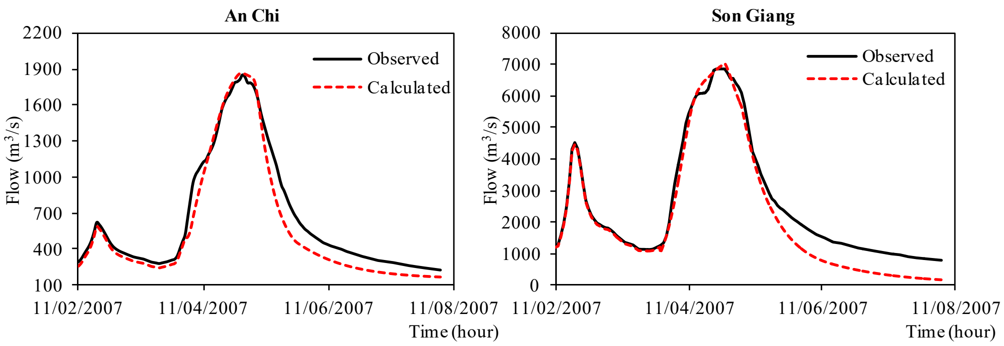

Fig. 3. Calibration of streamflow at An Chi and Son Giang stations in 2007.

The validation results of the flood events at the Son Giang and An Chi stations from September 27 to October 04, 2009 and November 15 to 18, 2013 illustrate a good agreement between the calculated and observed values with a little discrepancy (**Fig. 4**). For instance, the simulated peak discharge value is smaller than the observed one at An Chi station with a maximum peak discharge error of 2.58%; by contrast, the simulated peak discharge value is larger than the observed one at Son Giang station with the maximum peak discharge error about 2.88%.

The Nash-Sutcliffe efficiency (NSE) is calculated to evaluate the percentage of accuracy or goodness of the simulated values with respect to their observed values. The NSE values equal to 1 indicates the best (perfect) performance of the model (Nash and Sutcliffe, 1970). NSE values for the stream-flow calibration and validation ranged from 0.83 to 0.94. The simulation of stream-flow by using NAM model has good results which are absolutely appropriate to graphical results. The values of RSR are represented with varying degrees from 0.11 to 0.29 in calibration and validation respectively. These values demonstrate that the model's performance in the calculation of the streamflow residual variation obtained qualified success. In the meantime, PBIAS ranges from 1.31% to 2.2% for calibration and from -5.62% to 8.6% for validation (**Table 3**). Average scale of stream-flow simulation indicators is produced in a sterling selection (PBIAS < ± 10) in both calibration and validation. The parameters of NAM model in calibration and validation are displayed in **Table 4**. The simulation of NAM model for stream-flow was relevant to the tendency of NSE, RSR, and PBIAS.

Table 3. The results of streamflow calibration and validation of NAM model.

Test	Flood events	River	Station	NSE	RSR	PBIAS %	ΔQ_{max} (m^3/s)	ΔQ_{max} %
Calibration	02-11/11/2007	Ve	An Chi	0.83	0.11	1.31	-14.1	-0.76
		Tra Khuc	Son Giang	0.9	0.22	2.2	-116	-1.7
Validation	28/09 - 04/10/2009	Ve	An Chi	0.9	0.14	-5.62	-54.6	-2.58
		Tra Khuc	Son Giang	0.92	0.017	0.12	127	1.2
	15-18/11/2013	Ve	An Chi	0.89	0.27	7.04	-62.2	-1.95
		Tra Khuc	Son Giang	0.94	0.29	8.6	271	2.88

Table 4. The calibrated and validated parameters of the NAM model.

Sub-basin	U_{max} (mm)	L_{max} (mm)	C_{QOF}	C_{KIF} (hour)	C_{K1K2} (hour)	T_{OF}	T_{IF}	TG	C_{KBF} (hour)
BASIN1	11	100	0.88	797	14	0.1	0.2	0	2000
BASIN2	12	102	0.87	717	13	0.1	0.2	0	2000
BASIN3	10	100	0.99	650	10	0.12	0.1	0	2000
BASIN4	10	100	0.85	720	10	0.15	0.15	0	2000
BASIN5	10	100	0.85	600	10	0.2	0.15	0	2000
BASIN6	17	170	0.85	950	13	0.02	0.09	0	2000
BASIN7	20	200	0.85	980	13	0.03	0.09	0.01	2000
BASIN8	20	200	0.82	950	15	0.03	0.07	0.01	2100
BASIN9	10	102	0.87	640	15	0.1	0.15	0.01	2100
BASIN10	10	105	0.87	580	14	0.1	0.1	0.01	2100
BASIN11	10	100	0.85	600	10	0.15	0.1	0.01	2100

3.2 Telemac-2D model

3.2.1. Topography data

The topographic data (DEM, the slope map) was collected from data released in 2013 by the Ministry of Agriculture and Rural Development. The digital elevation model was established from assembling the topographic maps 1:10000 where the contours were identified with relatively high accuracy. The definition of the geometry of river channels is a fundamental step. The river topography and hydraulic structures have a major impact on the simulated results. In 2D models, the meshes provide the detailed information about the topography of the bed and bottom of the rivers. Thus, the more accurate data is, the closer to the reality of model estimation. In addition, the meshes are refined at the rivers' bed and bottom. It is therefore considering triangular meshes of about 10m to obtain maximum accuracy in the results. Then, we impose a lighter mesh of about 50m in the major bed, while to the rest of the field we impose a criterion of

200m. Finally, we get a geometry file for simulation in Telemac-2D model containing 51,058 nodes (**Fig. 5**). Figure 5 shows the uniformity in the cross-sections of the rivers, as shown in artificial waterways. The bathymetry mesh for the river channel is built from spatially interpolating from DEM and the slope map. The spatial interpolation of cross-section data affects the accuracy of two-dimensional hydraulic models significantly. Blue-Kenue, which is commonly used to generate the mesh and analyze simulation results for Telemac-2D, is an isotropic mesh generator. However, anisotropic interpolation methods are more appropriate than isotropic methods for generating the bathymetry of the river channels, especially in meandering rivers. Therefore, this paper has applied an approach combining an anisotropic interpolation method and Blue-Kenue for generating the bathymetry mesh in the study site.

3.2.2. Initial and Boundary conditions

Initial conditions which can be discharge or water level represent the state of the model at the start of the simulation. In this study, the computation commences from quiescent initial conditions. The initial water level in the model domain is that of the downstream outlet. The accuracy (tolerance) between two-time steps was set to 0.001 at all nodes for all variables (u, v and h). The computation continued until a steady state is reached throughout the model domain.

MATISSE (MATISSE is part of a processing sequence, namely the TELEMAC system) is used to build the grid of triangular elements. There are two types of boundaries in the computational domain, namely walls (solid boundaries) and open (liquid) boundaries. The types of boundary conditions used in the current modeling study were:

Imposed flow rate at the upstream boundary: A flow value is prescribed at the inlet of the channel. To accelerate the achievement of quasi-steady state conditions, a gradual (stepwise) increment of discharge (Q) with time is introduced in equation 7 as:

$$Q = \frac{t}{3600} Q_{ref} \text{ for } 0 < t \leq 3600;\ Q = Q_{ref} \text{ for } t > 3600 \quad (7)$$

Water level at the downstream boundary: In order to achieve and maintain the steady state condition in the channel, the water level at the downstream end (outlet) of the channel is used throughout the model computation.

3.2.3. Calibration and validation of the Telemac-2D model

Telemac-2D model is calibrated in order to determine the variations of hydraulic parameters during the flood events. The calibration model is calculated based on the observed data in the flood event during November 02-11, 2007. Validation model uses the water level data at Tra Khuc and Song Ve stations during September 29 to October 01, 2009 and November 15 to 18, 2013. The results of calculated and observed water level at two stations Tra Khuc and Song Ve are in good agreement with vibration amplitude, absolute value and the tide phases both for calibration and validation (**Fig. 6 and Fig. 7**). Graphical results for calibration and validation indicate adequate calibration and validation over the range of stream-flow, although the calibration results show a better match than the validation results. NSE values for the water level calibration and validation ranges from 0.9 to 0.96. The simulation of Telemac-2D model perfectly analyzes the direction of stream-flow as it can be seen in the statistics which are pertinent to graphical results. RSR values represent a wide range of value running from 0.13 to 0.32 < 0.5 in both calibration and validation. The values prove that the model functions stream-flow residual variations in an effective way. The PBIAS values, on the other hand, vary from -4.51% to -3.21% for calibration and from -8.37% to -1.42% for validation (**Table 5**). The average scale of stream flow simulation indicators was produced in a sterling selection (PBIAS < ± 10) in both calibration and validation. The simulation of Telemac-2D model for stream flow was relevant to the tendency of NSE, RSR, and PBIAS. The parameters of Telemac-2D model in calibration and validation are shown in **Table 6**. The trial-and-error method is utilized to determine the optimal parameters. The final parameters in the calibration process are used in the validation model process. The calibration results of Telemac-2D model show that the model could be utilized to calculate and simulate well with the floodplain problem in the study area. Figure 8 shows the floodplain water depths (**Fig. 8a**) and bottom elevation (**Fig. 8b**) in the study site. The calculated results from the model show that the flow regime in this study site is not complicated.

Table 5. The results of calibration and validation of Telemac-2D model.

Test	Flood events	River	Station	NSE	RSR	PBIAS	H_{max} (cm)	ΔH (cm)
Calibration	02-11/11/2007	Ve	An Chi	0.96	0.2	-3.21	512	-2
		Tra Khuc	Son Giang	0.92	0.28	-4.51	731	9
Validation	29/09/2009 - 01/10/2009	Ve	An Chi	0.95	0.17	-3.05	528	-9
		Tra Khuc	Son Giang	0.91	0.15	-1.42	811	-1
	15-18/11/2013	Ve	An Chi	0.94	0.13	-2.46	612	-9
		Tra Khuc	Son Giang	0.9	0.32	-8.37	867	-9

Table 6. The parameters of the Telemac-2D model.

Parameters	2007	2009	Final parameters
Bottom Smoothing	1	1	1
Friction Coefficient	1.53	1.25	0.94
Implicitation for Depth	0.35	0.44	0.39
Implicitation for Velocity	0.28	0.42	0.35
Maximum Number of Iterations for Solver	1000	1000	1000
Solver Accuracy	0.001	0.001	0.001

The achieved results in the validation model show that the flow distribution in the basin is quite consistent with reality. The computational simulation shows an overall picture of the flooding situation in the study area. The calculated results of the model are the basis for the analysis and assessment of the flood events in the past and establishment of the inundation scenarios.

3.2.4. Establishing inundation maps

To map floodplain for the study area, the analytical tools and map editor in ArcGIS software are used. Floodplain mapping is made based on the output results of the Telemac-2D model in the validation and simulation for two flood events in 2009 and 2013. The scenarios for developing inundation maps used water level at the control stations are analyzed, calculated, calibrated and validated by Telemac-2D model. The results of floodplain mapping are calculated from the Telemac-2D model combined with the GIS analysis technology to construct the layers of the floodplain use the water depths at the main stations to support the database for the inundation risk technology. A comparison between the calculated floodplain map and historical floodplain map recorded by surveys are relatively consistent in 2009 (**Figs. 9a and 9b**). An average error of the flood trace elevation is 0.3m. The maximum error of the flood trace elevation is 0.5m. The maximum floodplain area error at the elevation of 4m is 7.3 percent. The minimum floodplain area error at the elevation of 2 m is 1.3 percent (**Table 7**). Based on the results of calculated and validated the flood event in 2009, inundation maps continue to be constructed for the flood event during October 17-18, 2013 (**Figs. 10a and 10b**). An average error of the trace flood elevation is 0.4m. The maximum error of the trace flood elevation is 0.6m. The development of inundation risk maps plays an important role in planning and management, which is to support for plans of response and displacement/evacuation before and during severe flood events in history.

Table 7. A comparison between the calculated floodplain region and survey floodplain region in 2009.

Depth (m)	Inundation area (ha)		Error (%)
	Simulation	Survey	
	2009		
1m	3459	3606	-4.1
2m	1712	1734	-1.3
3m	872.8	931	-6.3
4m	38	41	-7.3

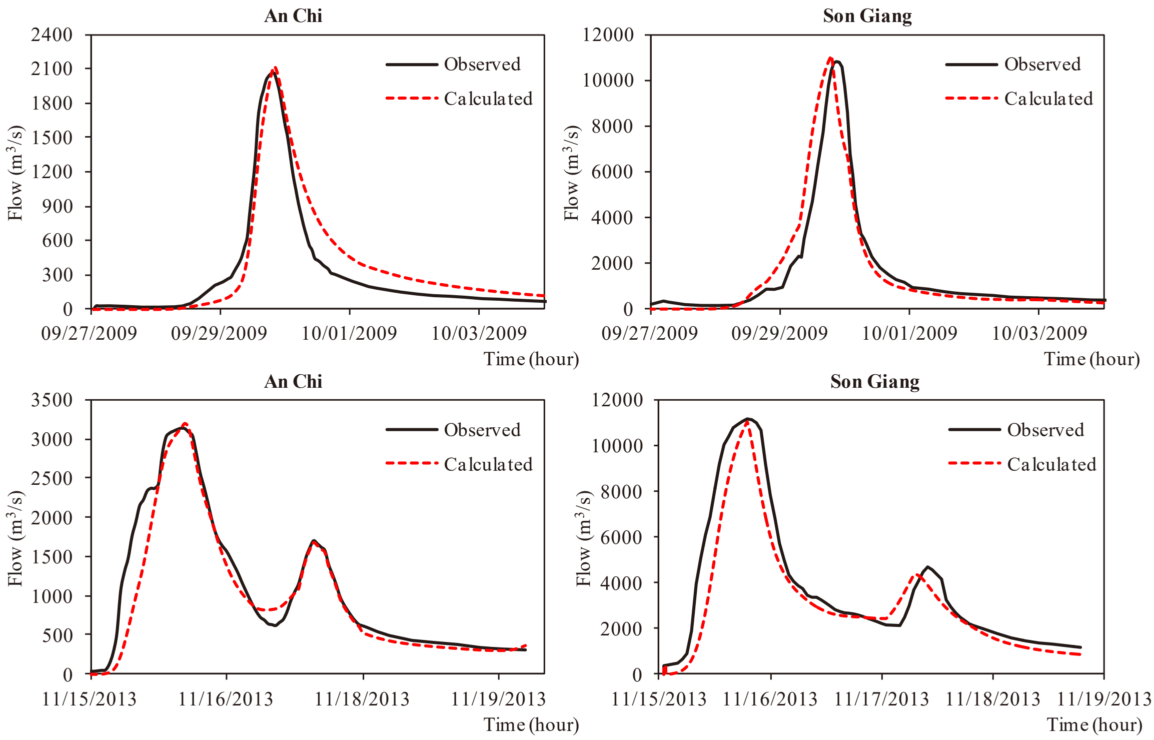

Fig. 4. Validation of stream flow at An Chi and Son Giang stations in 2009 and 2013.

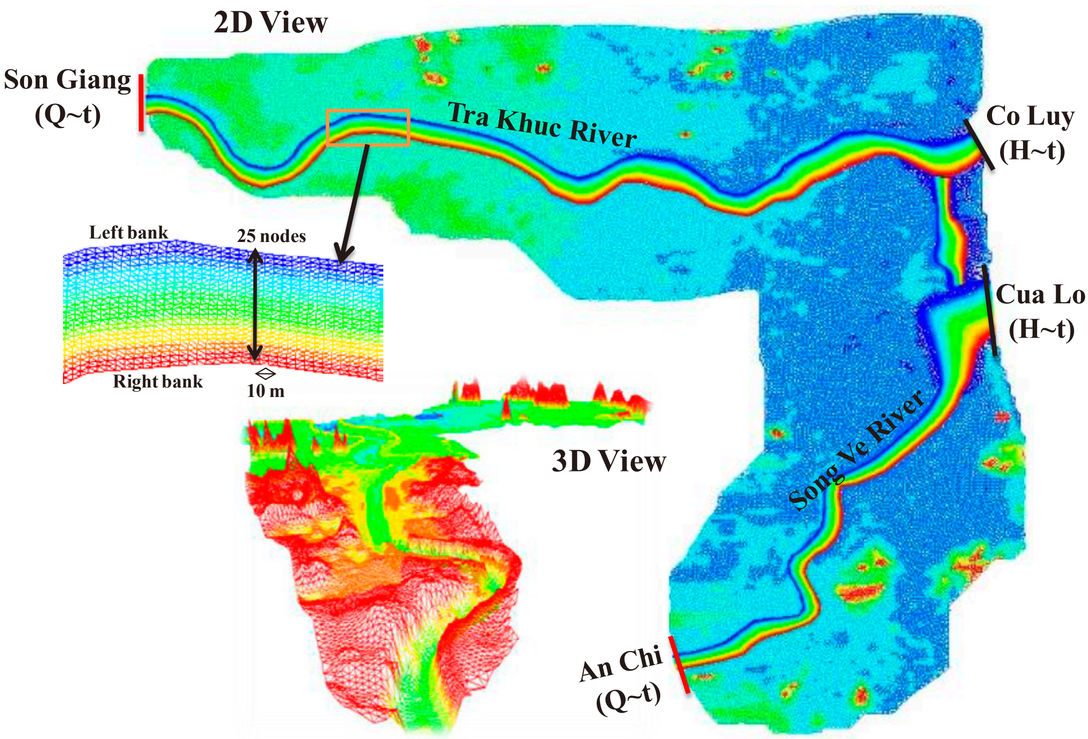

Fig. 5. Bathymetry mesh 2D, 3D in BlueKenue.

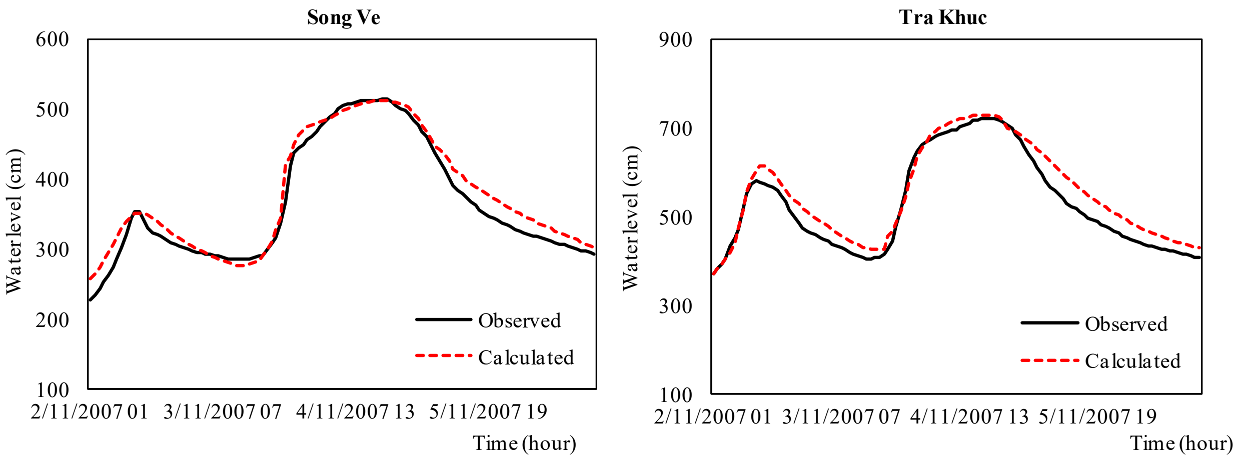

Fig. 6. Calibration of water level at Song Ve and Tra Khuc stations in 2007.

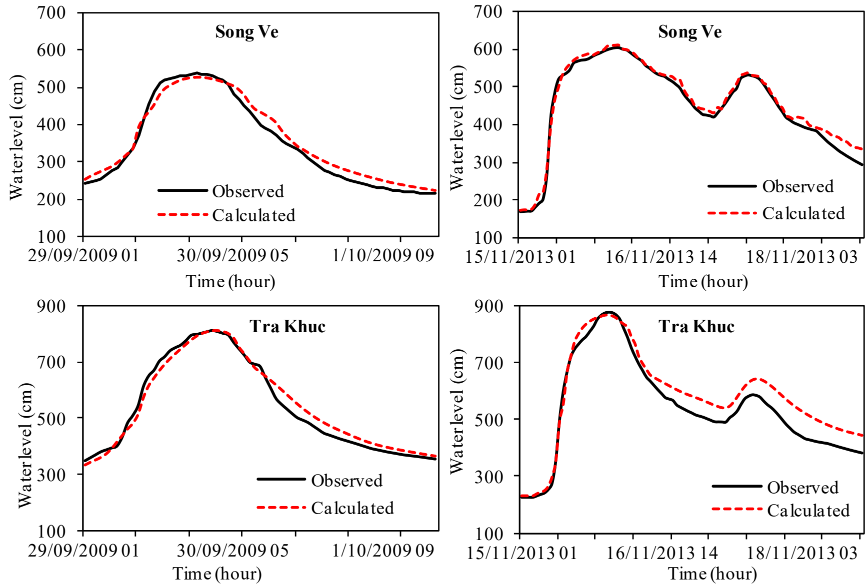

Fig. 7. Validation of water level at Song Ve and Tra Khuc station in 2009 and 2013.

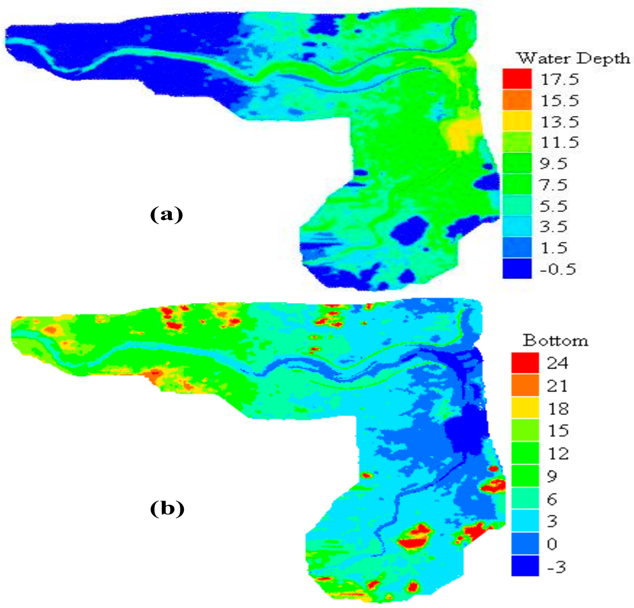

Fig. 8. Results of the Telemac-2D model in 2007: (a) Water depth (m), (b) Bottom elevation (m).

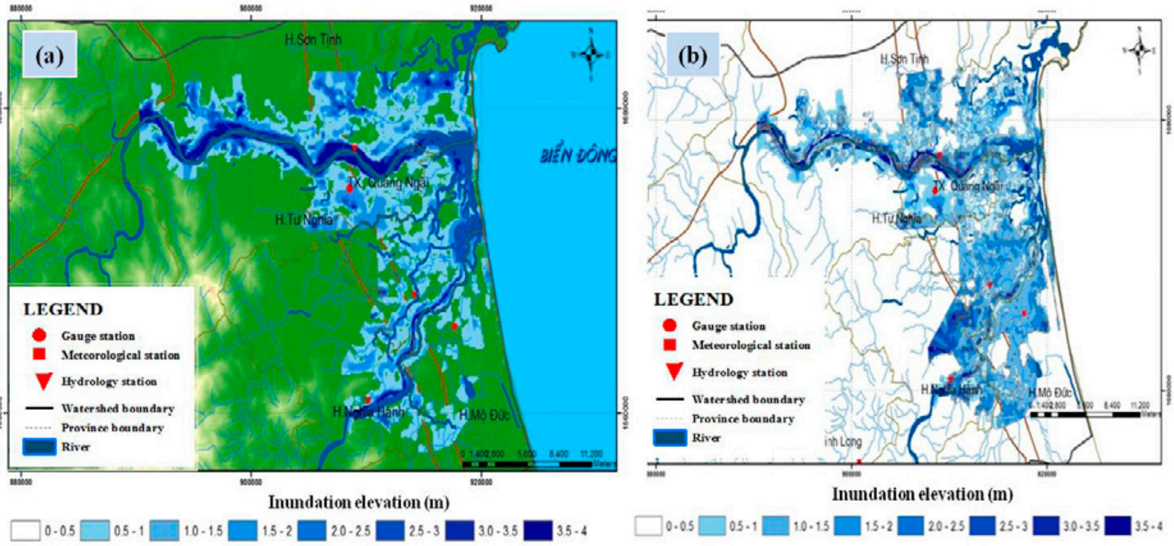

Fig. 9. (a) Calculated floodplain map, (b) Survey floodplain map during September 29 to October 01, 2009.

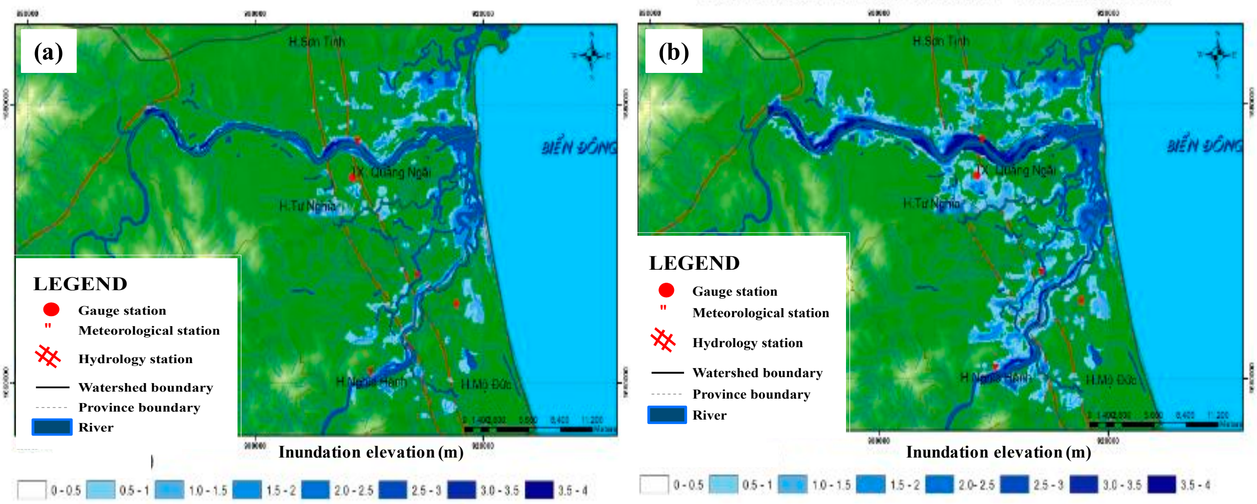

Fig. 10. The floodplain warning maps: (a) at 7 am on October 17, 2013; (b) at 7 am on October 18, 2013.

4. Conclusion

In this study, inundation maps and inundation risk maps are calculated and established in the Tra Khuc-Song Ve river catchment in Quang Ngai Province, Viet Nam. The hydrological model-NAM is successfully used to calculate the flow discharge at two hydrological stations namely Son Giang and An Chi. The results of calibration and validation have high agreement between the calculated and observed flow data in 2007, 2009 and 2013. The NSE, RSR and PBIAS statistics have a goodness-of-fit of the simulated values with their observed values. Thus, the hydrological model can simulate the stream-flow well and therefore, be a high-secured input data for the Telemac-2D model.

Telemac-2D model is successfully applied to calculate and simulate hydraulic regimes in the study area. The results of the calibration and validation model show a high conformity between the calculated and observed water level at Tra Khuc and Song Ve stations about the phase and amplitude in 2007, 2009 and 2013. The inundation maps were established based on the combination of the results of Telemac-2D model with the GIS analysis technology in the study area. The comparison between the calculated inundation map and historical inundation map recorded by surveys are relatively consistent in 2009 with a low error. The establishment of inundation risk maps plays an important role in planning and management in 2013. Finally, this paper has given us an opportunity to understand the application capabilities of the Telemac-2D model and GIS in the construction of inundation maps in the study area. The study results showed that the reliability and application of the Telemac-2D model in other watersheds in Viet Nam.

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Symbols and abbreviations

t	The time in seconds (s)
x,y	The Cartesian coordinates (m)
h	The water depth (m)
u, v	The depth-averaged flow velocities in x and y directions (m/s)
z_s	The water surface elevation
g	The gravitational acceleration (m/s^2)
ρ	The water density (g/m^3)
T_{xx}, T_{yy}	The depth-averaged turbulent stresses
F_x, F_y	The Coriolis forces
Q_i^{sim}	The ith simulated value for the constituent being evaluated
Q_i^{obs}	The ith observation for the constituent being evaluated
$\overline{Q}$	The mean of observed data for the constituent being evaluated
n	The total number of observations
Q	The flow value (m^3/s)
Q_{ref}	The flow value at the upstream boundary (m^3/s)