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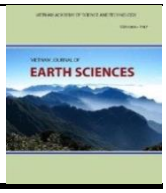

Combination of hydrologic and hydraulic modeling on flood and inundation warning: case study at Tra Khuc-Ve River basin in Vietnam

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ABSTRACT

Flooding caused by historically high flows, especially in Tra Khuc-Ve River basin in the Mid-Central region in Vietnam in November 2013, which caused widespread damage. The purpose of this paper was to establish the inundation maps in the downstream part of Tra Khuc-Ve rivers by using the coupling of the hydrological and hydraulic models (MIKE SHE/MIKE 11 and MIKE 11 GIS). Calibration and validation of the hydrological model were in good agreement in terms of the vibration amplitude, absolute value, and phases. The hydraulic model results showed good agreement between observed and simulated flood events in 2012 and 2013 after calibration and validation. The rainfall forecasting from the IFS model was also used to establish six flood warning scenarios based on the alarm level III (6.5 m) and the historical level (8.76 m). The inundation maps showed the extent of flooding and the water depth in the downstream part of the study area. The simulation results of historical data showed that Tu Nghia and Son Tinh Districts were the most affected areas by inundation with over 11% affected area while Quang Ngai Town inundated 8.1%. The study results will support decision makers in planning to reduce the impacts of natural disasters in Tra Khuc-Ve River basin in the future.

Keywords: MIKE SHE/MIKE 11 and MIKE 11 GIS; Flood and Inundation warning; Tra Khuc-Ve River basin.

1. Introduction

Floods are one of the natural disasters which cause a great impact on human activities. Besides, its frequency has been increasing during the last few years. Flood forecasting and warning in the Mid-Central region, especially in Tra Khuc-Ve river basins has been taken into consideration in many studies (Luong, 2011; Nguyen et al., 2018; Tran et al., 2018). Tra Khuc river is the biggest river in Quang Ngai Province originated from the high mountain ranges of Truong Son Nam in Kon Tum Province. It flows through Quang Ngai commune and pours into Cua Dai (Fig. 1).

40 km of the river flows through the lower coastal plain in comparison to 135 km in length and 3240 km^2 in total. The natural features of the Tra Khuc river are mainly affected by topographic conditions of the basin. The upstream is featured by mountain slope, as a

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result of big flow coefficient and rapid speed. Floods in Tra Khuc river often occur unexpectedly, with the amplitude ranging of 3–5 m and have a short duration (approximately 1 day on average). Flood intensity is usually 30–40 cm per hour, the maximum value was recorded of 78 cm per hour.

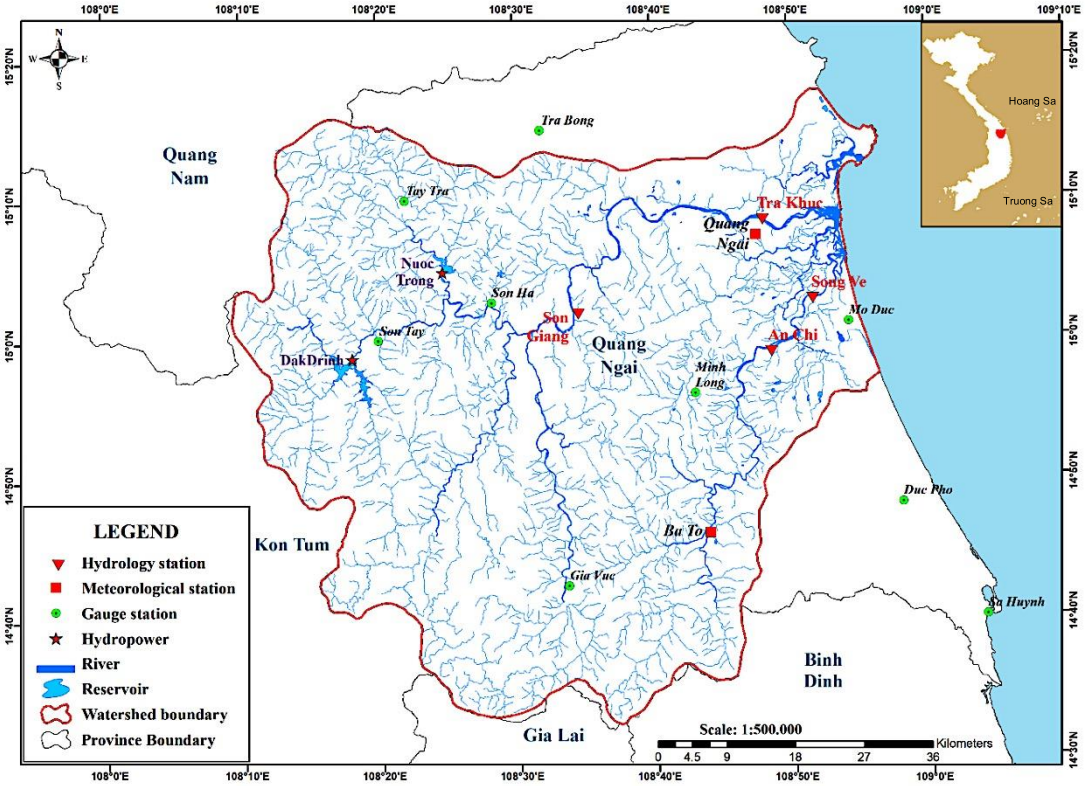


Figure 1. Map of study area

Floods are considered to be one of the major natural disasters in Tra Khuc-Ve River. Tra Khuc-Ve river basins have recorded many flood events in 2012, 2013, 2015, and 2016. November 2013 was the historical flood event since 1977. Many mathematical models have been developed for flood plain delineation, flood inundation mapping and flood simulation (Mason et al., 2002; Jaber and Shukla, 2005; Adib et al., 2011; Boonrawd and Jothityangkoon, 2018; Quan et al., 2018). The numerical models using one-dimensional (1D) approximation were commonly based on the finite difference method (Cunge et al., 1980; Chaudhry, 2007) and the finite element method (Nwaogazie and Tyagi, 1984; Szymkiewicz, 1991; Sen and Garg, 1998). Commercially available software packages like DWOPER, FLDWAV, MIKE-11, ISIS, SOBEK (1D) have been used extensively for dynamic 1D flow simulation in rivers (Kuntiyawichai et al., 2011; Doan, 2016). However, one-dimensional models fail to provide comprehensive information about the extent of flooding. In fact, there were many previous studies applying for combined MIKE SHE, MIKE 11, and MIKE 11 GIS models with some catchments in Vietnam but there were no studies at Tra Khuc-Ve River basin (Kameyama et al., 2013; Vo and Gourbesville, 2014; 2016). Nowadays, Tran et al. (2019) studied and applied the rainfall forecasting from IFS model input the hydrological model (MIKE SHE) to simulate

and predict the inflow in two reservoirs DakDrinh and Nuoc Trong at Tra Khuc-Ve River catchment. The study results will be an effective tool for forecasters in the reservoir forecasting in the future. The previous study results (Tran et al., 2019) will be input in 1D hydraulic (MIKE 11) and MIKE 11 GIS models to simulate and warn the flood and inundation in downstream areas at Tra Khuc-Ve River catchment. Therefore, the objective of the study is to simulate and calculate to establishing the flood and inundation maps with the scenarios of different flood levels by application of the numerical models MIKE SHE, MIKE 11 and MIKE 11 GIS.

2. Data and Method

The structure of how to establish the flood and inundation maps in the study area is presented in Fig. 2.

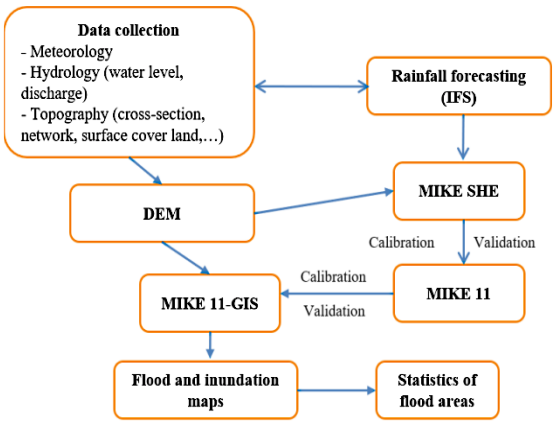


Figure 2. Flowchart of producing flood and inundation maps in study site

2.1. Data requirements

Input data for the models are basin boundary, topographic, rainfall (observed rainfall data were taken from the hydro-meteorological stations and rainfall forecasting data from IFS model). Rainfall forecasting from the IFS model supported by the Remote-Sensing, the office of National Center for Hydrometeorological Forecasting (NCHMF). This product is purchased annually according to the cooperation between the NCHMF with the European Centre for Medium-Range Weather Forecasts (ECMWF) from 2012. IFS product with the prediction data from 51 components of combinatorial forecasting system with the highest resolution in both space and time (Spatial resolution: 0.125° × 0.125° latitude; Time resolution: 03 hours for the first 5 days and 06 hours from the next 5 to 10 days). Various modules (MIKE SHE, MIKE 11 and MIKE 11 GIS) are used to diversify the data (Table 1). The topographic map of the study area is in the size of 12.5 m × 12.5 m grid resolution (https://vertex.daac.asf.alaska.edu/). This resolution is sufficient for the hydrological modeling MIKE SHE and MIKE 11 GIS. The 6 hourly rainfall in October 2012 and October 2013 at hydrometeorological stations are used to calibrate and validate models. Rainfall forecasting from the IFS model is used for flood forecasting and warning the historical flood event in November 2013. The 6-hourly water discharge at two stations namely Son Giang and An Chi is used for MIKE SHE calibration and validation. Furthermore, for calibrating and validating the hydraulic model (MIKE 11 HD) used the 6-hourly water level at two stations Tra Khuc and Song Ve.

Table 1. Data requirements for the models

Module	Data requirements
Overland flow	Manning's roughness coefficient, Detention storage, Initial water depth, Rainfall, DEM, Land use
River flow	River network data, river cross-sectional data, water level, discharge
Unsaturated Zone Flow	Soil map, Soil physical properties: Hydraulic conductivities, Water contents at saturation, Field capacity and wilting points
Saturated Zone Flow	Storage coefficient, Specific yields, Hydraulic conductivities
Evapotranspiration	Evaporation, Crop coefficients, Leaf area index (LAI), Rooting depth (RD)

2.2. Description of MIKE SHE model

The MIKE SHE model is a deterministic, fully distributed and physically-based model that allows for the simulation of the major processes occurring in the land phase of the hydrologic cycle (Refsgaard and Storm, 1995; DHI, 2004). It is a computationally intensive model simulating surface, subsurface, and streamflow separately for distributed grid points using numerical solutions of partial differential equations. The model allows using of spatially varying climate variables, vegetation, soil properties, and land uses. MIKE SHE has a module structure consisting of several modules such as the Water Movement (WM) module, Advection/Dispersion of Solutes (AD) module, and Soil Erosion (SE) module, and other modules (Fig. 3).

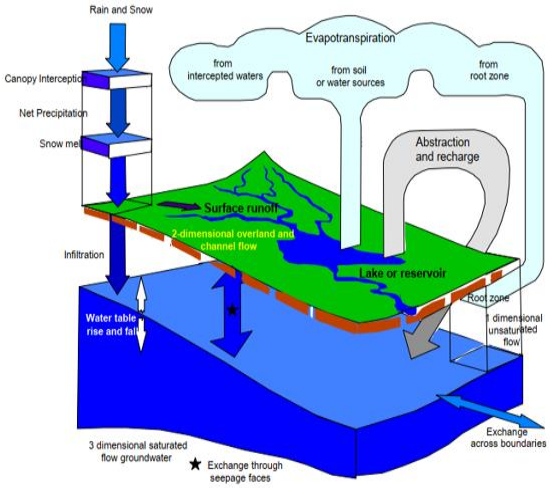


Figure 3. MIKE SHE conceptual hydrological model (Danish Hydraulic Institute, 1994)

2.3. Description of MIKE 11 and MIKE 11 GIS

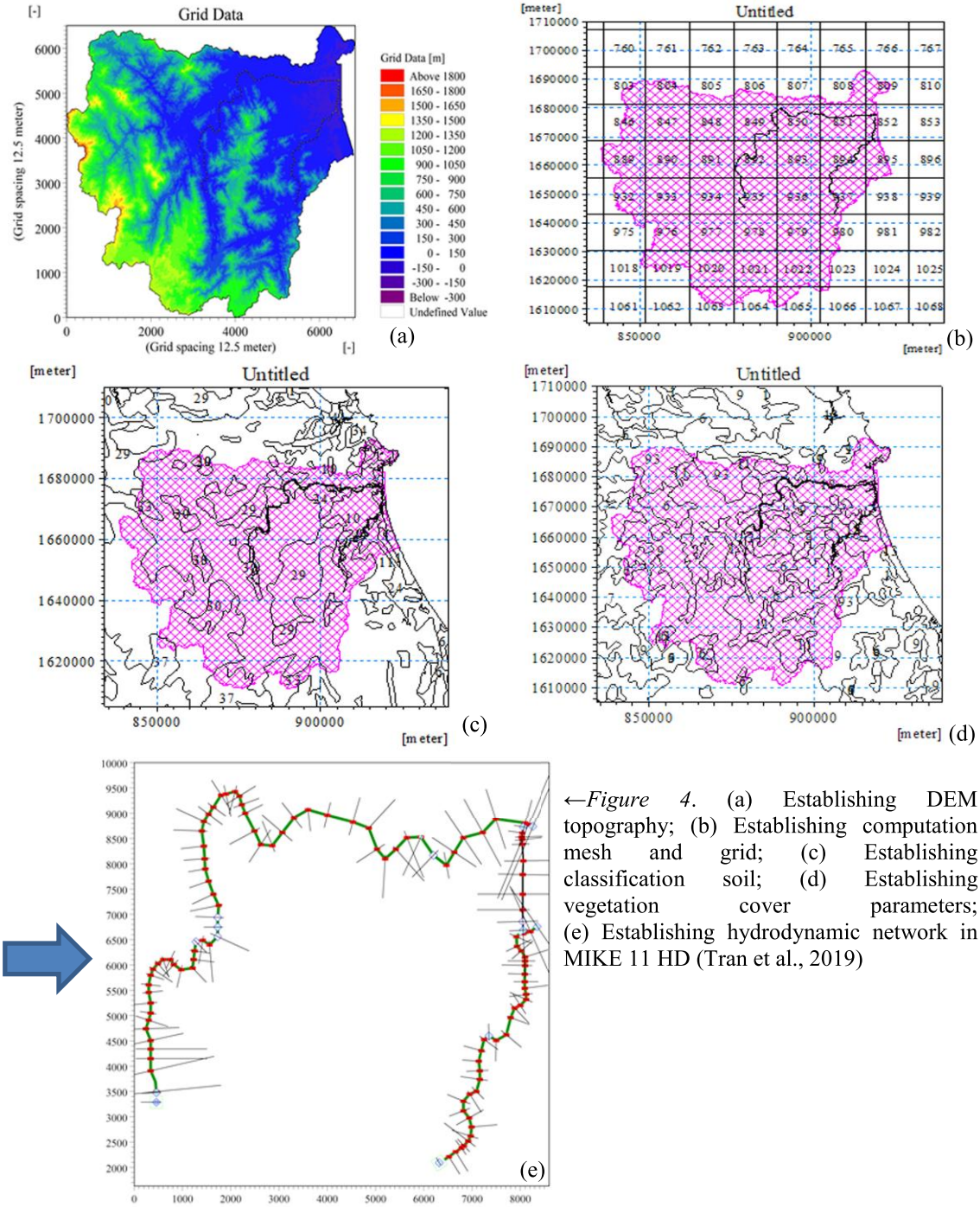
MIKE 11 model is a dynamic, one-dimensional modeling tool for the design, management, and operation of complex river systems. This software has four editors (simulation, river network, cross sections, and boundary conditions) and various modules hydrodynamic (HD), the Advection Dispersion (AD), Water Quality (WQ), runoff and rainfall, sediment transfer, and flood forecasting (DHI, 2007). One-dimensional equations governing the river flow are known as Saint-Venant equations (Shooshtari, 2008).

MIKE 11 GIS is based on the microcomputer modeling system for rivers and channels that has been developed by the Danish Hydraulic Institute (DHI) since 1972. The MIKE 11 GIS appears as a spatial oriented modeling system. The implementation of the hydrodynamic model in the GIS ArcView interface developed by Environmental Systems Research Institute (ESRI) has the potential to assist in clarifying and disseminating information through an enhanced mapping of the impacts on flood levels and the environment (DHI, 1997). The GIS technology is used to produce flood maps and to perform multi-sectoral analyses. Flood depths and levels are represented as layers of data in the GIS which can be geographically related and analyzed with data from other flood management components.

2.4. Model setup

The topography of Tra Khuc-Ve River basin area is processed from DEM by the support tool of ArcGIS 10.0. MIKE SHE model allows receiving the data with .dfs2 grid data, line shape/point shape (Fig. 4a). The computation mesh of the study site is delineated by the boundary for the whole region (Fig. 4b). Processing and integrating rainfall data into the model is carried out through the pre-processing process to create .dfs2 file as input for MIKE SHE model (Fig. 4c). Vegetation cover map is processed from the national vegetation cover map (Fig. 4d). Establishing the hydraulic network in MIKE 11 HD model is shown in Fig. 4e. Total cross-sections in the hydraulic network are 107 cross-sections with two main rivers Tra Khuc

River (68 cross-sections), Ve River (38 cross-sections), and a tributary Phu Nghia River (11 cross-sections). River discharge at upstream boundaries used at Son Giang and An Chi stations. The water level at the downstream boundary used the calculation water level at Co Luy station. The manning (n) coefficient varied from 0.1 to 0.35 in each river.



←*Figure 4*. (a) Establishing DEM topography; (b) Establishing computation mesh and grid; (c) Establishing classification soil; (d) Establishing vegetation cover parameters; (e) Establishing hydrodynamic network in MIKE 11 HD (Tran et al., 2019)

3. Results and discussion

3.1. Calibration and validation of MIKE SHE model

Calibration and validation of MIKE SHE model used two flood events in October 2012 and October 2013 at two hydrological stations Son Giang and An Chi (Fig. 5). Validation is very important using evaluation indicators in order to evaluate the ability of the models, (Bathurst et al., 2004; Jakeman et al., 2006; Moriasi and Wilson, 2012). In this study, Nash-Sutcliffe efficient (NSE) (Nash and Sutcliffe, 1970), Root mean square error (RMSE) (Moriasi et al., 2007) and Percent bias (PBIAS) (Gupta et al., 1999) were used to evaluate the quality of calibration and validation process. NSE values ranged from 0.81 to 0.86 in both calibration and validation at Son Giang and An Chi stations. RMSE values ranged from 0.12 to 0.37 and PBIAS values varied from -6.5 to 9.84 in both calibration and validation model. The average magnitude of the simulated values has a good performance rating (PBIAS < ± 10%) for both calibration and validation. The results of the calculated and observed water discharges are in good agreement in terms of the vibration amplitude, absolute value, and phases during both the calibration and validation processes (Figs. 5a-5d). The parameters of the hydrological model in the calibration and validation process were later used in simulation the hydrodynamic regime in MIKE 11 HD model.

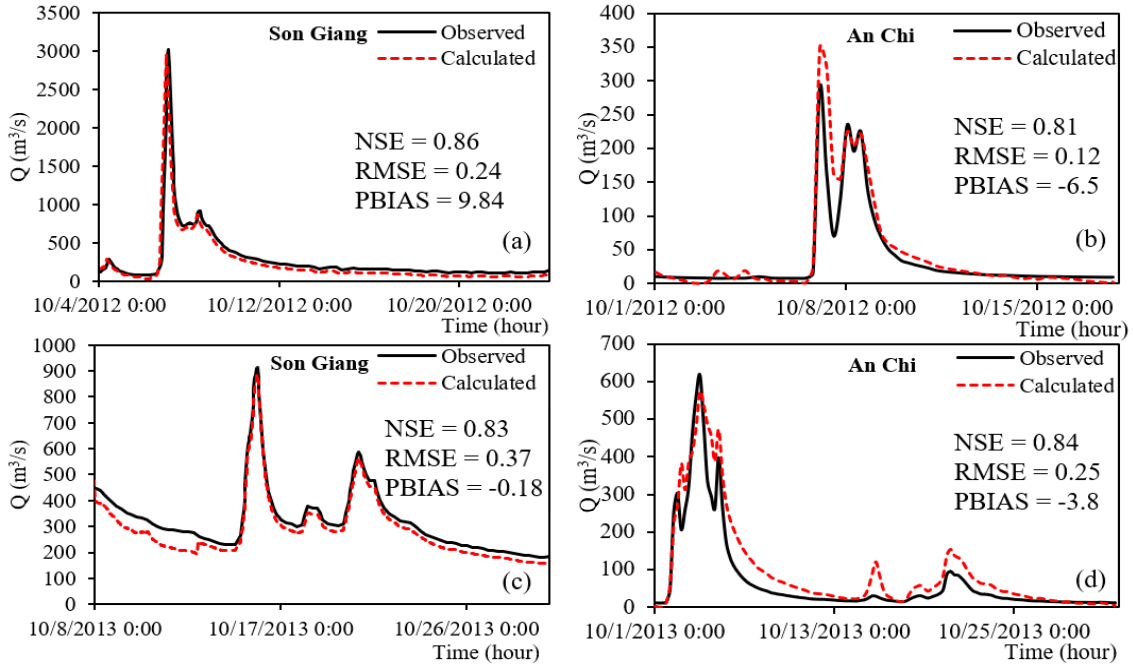


Figure 5. Calibration and validation of water discharge at Son Giang and An Chi stations in MIKE SHE model (Tran et al., 2019)

3.2. Calibration and validation of MIKE 11 model

Calibration and validation of MIKE 11 HD model used two flood events in October 2012 and October 2013. Two hydrological stations at Tra Khuc-Ve River basin were selected to evaluate the quality of model. Three criteria NSE, RMSE and PBIAS were used to evaluate the simulated and observed results at two downstream stations (Figs. 6a-6d). NSE

values ranged from 0.84 to 0.9; RMSE values ranged from 0.08 to 0.23; PBIAS values ranged from 5.2% to 9.01%. The calculated and observed results showed a good agreement in terms of the vibration amplitude, absolute value, and phases during both the calibration and validation processes (Figs. 6a-6d). As a result, MIKE 11 hydraulic model well simulated the flow regime in the river. The parameters of model were inputted in simulation flood and inundation forecasting for downstream of Tra Khuc-Ve River basins in next section.

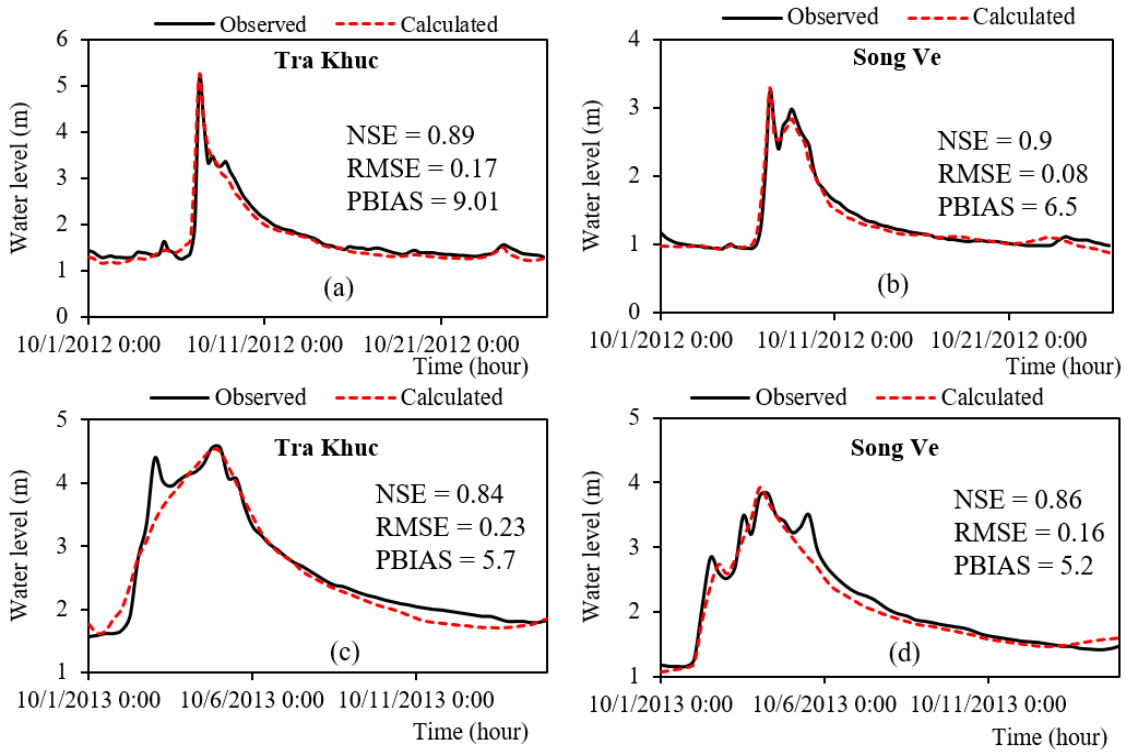


Figure 6. Calibration and validation of water level at Tra Khuc and Song Ve stations in MIKE 11 model (Tran et al., 2019)

3.3. Flood and Inundation Forecasting and Warning Scenarios

This study selected the flood event on November 15-18, 2013 because it was a historical flood event in Tra Khuc-Ve river basins. Due to the influence of the storm No. 15 (namely Podul) combined with the cold air and turbulence in the high east zone, Tra Khuc-Ve River basins experienced the heavy rainfall event. The total rainfall measured at Son Giang station was 656 mm, at Tra Khuc station was 270 mm, at An Chi station was 833 mm, at Song Ve station was 335 mm. Flood peaks in these rivers were over alarm level III and bigger than 1999 flood peak. Flood peak in Tra Khuc river at Tra Khuc station was 8.76 m, over 2.26 m of alarm level III. Flood peak in Ve river at Song Ve station was 6.03 m, over 1.53 m of alarm level III. Flood intensity was recorded as the greatest one since 1977. The characteristics of the historical flood event in 2013 are presented in Table 2.

Table 2. The flood characteristic from 15/11/2013 to 18/11/2013

Flood event	River	Station	Total rainfall (mm)	H_{leg} (cm)	H_{max} (cm)	Flood amplitude (cm)	Flood intensity max (cm/h)
15/11/2013 - 18/11/2013	Tra Khuc	Son Giang	656	2960	4162	1202	162
		Tra Khuc	270	224	876	652	144
	Ve	An Chi	833	458	1043	585	153
		Song Ve	335	170	603	433	148

The rainfall forecasting from the IFS model was an input for the hydrological (MIKE SHE) and hydraulic (MIKE 11) models. The simulation and calculation results of water discharge at Son Giang and An Chi and water level at Tra Khuc and Song Ve stations showed a good agreement in terms of the vibration amplitude, absolute value, and phases with high evaluation criteria NSE, RMSE, PBIAS (Figs. 7a-7d). NSE values ranged from 0.8 to 0.84 in simulating water discharge at Son Giang and An Chi stations. NSE values ranged from 0.89 to 0.91 in simulating water level at Tra Khuc and Song Ve stations. RMSE values ranged from 0.17 to 0.35 in simulating water discharge and water level at four stations. PBIAS values ranged from -7.8% to 5.46% with a good performance rating (PBIAS < ± 10%) in simulating water discharge and water level.

The rainfall forecasting from the IFS model was also used to establish six flood warning scenarios based on the alarm level III (6.5 m) and the historical level (8.76 m) (Figs. 8a-8f). The historical data showed that Tu Nghia and Son Tinh districts were the most affected areas by inundation with over 11% affected area while Quang Ngai Town inundated of 8.1% (Fig. 9).

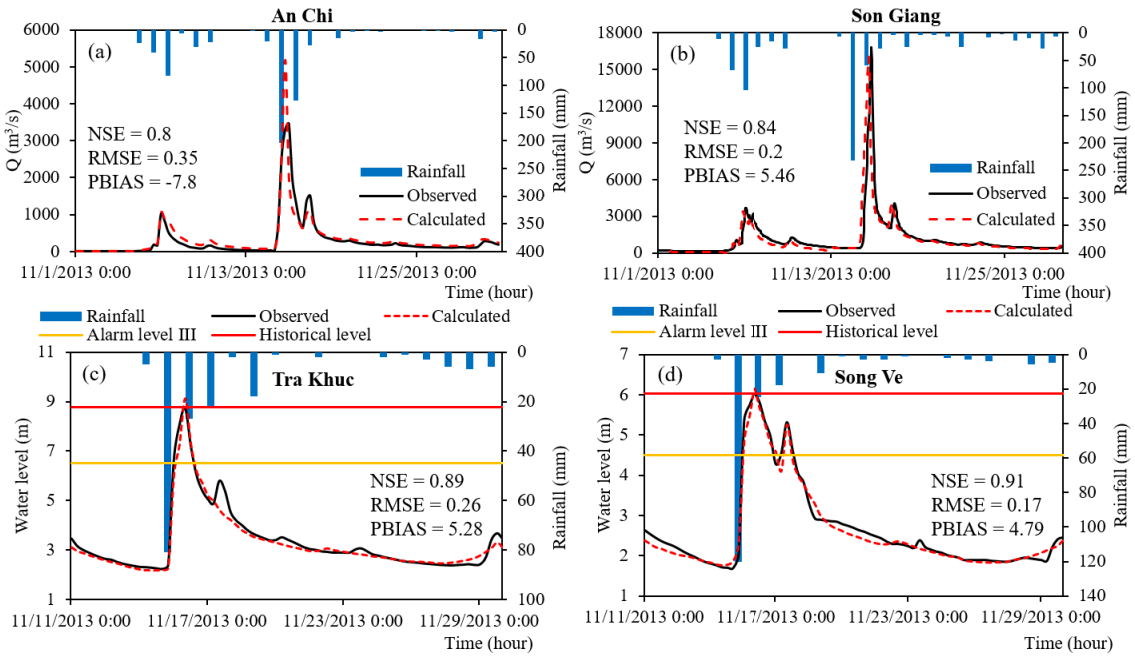


Figure 7. The simulation results of historical flood event on November 2013 at Tra Khuc-Ve River basins

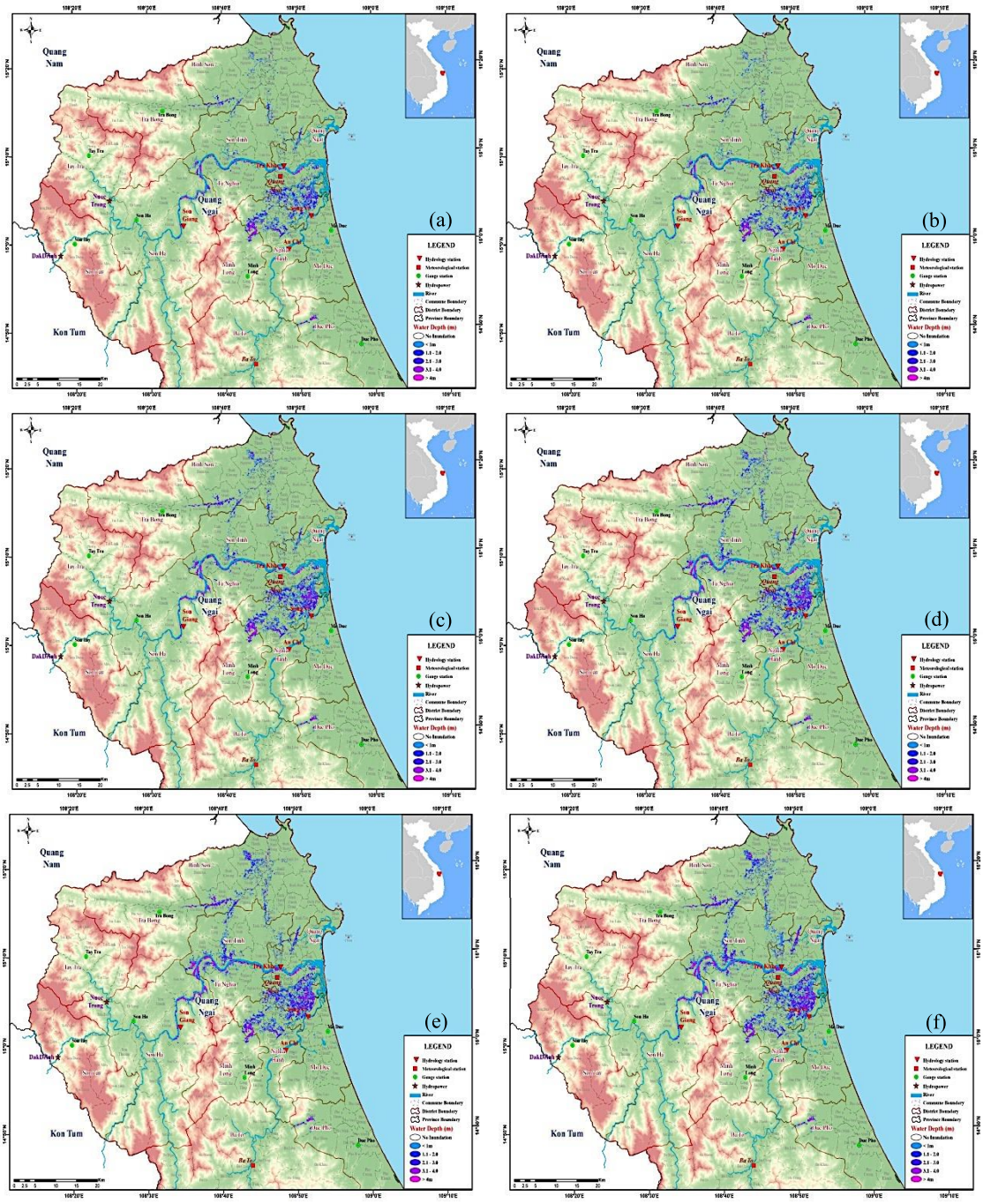


Figure 8. Flood Forecasting and Warning maps at Tra Khuc-Ve River basins: (a) Alarm level III (6.5 m); (b) 7.0 m; (c) 7.5 m; (d) 8.0 m; (e) 8.5 m; (f) historical level (8.76 m)

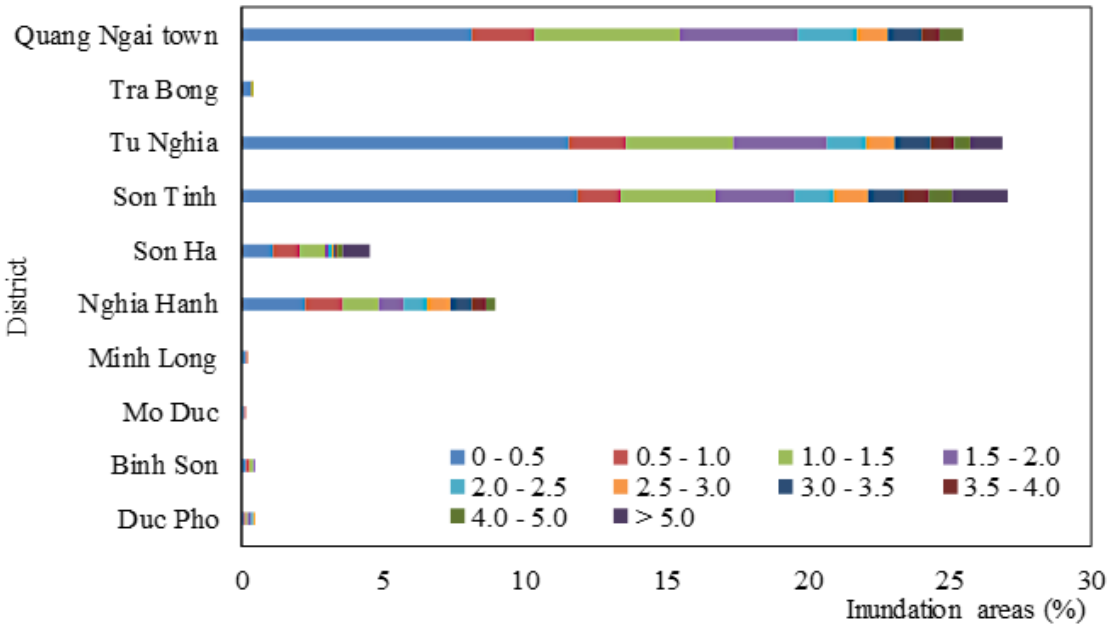


Figure 9. The affected areas in percentage in Quang Ngai Province during the historical flood event

4. Conclusions

This study applied the hydrological model MIKE SHE, hydraulic model MIKE 11, and MIKE 11 GIS to simulate and calculate inundation maps in Tra Khuc-Ve River basins. The calibration and validation results of the hydrological and hydrodynamic models showed a good agreement between observed and calculated data, especially for the phase and amplitude. NSE, RSR, and PBIAS indicated that MIKE SHE model was satisfied in simulating the drainage flow of the study site in the calibration and validation steps. The results of calibration and validation of water level in the hydrodynamic model MIKE 11 showed that MIKE 11 hydraulic model was well simulated the flow regime in the river. The rainfall forecasting from the IFS model was used to establish the inundation maps for the alarm level III and the historical flood level. The results of the historical event showed that Tu Nghia and Son Tinh districts were the most affected areas by inundation with over 11% of affected areas while that of Quang Ngai Town was 8.1%. The inundation maps presented in this paper can become a good reference for engineers, policy makers, planners and administrative bodies to make the decision in flood mitigation strategies in Tra Khuc-Ve River basin. For a future study, it is recommended that the uncertainty of the modeling needs to be reduced. The following aspects may be improved:

- The number of flood events went through calibration and validation in the hydrological and hydraulic models are limited. It may not be enough to evaluate the adequacy of the models in the study area.

- The simulation and warning results of inundation maps will be more useful and expanded if these are combined with the survey data of flood traces at downstream areas.

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References

Adib M.R.M., Saifullizan M.B., Wardah T., Rokiah D., Junaidah A., 2011. Flood inundation modeling for Kota Tinggi catchment by combination of 2D hydrodynamic model and flood mapping approach. Lowland Techno. Inter., 13(1), 27-35.

Boonrawd K., Jothityangkoon C., 2018. Assessing the climate change impact on floodplain inundation map in the Chiang Mai municipality upper Ping river basin of Thailand. Lowland Techno. Inter., 20(2), 213–220.

Bathurst J.C., Ewen J., Parkin G., O'Connell P.E., Cooper J.D., 2004. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. J. Hydrol., 287, 74–94. https://doi.org/10.1016/S0022-1694(96)80026-6.

Chaudhry M.H., 2007. Open-channel flow, 2nd ed., Springer, New York.

Cunge J.A., Holly F.M., Verwy A., 1980. Practical aspects of computational river hydraulics, Pitman, London.

Danish Hydraulic Institute (DHI) 1994. MIKE SHE-An Integrated Hydrological Modelling System. Denmark.

Danish Hydraulic Institute (DHI) 2014a. MIKE SHE User Manual, Volume 1: User Guide, p.370.

Danish Hydraulic Institute (DHI) 2014b. MIKE SHE User Manual, Volume 2: Reference Guide, p.444.

DHI 1997. MIKE 11 GIS Reference & user manual. Horsholm: Danish Hydraulic Institute.

DHI 2004. MIKE SHE User Manual. Hørsholm, Denmark: Danish Hydraulic Institute.

DHI 2007. MIKE 11 Reference Manual.

Doan Q.T., 2016. Application MIKE 11 model on simulation and calculation for saltwater intrusion in southern region. Scientific and Technical Hydrometeorological Journal, 671, 39–46.

Gupta H.V., Sorooshian S., and Yapo P.O., 1999. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydrol. Eng., 4, 135–143. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135).

Jaber F.H., Shukla S., 2005. Hydrodynamic modeling approaches for agricultural storm water impoundments. Journal of Irrigation and Drainage Eng., 131(4), 307–315. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:4(307).

Jakeman A.J., Letcher R.A., Norton J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Modell. Softw., 21, 602–614. https://doi.org/10.1016/j.envsoft.2006.01.004.

Kuntiyawichai K., Schultz B., Uhlenbrook S., Suryadi F.X., Corzo G.A., 2011. Comprehensive flood mitigation and management in the Chi River basin, Thailand. Lowland Techno. Inter., 13(1), 10-18.

Kadam P., Sen D., 2012. Flood inundation simulation in Ajoy river using MIKE-FLOOD. ISH J. Hydrau. Engine., 18(02), 129–141.

Kameyama S., Shimazaki H., Nohara S., Sato T., Fujii Y., and Kudo K., 2013. Hydrological and Sediment Transport Simulation to Assess the Impact of Dam Construction in the Mekong River Main Channel. American Journal of Environmental Science, 9(3), 247–258. Doi:10.3844/ajessp.2013.247.258.

Luong T.A., 2011. Application of Hydro-mathematical Models for Flood Forecast and Inundation Warning of Tra Khuc-Ve River Basins. VNU Journal of Science, Earth Sciences, 27(1), 47–53.

Mason D.C., Cobby D.M., Horritt M.S., Bates P.D., 2002. Two-dimensional hydraulic flood modeling using floodplain topographic and vegetation features derived from airborne scanning laser altimetry, EGS XXVII General Assembly, Nice, France, book of abstracts.

Moriasi D., and Wilson B., 2012. Hydrologic and water quality models: use, calibration, and validation. Trans. ASABE, 55, 1241–1247. Doi: 10.13031/2013.42265.

Moriasi D.N., Arnold J.G., Van Liew M.W., Bingner R.L., Harmel R.D., Veith T.L., 2007. Model evaluation guidelines for systematic quantification

of accuracy in watershed simulations. Trans. ASABE, 50, 885–900.
http://dx.doi.org/10.13031/2013.23153.

Nash J.E., Sutcliffe J.V., 1970. River flow forecasting through conceptual models part I-a discussion of principles. J. Hydrol., 10, 282–290. https://doi.org/10.1016/0022-1694(70)90098-3.

Nguyen T.M.L., Doan Q.T., Tran H.T., Nguyen C.D., 2018. Application of a two-dimensional model for flooding and floodplain simulation: Case study in Tra Khuc-Ve river in Viet Nam. Lowland Techno. Inter., 20(3), 367–378.

Nwaogazie F.I.L., Tyagi A.K., 1984. Unified streamflow routing by finite elements. J. Hydraul. Eng., 110(11), 1595–1611. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:11(1595).

Quan N.V., Nguyen C.D., Kim G.S., 2018. Integrated impacts of climate change and land use change on surface hydrology in the future in Nakdong river basin in Korea. Lowland Techno. Inter., 20(3), 379–392.

Refsgaard J.C., Storm B., 1995. MIKE SHE. In Computer Models of Watershed Hydrology, 809–846. V. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Sen D.J., Garg N.K., 1998. Efficient solution technique for dendritic channel networks. J. Hydraul. Eng., ASCE, 124, 831–839.
https://doi.org/10.1061/(ASCE)0733-9429(1998)124:8(831).

Shooshtari M.M., 2008. Principles of flow in open channels. Shahid Chamran University Press, 15(2), 643–745.

Szymkiewicz R., 1991. Finite element methods for the St. Venant equations in an open channel network. J. Hydrol., 122, 275–287. https://doi.org/10.1016/0022-1694(91)90182-H.

Tran T.D., Dinh D.T., Doan Q.T., Tran Q.T., 2018. Applications of numerical modelling for the study on storm surge in typhoon Xangsane in the central coast of Vietnam. Tropical Cyclone Research and Review, 7(3), 179–192. Doi: 10.6057/2018TCRR03.04

Vo N.D., Gourbesville P., 2016. Application of deterministic distributed hydrological model for large catchment: a case study at Vu Gia Thu Bon catchment, Vietnam. Journal of Hydroinformatics, 18(5), 885–904.
https://doi.org/10.2166/hydro.2016.138.

Vo N.D., Gourbesville P., 2014. Rainfall uncertainty in distributed hydrological modelling in large catchments: an operational approach applied to the Vu Gia-Thu Bon catchment-Vietnam. In: 3rd IAHR Europe Congress, Book of Proceedings, Porto, Portugal.