VIETNAM JOURNAL OF HYDROMETEOROLOGY

Research Article

The advantage of using satellite data together with the hydraulic model in flood hazard assessment: A case study in Ca River downstream

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Received: 10 May 2021; Accepted: 08 July 2021; Published: 25 August 2021

Abstract: In Vietnam, the Central area faced the highest frequency of flood; in 2020, 13 tropical depressions landed in Vietnam, 8 of them came to the Central area within more than one month, from the 7th October to 15th November caused a loss estimated at 30000 billion in Vietnam Dong(VND), and 249 people died. Flood management in this area is a crucial task for local authorities. In flood management, flood simulation is the critical task needed for every flood management strategy. Many methods can make the flood simulation. In those methods, hydraulic modeling is the widest apply in Vietnam. This method shows its advantages in many aspects, but they also have limitations compare to other methods. The hydraulic model can predict floods with complex conditions and multi–input. In this study, flood simulation is made by applying hydraulic modeling. The study area is downstream of the Ca river basin, affected area by flood in Central Vietnam. The flood simulation is made with four flood scenarios in MIKE packages: 1%, 2%, 5%, and 10%, representing the flooding return period of 100, 50, 20, and 10 years. The flood simulation provides flood map based on the modeling result. Those data is validated and compare with flood areas from satellite images in the study area. The study shows the advantages and disadvantages of hydraulic modeling in flood simulation and flood mapping from satellite images. There is a very high potential of using the hydraulic model together with satellite data for flood hazard assessment.

Keywords: Flood mapping; Hydraulic model; MIKE; River basin flood; Sentinel 1.

1. Introduction

Flood and inundation is a most dangerous disaster in Vietnam [1]. Flood prediction for flood management is essential to work, especially downstream of rivers, coastal areas. Those areas are high population density, high development with the concentration of economic values but strongly affected by the flood, combined with heavy rainfall and high tides. Ca river is the biggest river basin in North Central of Vietnam, the flood is frequently occurred in this area, especially the downstream. Therefore, Ca's downstream area is attractive in flood studies.

Flood prediction is the essential value in flood risk assessment and flood management. The flood prediction can be made by simulation in hydraulic modeling or flood susceptible modeling in GIS. Both of them have advantages and disadvantages. The GIS modeling methods commonly use Multi–criteria analysis (MCA)with several criteria and define flood hazard by combining them in GIS environment [2–6]. Using GIS modeling, the flood can be drawn based on criteria as DEM, land use data, hydraulic network, infrastructures. Other characteristics of a flood as frequency, duration, and velocity, are challenging to simulate in GIS. On the other hand, the hydraulic model simulation can provide valuable characteristics for flood risk assessment and preparedness. In Vietnam, there are several pieces of research applied the flood simulation, MIKE package dominated in flood modeling in Vietnam, the researches can be found from North [7] to Central coastal [8–9] to the Highland [10], some using SWAT [11] or FLO2D [12], Quasi2D [13], Probabilistic model (POT) [14]. The flood simulation started by designing flood scenarios. A flood simulation was designed by one of two designing methods: Flood frequency analysis (FFA) and Rainfall–Runoff analysis (RRA) [15].

The first method is based on the statistical analysis of flow monitoring data. This method is applied to define a maximum flow point in the flood model. The second one designs a flood by estimating runoff based on rainfall data analysis in the basin area. This design can be used to find the maximum flood area and hydraulic characteristics of a flood. In the developed countries like the USA and the developed countries, the FFA method is widely used in flood designing because they have a very dense flow monitoring system covering all areas of a river basin [16–18]. However, for the less developed countries like Vietnam, applying the FFA is challenging because lacking monitoring data. In order to overcome the data problem, many research pieces suggest that using the RRA is suitable for the basin with lesser monitoring data [19].

Some technical standards were issued in the flood prediction design in Vietnam, such as TCVN 9845:2013 (Flood characteristic calculation) [20] and TCVN 7957:2008 (Hydraulic network and construction) [21], are tricky to apply in flood prediction of river basins. The flood simulation design is recently based on historical events to reference and extend to flood frequencies. In this design, the rainfall in the river basin is considered the main factor of flooding. This study uses a hydraulic model to predict floods by applying the MIKE package and the RRA method. The modeling is applying for downstream of the Ca River basin.

The SAR data have been using in flood monitoring for a long time. However, in recent years, the open data from European Space Agency (ESA) boosted Sentinel 1 data in research [22–23]. Many researchers have used Sentinel 1 in the GEE platform for flood monitoring, from urban [24–25] to river basin scale [26–28]. In Vietnam, the SAR application is commonly used for flood monitoring, from the Mekong delta [29–30]to the Red River delta [31–32]. In this study, the Sentinel 1 data automatically processed in GEE by applying the UN–SPIDER practice for flood monitoring [33].

2. Materials and methodology

2.1. Study area

According to [34], the Ca River is one of the most significant rivers in the center–north of Vietnam; it is an international river with 531 km length, and the basin area is 27,000 km^2. The river flows from Lao to Vietnam and lying in Thanh Hoa, Nghe An, and Ha Tinh provinces before reaching the sea at the Cua Hoi river mouth. The river basin received 1100–2500 mm annually, precipitation concentrated in May to October in upstream and August to

November downstream. The flood season occurred from April to November with several tributaries.

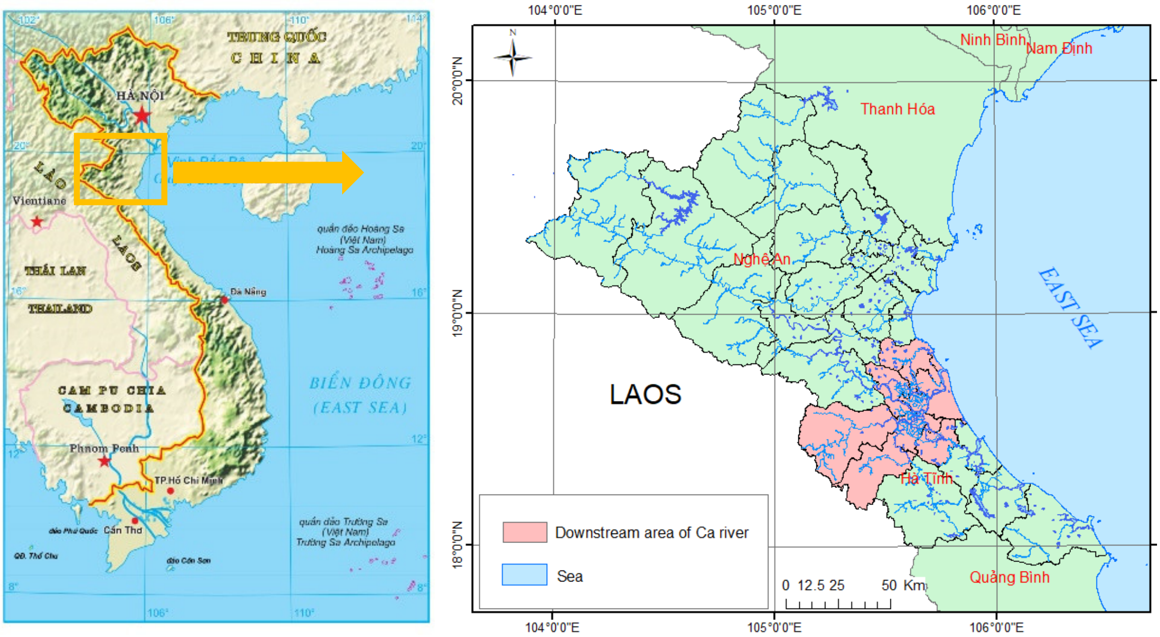


Figure 1. The downstream of Ca River.

Flood in this river basin is one of the most damaging disasters. From 1990 to 2010, the statistics showed the loss from flood only is 3300 billion VND, in 2011 and 2012, the loss from flooding about ~ 1000 billion VND each year, then from 2013 to 2016, the loss is ranged from 150 to 500 Billion VND (http://phongchongthientai.mard.gov.vn).

2.2. Data collection

The data used in the study include:

- Observed rainfall, discharge and water level from 1987–2017 have been collected for model calibration and validation and design scenarios.
- Topographic maps from MONRE with a scale of 1:10000 and 1:5000, river cross–sections from 2001–1014 collected from Vietnamese Disaster Management Authority.
- Land use map dated 2015 from MONRE.
- Data of disaster risk reduction infrastructure: dykes, dams, pumps, gates, etc., collected from the Disaster management authority in 2017.
- Infrastructure and transportation data from Open Streetmap 2017.
- Sentinel 1 data from GEE with the time of acquiring is 25th September 2020 for non–flood and 15th October 2020, and 2nd November 2020 for floods.

2.3. Modeling methodology

Figure 2 presents the workflow of the modeling process. The workflow includes five steps and using three groups of data (Meteorological–hydrological; hydraulic works and infrastructures; DEM).

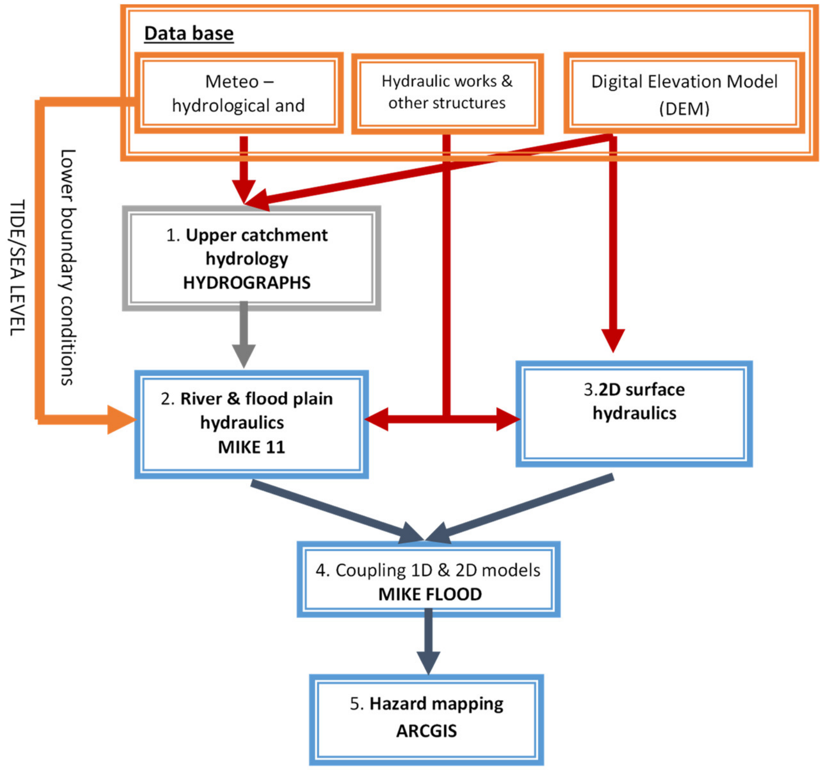


Figure 2. Modeling process.

2.3.1. Sub–basin defined

The boundary conditions needed for the one dimension (1D) hydraulic model are upstream, downstream, and lateral boundaries. Usually, the upstream and lateral boundaries are discharged, while downstream boundaries are water levels. Rainfall–runoff models are usually applied to estimate the inflows and their influences and confluences in relevant sub–basins to identify upstream and lateral boundaries. In this study, sub–basins are defined based on the following criteria: (1) Strategic hydraulic works in the system such as reservoirs, hydropower, and division nodes; (2) Influences and confluence streams discharge into modeled river network; and (3) Lateral boundaries of modeled rivers account for every 20% of the total basin area.

For flood analysis, the 1D hydrodynamic model is set up for the lower part of the basin from the reservoir to the sea. Furthermore, the lateral flows from other sub–basins along the leading river network need to be estimated. Therefore, the whole basin is divided into 27 sub–basins, as shown in Figure 3.

All hydrological features are identified for each sub–basin, including basin area, main river length, riverbed slope, basin slope, lowest/ highest/ medium elevation of the basin. The distribution of meteorological and hydrological stations in the basin is present in Figure 4.

In this study, the Intensity–Duration–Frequency (IDF) curves are used to established designed rains, in which the rainfall layer is used instead of the intensity to make it easier in later stages, calculated by the equation (1).

$$h=a\times t^{n} \quad (1)$$

where h is the rainfall layer (mm) with the period of rain; a, n are parameters calculated from the data series; and i=h/t is the intensity of rain.

The IDF curve series are calculated using this procedure for different repetitions: 10 years, 20 years, 50 years, 100 years, and 200 years for each station with data available in the basin, as shown in Figure 5.

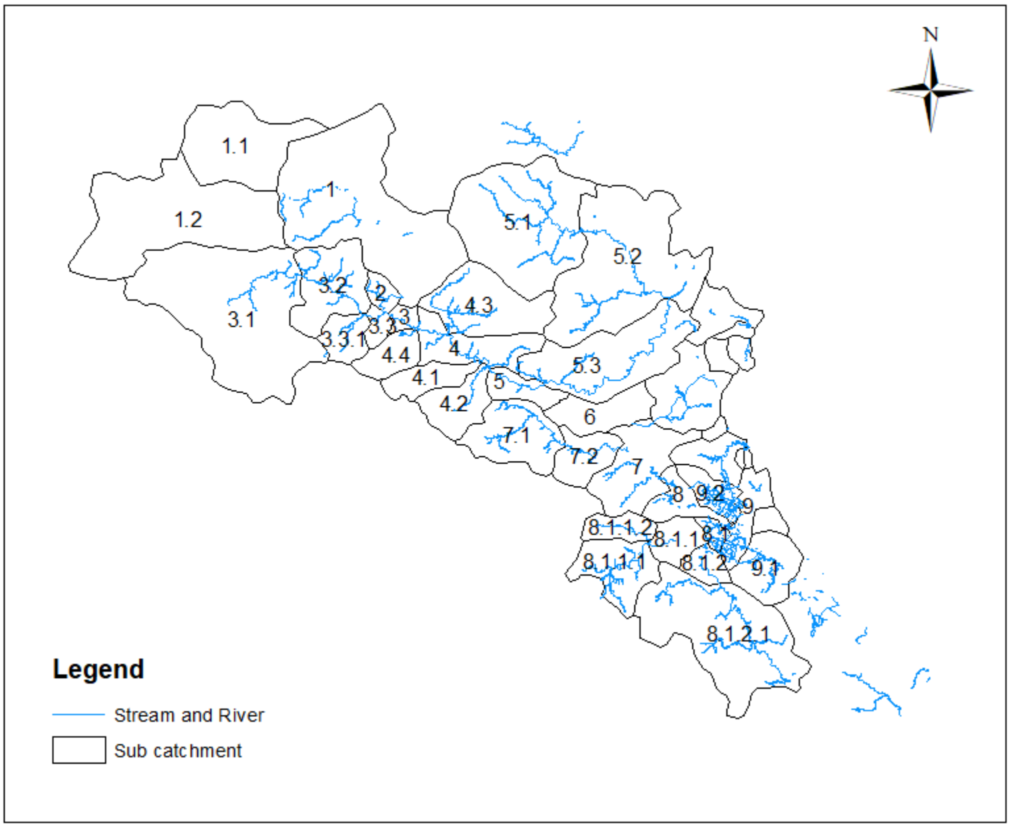


Figure 3. Sub–basins defined for flood analysis.

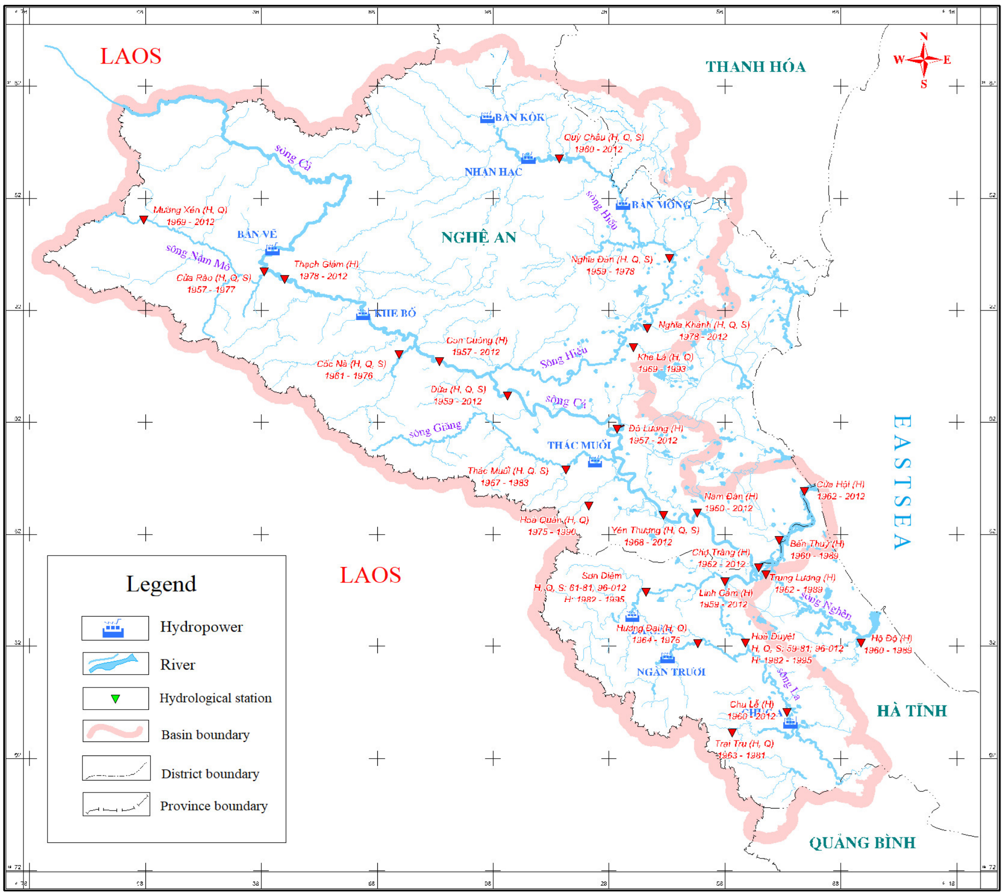


Figure 4. Hydrological and meteorological station in the river basin.

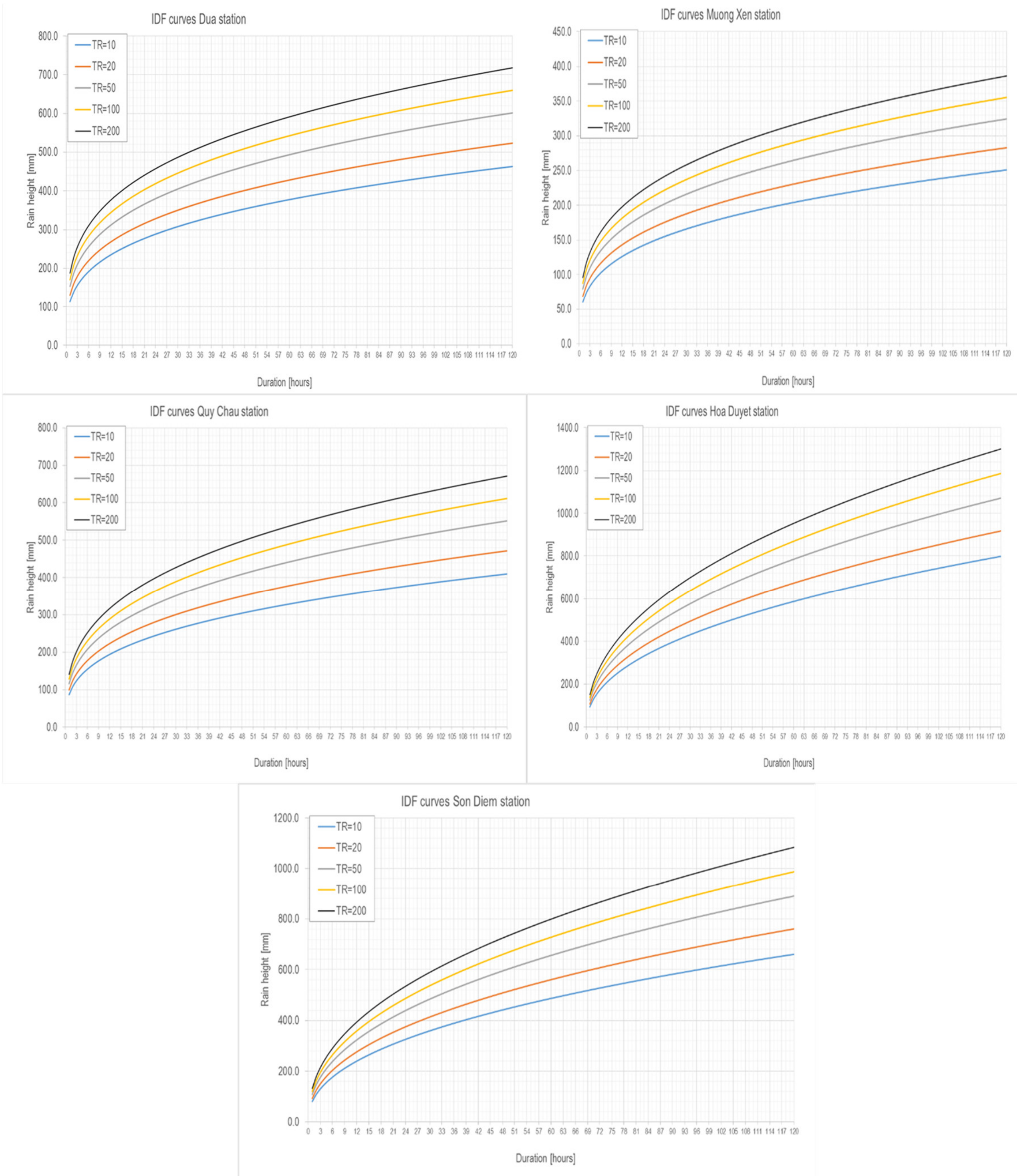


Figure 5. Hydrological and meteorological station in the river basin.

2.3.2. The design hydrograph flood

Design flood process lines are constructed from design rainfalls with a rainfall time equal to concentrating water in the basin by applying a rainfall–runoff model. According to this method, the shape of the flood process line is a shape triangle with a total flow time twice the sub–basin's water concentration time.

a) Sub–basins of characteristics

As stated above, for each sub–basin, the main parameters from available DEM are defined as an area, average and minimum elevation, river length (of the main branch), river slope, hillsides average slope. These values were estimated for the entire basin upstream of each river closing section, not only for the added area of a single sub–basin. The other parameters, runoff coefficient and Curve Number (C.N) coefficient of each sub–basin, were estimated from the land use map considering that land use is classified into seven types: cropland, forestland, grassland, settlement, water, other uses, and no data.

b) Runoff concentration–time of each sub–basin

For each sub–basin, the concentration–time is computed using Giandotti [35] and Soil Conservation Service (SCS) formula [36] as expressed:

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8 \times \sqrt{Hmed} - Hmin} \quad (2)$$

$$t_c = \frac{0{,}342}{0{,}6} \cdot \frac{L^{0{,}8} \cdot (S+1)^{0{,}7}}{\sqrt{y}} \quad (3)$$

where A is the sub–basin area (km^2); L is main river length (km); H_{med}, H_{min} are the average and minimum basin elevation (m); S is the potential maximum retention (S=(1000/CN–10) *25,4) (mm); y is the slope of the average hillside (%).

Giandotti formula is used for most sub–basins; The formula has been established for mountainous basins covering an area of 140 km^2 to 70,000 km^2, so this is a suitable formula for the study basins. Smaller sub–basins, especially sub–basins in the downstream area, where there is a slight slope of the study area, are more accurately described with the SCS formula created for small rural basins.

In this analysis, the following rule provided the most representative results:

River slope < 2%, area < 100 km^2: SCS formula.

River slope < 2%, area > 100 km^2: average value between the two formulas.

River slope > 2%: Giandotti formula.

This methodology is the most effective, and Vietnamese formulas found in local regulation do not apply to this large basin area (because they are developed for small basins).

c) ARF values assigned for each sub–basin

According to various R.P. (100, 50, 20, 10), for each sub–basin, critical rainfall height is evaluated based on the IDF curves (h = axt_n), considering a duration t equal to concentration–time tc. An area reduction factor is applied to resulting height, considering the USWB formula (from U.S. Weather Bureau with coefficients recalibrated [36]):

$$ARF(t, A) = 1 - (1 - e^{-0.01298A}) \times e^{-0.6786 \times t^{0.332}} \quad (4)$$

d) Flood peaks of relevant frequencies for each sub–basin

The flood peak discharge is computed using a simple rainfall–runoff model as the rational method (or kinematic method). Thus the flood peak for a given return period (R.P) will be computed as:

$$Q[m^3/s] = \frac{\phi \times h \times A}{3.6 \times t_c} \quad (5)$$

where Φ is the runoff coefficient, h the rainfall height for given R.P. (reduced by ARF coefficient as stated above), A is the basin area, and tc the basin concentration time.

e) Hydrograph of relevant frequencies for each sub–basin

According to flood peak estimation methodology, the schematic flood hydrograph is developed with an isosceles triangular shape, with a duration equal to double the concentration time. This can be smoothed using UHM module of MIKE software, i.e., with SCS model, with parameters calibrated to obtain the same flood peak resulting from the previously described methodology. However, this passage is not necessary, as the two shapes are very similar, considering that the triangular hydrograph will soon smoothen due to hydraulic propagation in the MIKE11 model. The triangular shape is easier to combine to define the lateral contribution of downstream sub–basins, as described in the following point.

The basic flow is included if necessary for modeling purposes; this is not necessary when the designed rain period is long and focuses on the hydrograph's upper boundary (large volume). However, each basin's minimum flow rate can be determined based on the low flow's average annual flow value. Note: this basic flow is not included in hydrological calculations, except only used to increase the flow at the foot of the hydrograph up to the minimum value.

Hydrographs are defined for every Return Period (R.P.) (scenario) and every sub–basin with a closing section within modeled branches.

f) Upper and lateral boundaries with relevant frequencies

The contribution of sub–basins downstream the same main (modeled) river branch has been added as the difference between the hydrological (theoretical) triangular hydrographs computed for two consecutive closing sections. This contribution (lateral discharge) was added as distributed along the model cross–sections between the two closing sections or concentrated if there is a relevant tributary in this sub–branch.

g) Lower boundary

The lower boundary uses the tide level measured at Hoi mouth. In scenario simulation, the aggregate sea level value is related to the model and is determined as the high tide cycle; In some scenarios, the sea levels are increased by storm surge values is taken from previous research. In this study, a frequency curve of sea level during storm surge is based on Vietnam Standard TCVN 9901: 2014 for irrigation works – Requirements for sea dike design. According to this national standard, sea level at Cua Hoi, in Nghi Xuan Ha Tinh district (MC25). Tide is taken from the tidal regulation function of this region.

2.3.3. Scenarios

In this study, the scenarios are constructed based on a combination of design–heavy rains and tidal water cases, as shown in the table 1 . The core of these combinations is to consider the impact of heavy rains and different tidal regimes, creating flood areas with the most significant depth and inundation. First, consider the combination of high–frequency floods and low–frequency tides (scenarios 1 and 2). Next, consider the combination of low–frequency floods with low and high tide (3A, 3B, 4A, 4B). Therefore, there are six design scenarios summarized in Table 1.

Table 1. Scenarios according to each calculation timeline.

Scenario	Simulation mode	R.P. (Frequency)	Downstream boundary conditions (sea level *)
1	Unsteady	100 years (1%)	20 years (5%)
2	Unsteady	50 years (2%)	20 years (5%)
3A	Unsteady	20 years (5%)	10 years (10%)
3B	Unsteady	20 years (5%)	100 years (1%)
4A	Unsteady	10 years (10%)	10 years (10%)
4B	Unsteady	10 years (10%)	100 years (1%)

After all scenarios and parameters are set, the model setup in the MIKE package includes the following tasks:

- Setup the 1D model in Mike 11
- Setup the (2 dimensions) 2D model in MIKE 21
- Combining MIKE 11 and MIKE 21 to create MIKE FLOOD.
- Calibration and validation of the model in MIKE NAM
- Compare with flood data processed from Sentinel 1 satellite by Google Earth

2.4. Flood monitoring with Sentinel 1 in Google Earth Engine.

2.4.1. Workflow of flood mapping by UN–SPIDER

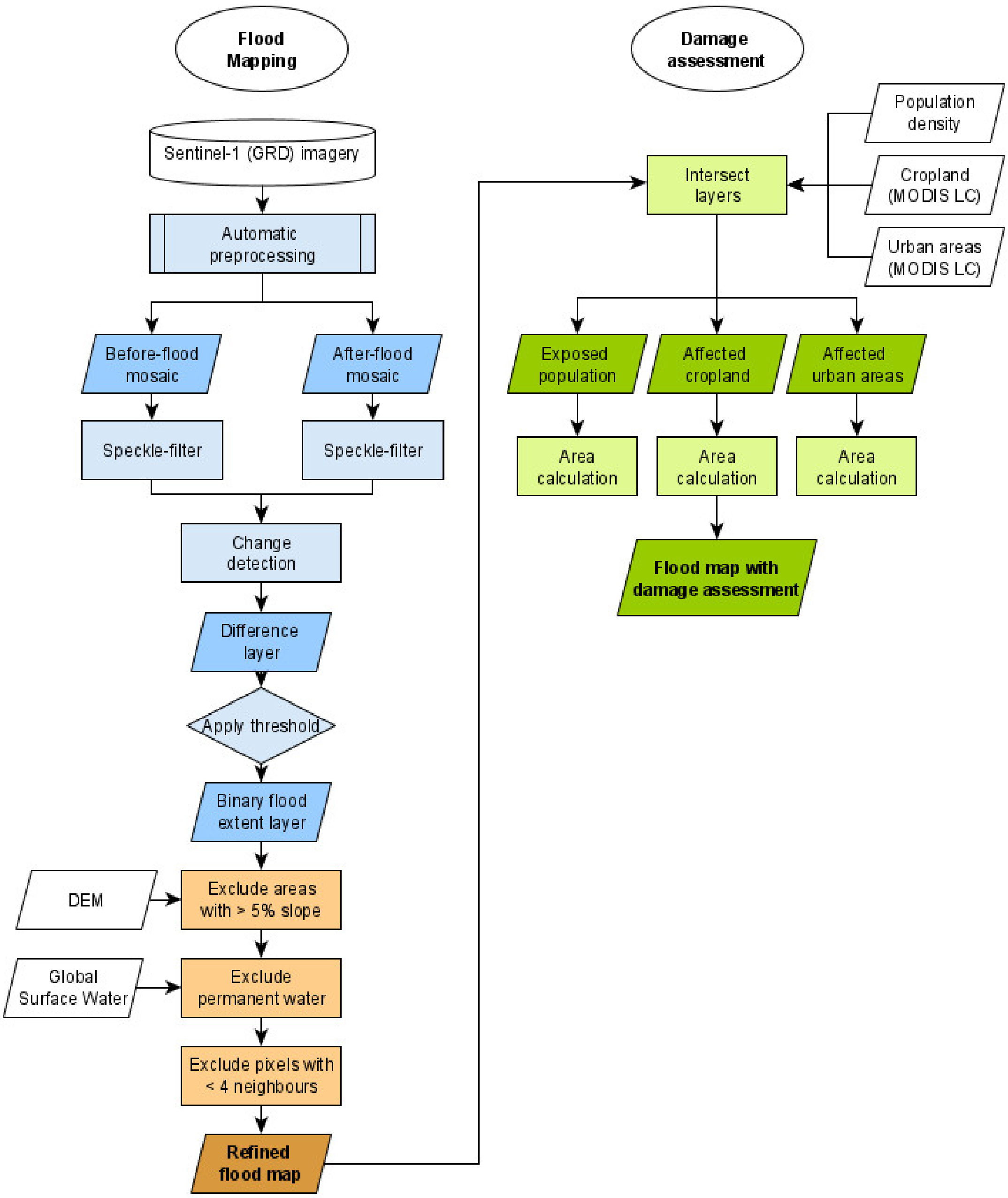


Figure 6. Flood mapping in GEE using Sentinel 1 data (Source UN–SPIDER).

The workflow of flood mapping in GEE (figure 6) is an automation process with pre–define code (Javascript). All of the code and data run on cloud computing inside the GEE. The user needs to define the boundary of the study area, the time frame of the flood that occurred. The processing of satellite images is in cloud computing. This workflow gives fast, on–time flood maps of natural floods. Those data will be used to compare with flood simulation results to help improve the accuracy of the flood model.

2.4.2. Selection of data

The floods in the Ca river basin in 2020 are occurred in 2 periods: 12 to 18th October, 28 to 04th November. The Sentinel data in these periods need to available to perform the flood mapping. The following table (Table 2) describes the flood information and corresponded data available.

Table 2. Flood periods and availability of Sentinel data.

No	Period			Sentinel1 date
	Start	Peak	End	
1	14th October	17th October	18th October	15th October
2	27th October	28–29th October	4th November	2nd November

In this research, there are only two available data set of Sentinel 1 for two periods of flood, and those data are not in peak flood dates.

3. Result and discussion

3.1. Model calibration and validation

The rainfall–runoff model has been calibrated with the flood event in 2013, and the result shows well with Nash coefficient ranging from 0.7 (Muong Xen) to 0.91(Hoa Duyet). The peak errors are minor than 5%, and the total volume errors are minor than 10%, as shown in Figure 7 below.

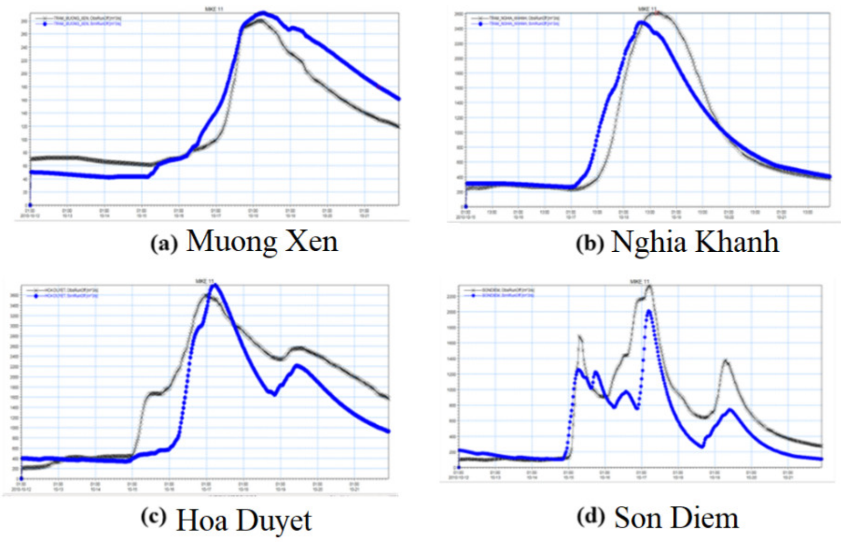
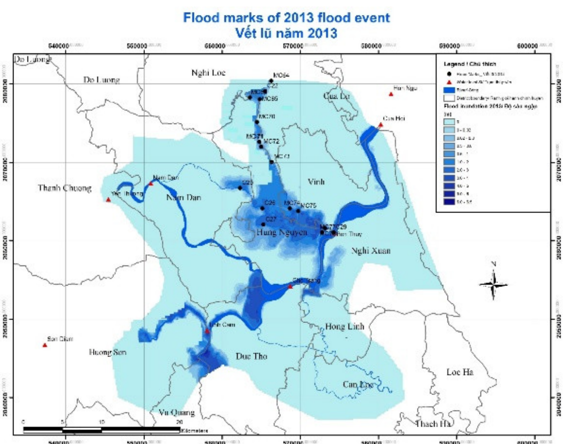


Figure 7. Model calibration.

The flood model has been validated with the same event in 2013 using 13 flood marks. The results are acceptable, as in figure 8 below.



No	ID	X (m)	Y (m)	H^{obs}[m]	H^{est} [m]	H^{est} - H^{obs} [m]
1	C25	588491	2067554	3.84	4.3	0.46
2	C26	591364	2064961	3.23	2.85	-0.38
3	C27	591492	2062894	3.65	3.29	-0.36
4	C29	600483	2061904	2.99	3.34	0.35
5	MC65	591000	2078885	2.45	2.6	0.15
6	MC70	590636	2075984	2.33	2.6	0.27
7	MC71	590945	2073445	3.40	3.55	0.15
8	MC72	591194	2072822	3.48	3.78	0.30
9	MC73	592534	2070874	3.89	4.21	0.32
10	MC74	594864	2064950	4.01	4.21	0.20
11	MC75	595940	2064607	4.00	4.31	0.31
12	MC76	599369	2062448	3.10	3.70	0.60
13	MC77	598999	2061909	1.99	2.24	0.25

Figure 8. Model validated.

3.2. Flood modeling

Hydrological modeling provides the result as a set of models and floodwater depth. The results of 1D and 2D models are shown as hydraulic networks as the following figure 10. The 1D model considers 12 rivers and 320 cross–sections in modeling to ensure the model's quality and accuracy. This model also includes hydraulic constructions and the main transportation infrastructure in the study area. The 2D model is constructed with more detailed with all transportation infrastructures, gates, and hydraulic structures in the Ca river's lower basin. The water depth data are a mesh of triangular polygons with water lever information. The data include six defined scenarios and mapping in GIS software (Figure 10).

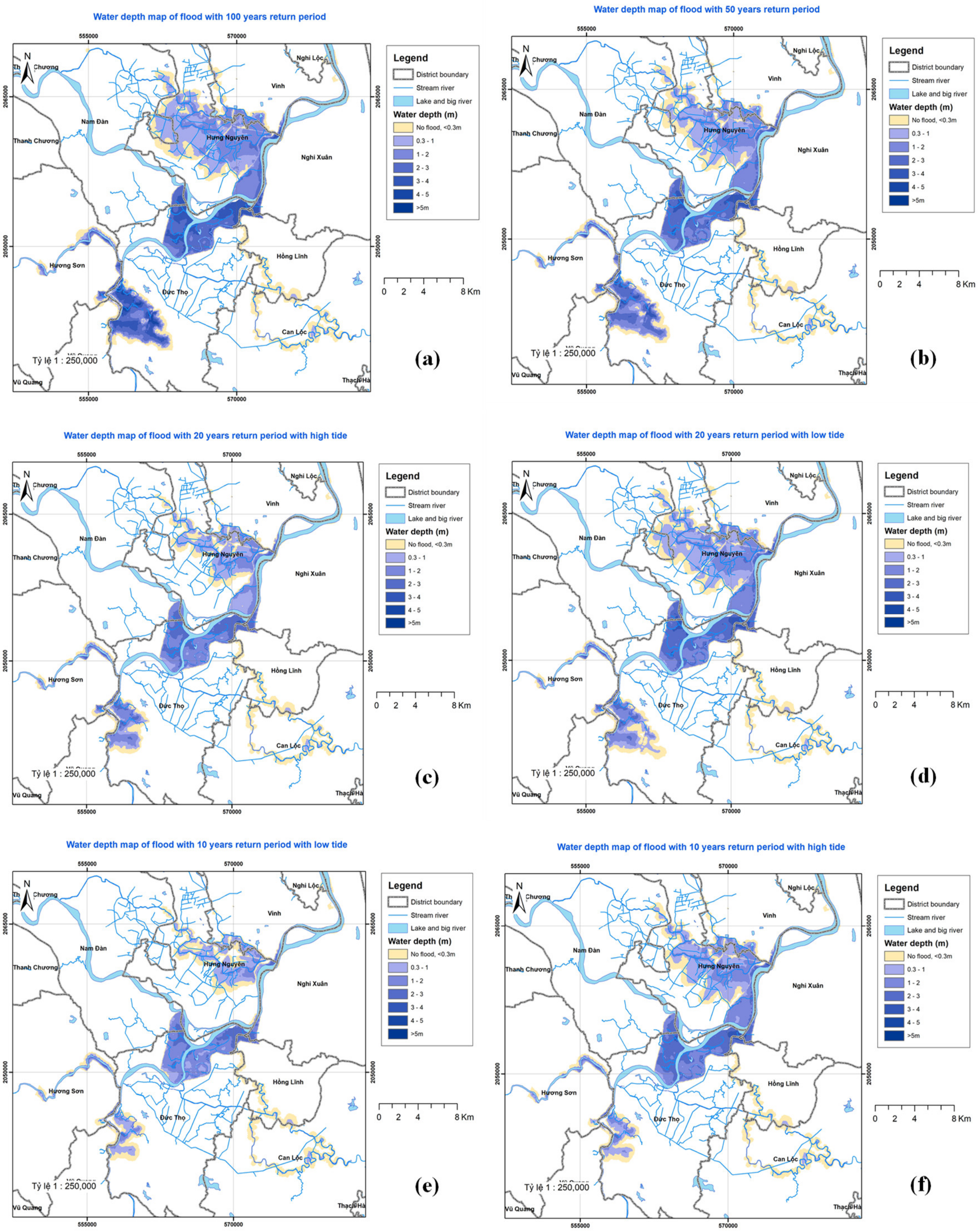


Figure 10. Result of hydraulic modeling (Scenario 1, 2, 3A, 3B, 4A, 4B from right to left and top–down).

3.3. Flood mapping by using Sentinel 1 data in GEE

The results of flood data from Sentinel 1 are created, as in Figures 11 and 12.

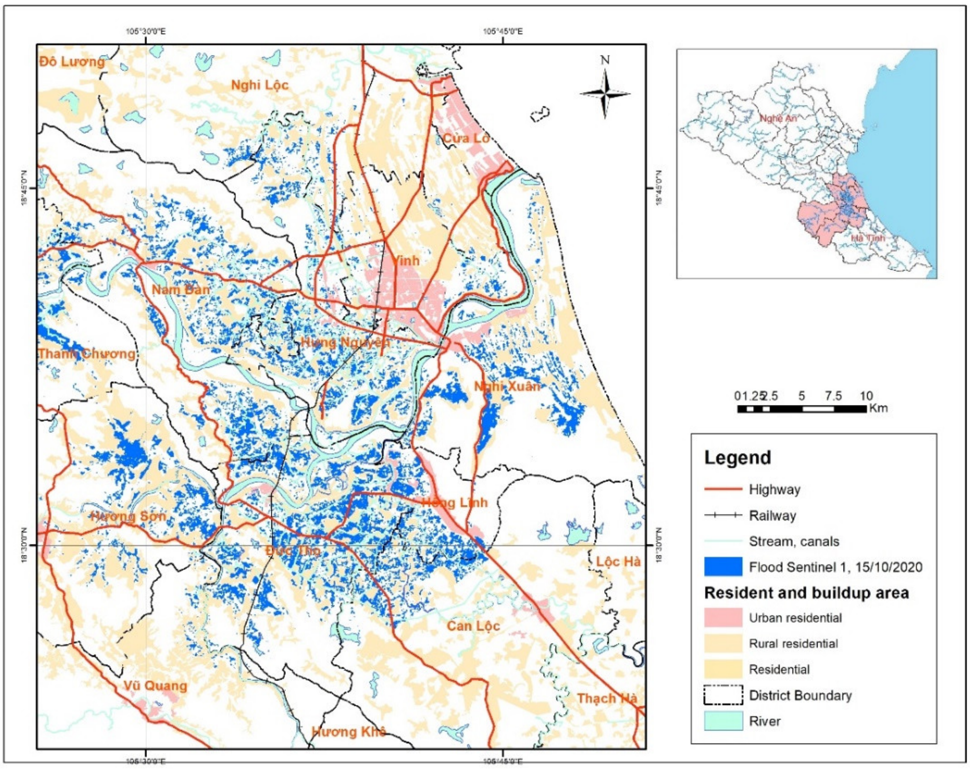


Figure 11. Flood data from Sentinel 1 date 15/10/2020.

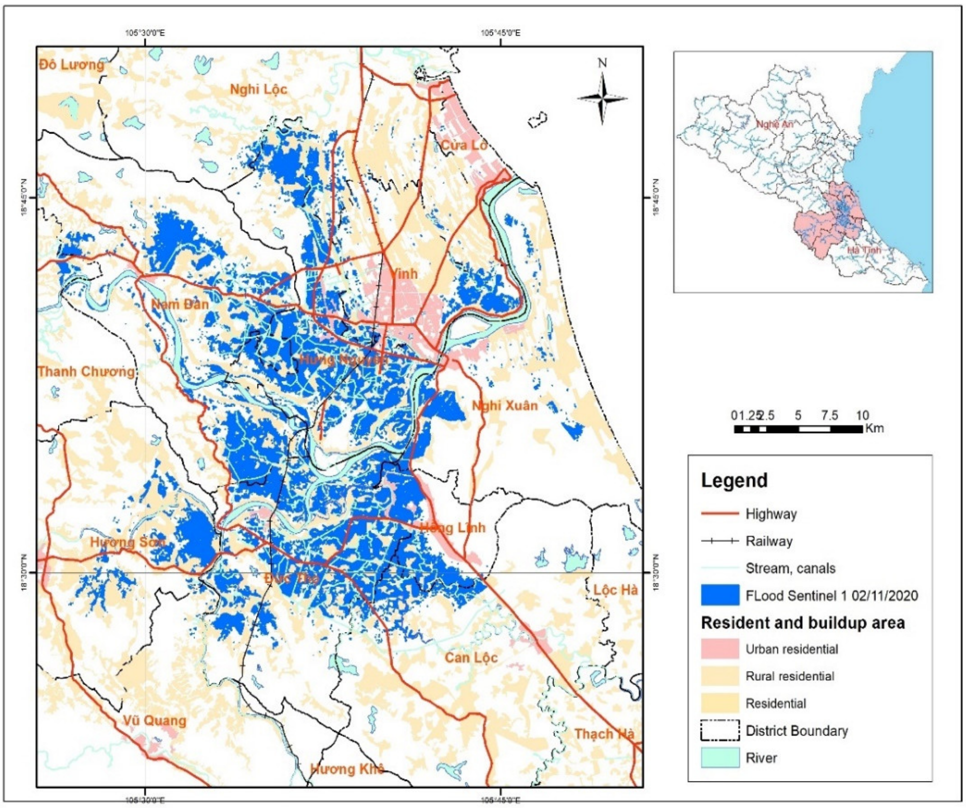


Figure 12. Flood data from Sentinel 1 date 02/11/2020.

Because of the difference in time and peak of the flood, the flood extent of the 2nd November data is more extensive than 15th October. On the other hand, the distribution of floods is similar in both flood maps.

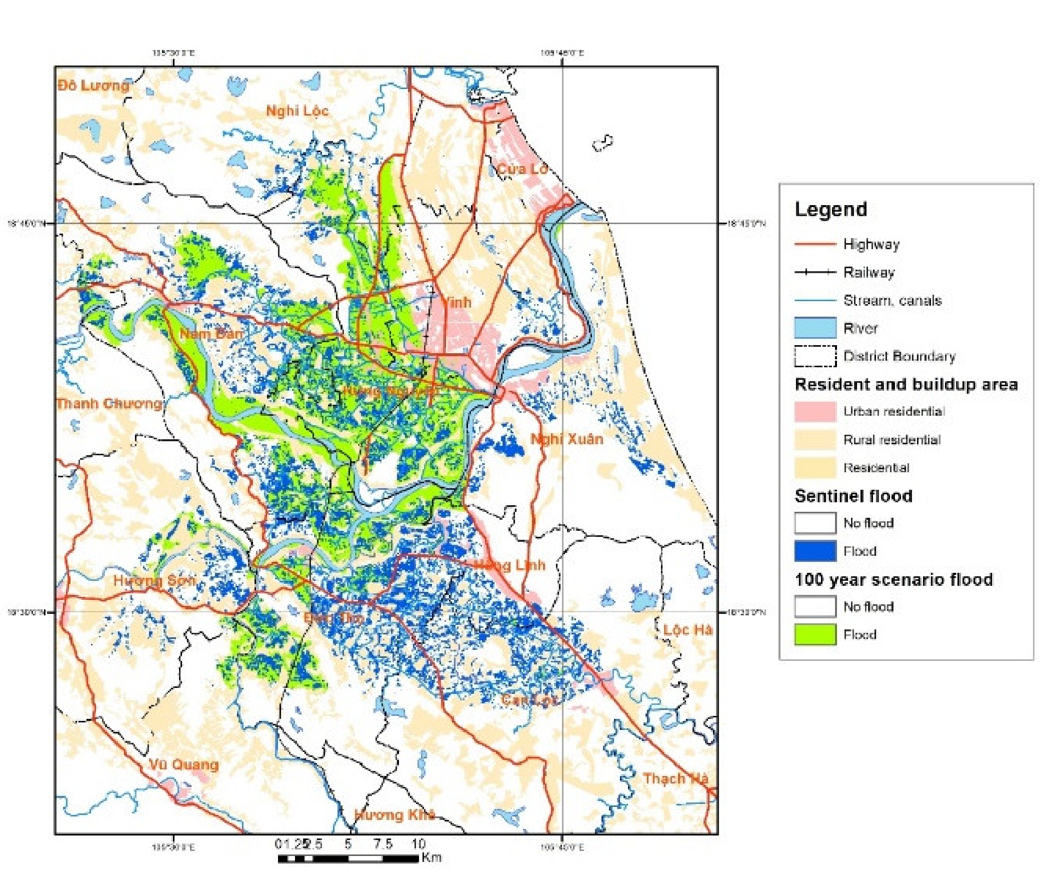


Figure 13 Compare the result of 100 years return period with flood data from Sentinel 1 date 17/10/2020.

Figure 13 provides a better comparison between the results of flood simulation and satellite image processing. Compare to the flood map provided by flood simulation modeling; the flood extends from Sentinel1 data are larger. The most significant difference is the Huong Son, Duc Tho, and Hong Linh district areas in Ha Tinh Province. Modeling considers all water a free run from the river, but in reality, the rainfall was concentrated in the field, making flood inside the dyke system. That means the modeling may not present a good accuracy of the flood. Most of the modeling is based on input data, which have low quality or out of date. It is tough to model all hydraulic systems, and the cost of data processing is unacceptable.

The flood mapping from satellite data is fast, accurate, and automated compared to the traditional flood modeling by simulation software. Nevertheless, the satellite data depend on the revisit time frame of the satellite; the peak flood dates rarely are the same as data acquiring dates. This problem may solve very soon with new satellites coming in the next few years. The combination of flood simulation and flood monitoring by satellite is very potential; the satellite can be used as validation and calibration sets for flood simulation.

4. Conclusion

The result shows that modeling the flood is needed for flood risk assessment. The modeling output is useable but limited in risk assessment, especially in disaster risk management. The hydraulic modeling can be applied in other river basins to help authorities understand the flood and plan the response strategies.

The hydraulic modeling is enormously dependent on input data. In this study, the DEM taken from the 1:5000 topographic map and infrastructure taken from the Open street map may not provide an exact flood map. That suggested the following study should using better quality of data.

The Sentinel1 flood mapping was limited by the revisiting time of the satellite; the data acquired may not in the peak time flood, which may give an underestimated flood extend. On the other hand, the flood mapping from the satellite images can be done rapidly, automatically in free cloud computing of GEE. These advantages give this method a priority in an emergency, search and rescue, post–flood recovery tasks.

Author's contributions: D.A.Q. is the first author, written most of the paper; T.V.A., T.X.Q. contribute the modeling in MIKE; B.N.Q. response to the review and graphic design; P.V.H., T.T.M.A., N.D.D. build the maps.

Acknowledgment: The paper results from research project No T20–11 from Hanoi University of Mining and Geology.

Conflicts of Interest: The authors declare no conflict of interest.

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