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Impacts of reservoir operation and urbanization on flood inundation in the Vu Gia Thu Bon Basin, Vietnam

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ABSTRACT

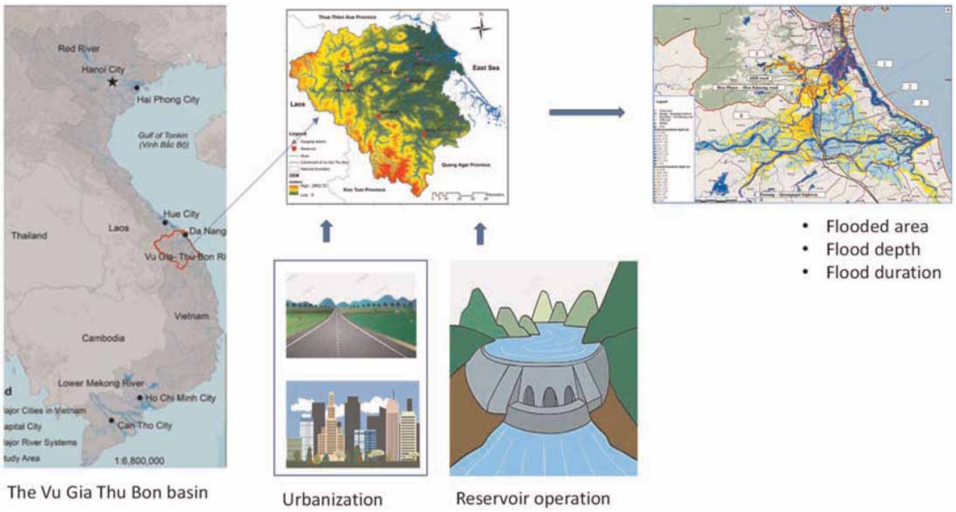
This study examines the effects of upstream reservoir operation and urbanization on flood inundation in the Vu Gia Thu Bon river basin. The alternative reservoir operation strategies corresponding to the flood storage capacity (V_{pl}) of 10, 20, and 30% of the active storage capacity (V_{hi}) are evaluated and compared with the prevailing inter-reservoir operation procedure in terms of inundation effects. The results reveal that increasing the V_{pl} from 10% to 30% of the V_{hi} reduces the flooded area by 11.8% and lowers the water level at downstream stations from 6% to 30%. The government's procedure is considered safe to supply water, but the inundation duration is longer, resulting in more damage than the scenario of V_{pl}=20%V_{hi}. Regarding urbanization, the expansion of newly urbanized areas has resulted in increased flooding in their surrounding areas, with an increase in flood depth of more than 3 m. Moreover, the new roads have reduced the capacity of flood drainage and caused severe flooding. The water level difference between the two sides of the road can be as high as 2 m. This research will assist managers in developing and implementing appropriate downstream flood control measures.

Key words: flood, reservoir operation, urbanization, Vu Gia Thu Bon

HIGHLIGHTS

- Three characteristics including flooded area, flood depth, and flood duration are analyzed.
- More detailed analysis of the impact of reservoir operation.
- In some areas, the highway increases the risk of flooding.
- The new urban areas are not flooded, but the surrounding areas are.
- Providing a basis for improving the government reservoir operations procedure.

GRAPHICAL ABSTRACT



INTRODUCTION

Flooding is one of the most common natural disasters occurring in the world and its frequency is often higher than that of other disasters. According to recent estimates, flood-related economic losses account for 40% of the overall loss due to all natural disasters (Lyu *et al.* 2020). One of the factors affecting inundation is the process of urbanization. Urbanization has a major impact on flooding, such as increasing flow rates and widening flood peaks (Grove *et al.* 2001; Weng 2001; Li & Wang 2009). Miller & Hutchins (2017) conducted a comprehensive review of the impact of urbanization on flooding, focusing on case studies conducted in the United Kingdom. Generally, four methodologies have been used in order to assess flood inundation: (1) the historical data-based method (Adikari *et al.* 2010), (2) the index-based method (Chen *et al.* 2015; Waghwala & Agnihotri 2019; Lyu *et al.* 2020), (3) the scenario simulation method (Huong & Pathirana 2013; Yin *et al.* 2016; Huang *et al.* 2017; Mei *et al.* 2020), and (4) geographic information system and remote sensing techniques (Suriya & Mudgal 2012; Wang & Xie 2018; Thanh Son *et al.* 2021). It can be seen that the scenario simulation is commonly used to predict flood inundation. Furthermore, simulation is one of the most frequently used tools in analyzing flood inundation related to reservoir systems. The behavior of the study region as well as the operation of the reservoir system are investigated in these simulation models under a variety of variable conditions. Mateo *et al.* (2014) used a combination of hydrological, reservoir management, and hydrodynamic models to assess the effects of reservoir operation on floodplain inundation. Ridolfi *et al.* (2019) investigated the influence of different reservoir operation strategies on flood inundation maps. Each operating strategy is developed based on a specified initial water level in the reservoir and discharge, resulting in varying degrees of flooding. Recently, Cong developed the relationship between the flood-limited water level in the reservoir and the flooded area downstream, proposing an effective flood-limited water level (Vu *et al.* 2021).

Vietnam is known as a flood-prone country as it suffers from an average of 12 storms per year. Statistics of major storms (categories 6 to 12) that hit Vietnam from 1961 to 2014 show an increasing frequency of storms, indicating a higher level of danger of flooding in the future (Luu *et al.* 2015). In central region, the shoreline stretches for 1,200 km and is divided by rivers that originate in the western mountain ranges and flow into the East Sea. Given these conditions, this region often suffers from natural disasters such as storms and floods, causing huge loss of life and property (Tran *et al.* 2008; Chau *et al.* 2015). Total damage caused by various types of natural disasters in Vu Gia Thu Bon basin was estimated at up to 3,500 billion VND in 2009, of which 90% was caused by floods (Satriagasa *et al.* 2014). Many major flood events occurred in the last 15 years, particularly in 2017 and 2020, when there were multiple floods in a single year. The floods claimed many lives and destroyed a lot of property, especially in low-income communities; floods wreaked havoc on crops and homes, leaving many people in poverty.

Flood studies have become increasingly necessary in this basin given the modified topography caused by urbanization. Many urban areas and big routes have been built in this basin serving socio-economic development. Danang, in particular, is one of Vietnam's key economic cities, located in the lower part of the Vu Gia Thu Bon river basin, and Danang has experienced rapid urbanization in recent years (Do *et al.* 2013). According to statistics in 2018, while the population growth rate in Vietnam's metropolitan areas is 34.75%, it is 84.11% in Danang. The leveling of flood drainage areas to form residential areas along with new roads can impede the floodways, leading to a change in flood inundation distribution patterns and a significant increase in flood levels in the surrounding areas.

Structural and non-structural measures can be applied to manage and mitigate the consequences of floods. Changing the operation procedures of the existing upstream reservoirs can be considered the most effective approach to reduce downstream flooding. It is therefore essential to analyze different reservoir operation scenarios to find out which ones are best for flood control. It is also critical in aiding the current government-promulgated inter-reservoir procedure, which has been shown to have limitations (Le *et al.* 2021). In addition to reducing flood flows via reservoir operation, it is critical to improve flood preparedness. A necessary tool for this is an inundation map, which can help determine the extent and depth of flooded areas as well as the flood flow direction. It's also a valuable resource for planners looking to identify high-risk areas, evaluate the performance of various adaptation strategies, or put measures in place to mitigate hazards. In the past, there were several studies on flood mapping for the Vu Gia Thu Bon river basin. Nguyen Hoang Son studied and developed flood maps for the Vu Gia Thu Bon rivers in 2004 and 2009 (Nguyen 2014). Another study on flood mapping of the lower Vu Gia Thu Bon river basin was conducted by Tran (2013). However, these studies have become out of date due to the construction of major traffic routes passing through the basin. Construction of the Danang–Quangngai expressway, for example, began in 2013 and was completed in 2018, which is expected to have significant impacts on inundation. In 2013, Do also investigated urbanization and changes in flood risks in Danang, which is located downstream of the Vu Gia Thu Bon basin (Do *et al.* 2013). The most recent is a study conducted in 2019 by To on the impact of urbanization on flooding in Danang City (To *et al.* 2019). Despite the fact that these studies were recently conducted, they all focused on the impact of urbanization in Danang City, a small section of the Vu Gia Thu Bon river basin. None of these previous studies investigated and discussed the effects of reservoir operation on flood inundation, or on an entire basin. Therefore, it is essential to conduct new flood effect studies in alignment with the upstream reservoir operation and the recent modified topography caused by urbanization for this basin.

In this study, reservoir operation strategies and impacts of urbanization on inundation will be analyzed. The reservoir operation scenarios are developed based on two groups, including the current inter-reservoir operation procedures, and the operations according to the flood storage capacity (V_{pl}) of 10, 20, and 30% of the active storage capacity (V_{hi}). These operations scenarios lead to different releases, resulting in different impacts on inundation. The respective urbanization scenarios are simulated with the terrain in 2009 and compared with the terrain in 2020. The flood event selected for simulation is the 2009 flood.

STUDY AREA

With a catchment area of 10,350 km^2, the Vu Gia Thu Bon river basin is one of the largest in central Vietnam (see Figure 1). The basin is formed by two major rivers named Vu Gia and Thu Bon. The two rivers are connected by the Quang Hue river, which has a significant impact on the downstream flow distribution. Furthermore, the downstream river network is linked by numerous tiny rivers and flows into the sea through the estuaries of Song Han, Cua Dai, and Cua Lo, forming a relatively complex hydraulic regime.

This basin is characterized by the highest rainfall in the country. The rainy season lasts from September to December. The average annual rainfall in the basin's highlands is about 3,000–4,000 mm. Approximately 60–76% of the annual rainfall received during the rainy season is the result of hurricanes and storms that cause flooding (Ho & Umitsu 2011). The number of severe floods caused by storms or tropical depressions combined with high rainfall accounted for 49% of the total flood events. According to statistics, the Vu Gia Thu Bon river basin is the most affected by storms and tropical depressions in Vietnam, with about 16% of the total number of storms and tropical depressions entering and directly affecting the basin (Vân 2015).

In this area, overflow of major rivers and tributaries primarily cause flooding, particularly near tributary outlets during peak flood periods. According to statistics, flood catastrophes have severely impacted people in the area throughout the years, with no signs of abating (Satriagasa *et al.* 2014; Luu *et al.* 2015). Since 2010 floods have killed 601 people, collapsed and damaged over 584,000 houses, reservoirs, dams, bridges, and traffic culverts. The total estimated damage is nearly 24,000 billion VND (NDPC 2020). In this case, upstream hydropower reservoirs play a very important role to mitigate the flood impacts. There are four annual regulating reservoirs, including A Vuong, Song Tranh 2, Song Bung 4, and Dak Mi 4. Besides their power

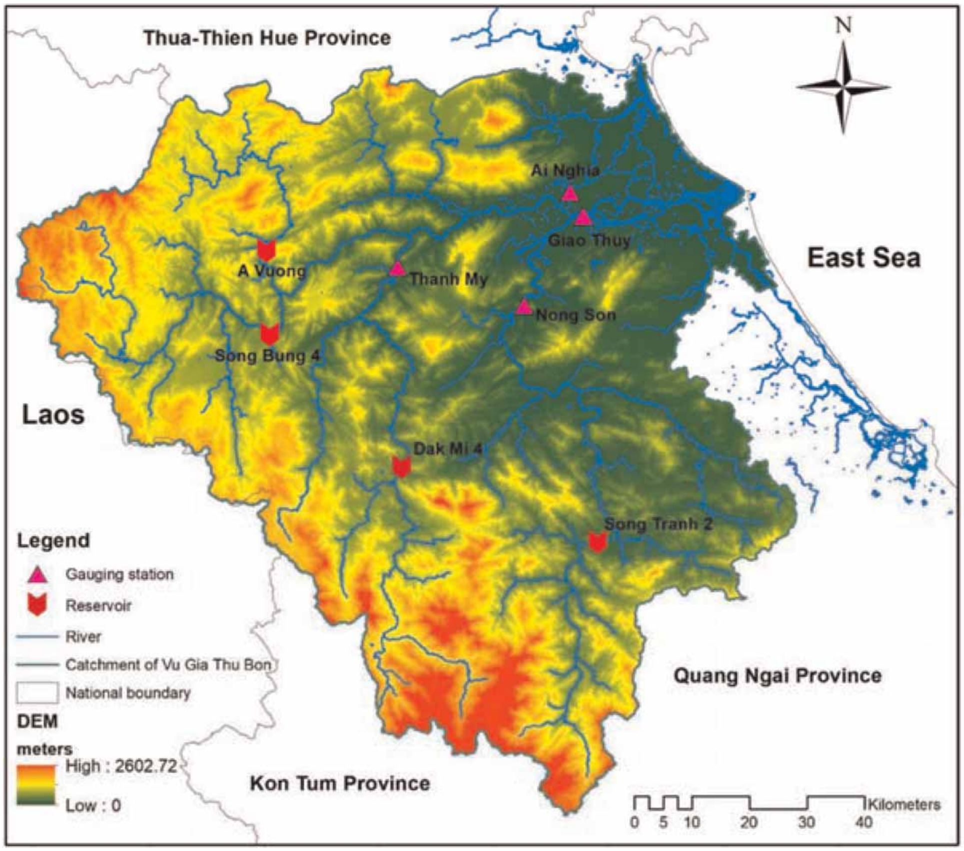


Figure 1 | The study area.

generation purpose, these reservoirs are assigned with the task of flood control for the basin, so they were chosen for the simulations. These four reservoirs also have the largest power generation capacity. The installed capacities of A Vuong, Song Tranh 2, Song Bung 4, and Dak Mi 4 hydropower plants are 210, 190, 156, and 148 megawatts (MW) respectively. Specifications of the reservoirs are presented in Table 1.

In addition, the basin's topography has experienced important changes from 2009 to the present. Many low-lying areas and flood drainage areas were leveled to construct new urban areas because of rapid urbanization. New urban areas, such as Hoa Xuan, Cam Le, Dong No as well as urban areas along the Co Co river, had been established. Several major roads including the Danang–Quangngai highway, the ADB, and the Hoa Phuoc–Hoa Khuong roads have additionally been built to support socio-economic development. The locations of these urban areas and roads are shown in Figure 2. In particular, a part of the

Table 1 | Specifications of the large reservoirs in the Vu Gia Thu Bon basin

Item	Unit	A Vuong	Song Tranh 2	Dak Mi 4	Song Bung 4
Location		Vu Gia river	Thu Bon river	Vu Gia river	Vu Gia river
Catchment area	km^2	682	1100	1125	1448
Mean annual flow	m^3/s	39.8	114	67.8	73.7
Total storage	10^6 m^3	343.6	729.2	312.38	510.8
Retention water level	m	380	175	258	222.5
Dead water level	m	340	140	240	205
Total turbine design discharge	m^3/s	78.4	209.7	121	172.7
Installed capacity	MW	210	190	148	156

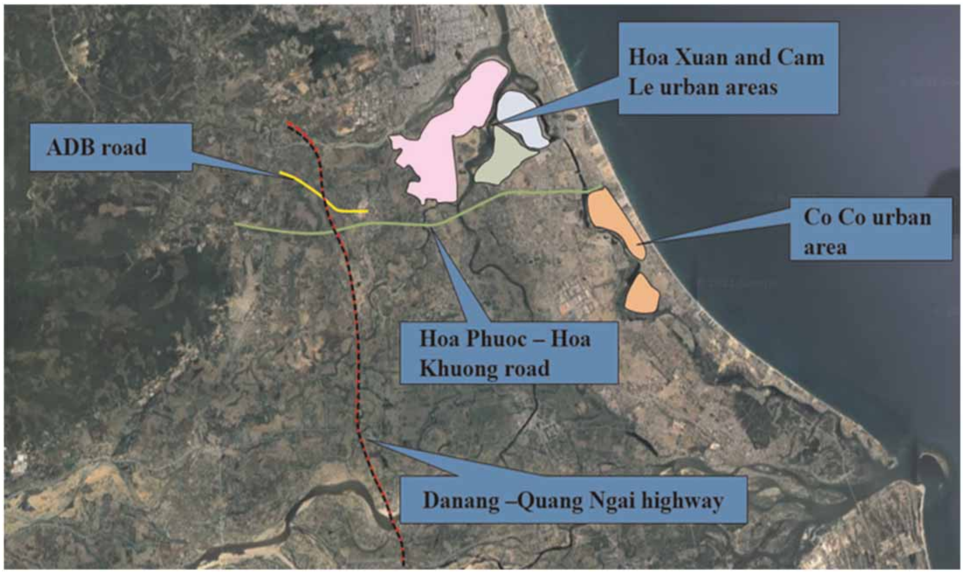


Figure 2 | A map showing the location of new roads and urban areas.

Co Co river that has been dredged (2020) will have a significant impact on flood drainage. In this study, these changes were updated and evaluated.

METHODOLOGY AND DATABASES

Numerical models were used, including the MIKE NAM, HEC-ResSim, and the MIKE FLOOD models. Figure 3 depicts a diagram of research application models.

The river network of the Vu Gia Thu Bon river basin is quite complicated and there are only a few monitoring stations in the basin (see Figure 4). There are two hydrological stations, Nong Son station on the Thu Bon river and Thanh My station on the Vu Gia river, providing flow data measured since 1976. Therefore, some boundaries in the river basin where there is no measured data were reconstructed using the MIKE NAM hydrological model, supported by data measured since 1980 from 17 rain gauge stations and 3 other meteorological stations (Firoz *et al.* 2018).

The HEC-ResSim model was used to simulate different reservoir operation scenarios. Each regulation strategy is a combination of the flow discharge and the initial water level in the reservoir. The outputs of the operating scenarios were then

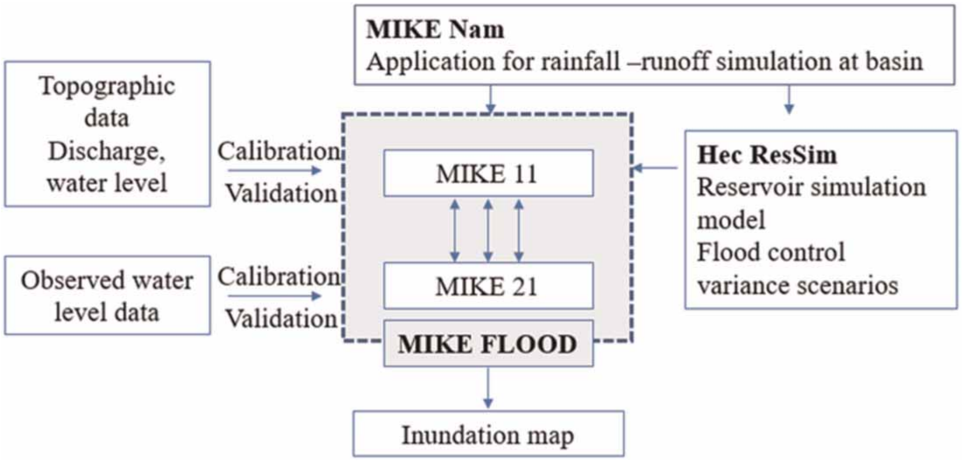


Figure 3 | The diagram of research application models.

employed as upstream boundary conditions in a MIKE FLOOD hydraulic model that simulates flood propagation and inundation processes. The MIKE FLOOD model connects the MIKE 11 and MIKE 21 models.

The time series of hourly discharge, water level, and rainfall of different gauging stations, river cross-sections at various locations, topographical map, and published data related to floods in the study area from various sources were used in this study. Although the floods of 2017 and 2020 were recent and also had significant consequences, they are not considered typical floods. The flood event in 2020, for example, only affected the Thanh My and Nong Son sub-basins. Furthermore, this flood was caused by tropical depressions and heavy rainfall in a short time. The 2017 flood was severe in three sub-basins: Nong Son, Thanh My, and Song Bung 4, but minor in A Vuong sub-basin. The 2009 flood was widespread throughout the basin, with most places suffering floods at a frequency of 5% to 10%. This flood is also considered a typical flood in previous flood simulation studies for this basin (Tran 2013). Therefore, the 2009 flood event is also considered in this study. The hydrological and hydraulic models were calibrated and validated against two flood events in 2009 and 2007.

The digital elevation model (DEM) was compiled from https://earthexplorer.usgs.gov/, together with field visits, and published literature, including the research funded by the Danang City titled 'Assessing the impact of roads and bridges on flood in Danang City' (To & Le n.d.). The topographic database was later updated to the present time. Major roadways (see Figure 2) will have a significant impact on floods in the study area. The sluices on the roadways were also noted and built up in the model for accuracy. There are around 60 sluices, including the Danang–Quangngai Expressway (26 sluices), the Hoa Phuoc–Hoa Khuong road (17 sluices), and the ADB road (16 sluices). The model includes detailed settings for parameters of sluice systems such as elevation, sluice aperture, number of sluice gates, length, and roughness coefficient. Figure 5 shows the location of the sluices on the major roads.

MIKE NAM model

The MIKE NAM hydrological model was used to reconstruct flows for the hydraulic model's boundaries. The 10,350 km^2 Vu Gia Thu Bon basin is divided into sub-basins as shown in Figure 6.

In order to predict flows for upper sub-basins, the authors used the MIKE NAM model combined with the Muskingum method (Gill 1978) in calculating flood propagation to Nong Son and Thanh My stations. The Muskingum method is a hydrological approach that has been used for flood routing for many years due to its simplicity and reasonable accuracy when compared to other methods (Norouzi & Bazargan 2020). The coefficients k and x in the Muskingum equation are determined for each river section and are shown in Table 2.

Flow data measured at Nong Son and Thanh My stations during the 2009 and 2007 flood events were used to calibrate and validate the model, respectively. The results are shown in Figures 7 and 8. The calibration and validation performances were assessed using different performance indices such as coefficients of correlation (R^2) and Nash.

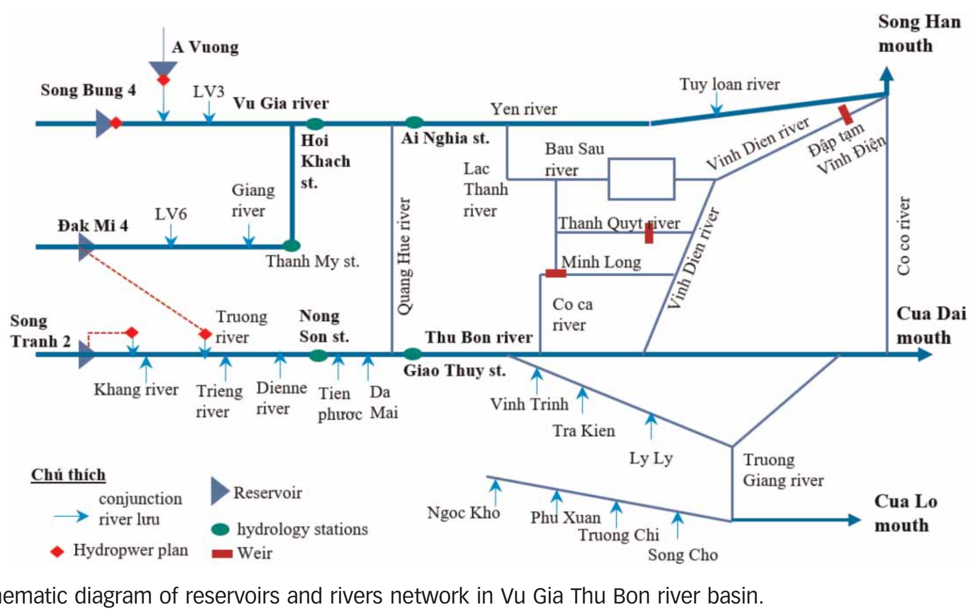


Figure 4 | The schematic diagram of reservoirs and rivers network in Vu Gia Thu Bon river basin.

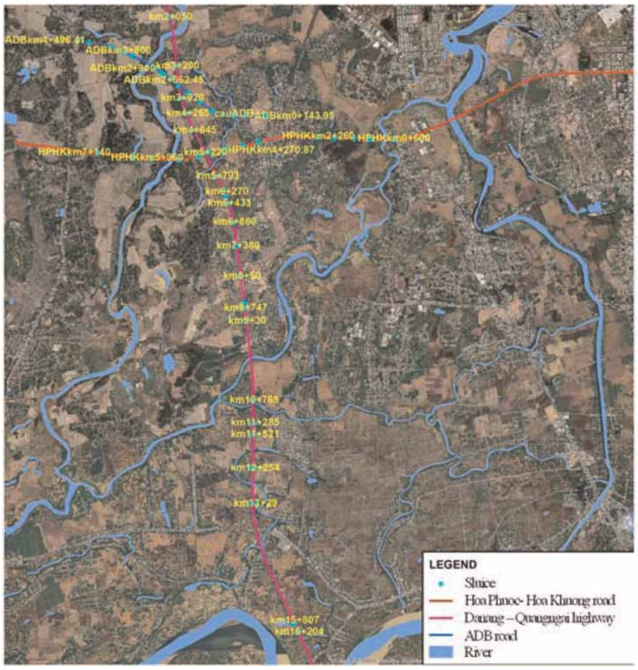


Figure 5 | The location of the sluices on the major roads.

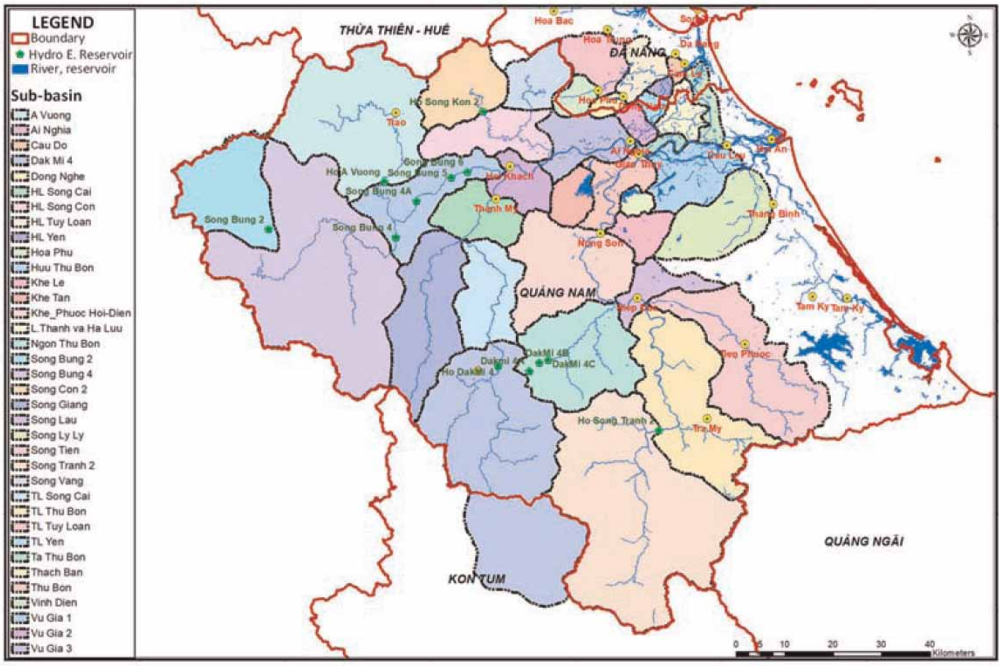


Figure 6 | The sub-basins in the study area.

At Nong Son station, the calibration results for the 2009 flood event show that the simulated values are closely matched with the measured data. The peak and simulated flows were also in close agreement along with their timings. The Nash and correlation coefficients are 0.974 and 0.988, respectively. At Thanh My station, the observed discharge values are slightly higher than the simulated ones. The Nash and correlation coefficients are 0.83 and 0.96, respectively.

The calibration results for the 2007 flood event at the two stations above show that the simulated flow is fairly close to the measured one. The times to peak for the calibration data show a lag of about a couple of hours. The Nash and correlation

Table 2 | The coefficients *k* and *x* in the Muskingum method

No.	River sections	*K*	*x*
1	Tranh 2 river –Truong river	0.8	0.25
2	Truong river – Tum river	2.2	0.25
3	Tum river – Tien river	1.4	0.25
4	Tien river – Trau river	0.7	0.25
5	Trau river – Trieng river	0.6	0.25
6	Trieng river – X river	1.0	0.25
7	X river – Dien Ne river	0.7	0.25
8	Dien Ne river – Nong Son	0.7	0.25
9	Dak Mi 4 – Giang river	1.5	0.25
10	Giang river – Thanh My	1.0	0.25
11	Bung 2 river – SBN2	1.0	0.25
12	SBN2 – SBN3	0.22	0.25
13	SBN3- Bung 4 river	0.25	0.25
14	Bung 4 river+A Vuong – LV3	2.0	0.25
15	Thanh My +LV3- Hoi Khach	2.0	0.25

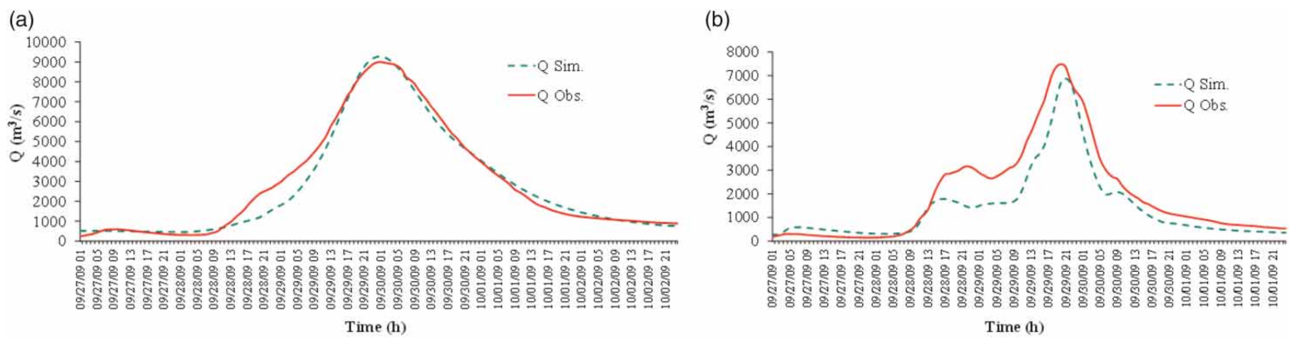


Figure 7 | Calibration of flow in the 2009 flood event at (a) Nong Son, and (b) Thanh My stations.

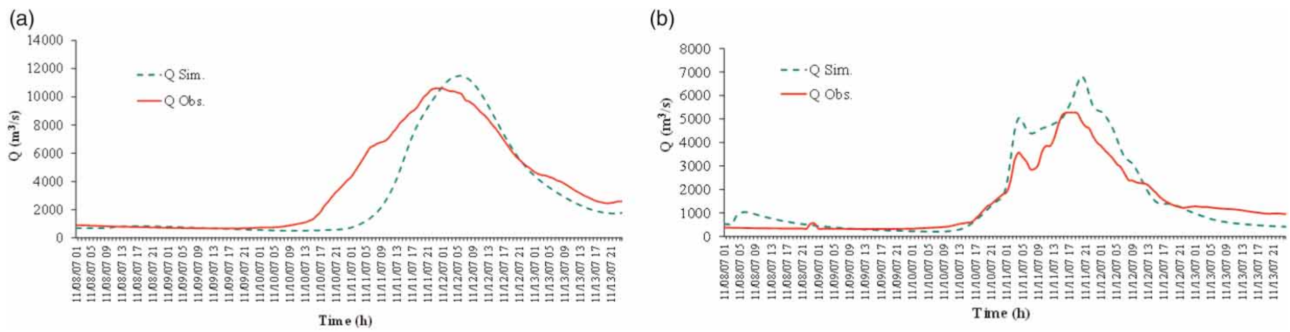


Figure 8 | Validation of flow in the 2007 flood event at (a) Nong Son, and (b) Thanh My stations.

coefficients at Nong Son station are 0.77 and 0.91, respectively. These two coefficients are 0.8 and 0.98 at Thanh My station, respectively. The obtained Nash coefficients and correlation coefficients are at a good level, according to Moriasi *et al.* (2007) hierarchy. Because of these calibration and validation performances, this set of parameters was used to simulate the inflow to the Vu Gia Thu Bon sub-basins, then providing boundary values to simulate the reservoir operations and flooding in river basins.

HEC-ResSim model

The HEC-ResSim model was validated at Nong Son and Thanh My stations for the 2009 flood event, as shown in Figure 9. There is reasonable consistency between the observed and simulated discharges at Nong Son station, whereas there is a slight difference in the time of peak at Thanh My station. The Nash coefficients at the stations are 0.945 and 0.85, respectively. The correlation coefficients are 0.973 and 0.93, respectively. The percentage errors in peak flow at two stations are 3.14% and 1.27%, respectively. These results indicate that the model works reasonably well during validation.

MIKE Flood model

The MIKE 11 and MIKE 21 models were linked together using lateral linkages to form the MIKE FLOOD model, which was used to simulate two-dimensional flood inundations. Whenever overflow occurs in MIKE-11, MIKE-21 calculates the overflow through each cell using the weir formula. The inundation extent and depth of flood for overflow were calculated using MIKE-21 (Kadam & Sen 2012). The MIKE FLOOD model was calibrated and validated for the flood events in 2009 and 2007, respectively. The water levels measured at Hoi Khach, Ai Nghia, and Giao Thuy stations were used to calibrate and validate the model. Figures 10 and 11 and Table 3 show the results of calibration and validation.

The calibration results show a good agreement between the simulated line shape and the measured line shape except for a slight difference that occurs during the recession. However, the peak water level is preserved at the stations, which is crucial in flood modeling studies (Patro *et al.* 2009). The Nash coefficients vary in the range of 0.765 to 0.785, while the R^2 coefficients vary from 0.967 to 0.993. The percentage errors in peak flow at the three stations are less than around 2.5%.

For validation performance, it is observed from Figure 11 that there is a reasonably good agreement between the observed and simulated discharges at Ai Nghia and Giao Thuy stations, whereas at Hoi Khach station there is a slight difference during the recession. The Nash coefficients were found in the range of 0.89 to 0.98, and the correlation coefficient is greater than 0.97 for all the three stations. The percentage error in peak flow is small, ranging from 0.34% to 1.5%.

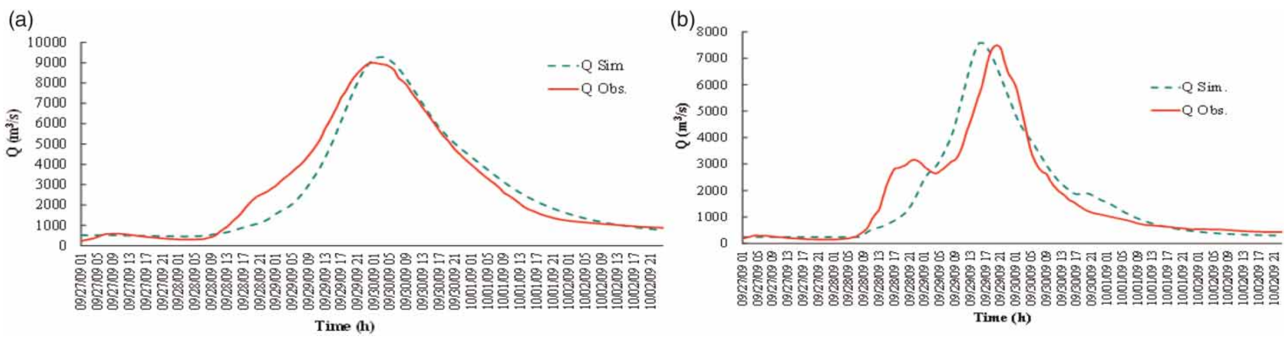


Figure 9 | Validation of flow in the 2009 flood event at (a) Nong Son, and (b) Thanh My stations (HEC ResSim model).

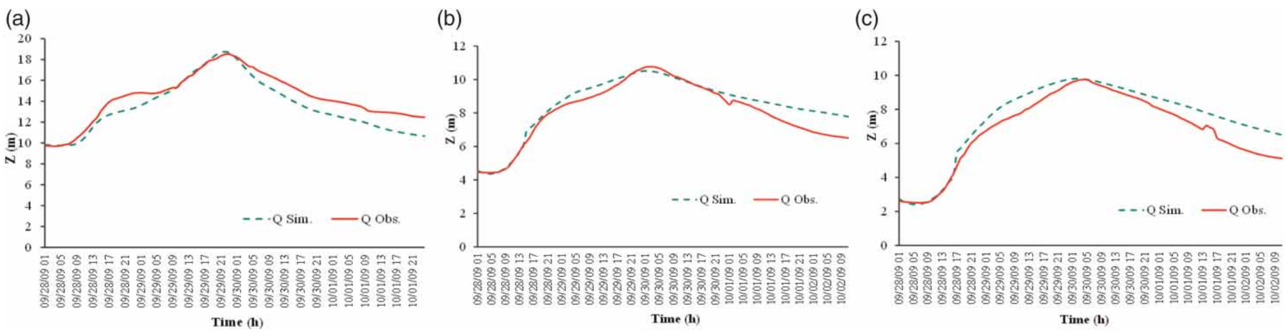


Figure 10 | Calibration of water level in the 2009 flood event at (a) Hoi Khach, (b) Ai Nghia, and (c) Giao Thuy stations (MIKE FLOOD model).

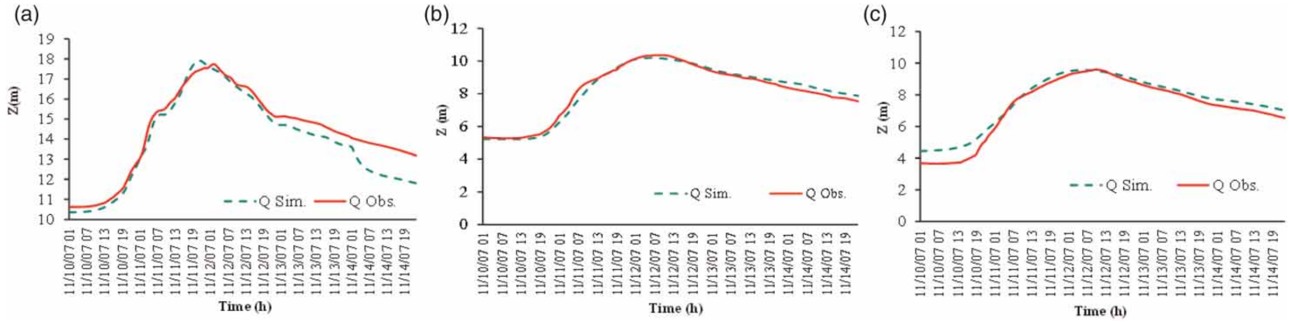


Figure 11 | Validation of water level in the 2009 flood event at (a) Hoi Khach, (b) Ai Nghia, and (c) Giao Thuy stations (MIKE FLOOD model).

Table 3 | Statistics of the peak water level value in calibration and validation

Station	Flood event	Peak water level Obs. (m)	Peak water level Sim. (m)	Error (m)
Hoi Khach	2009	18.53	18.75	0.22
	2007	17.74	17.93	0.19
Ai Nghia	2009	10.77	10.51	0.26
	2007	10.36	10.20	0.16
Giao Thuy	2009	9.75	9.81	0.06
	2007	9.60	9.57	0.03

The MIKE Flood model was additionally validated using investigation of flood traces obtained during the flood event in 2009 (22 values). The locations of flood traces are depicted in Figure 12. The simulated and observed flood traces are shown in Figure 13. Most of the flood traces closely followed the simulation results, but there are also some locations with a difference of 0.5 m (locations of 1, 5, 7, and 12). It should be noted that these flood traces have not only been recorded on flood warning columns (high accuracy), but also several flood traces have been obtained through surveys of living people (low certainty). Large disparities in some locations can be attributed to the above-mentioned data. In general, the calibration and validation results are very well demonstrated through the measurement data recorded at the measuring stations as described above, indicating that the model is reliable.

Simulated scenarios

In order to assess the extent of inundation changes due to different operating modes of upstream hydropower plants and urbanization, different scenarios were defined as shown in Table 4.

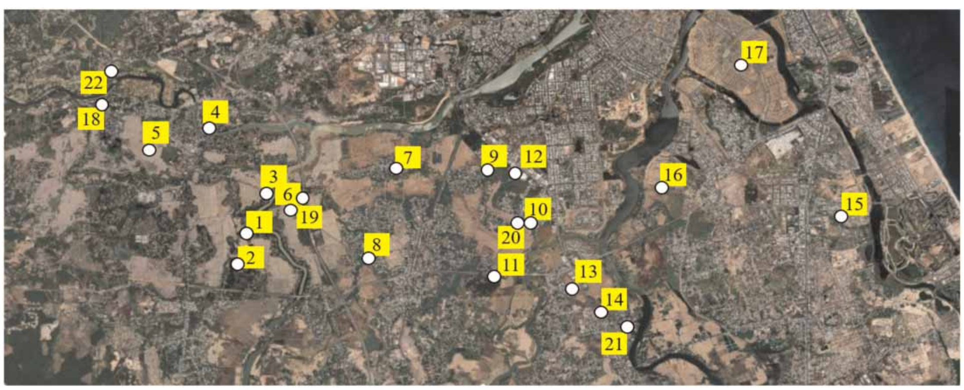


Figure 12 | Location of flood traces of 2009 flood event.

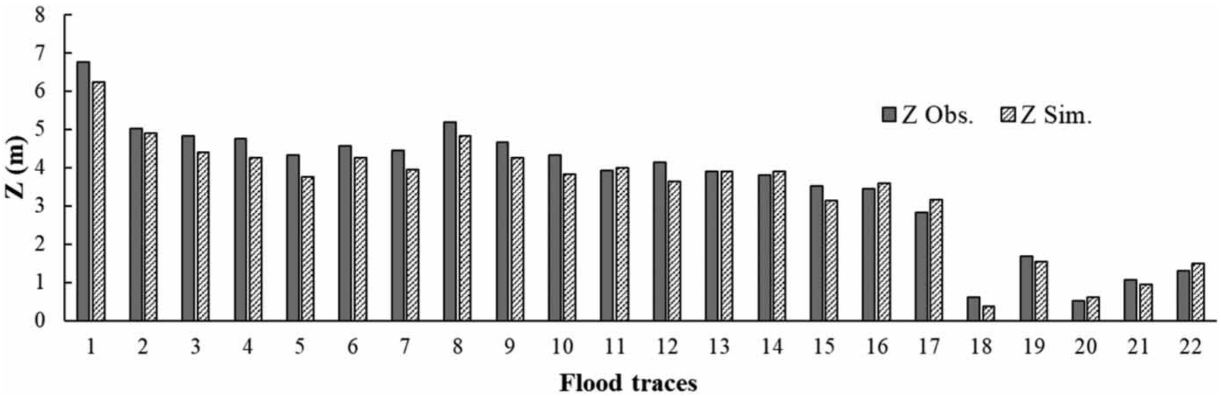


Figure 13 | Comparison of flood traces and simulation results for 2009 flood event.

Table 4 | Simulated scenarios

No.	Scenario	DEM	Reservoir operation
1	KB1A	2009	No
2	KB1B	2009	Yes, inter-reservoir operation procedure
3	KB2A	2020	No
4	KB2B	2020	Yes, inter-reservoir operation procedure
5	KB3A	2020	Yes, V_{pl}=10% V_{hi}
6	KB3B	2020	Yes, V_{pl}=20% V_{hi}
7	KB3C	2020	Yes, V_{pl}=30% V_{hi}

Table 4 shows two categories of reservoir regulation that are simulated and analyzed. In category 1 (scenarios KB1B, KB2B) the reservoirs are regulated pursuant to the present inter-reservoir procedure. It should also be noted that the regulations according to category 1 have the following characteristics: (1) the initial water level is equal to the retention water level; (2) in the 24 hours before the flood peaks occur, the release starts to increase to offer adequate storage to prevent floods. In category 2, the scenarios KB3A, KB3B, and KB3C were determined according to the V_{pl} of 10, 20, and 30% of the V_{hi}, respectively.

Figure 14 shows different operation scenarios of the four reservoirs in the basin. In scenarios KB3A, KB3B, and KB3C, the flood-limited water levels are maintained at different levels, corresponding to the V_{pl} of 10%, 20%, 30% of the V_{hi}. This water level is kept constant before the flood arrives, or in other words, during this time the release is equal to the inflow. When the flood arrives, the release will increase but still be much smaller than the peak flood discharge to ensure flood reduction for downstream. The release will be largest in scenario KB3A and decrease in scenarios KB3B and KB3C. For the KB2B scenario, the reservoirs are required to release earlier to lower the water level and create room to catch floods.

Figure 15 depicts the flow variance at Nong Son and Thanh My stations, corresponding to the above regulation strategies. It can be seen that the reservoirs have significantly reduced peak flood. In scenario KB2B, the flood peak discharge decreases from around 9,200 m^3/s to around 7,800 m^3/s, equivalent to a decrease of 15.2% at Nong Son station. At Thanh My station, the flood peak discharge decreases by 28% for scenario KB2B. The study also shows that the flows at Nong Son station are equal in scenarios KB2B and KB3B.

RESULTS AND DISCUSSION

The impacts of reservoir operation and urbanization on flooding are shown via the inundation maps (see Figures 16–20). These maps are developed based on the superposition of inundation maps between the simulation scenarios. They show where the areas of increased or decreased inundation depth are located. The areas with reduced inundation depth are

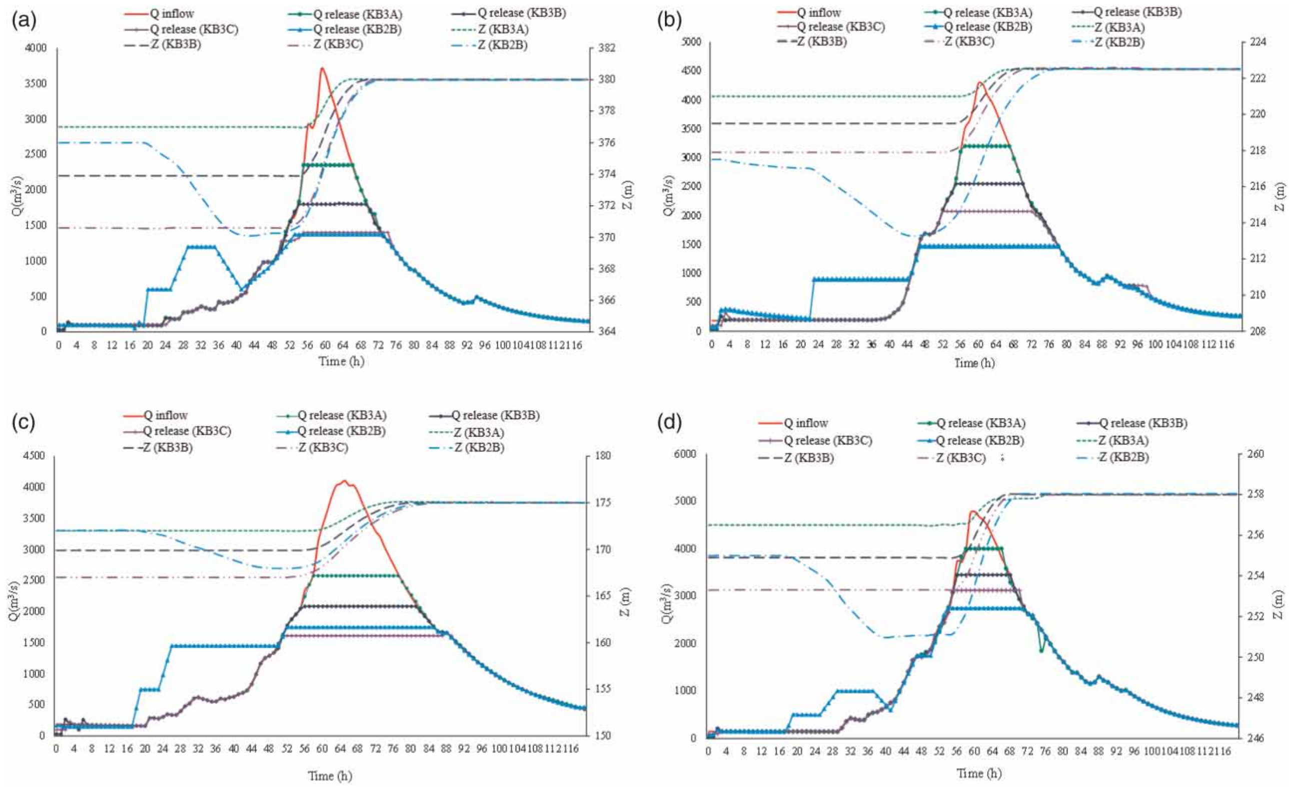


Figure 14 | The discharge and water level time series at the reservoirs under different operation scenarios (a) A Vuong, (b) Song Bung4, (c) Song Tranh 2, and (d) Dak Mi 4 reservoirs.

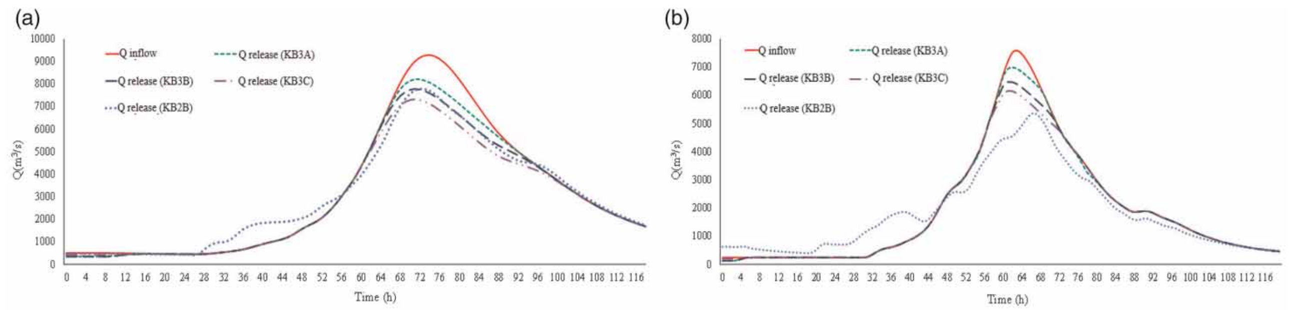


Figure 15 | Discharge time series at (a) Nong Son, and (b) Thanh My stations.

shown in blue, while the areas with increased inundation depth are shown in yellow or red. The flooded areas with increased or decreased inundation depth are also listed in Tables 5–7.

Impact of reservoir operation scenarios on flooding

Figure 16 shows the flood results when comparing the two scenarios (KB2A and KB2B). In the absence of a regulating reservoir, the upstream boundary is a natural flow, so it will cause large-scale flooding. When there are regulating reservoirs, the flow to downstream is reduced, resulting in a deep reduction in inundation. Figure 16 shows that the flooding has decreased in most areas, and there has been no increase in flooding in any location. The areas with reduced inundation depth appear in many places, with the reduction of 0–0.2 m predominantly. Areas with inundation reductions of 0–1 m account for 537.74 km^2 (see Table 5). Areas with a reduced inundation depth of more than 1 m account for 3.16 km^2 and are concentrated in Area 1. This area is frequently inundated by river overflowing due to its low topography and twisting and shallow river segment, which leads to inadequate drainage capacity.

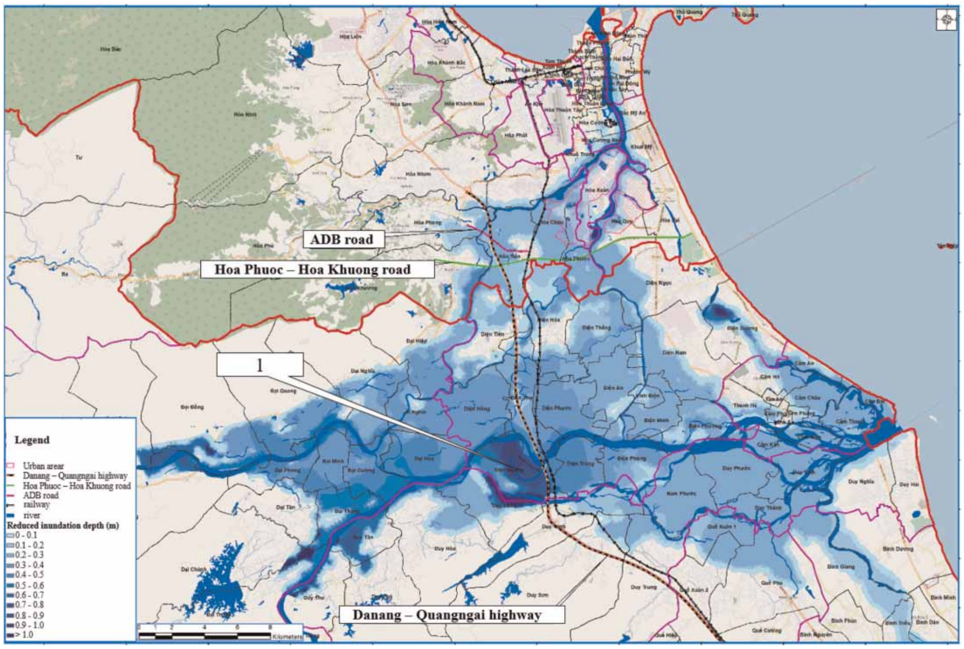


Figure 16 | Map showing locations with increased and decreased inundation depth (results of comparison between the two scenarios KB2A and KB2B).

Impact of urbanization scenarios on flooding

Figure 17 shows the inundation variation due to topographic change when comparing the two scenarios (KB2B and KB1B). The statistics on the surface area corresponding to the variation in inundation depth are presented in Table 6. The results show that there is a large variation in the extent and depth of inundation. The zones with largely reduced flood depth are typically found on the right side of the highway (Areas 1, 2, and 5), of which, the areas with flood depths reduced by

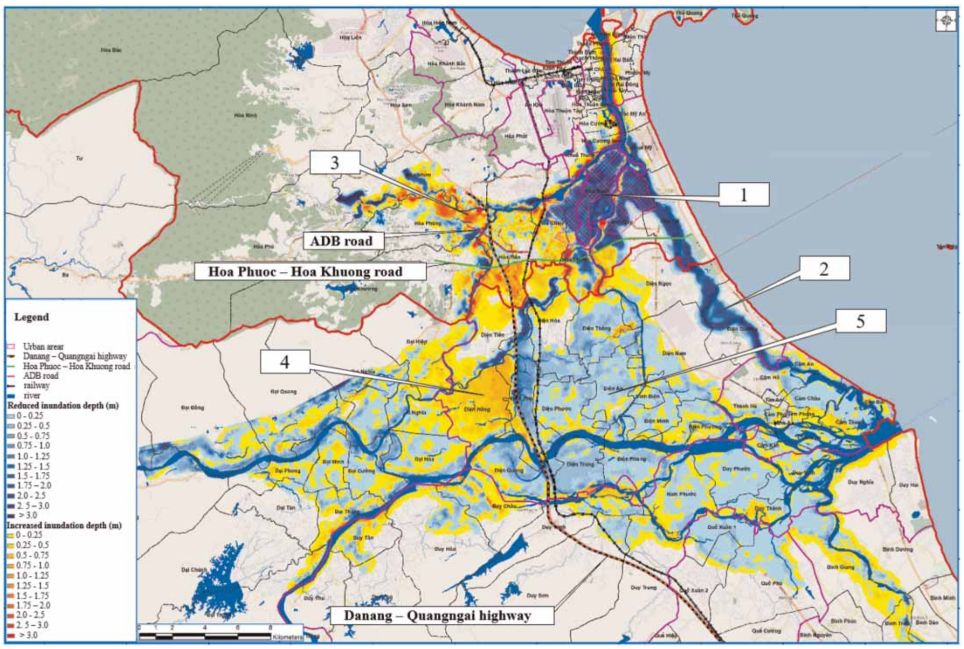


Figure 17 | Map showing locations with increasing and decreasing inundation depth (results of comparison between two scenarios KB2B and KB1B).

0–0.5 m cover 233.19 km^2, which occurs mainly around Area 5. The area with the flood depth reduced by more than 2 m, accounting for 26.62 km^2, is found mainly in Areas 1 and 2. This area has now higher terrain due to urbanization and the construction of urban areas such as the Hoa Xuan urban area and the Co Co riverside urban area. This explains why the flood depth in this area is significantly reduced. In contrast to the zones with flood reduction, the areas facing increased flooding are primarily found on the left side of the highway, in Area 4.

Furthermore, in Area 3 where Hoa Phuoc and ADB roads intersect the expressway, the flood level rises on both sides of the expressway. The inundation increased by more than 3 m in Area 3 and may be due to urbanization in Area 1, where the low-lying areas are now leveled. Because of the elevated topography, flood flow into the Cam Le – Han river has been blocked, creating local water-logging in this area. The above simulation results are completely consistent with reality and the experts' opinions at a workshop in Danang on reducing the risk of flooding due to urbanization when they stated that leveling in the flood drainage area (Area 1) has obstructed water drainage, significantly increasing flood levels in neighboring low-lying communes (Tran 2015). From the above analysis, it is shown that building urban areas with raised foundations will most likely prevent flooding for those urban areas, but may also flood other areas. Obviously, this is a problem that needs to be analyzed overall, including the surrounding areas, to choose an appropriate flood control frequency for all areas. This study will be the basis for policy decisions on smart urban planning in Quang Nam province and Danang City.

In addition to the impact of urban areas, road construction has resulted in a significant change in flood distribution. These roads restrict the flow, resulting in severe flooding on one side and a drastic drop on the other side, as shown in Area 4. The flood depth on the left side of the expressway increased by about 1 m, while it decreased by about 1 m on the right side; the water level difference between the two sides of the road was about 2 m. In Area 3 (the area adjacent to Hoa Phuoc–Hoa Khuong road and ADB road), the increase in flood depth also differs markedly between the two sides of the road.

Impacts of V_{pl} scenarios on flooding

The effects of various operation scenarios for different V_{pl} (KB3A, KB3B, and KB3C scenarios) are shown in Figures 18–20. Statistics on the flooded area and flood depth are shown in Table 7. As V_{pl} increases, the reservoir's storage capacity during floods will increase, reducing downstream flooding. When comparing the inundation maps of all three scenarios (KB3A, KB3B, and KB3C), it is clear that several areas, such as Areas 1, 2, and 3, have changed from flooded to non-flooded. Besides, many areas also have inundation depth reductions. Table 7 shows that in scenario KB3C the flooded area is the smallest, which covers 488.05 km^2 or 4.72% of the basin's total area. The flooded area reduces from 553.11 km^2 to 488.05 km^2 (decrease by 11.8%) as V_{pl} increased from 10% to 30% of the V_{hi}.

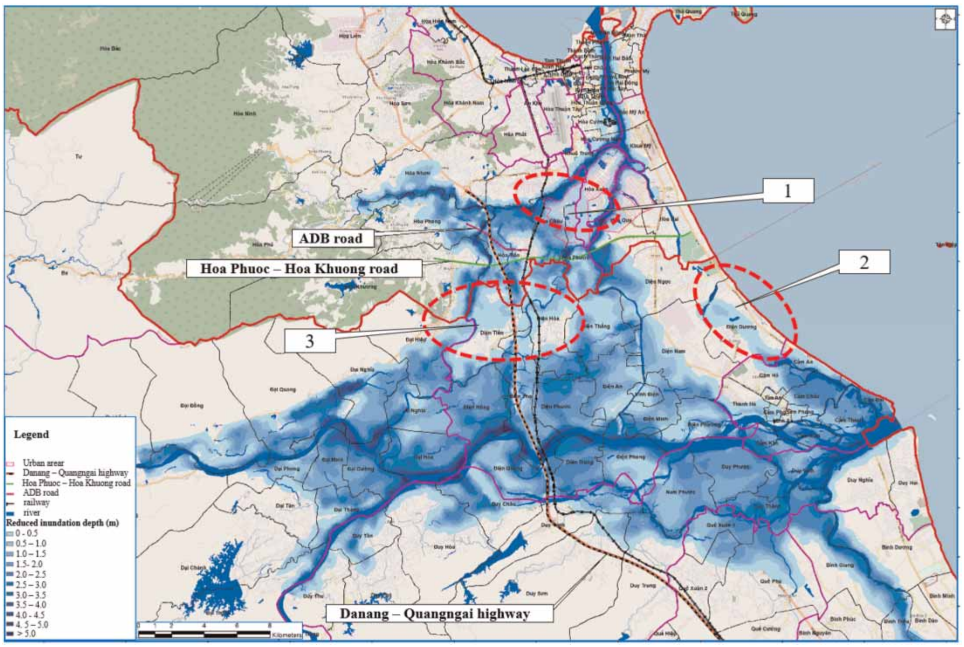


Figure 18 | Flood inundation map (scenario KB3A).

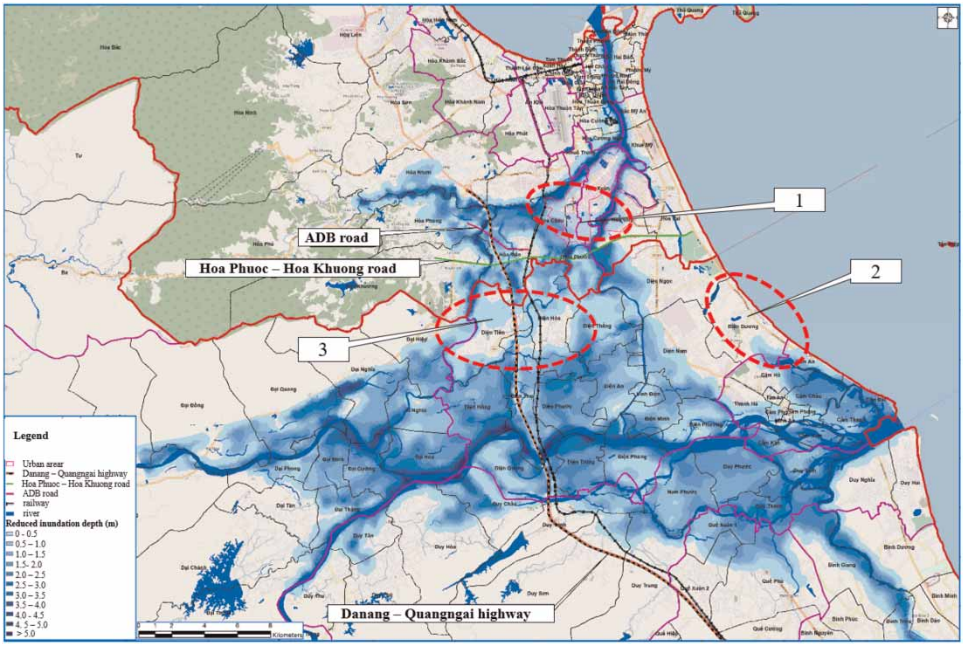


Figure 19 | Flood inundation map (scenario KB3B).

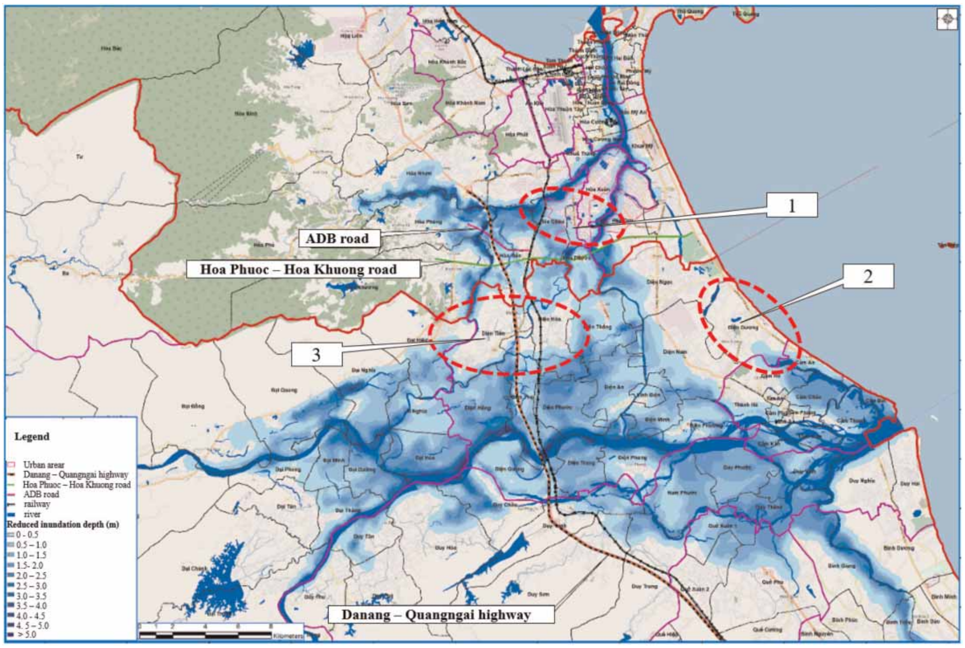


Figure 20 | Flood inundation map (scenario KB3C).

The area with over 5 m flood depth decreases from 6.65 km^2 (KB3A) to 3.28 km^2 (KB3C), making a decrease of about 50.6%. Meanwhile, the area with a flood depth of 1.5 to 5 m decreases from 255.71 km^2 to 150.62 km^2, making a decrease of about 41.1%. In many locations, the depth of flooding decreased from more than 1.5 m to less than 1.5 m, which explains why the area with a flood depth of 0–1.5 m in KB3C increased by 14.9% compared to KB3A. Table 7 also shows that areas with inundation depths ranging from 0 to 0.5 are dispersed, accounting for approximately 1.3–1.5% of the total basin area.

Table 5 | Statistics of areas with reduced inundation depth (KB2A and KB2B)

Level (m)	Area (km^2)	Level (m)	Area (km^2)
0–0.1	87.25	0.6–0.7	6.39
0.1–0.2	69.65	0.7–0.8	5.75
0.2–0.3	214.16	0.8–0.9	4.00
0.3–0.4	84.55	0.9–1	2.81
0.4–0.5	41.78	>1	3.16
0.5–0.6	21.40		
Total (km^2) 540.88			

Table 6 | Statistics of areas with reduced and increased inundation depth (KB2B and KB1B)

Increased		Reduced	
Level (m)	Area (km^2)	Level (m)	Area (km^2)
0–0.25	171.58	0–0.25	141.74
0.25–0.5	61.61	0.25–0.5	40.61
0.5–0.75	25.52	0.5–0.75	21.56
0.75–1	14.61	0.75–1	11.70
1–1.25	8.78	1–1.25	6.13
1.25–1.5	6.14	1.25–1.5	3.99
1.5–1.75	5.75	1.5–1.75	3.09
1.75–2	6.17	1.75–2	2.14
2–2.5	12.56	2–2.5	3.00
2.5–3	9.32	2.5–3	1.83
>3	4.74	>3	4.59
Total area (km^2)	326.79	Total area (km^2)	240.37

Table 7 | Statistics on the inundation area and inundation depth

Level (m)	KB3A	%[a]	KB3B	%[a]	KB3C	%[a]
0–0.5	134.15	1.30	136.35	1.32	155.01	1.50
0.5–1	73.86	0.71	77.25	0.75	86.34	0.83
1–1.5	82.75	0.80	88.58	0.86	92.82	0.90
1.5–2	99.39	0.96	96.96	0.94	70.72	0.68
2–2.5	75.73	0.73	63.58	0.61	37.63	0.36
2.5–3	37.94	0.37	31.58	0.31	16.01	0.15
3–3.5	17.99	0.17	14.55	0.14	10.06	0.10
3.5–4	10.36	0.10	9.49	0.09	8.13	0.08
4–4.5	8.41	0.08	7.83	0.08	5.19	0.05
4.5–5	5.89	0.06	4.87	0.05	2.88	0.03
> 5	6.65	0.06	5.47	0.05	3.28	0.03
Total area (km^2)	553.11	5.34	536.51	5.18	488.05	4.72

[a] Inundation area (km^2)/Total catchment area: 10,350 (km^2).

Water level at downstream stations and flooding duration

The changes in water level at Hoi An, Giao Thuy, Cam Le, and Ai Nghia stations under the influence of the above scenarios are shown in Figure 21.

In the scenarios related to urbanization, the construction of roads and residential areas has led to a large change in flood distribution. Many areas are inundated more deeply, while others saw a reduction in flooding. This is also reflected in the water level of the four stations above. Comparing scenarios KB1B and KB2B, it can be seen that the water level drops at Hoi An, Cam Le, and Ai Nghia stations, while it rises at Giao Thuy station.

In the scenarios related to V_{pl}, increasing V_{pl} from 10% to 30% of the V_{hi} (i.e., an increase of about 105.405 million m^3) leads to a significant decrease in water levels at the downstream stations. Water levels at Hoi An, Giao Thuy, Cam Le, and Ai Nghia stations decreased by 29.5, 6.4, 21.4, and 6.0%, respectively. It is interesting to notice that when regulating with V_{pl}=20% of the V_{hi} (scenario KB3B) and with the inter-reservoir procedure (scenario KB2B), the water level at downstream stations is similar, thus the downstream flooding is almost the same. In terms of water supply capacity, the inter-reservoir regulation (KB2B) produces better results as the water level in the reservoirs is kept higher, and the possibility of water shortage is, therefore, smaller. However, regulation by the inter-reservoir process requires more accurate forecasts to allow timely discharge before the flood arrives.

Figure 21 also shows the water level exceeding Alarm level III (AL-III) which is the value of the water level regulated by the government (Decision No. 05/2020/QD-TTg 2020; Prime Minister 2020). When the water levels are above the Alarm level III, massive floods will happen, putting people's daily lives and livelihoods in jeopardy, as well as endangering their lives and property. The 2009 flood event was a major flood, with the water levels at all stations exceeding Alarm level III and constituting a threat. From Figure 21, it can be seen that the KB3C scenario helps reduce flood the best, even though the water level is still higher than the Alarm level III by 0.03 m and 0.37 m at Hoi An and Giao Thuy stations, respectively, and especially for Ai Nghia station, where the water level exceeds Alarm level III by 1.04 m. In the other scenarios, water levels exceed Alarm level III by 0–1.5 m at the four stations, by 0.74 m, 063 m, 0.36 m, and 1.42 m, respectively, in the current inter-reservoir operation scenario (KB2B). In particular, in the case of no reservoirs (scenario KB1A), the water level at the four stations exceed Alarm level III by 1.26 m, 0.85 m, 0.9 m, and 1.93 m, respectively.

The inundation duration is also an important factor in flood analysis. This factor will undoubtedly have a significant impact on plant, animal, and human resilience. It also has a significant impact on the resilience of flood prevention works, particularly earth-filled embankments and dikes, which are common in Vietnam. Figure 22 shows the period when the water levels at the stations remain higher than the Alarm level III (hereinafter referred to as $T_{BĐ3}$). The longer this period is, the greater the damage. This figure also shows the line graph connecting the average $T_{BĐ3}$ values of the stations.

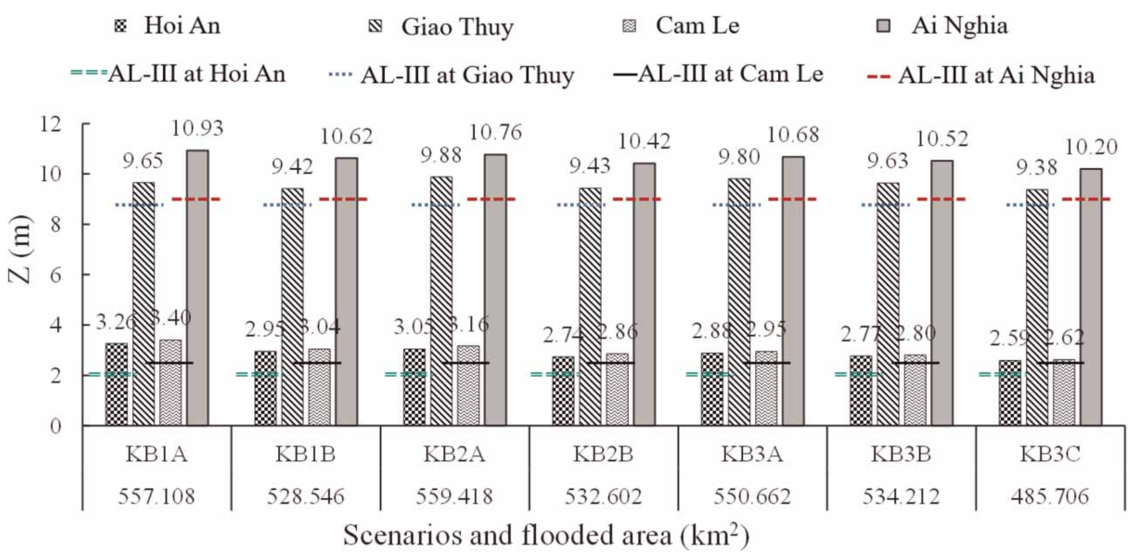


Figure 21 | Water level at the downstream stations corresponding to the simulation scenarios.

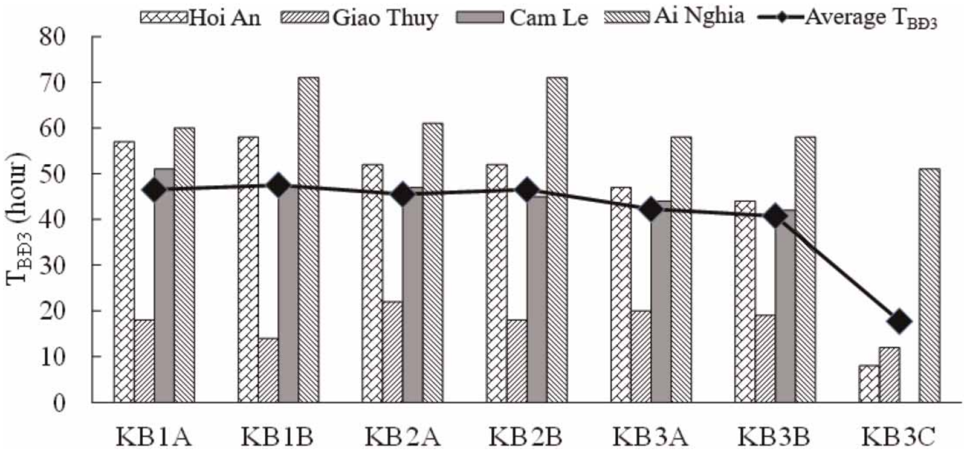


Figure 22 | Duration of water level exceeding the Alarm level III at the stations.

When increasing V_{pl} from 10 to 20% or 30% of the V_{hi} (scenarios KB3A, KB3B, KB3C), the $T_{BĐ3}$ decreases dramatically. The water level in scenario KB3C is even lower than the Alarm level III at Cam Le station. Comparison between scenarios KB1B and KB2B reveals that roads and new urban areas have little effect on $T_{BĐ3}$ at the stations. This is apparent at the Ai Nghia and Cam Le stations. The average $T_{BĐ3}$ value of the stations in the two scenarios above is similar and equal to around 47 hours. Scenario KB2B has a higher $T_{BĐ3}$ than scenario KB3B for most stations, except for Giao Thuy. In other words, from the standpoint of flooded duration, scenario KB2B may cause more damage.

This necessitates considerations while making decisions between operating options KB2B and KB3B. Indeed, in terms of the flooded area, scenarios KB2B and KB3B have similar results. In terms of downstream water supply safety and power output, scenario KB2B is better. However, the longer duration of inundation ($T_{BĐ3}$) in scenario KB2B could result in more damage. It is possible for the decision-makers to select the most suitable solution depending on their interest in flood damage, or power output, or water supply safety.

CONCLUSIONS

The different reservoir operation strategies and the urbanization process had a significant impact on the magnitude and distribution of inundation in the Vu Gia Thu Bon river basin. For the impact of urbanization, the establishment of urban areas increased the flooded area in the surrounding areas with flood depths of more than 3 m. This is an important consideration when developing new urban areas and should be avoided in the future. Furthermore, when new roads are constructed, they must be raised to accommodate traffic during the flood season, thereby limiting flood drainage and significantly altering flooded areas. The difference in water levels between the two sides of the roads might be up to 2 m.

For the impacts of reservoir operation, when V_{pl} increases from 10% to 30% of the V_{hi}, the water levels decrease by 29.5, 6.4, 21.4, 6.0%, at the stations of Hoi An, Giao Thuy, Cam Le, and Ai Nghia, respectively; meanwhile the flooded area decreases by 11.7%. The results also reveal that the current inter-reservoir operation procedure scenario and the V_{pl}=20% of the V_{hi} scenario produce equal results in terms of flooded area. The reservoir operation according to the inter-reservoir operation procedures is considered safe to supply water since the reservoir water level is maintained at a higher level, but the inundation duration is longer, resulting in more damage than the scenario of V_{pl}=20% V_{hi}. The findings of this study will assist authorities in considering damages while making judgments on flood mitigation solutions and noting the corresponding economic losses. Moreover, they will be extremely valuable in improving the current inter-reservoir procedure, which has shortcomings.

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CONFLICT OF INTEREST

The authors declared that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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