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Impacts of climate change and land use change on flood flow in the Ca River basin (Viet Nam)

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Abstract

The Ca River Basin, one of the largest transboundary basins in Viet Nam, located in the North Central region, regularly faces large flood events causing great damage to people's lives and livelihoods. Enhanced extreme rainfall events induced by global warming could increase flood hazards over the basin, yet the risks remain poorly quantified. This study fills some of the research gaps on future flood hazards by providing the first flood risk assessment for global warming levels ranging from 1.5°C to 4°C above preindustrial level, also taking into account the major reservoirs. Changes in flood flow and downstream flooding situation for a typical flood event are simulated with coupled hydrological and hydraulic models. Results show a large increase in flood flow, with a doubling of peak discharge at the upstream stations on the Ca and Hieu river. Consistently, flooding status in downstream areas also presents more severe conditions, with increased depth and extent of the flood. At 3°C of global warming, the total simulated flooded area increases by up to 43% and an additional 24 communes are exposed to flood depths between 1.5–2.5 m. Reservoir inflows to Ban Ve, Ban Mong, and Ho Ho increase by 40–130%, exceeding designated flood storage. We conclude that addressing these challenges will require not only technical innovation but also institutional coordination and long-term strategic planning.

Keywords
Vietnam; Ca River; Heavy rainfall; Flooding; Global warming; Reservoir operation.

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Résumé

Le bassin de la rivière Ca, l'un des plus grands bassins transfrontaliers du Vietnam, situé dans la région du centre-nord, est régulièrement confronté à des inondations de grande ampleur causant de graves dommages aux populations et à leurs moyens de subsistance. L'augmentation des précipitations intenses liée au réchauffement climatique pourrait accroître les inondations dans le bassin, mais les risques demeurent mal quantifiés. Cette étude contribue à combler certaines lacunes de la recherche sur les risques d'inondation futures en réalisant la première évaluation de ces risques pour des niveaux de réchauffement global allant de 1,5°C à 4°C par rapport au préindustriel, en incluant également les principaux réservoirs. Les changements dans le débit de crue et le niveau d'inondation en aval pour un événement typique sont simulés grâce au couplage d'un modèle hydrologique et d'un modèle hydraulique. Les résultats montrent une forte augmentation du débit, avec un doublement du pic de crue dans les stations situées en amont sur les rivières Ca et Hieu. Les conséquences dans les zones en aval sont donc plus sévères, avec une augmentation de la profondeur et de l'étendue de l'inondation. A 3°C de réchauffement global, l'étendue totale de la zone inondée simulée augmente de 43 % et 24 communes supplémentaires sont confrontées à une profondeur d'eau allant de 1,5 à 2,5 m. Les débits entrants au niveau des réservoirs de Ban Ve, Ban Mong et Ho Ho augmentent de 40 à 130 %, dépassant les capacités prévues pour réguler les inondations. Nous concluons que relever ces défis nécessitera non seulement des innovations techniques, mais également une bonne coordination institutionnelle et une planification stratégique à long terme.

Mots-clés

Vietnam, rivière Ca; précipitations intenses ; inondation ; réchauffement global ; gestion des réservoirs.

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1. Introduction

Floods are among the most devastating natural disasters, causing significant loss of life, economic disruption, and extensive property damage. Between 1998 and 2017, floods accounted for 43.4% of recorded disasters worldwide, with 3,148 events impacting 2 billion people and resulting in 142,088 fatalities (CRED & UNISDR, 2018).

Climate change is increasingly recognized as a critical driver of changes in flood dynamics, with intensifying impacts on both the frequency and magnitude of flood events in many regions of the world, including Southeast Asia. Rising atmospheric temperatures have amplified the hydrological cycle, leading to increased evaporation and more intense precipitation events (Trenberth, 2011; Stott et al., 2015). These changes have been linked to the growing prevalence of extreme flood events, particularly in regions already vulnerable to hydrological variability (IPCC, 2022). Coastal regions face dual threats from storm surges and rising sea levels, which have increased the frequency and severity of coastal flooding events (Oppenheimer et al., 2019). Furthermore, land subsidence can magnify these risks in densely populated deltas (Syvitski et al., 2009). Projected changes in climate variability, including enhanced rainfall variability related to ENSO (IPCC, 2021), are also expected to alter regional flood regimes. For instance, Cai et al. (2014) reported that historically, extreme El Niño events are associated with severe flooding in Ecuador and Peru. Climate models also project increases in monsoon precipitation in South, South-East and East Asia and in the central Sahel (IPCC, 2021). The impacts of these changes will be particularly acute in urban areas, where impervious surfaces and inadequate infrastructure exacerbate the effects of heavy rainfall (Hirabayashi et al., 2013).

Research on the impacts of land use and land cover (LULC) change on flooding has highlighted significant alterations in hydrological processes due to human activities such as deforestation, urban expansion, and agricultural intensification. Numerous studies have established that deforestation reduces canopy interception and soil infiltration capacity, resulting in increased surface runoff and peak discharge during rainfall events (Bruijnzeel, 2004 ; Bonell & Bruijnzeel, 2004). Similarly, urbanization exacerbates flood risks through impervious surface expansion, which limits infiltration and accelerates runoff, thereby increasing flood frequency and magnitude (e.g. Huong & Pathirana (2013); Feng et al. (2021)). Conversely, ecosystems such as forests and wetlands play a critical role in flood regulation by enhancing water retention and attenuating flow velocities (Arthington, 2012). For instance, Acuña-Alonso et al. (2024) proposes a methodological framework using the Hydrological Modeling System HEC-HMS model for analysing flood disaster and its relationship to agricultural and forestry land in Umia Basin (Spain) and the Voglajna Basin (Slovenia). The results shows that the increase in agricultural use could increase the peak flow in the two basins. However, the respective contribution of climate change and land use changes on floods depends on the region and time period considered. Hence, for the Sirba catchment (Sahel) land use changes and climate change contributions to the observed increase in flooding are roughly equal (Aich et al., 2015), while for the Schijn River (Belgium) climate change will contribute more than urbanization to increasing peak flows in coming years (Akter et al., 2018).

The Ca River Basin, one of the largest river basins of Vietnam, is located in the North Central region of Vietnam. Floods in the Ca River basin regularly cause great damage to local people and their properties, seriously affecting production and people's lives. Flooding and water resources in the Ca river basin have been documented well. Several studies have investigated the hydrological dynamics and management of the Ca River Basin using advanced modeling techniques and analytical methods. Nguyen et al. (2016) applied the IFAS system with satellite-derived rainfall data to forecast flow from upstream to downstream of the Ca River Basin, achieving a Nash efficiency of 0.7–0.75 and an error range of 6.8–7.5%. Additionally, Nguyen et. al (2018) employed the Muskingum routing method and gradient method to simulate reservoir operations for flood reduction, demonstrating that reservoir systems in the Ca River significantly contribute to flood regulation. Similarly, Nguyen et al. (2020) assessed the impacts of reservoirs on downstream flooding by employing MIKE models, revealing that the Ban Mong and Ban Ve reservoirs have a significant influence on flood levels. Specifically, the downstream water level could increase by up to 1.8 m when Ban Mong reservoir release designed discharge in flood 200-year return period. If Ban Ve releases the discharge corresponding to designed flood (1000-year return period), the water level at Cho Trang station increases by 2.3 m. If Ban Ve and Ban Mong simultaneously release, the change of water level at downstream (Cho Trang station) would rise by 3.4 m. The efficiency of reservoirs in Ca river system is also highlighted in the research of Le (2014) where a simulation module with a GEN algorithm module is used to determine the optimal multi-objective coordination for the reservoir system. More recently, Nguyen (2023) investigated the impact of different future land cover scenarios on the hydrology of the Ca River Basin. Using Markov Chain and Cellular Automata analysis methods integrated with the hydrological SWAT model to project daily discharge changes, they quantitatively assessed the combined impacts of land cover changes and climate change on future river flows. Land use projections suggest that forest land tends to decrease and be converted to agricultural land, construction land, or bare ground. Under these conditions, coupled with climate change, flood flows are projected to intensify downstream, exacerbating flooding, while reduced dry-season rainfall may decrease dry-season flows, increasing the risk of saltwater intrusion into inland rivers. This study focused on future upstream and midstream seasonal flood changes but did not investigate flood changes in downstream areas. Flooding risk was also assessed at the district scale for several typical flood events, considering flood hazard, exposure and vulnerability (IMHEN, 2023).

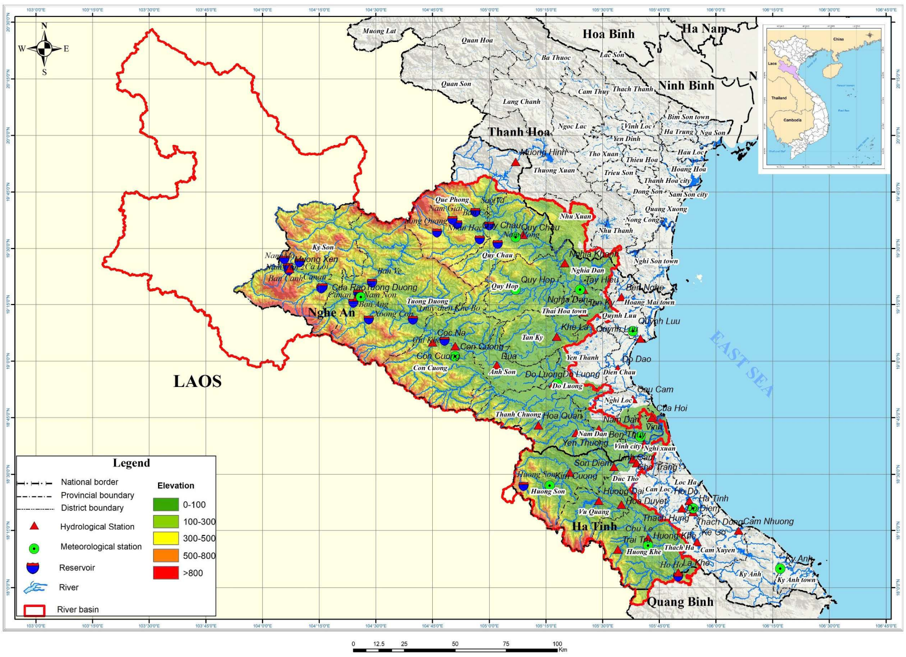
However, so far, no study has provided an integrated assessment of future floods in the Ca River basin for different levels of global warming with explicit reservoir operation analysis. To address this research gap, we investigate the impact of future extreme rainfall changes on flood flow and flooding status at global warming levels of +1.5°C, 2°C, 3°C and 4°C above preindustrial level (1850 – 1900). Specifically, we (i) propagate extreme rainfall changes through hydrologic-hydrodynamic models, using a historical extreme flood event as a baseline; (ii) evaluate two operations scenarios of the Ban Me reservoir for flood regulation. Changes are analyzed by considering the variation of upstream river discharge at different hydrological stations, as well as flooding status in downstream areas. We complement our study with a short assessment of the impacts of land use and land cover changes between 2010 and 2020, provided in Appendix.

2. Study area

2.1. Location and topography

The Ca River Basin (Figure 1) occupies an area of 27,200 km², with 17,900 km² in Vietnam. The river basin is located in Nghe An and Ha Tinh provinces, in the North Central of Vietnam. The river originated in Lao PDR, flowing in the Northwest to Southwest and draining to the East Sea (Tran, 2007). The major tributaries such as Hieu, Giang and La (including Ngan Pho and Ngan Sau streams) rivers contribute most of water resources of the Ca river basin. The average slope of the basin is about 1.83%. The terrain is strongly divided, integrating short and steep rivers which make flooding becomes fiercer and more dangerous. Flood water from upstream quickly concentrates to downstream, accelerating with heavy rainfall and high tide which cause extreme flooding in the river basin.

Figure 1. Map of the Ca River basin



Note: the elevation data (in meters above mean sea-level) are plotted based on a 10,000 scale topography map (IMHEN, 2023). Source: Authors' own elaboration, original.

2.2. Rainfall regime, hydrology and regulation

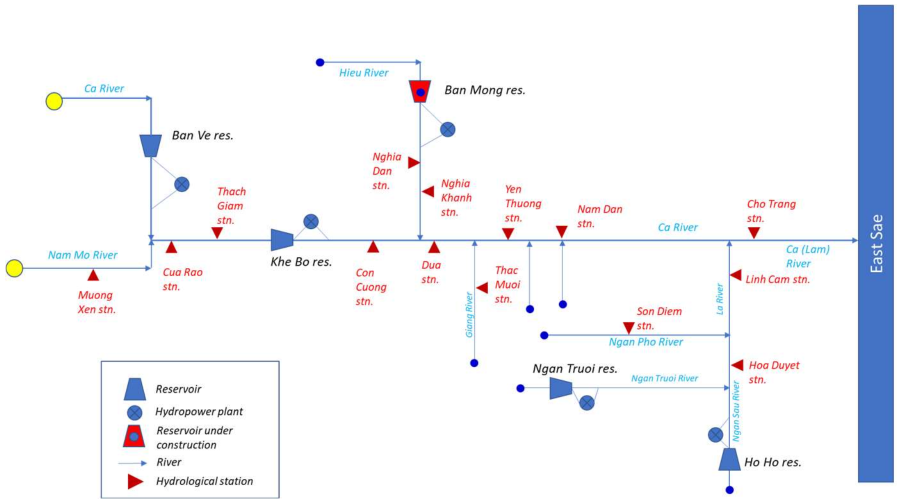
The rainy season in the Ca River basin lasts from May to November with annual rainfall ranging from about 1,100 mm/year to 2,700 mm/year. The average annual rainfall over the basin is high compared to the North of Vietnam but is unevenly distributed. The southwest and south of the basin have the highest annual rainfall amount, with about 2,300 mm/year in the Ngan Sau stream, while in the Muong Xen region annual rainfall is only about 1,080 mm/year. Very wet areas in the Hieu and La tributaries also correspond to steep terrain conditions, resulting in a great hydroelectric potential. Thus, numerous reservoirs have been constructed in the Ca river basin to meet multiple purposes such as hydropower, water supply, irrigation. Eleven of those reservoirs are operated following the inter-reservoir procedure released in Decision No.1605/QD-TTg (2019) (Figure 1). The schematic map of river network, major hydrological stations and reservoirs of the Ca river basin is given in Figure 2.

Flood season usually lasts from August to November due to the occurrence of heavy rainfall during this period. A secondary flood season can appear around the end of May or early June. Due to the strong influence of topography, the flood season varies on the main stream of the Ca River and its tributaries. For example, the flood season in the Ca river is from July to early November in the upstream and to end November in midstream and downstream, whereas in the Hieu tributary the flood season lasts from August to early November. Sometime, floods occur at the same time in the different subbasins, covering the whole area with a very high water level. Big floods occur almost every year (3-year return period).

2.3. Monitoring network

The monitoring network over the Ca river basin includes 15 hydrological stations monitoring water level (Figure 2) – six of them collecting discharge data – and 10 meteorological stations recording weather variables such as temperature, rainfall, evaporation, radiation, etc (Figure 2). Rainfall monitoring also includes automatic gauges, bringing the total number to 19 stations (Decision 90/QD-TTg, 2016).

Figure 2. Schematic map of the river network and major reservoirs in the Ca River basin



Source: Authors' own elaboration, original.

3. Methodology

3.1. Data collection

The data used to assess the impacts of climate change and local anthropogenic changes on flood flow in the Ca River basin, are provided in Table 1. These data include:

- **Meteorological records**: daily temperature and precipitation data recorded at 5 and 10 meteorological stations respectively for the period 1961-2023, representing the weather conditions of river branches of the Ca river basin. In addition, hourly precipitations records at 7 or 8 meteorological stations are collected for 4 flood events (Table 2).

- **Hydrological records:** hourly discharge and water level recorded at stations in typical flood events will be used for hydrological and hydraulic modelling (Table 3).

- **Projections of extreme rainfall changes** at different global warming levels: from the projections of 4 regional climate models (RCMs), forced by 9 CMIP5 global climate models (GCMs) under the RCP4.5 and RCP8.5 scenarios (medium and high global greenhouse gas emission scenarios respectively) for the period 2015-2099 (MONRE, 2020). In total, we consider 28 simulations, corresponding to the combinations of the 9 GCMs, 4 RCMs and 2 RCP scenarios. The projections have been bias-corrected based on observations of 150 meteorological stations in Vietnam (details provided in table A1). The extreme rainfall indices considered are the maximum 1-day rainfall (Rx1day) and the maximum 5-day rainfall (Rx5day) (Pham-Thi-Thanh et al., 2025).

- **Cross-section data** of the rivers of the Ca River basin.

- **Reservoir data:** designs and operation rules of reservoirs in the Ca River basin following the Decision 90/QD-TTg (2016).

- **Topography map:** 1:10,000 scale (~5m resolution) for the Ca River basin (IMHEN, 2023).

- **Soil type and land use maps:** The soil map is extracted from FAO/UNESCO (1988) and classified into four hydrological soil groups (NRCS, 2007). The land use maps developed by JAXA at 30m resolution (JAXA, 2021) are collected for the Ca River basin for the years 2010, 2016, and 2020. The soil and land use map are used to analyze the basin characteristics such as runoff coefficient, infiltration ability, etc. These assessments support the definition of the parameter ranges for MIKE NAM model. These maps also used to calculate the Curve Number (CN), representing flow coefficient, using a lookup table (NRCS, 2007). See Appendix A3.

Table 1. Description and purpose of the collected data.

Type	Description	Period covered	Purpose	Source
Meteorology	Daily rainfall and temperature at meteorological stations	1961-2023	Assessment of long-term climate variability; Calibration and validation of the hydrological and hydraulic models; Extreme rainfall scenario generation	VNMHA
	Hourly rainfall at meteorological stations	Oct 2010, Oct 2013, Sep 2016, Aug 2018	Calibration and validation of the hydrological and hydraulic models; Extreme rainfall scenario generation	
Hydrology	Daily water level and discharge at hydrological stations	1961-2022	Assessment of long-term hydrological variability;	VNMHA
	Hourly discharge at Muong Xen, Quy Chau and Son Diem stations	Oct 2010, Oct 2013, Sep 2016, Aug 2018	Calibration of the hydrological model; Inputs for the hydraulic model	
	Hourly water level at Nam Dan, Linh Cam and Hoa Duyet stations	Oct 2010, Oct 2013, Sep 2016	Calibration of the hydraulic model	
Climate change scenarios	Extreme rainfall projections (Rx1day & Rx5day) from 4 bias-corrected RCMs forced by 9 GCMs under RCP4.5 and RCP8.5 scenarios	1986-2099	Extreme rainfall scenario generation	MONRE, 2020 Pham-Thi-Thanh et al. (2025)
Cross-section	575 cross-sections in 15 river branches	2015	1D hydraulic modeling	IMHEN, 2023
Reservoir data	Design parameters and operation rules		Assessing impact of reservoir	Decision 90/QD-TTg, 2016
Geographical maps	1:10,000 scale maps (approximate 5m resolution maps)	2015	2D hydraulic modeling	IMHEN, 2023
Soil type maps	1:5,000,000 scale Classified into four hydrological soil groups (NRCS, 2007)	1979	Hydrological modeling; calculation of the Curve Number (CN)	FAO/UNESCO (1988)
LULC maps	Developed by JAXA at 30m resolution	2010, 2015, and 2020	Hydrological modeling, calculation of the Curve Number (CN)	(JAXA, 2021)

Table 2. Climatic data at meteorological stations.

No.	Station name	Province	Lat	Lon	Daily mean temperature	Daily rainfall	Hourly rainfall			
							Oct 2010	Oct 2013	Sep 2016	Aug 2018
1	Tuong Duong	Nghe An	19°17'	104°26'	1961-2023	1961-2022	x	x	x	x
2	Tay Hieu	Nghe An	19°19'	105°24'	1961-2023	1961-2022	x	x	x	x
3	Quy Chau	Nghe An	19°34'	105°07'	1963-2023	1962-2022	x	x	x	x
4	Quy Hop	Nghe An	19°19'	105°09'		1968-2022	x	x	x	x
5	Quynh Luu	Nghe An	19°10'	105°38'		1961-2022				
6	Con Cuong	Nghe An	19°03'	104°53'		1961-2022	x	x	x	x
7	Do Luong	Nghe An	18°54'	105°18'		1961-2022				x
8	Huong Khe	Ha Tinh	18°11'	105°43'	1973-2023	1961-2022	x	x	x	x
9	Huong Son	Ha Tinh	18°31'	105°26'		1961-2022				x
10	Vinh	Nghe An	18°40'	105°40'	1961-2023	1961-2022	x	x	x	x

Table 3. Hydrological data at stations.

No.	Station name	River	Water level					Discharge				
			Daily	Oct 2010	Oct 2013	Sep 2016	Aug 2018	Daily	Oct 2010	Oct 2013	Sep 2016	Aug 2018
1	Muong Xen	Nam Mo	1969-2022					1969-2022	x	x	x	x
2	Quy Chau	Hieu	1961-2022					1961-2022	x	x	x	x
3	Dua	Ca	1960-2022					1959-2022				
4	Nam Dan	Ca	1962-2022	x	x	x	x					
5	Cho Trang	Ca	1962-2022									
6	Son Diem	Ngan Pho	1961-2022					1961-2022	x	x	x	x
7	Hoa Duyet	Ngan Sau	1975-2022	x	x	x	x					
8	Linh Cam	La	1962-2022	x	x	x	x					

3.2. Modeling framework

3.2.1. General framework

Climate change impacts on hydrology is well documented in the literature. The common approach to assess these impacts includes three major steps: (1) develop global climate change scenarios using general circulation models (GCMs), (2) downscale the GCM outputs to the scale of hydrological models, (3) simulate the change of hydrological regime under climate change scenarios (Xu et al., 2005). Due to large inter-model spread precipitation projections, it is recommended to use multiple climate models for climate change impact assessments (Haddeland et al., 2011). In this study, we want to evaluate changes of an extreme flood events at different GWLs using ensemble climate change scenarios (MONRE, 2020). The flood event of August 2018 is selected as a typical flood for further assessment.

The study of the effects of climate change and reservoir operation (in particular Ban Ve reservoir) on extreme flooding in the Ca River basin is conducted according to the following steps (Figure 3).

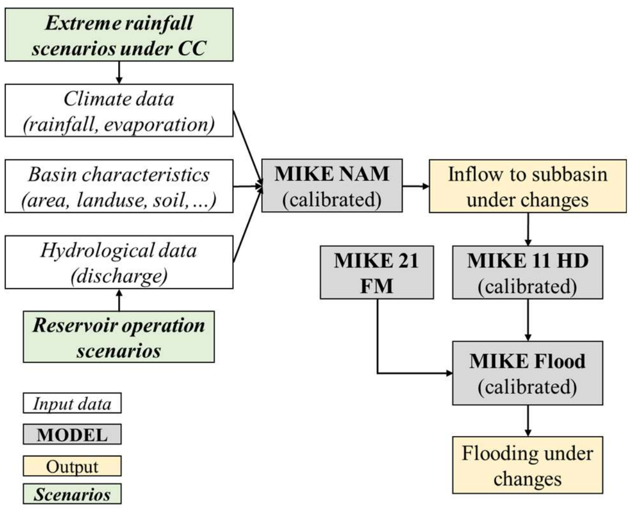
Step 1: Implement and calibrate hydrological and hydraulic models simulating flood flow in the Ca River basin (Figure 3). Flood patterns, including flood peaks and downstream flooding, are simulated using the MIKE package (MIKE NAM, MIKE 11 HD, MIKE 21 FM and MIKE Flood) (DHI, 2014). The rainfall-runoff model (MIKE NAM) is implemented to assess the change of flood flow at upstream hydrological stations under different extreme rainfall projections. The hydraulic model MIKE FLOOD, coupling one-dimensional flow simulation in the rivers with two-dimensional flow simulation in flood plains, simulates flooding situation in the river basin. In the study, implementation and calibration are performed for October 2013 and September 2016 floods.

Step 2: Generate extreme rainfall scenarios for different GWLs. These scenarios are built based on the downscaled climate change scenarios released by Vietnam Ministry of Natural Resources and Environment (MONRE, 2020). The detailed steps are given in Subsection 3.2.2.

Step 3: Simulate flood flow and inundation in the Ca River basin according to extreme rainfall scenarios. The hydrological and hydraulic models are used to achieve flood flow and inundation in the Ca River basin.

Step 4: Assess the impact of climate change on flood flow and inundation.

Figure 3. Flowchart of climate change impact assessment on flooding.



Source: Authors' own elaboration. Original.

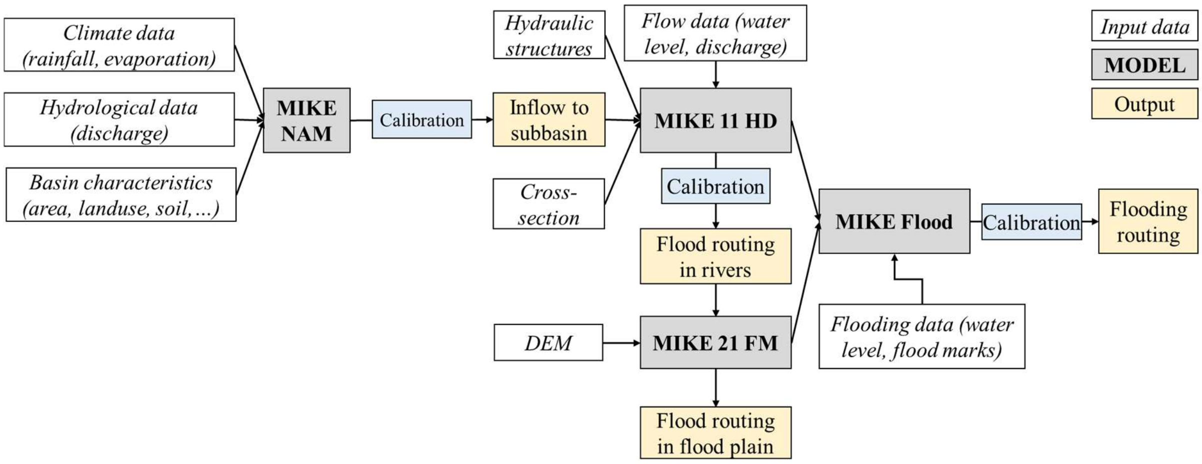
3.2.2. Hydrological and hydraulic models

3.2.2.1. MIKE model package

The MIKE model package used in this study includes MIKE NAM, MIKE 11 HD, MIKE 21 FM and MIKE Flood. MIKE NAM is a deterministic, lumped and conceptual hydrological model that transforms rainfall to runoff in a watershed using four storages, namely snow, surface, root zone and groundwater storages. Nine default parameters describe the surface zone, root zone and ground water storage (see Appendix A.2). The inputs of MIKE NAM model are climatic data (rainfall, evaporation) and basin characteristics (areas, parameters of storages, etc). The MIKE 11 hydrodynamic module (HD) is a one-dimensional hydraulic model that simulate unsteady flows in rivers and estuaries. The module uses an implicit, finite difference scheme to solve Saint-Venant equations (DHI, 2017). This model inputs include hourly river flow (water level and discharge), river cross-sections, hydraulic structures and information of hydrodynamic parameters. The discharges flow is retrieved from MIKE NAM by connecting editor. MIKE 21 flexible mesh (FM) describe the domain topography on a triangulated and unstructured mesh. The module simulates flow on two dimensions by solving two dimensional incompressible Reynolds averaged Navier-Stokes equations with Boussinesq and hydrostatic pressure assumptions. The governing equations represent continuity, momentum, temperature, salinity and density (DHI, 2019). MIKE Flood combines the one-dimensional model MIKE 11 HD and the two-dimensional model MIKE 21 FM into a coupled model that can route flow in both river channels and flood plain.

In this study, the MIKE modules are integrated in a single modeling system to simulate flooding in the Ca River basin. More specifically, rainfall observation (Oct. 2010, Oct. 2013, Sep. 2016, Aug. 2018) and evaporation (assumed to remain stable, at 0.1 mm/day) are provided to MIKE NAM to calculate inflow runoff of the subbasins. These inflows can be assigned as upstream and lateral boundaries in the MIKE 11 HD model. MIKE 11 HD is applied to route flood flow in river system on one-dimensional simulation. The flood plain along major rivers are simulated using MIKE 21 FM. These two hydraulic models are combined in MIKE Flood modeling system. The modelling framework is described in Figure 4.

Figure 4. MIKE package modelling system.



Note: DEM: Digital Elevation Model. Source: Authors' own elaboration, original.

3.2.2.2. *Model calibration*

Calibration processes are implemented for MIKE modules to properly simulate flood in the Ca River basin. The major calibrating approach is Trial-Error in which the best fit parameters are determined by comparing the simulated and observed flood flow at hydrological stations. Nash-Sutcliffe criteria (Nash and Sutcliffe, 1970) is used to evaluate the simulation efficiency of the models (Eq.1). For an ideal model perfectly reproducing observations, Nash-Sutcliffe Efficiency (NSE) would be equal to 1, whereas for the worst model the NSE would be zero.

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_{obs}(t)-Q_{sim}(t)\right)^2}{\sum_{t=1}^{T}(Q_{obs}(t)-\bar{Q})^2} \qquad \text{(Eq. 1)}$$

Where,

$Q_{obs}(t)$ and $Q_{sim}(t)$ are observed and simulated discharges at time *t*, respectively;

$\bar{Q}$ is the mean observed discharge;

T is the total number of time steps of the simulation.

In this study, we consider the flood events of October 2013 and September 2016 to calibrate and validate the hydrological and hydraulic models. For the hydrological model (MIKE NAM), the major parameters of the surface-rootzone bucket and ground water are tuned to make modelled runoff mimics inflow observations during the 2013 flood at Quy Chau and Son Diem stations. The set of parameters is then used to simulate the 2016 flood and validate the calibration. The hydraulic-flooding model i.e. Mike Flood is calibrated using water level data at Nam Dan, Linh Cam and Hoa Duyet stations during the 2013 and 2016 floods. The bed resistances of main channel and flood plain zones are defined to have proper NSE considering flood peak errors.

3.2.3. Future extreme rainfall scenarios

Extreme rainfall scenarios are generated by downscaling the climate change scenarios for the Ca river basin for different global warming levels. The different steps are outlined below.

Step 1: Define the periods corresponding to the global warming levels (GWLs). For each global climate model (GCM) and RCP scenario, GWLs of 1.5°C, 2°C, 3°C and 4°C are defined as the period at which the global mean surface temperature (GMST) exceeds these thresholds compared to the pre-industrial period (1850–1900). Following Hauser et al. (2022), a 20-year period is employed, with the year when the 20-year centered average GMST first reaches the threshold as the central year. For each regional climate model (RCM), the period of a given GWL correspond to the same period as in the forcing GCM (see Table A1). A total of 28 RCM simulations is considered. Then, the climate response pattern for a given GWL is calculated as the average across all models and scenarios that reach that GWL.

Step 2: Retrieve extreme rainfall changes at station level. For this study, we consider two extreme rainfall indices: the annual maximum 1-day rainfall (Rx1day) and the annual maximum 5-day (Rx5day), which corresponds to the annual maximum precipitation in a single day and the annual maximum accumulated precipitation over any 5 consecutive days respectively (in mm). The average values of Rx1day and Rx5day for the baseline period (1986-2005) and the different GWLs, as simulated by the climate models, are obtained at the station level by interpolating data from the four nearest neighbors in the model outputs. We consider the seven meteorological stations with available hourly rainfall data (Table 2), i.e. Con Cuong, Quy Chau, Quy Hop, Tay Hieu, Vinh, Tuong Duong, Huong Khe.

Step 3: Calculate the projected changes of Rx1day and Rx5day compared to the baseline period (1986-2005) (ΔRx1day and ΔRx5day, in %) for each GWL.

Step 4: Select a typical historical rainfall event and determine the maximum daily rainfall and maximum 5-day rainfall ($Rx1day_{obs}$, $Rx5day_{obs}$) during this event, at each station.

Step 6: Combine extreme rainfall projections and historical data to generate future extreme rainfall scenarios. The analysis of rainfall data recorded at the meteorological stations of the Ca River basin shows that more than 50% of the annual maximum 5-day rainfall also contains the annual maximum daily rainfall. We assume that the changes of Rx5day as projected by the climate models corresponds to the changes during a future typical flood event. Hence, future extreme rainfall scenarios are computed as follows:

$$X_{CCmax}(i) = Rx1day_{obs}(i) \times (1 + \Delta Rx1day/100) \quad \text{(Eq.2)}$$

$$X_{CCmax}(j) = Rx5day_{obs}(j) \times (1 + \Delta Rx5day/100) \quad \text{(Eq.3)}$$

Where,

X_{CCmax} is the projected hourly rainfall amount for a future extreme flood event scenario;

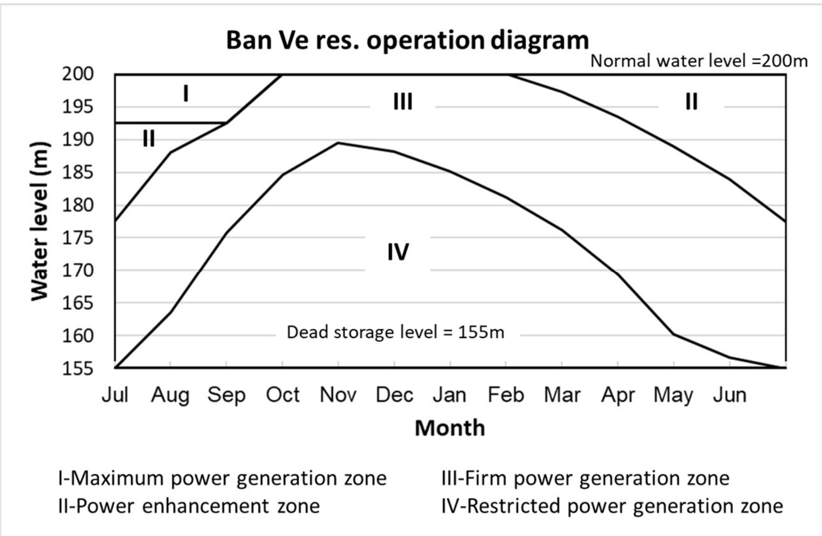
$Rx1day_{obs}$ (i) is the rainfall amount in the i^{th} time step (hour) in the day having the maximum 1-day rainfall during the typical historical flood event. Note that the date of the maximum 1-day rainfall depends on the meteorological station.

$Rx5day_{obs}$ (j) the rainfall amount in the j^{th} time step (hour) in the resting days of the typical historical flood event

3.2.4. Reservoir operation scenarios

Among the eleven reservoirs assigned in the inter-reservoir operation procedure (Decision 90/QD-TTg, 2016), Ban Ve is the largest constructed reservoir, notably contributing to flood control in the Ca River basin. This reservoir spends 300 million m^3 of its total effective storage (1834.6 million m^3) for flood storage during flood season from 1st June to 30th November. Precipitation changes driven by climate change will change the flood flow to the Ban Ve reservoir, and hence impact the reservoir operation and downstream flood control. In this study, we generate operation scenarios for Ban Ve reservoir based on the operation diagram (Figure 5). In flood season, water is released following several rules to ensure flood safety (Decision 0153/QD-BCT, 2011).

Figure 5. Operation diagram of the Ban Ve reservoir



Rule 1: During the early stage of the flood season (1st June to 31st August), water level in the reservoir before flood events is maintained below 192.5m. The total released discharge is not higher than 65% of total inflow to the reservoir. The spillway gates shall be operated in accordance with the procedures specified in Decision 0153/QD-BCT (2011). Reservoir water level shall be 192.5m after flood events. The maximum water level is 200m and water shall not be allowed to overflow the top of the spillway gates under any flood discharge operation

Rule 2: During the main stage of the flood season (1st September to 30th November), water level shall not be higher than the normal level (200m) to ensure the reservoir's safety. In all normal operating scenarios, from the onset of flood inflow to the reservoir until the flood peak, the spillway gates shall be operated in a sequential manner, ensuring that the total released discharge does not surpass the natural inflow into the reservoir. Overtopping of spillway gates is strictly prohibited during any flood release operation.

In this study, we consider 2 operation scenarios:

- **Operation 1**: the actual operation during a typical historical flood event, i.e. the real-time released discharge during the event.
- **Operation 2**: the most beneficial operation rules following the operation diagram, i.e. the proper discharge reanalyzed after the flood event.

These discharges will be the upstream boundaries of the MIKE 11 HD model.

4. Results

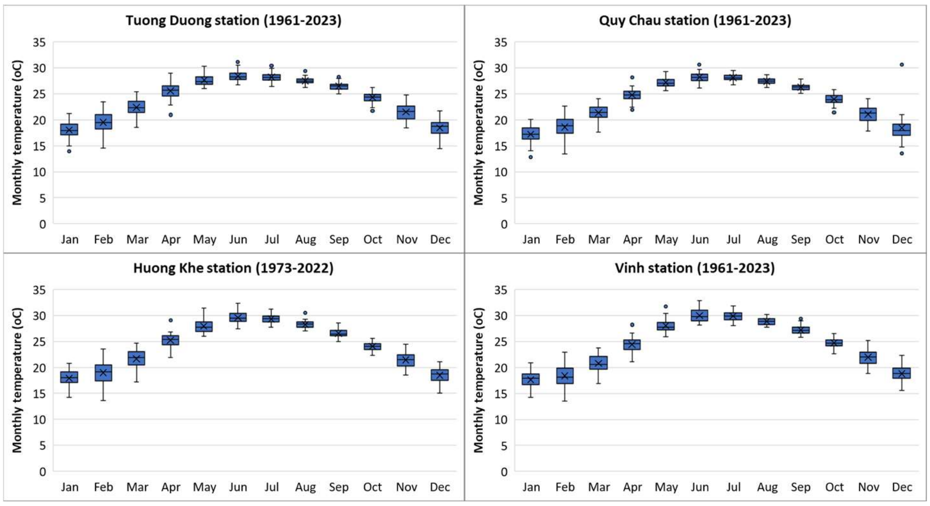
4.1. Historical climate and projections

4.1.1. Average climate and historical trends

In the Ca River basin, the mean annual temperature is around 24°C, with the highest temperature recorded at Vinh station in the urban area and the lowest at Kim Cuong Station in the southern mountainous region.

June and July are the two hottest months while January and December are the coolest months (Figure 6). The average temperature in summer time (May to July) ranges from 27 to 30°C with small variance at Vinh, Kim Cuong and Tuong Duong stations. Monthly temperature variance higher in winter time. January is the coldest month at most of station, with an average monthly temperature often around 15°C at Vinh and Tuong Duong stations and approximately 12-13°C at Quy Chau and Kim Cuong stations.

Figure 6. Seasonal cycle and interannual variability of monthly temperature in the Ca River basin.

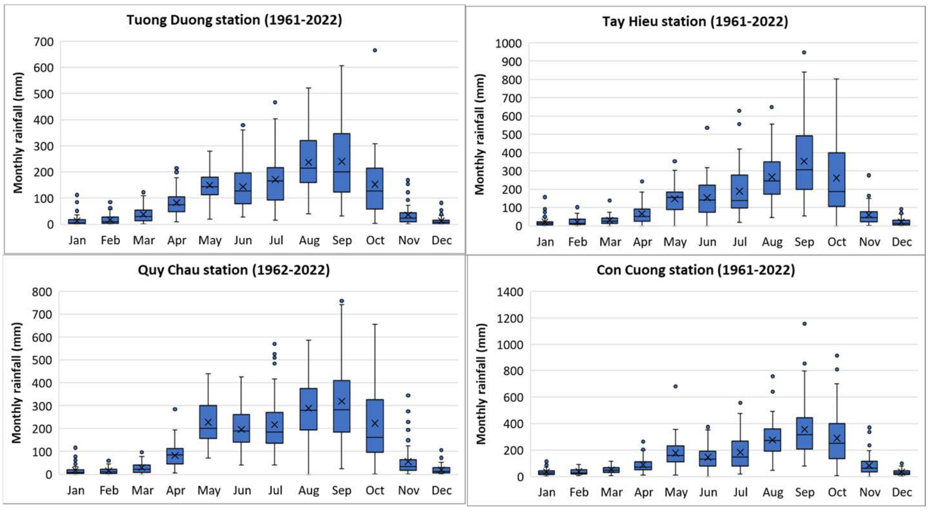


Note: Boxplots visualize the monthly temperature variability, with boxes representing the interquartile range (IQR), horizontal band showing the median, black cross the mean and whiskers extending to the maximum and minimum values (±1.5xIQR). Dots indicate outliers.

Regarding the mean annual rainfall, the basin can be divided into two zones: a drier area in the northwest (Quy Chau and Tuong Duong stations) with an average annual rainfall of less than 2000 mm/year, and a wetter area covering the rest of the basin with annual rainfall exceeding 2000 mm/year. Monthly rainfall patterns are also different in these 2 subregions (Figures 7-8). In the northern region, the highest rainfall amount is recorded in September, with an average value of about 300 mm, while the maximum recorded amount is lower than

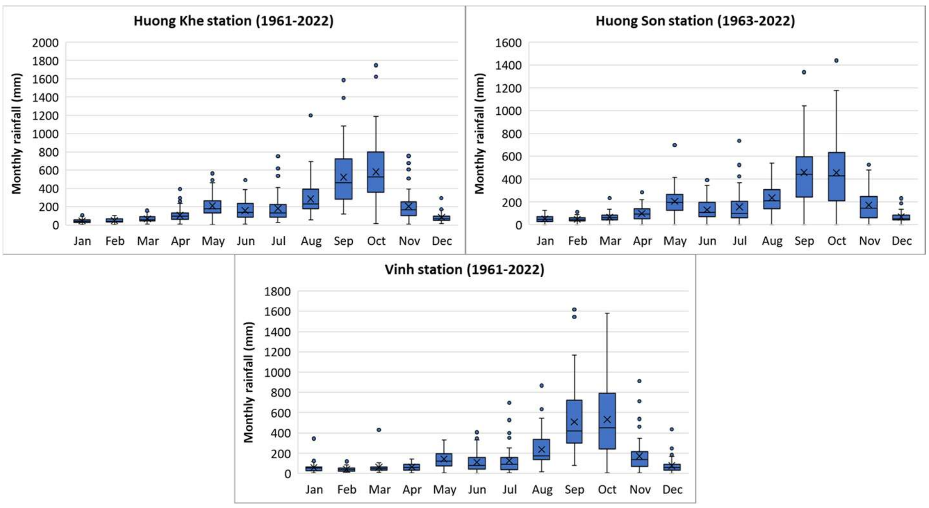
1000 mm. The rainy season lasts from June to October with a minor peak in May (Figure 7). In the southern region, October is the wettest month with average values far exceeding the remaining months, and a large inter-annual variability with extreme values above 1000 mm (Figure 8).

Figure 7. Same as Fig.6 but for monthly rainfall in the northern region of the Ca River Basin.



Note: the box plots are generated by Excel 2019 with Q1=25th percentile, Q2=50th percentile, Q3= 75th percentile, interquartile range (IQR)=Q3-Q1, maximum = Q3+1.5×IQR, minimum=Q1-1.5×IQR.

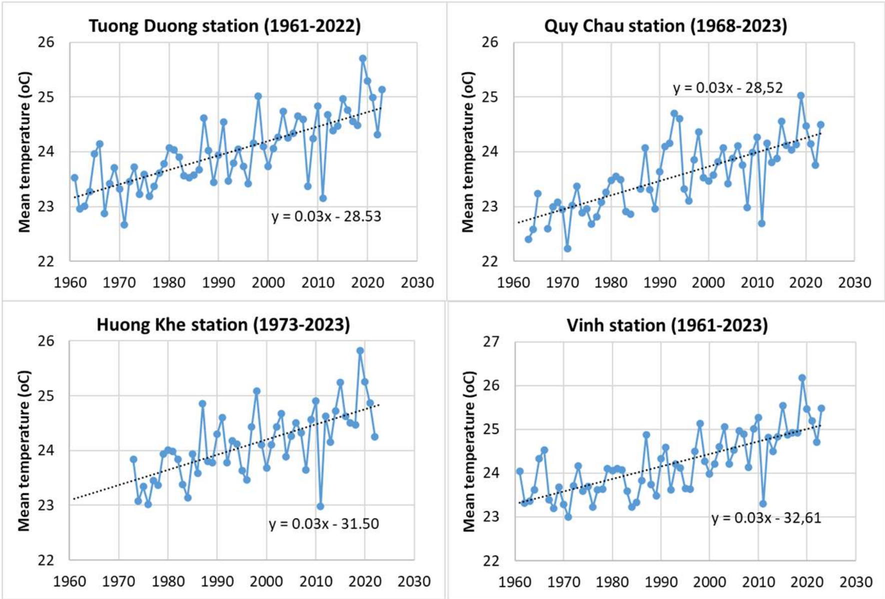
Figure 8. Same as Fig.6 but for monthly rainfall in the southern region and downstream area of the Ca River basin.



Note: the box plots are generated by Excel 2019 with Q1=25th percentile, Q2=50th percentile, Q3= 75th percentile, interquartile range (IQR)=Q3-Q1, maximum = Q3+1.5×IQR, minimum=Q1-1.5×IQR.

Annual temperature records over the last 6 decades indicate a statistically significant warming trend at all stations (t-test, p-values < 0.05), in agreement with the global warming trend (Figure 9). The warming rate is ~0.3°C/decade at all stations. At most stations, 2019 is recorded as the hottest year, with a mean annual temperature of 25-26°C.

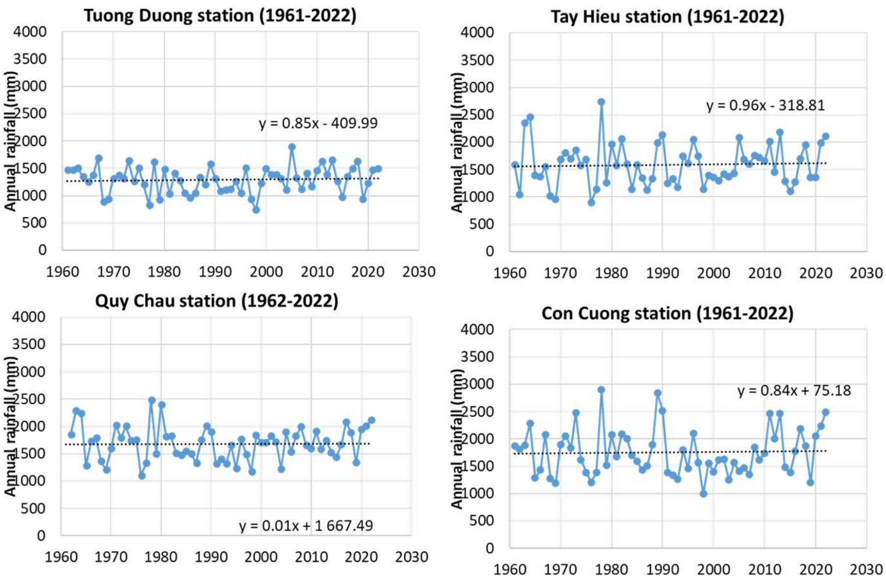
Figure 9. Mean annual temperature recorded at 4 major meteorological stations in the Ca River basin.



Note: Blue line: mean annual temperature (°C); dashed line: linear regression. The equation of the linear regression at each station is provided on the figures.

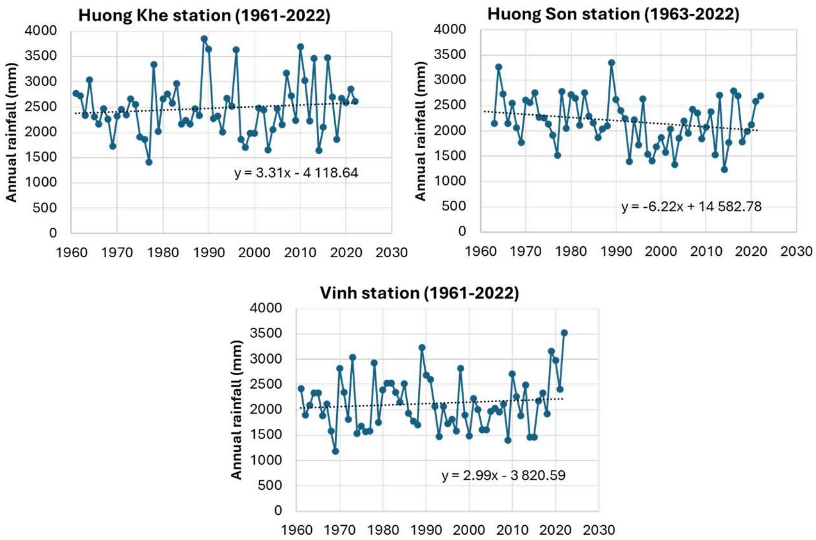
By contrast, no significant trend is recorded for the mean annual rainfall (Figures 10-11, t-test, p-values > 0.05). In the northern upstream region, non-significant increasing trends are observed at Tuong Duong, Tay Hieu, and Quy Chau stations, with rates of only 0.85 mm/year, 0.96 mm/year, and 0.01 mm/year, respectively. In the southern upstream, rainfall shows contrasting patterns: increase at Huong Khe station (+3.31 mm/year) in the Ngan Pho sub-basin and decrease at Huong Son station (-6.2 mm/year) in the Ngan Sau sub-basin, both not statistically significant. In the downstream area, rainfall at Vinh station shows a non-significant increasing trend (+2.99 mm/year), accompanied by high inter-annual variability.

Figure 10. Mean annual rainfall at 4 major meteorological stations in the northern branches of the Ca River basin.



Note: Blue line: mean annual rainfall (mm/year); dashed line: linear regression. The equation of the linear regression at each station is provided on the figures.

Figure 11. Mean annual rainfall at 3 major meteorological stations in the southern branches of the Ca River basin.



Note: Blue line: mean annual precipitation (mm/year); dashed line: linear regression. The equation of the linear regression at each station is provided on the figures.

4.1.2. Extreme rainfall projections from climate models

The projected changes in extreme rainfall indices (maximum 1-day and maximum 5-day precipitation) at different GWLs compared to the baseline period 1986-2005 are calculated as the average across all models and scenarios that reach this GWL. Results are provided in Table 4 for the 7 meteorological stations of the Ca River Basin.

Large increases in Rx1day and Rx5day are projected at all stations. Rx1d (resp. Rx5d) increases range from 11%-29.9% (resp. 19.3%-29.5%) at 1.5°C GWL to 23.4%-49% (resp. 25.8%-48.7%) at 4°C GWL, depending on the station. The largest changes are projected for the Con Cuong station, and the lowest changes at Huong Khe station.

There is a general trend of extreme rainfall increases with higher GWLs. However, this positive correlation is not verified at each station and GWL. At Vinh station for instance, the projected change of Rx5d at 3°C GWL is lower than at 2°C GWL, while at Tay Hieu station projected change of Rx1d at 4°C GWL are smaller than at 3°C GWL, highlighting non-linear precipitation changes.

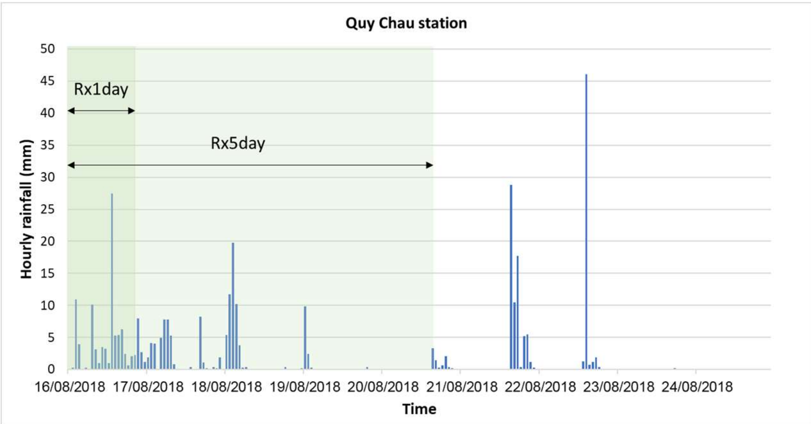
Table 4. Change in extreme rainfall indices(%) projected at meteorological stations level compared to the baseline period (1986-2005).

GWLs	Quy Chau	Tay Hieu	Con Cuong	Tuong Duong	Vinh	Huong Khe
			Rx1day			
+1.5°C	21.0	28.9	29.9	20.1	19.8	11.0
+2.0°C	17.1	29.6	34.2	23.5	27.0	12.1
+3.0°C	23.1	38.1	40.6	28.0	20.7	16.3
+4.0°C	21.8	35.0	49.0	33.4	37.1	23.4
			Rx5day			
+1.5°C	22.1	29.0	29.5	25.0	21.4	19.3
+2.0°C	19.6	31.0	34.1	20.7	31.7	19.8
+3.0°C	27.3	35.8	39.9	32.1	28.5	18.9
+4.0°C	27.3	38.5	48.7	36.3	39.1	25.8

4.1.3. Extreme rainfall scenarios for a typical flood event

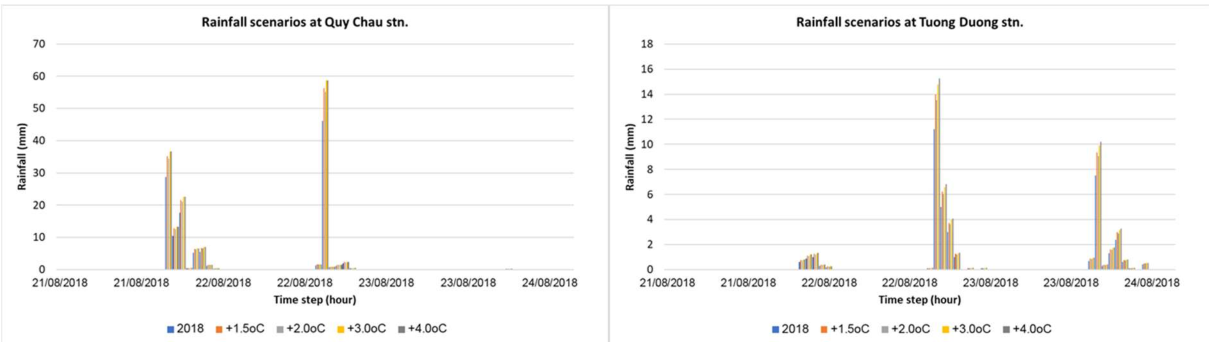
The flood event in August 2018 is selected as typical extreme flood event to generate extreme rainfall scenarios. During 3 days from 16th to 18th August, the total cumulated amount of precipitation in most rainfall gauges was about 100-200 mm on average, but larger values were recorded at Quynh Luu and Quy Hop stations (not shown) where 3-day rainfall amount reached 307 mm and 280 mm, respectively (NCHMF, 2017). This heavy rainfall event caused large flooding in the Ca River basin. In the upstream area, water level[1] at Thach Giam station reached a historical record (71.82m), but water level at Muong Xen station was lower than the historical record (145.34 m in 2011) by 2.16 m. Downstream, the water level was 0.46-0.96 m lower than Alarm Level 3 (24.5 m) and Alarm Level 2 (6.9 m)[2] at Dua and Nam Dan stations, respectively. The hyetograph at Quy Chau station during the flood event is presented on Figure 12.

Figure 12. Hyetograph at Quy Chau station during the flood event of August 2018. Unit: mm/hour.



From the hourly rainfall data during the 2018 flood event and the projected changes of maximum 1-day and 5-day rainfall (Table 4), we calculated the extreme rainfall scenarios for the different GWLs, following Eq.2-Eq.3 (Figure 13 and Table 5). Each scenario covers the period from 16th August to 9th September.

Figure 13. Hourly rainfall (mm) at some stations in the Ca River basin during the 2018 flood event (observed) and for different GWLs (projected).



Note: the figure shows only the days with the maximum rainfall amounts during the period covered by the scenarios (16th August – 9th September).

[1] Water level is defined as the altitude of the water surface compared to the mean sea level.

[2] Alarm levels are defined in Decision no. 05/2020/QD-TTg.

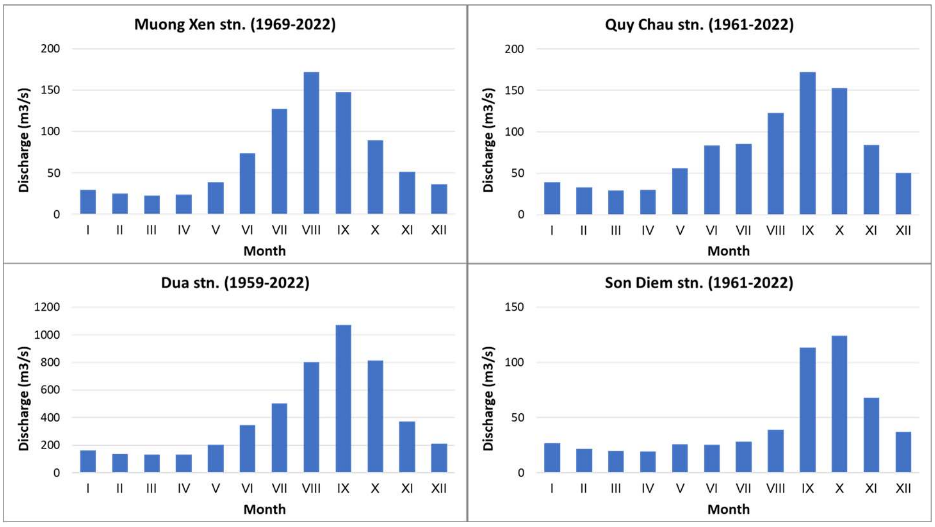
Table 5. Cumulated rainfall amount (mm) at the station level observed during the 2018 flood event and projected at different GWLs.

GWLs	Quy Chau	Tay Hieu	Con Cuong	Tuong Duong	Vinh	Huong Khe
			Rx1d			
Obs. in 2018	101.1	84.1	70.4	96.3	63.1	25.6
+1.5°C	122.3	108.5	91.1	115.6	75.6	30.5
+2.0°C	118.4	110.1	94.3	118.9	80.2	30.7
+3.0°C	124.5	114.2	98.5	123.3	76.2	30.4
+4.0°C	123.2	116.5	104.7	128.4	86.5	32.2
			Rx5d			
Obs. in 2018	215.6	294.5	209.7	221.2	94.2	32.5
+1.5°C	262.1	379.8	272.1	271.7	113.3	38.8
+2.0°C	255.3	382.9	281.3	269.6	121.1	38.9
+3.0°C	270.2	404.7	294.3	288.2	116.1	38.6
+4.0°C	268.9	400.8	312.2	298.6	129.8	40.9

4.2. Hydrological characteristics of the basin

In response to different rainfall patterns over the basin (Figures 7 & 8), flooding season also varies over river branches (Figure 14). In the upstream area, the flood season lasts from July to October at Muong Xen stations, but from September to November in the upstream of the Ngan Pho river (Son Diem station). At the midstream area, the flood season occurs from August to October, with the highest flow in September. In the Hieu River (Quy Chau station), a minor flood season is noticed in June and the major season in August to October. Asynchronous flood seasons across tributaries increase the risk of compound flooding downstream. This complicates forecasting and reservoir coordination.

Figure 14. Average monthly discharge (m^3/s) recorded at hydrological stations.



Flood warnings in Vietnam rely on an alarm system based on water level at hydrological stations. According to Decision No.05/2020, there are three alarm levels corresponding to three warning status based on the characteristics and magnitude of flood water level, as well as on the level of flood impacts on the safety of dikes, river banks, works and people's lives, and socio-economy in the area. Flood events in the La River (including Ngan Sau and Ngan Pho branches) and Hieu River are more severe, with several annual flood peaks over water alarm level 3, the highest alarm level of flood warning (Figure 15). Over the past 5 to 6 decades, the annual maximum water levels in these rivers surpassed alarm 3 by 2.3-3.7 m for 13 to 17 years depending on the station. Consistently with the absence of statistical trends on extreme rainfall indices over the past decades (section 4.1), there is no discernable trends in the annual maximum water level monitored at the different hydrological stations, except at Muong Xen where 3 flood events above level 3 occurred during the period 2006-2020 but none before 2005. Due to flood regulation by the reservoir system, water levels in the downstream area (Nam Dan and Cho Trang stations) remained lower than alarm 3 level over the past 2 decades.

Figure 15. Annual maximum water level at hydrological stations.

4.3. Modelling past and future floods

4.3.1. Calibration of the hydrological and hydraulic models

The calibration process is implemented for the hydrological model (MIKE NAM) and hydraulic models (MIKE 11HD and MIKE Flood). The hydrological model is established for watershed to Quy Chau and Son Diem stations which are the upmost stations of the Ca River's branches. At Quy Chau station, the three flood events in 13-28 October 2010, 14-23 October 2013 and 12–25 September 2016 are selected for calibration and verification. Tables 6 provide the calibrated results. Best fit parameters of the MIKE NAM model are provided in Appendix A.2.

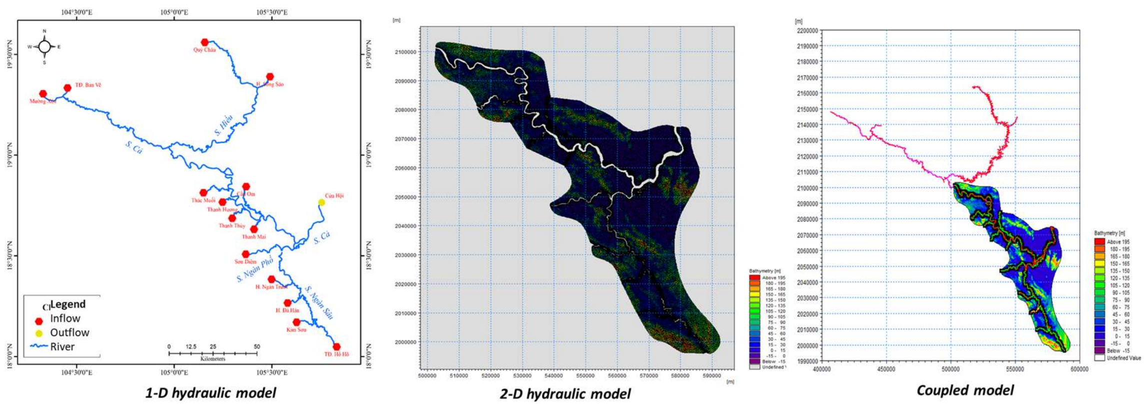
Table 6. Validation results of hydrological model (MIKE NAM).

Station	Process	Flood event	NSE	Flood volume error
Quy Chau	Calibration	13 - 28/X/2010	0.93	0.2%
		12 - 25/IX/2016	0.83	25.1%
	Verification	14 - 23/X/2013	0.75	4.3%
Son Diem	Calibration	13 - 28/X/2010	0.90	16.4%
		12 - 25/IX/2016	0.93	0%
	Verification	14 - 23/X/2013	0.85	20%

Results show that the calibrated hydrological model performs well for the Quy Chau and Son Diem stations. Hydrograph criteria i.e. NSE is higher than 0.75 representing very good performances. The error on the total flood volume presents insignificant difference for the 2010 and 2013 floods at Quy Chau station, while a large error (25%) is simulated for the 2016 flood. This error is mainly attributed to the influence of underestimated initial conditions, which caused the simulated discharge during the early stage of the flood event (before the rising limb) to be lower than the observed values.

At Son Diem station, the best results are obtained for the 2016 flood. However, even if the hydrograph shapes of the 2010 and 2013 floods are close to observations, the total flood volume error is still 16-20%.

Figure 16. Hydraulic model simulating flooding in downstream of the Ca River.



Note: River channels for the 1-D hydraulic model (MIKE 11 HD), with locations of inflow and outflow discharge (left); Topography (in m) of the flood plain in the 2-D hydraulic model (MIKE 21 FM) (middle); coupled model with river channels and floodplain (right). Source: Authors' own elaboration. Original.

Flooding condition downstream are simulated with MIKE Flood (Figure 16). The upstream boundaries are inflow discharge at hydrological stations (Muong Xen, Quy Chau, Son Diem) and sub-basins and released discharge from reservoirs (Ban Ve, Ngan Truoi, Song Sao, etc). The downstream boundary is at Cua Hoi station. The hourly water levels at Nam Dan (Ca River), Hoa Duyet (Ngan Sau River) and Linh Cam (La River) are used to calibrate the hydrodynamic parameters of MIKE 11 HD and MIKE 21 FM models, using the 2013 flood (calibration) and the 2016 flood (validation) (Tables 8-9). Due to time constraints, it was not possible to include flood marks or satellite imagery for model-data comparison and further improvement of the model calibration.

Table 7. Validation results of flood simulation models using MIKE Flood

Station	Nash-Sutcliffe	
	Flood 2013	Flood 2016
Nam Dan	0.88	0.71
Linh Cam	0.97	0.80
Hoa Duyet	0.92	0.54

Note: The Nash-Sutcliffe criteria is computed for the simulated flood flow at hydrological stations. Source: Authors' own calculations. Original.

Table 8. Maximum water level (flood peak) simulated at 3 stations for 2 flood events.

Station	Flood 2013			Flood 2016		
	Hmax obs (m)	Hmax sim (m)	Error (m)	Hmax obs (m)	Hmax sim (m)	Error (m)
Nam Dan	6.72	6.724	0.004	5.65	5.594	-0.056
Linh Cam	5.74	5.759	0.019	5.1	5.554	0.454
Hoa Duyet	11.26	11.272	0.012	10.98	10.09	-0.89

The bed resistance parameter of the rivers and flood plain are tuned to fit the simulated water level with observations at hydrological stations. The calibrated MIKE Flood model shows very high NSE for the flood 2013 (NSE>0.8). The verification simulation for the 2016 flood shows good performances at Nam Dan and Linh Cam stations and acceptable result at Hoa

Duyet station. Simulated flood peak at Nam Dan and Linh Cam meets the observations, with an error smaller than 10 cm, except for the 2016 flood. At Hoa Duyet station, the simulated flood peak error is significant in flood 2016. Despite these limitations, the MIKE Flood model still presents promising capability in flooding simulation in the main river branches and downstream areas. Therefore, the model is acceptable to simulate flood flow in the Ca River basin.

4.3.2. Projections of discharge changes

Using the hourly extreme rainfall scenarios at different GWLs as an input to the calibrated hydrological and hydraulic models (Subsection 0), we assess the resulting changes in peak discharge. In the upstream area, inflows to hydrological stations along the Ca and Hieu Rivers are projected to increase significantly, with the largest changes at Quy Chau station on the Hieu River (Table 10). At the mid-stream station i.e. Dua station, the natural flood peak would increase by 65% at GWL 1.5°C and by 98% at GWL 4°C. However, the flood flow to this station is actually regulated by reservoir operation and therefore differ from the natural flow (see section 4.4). In contrast, a smaller increase is projected at Son Diem station on the Ngan Pho branch. At most stations, flood peaks rise with increasing GWLs, except at Quy Chau station, where the peak change is greatest at 3°C GWL.

Table 10. Flood peak at upstream stations for the 2018 flood event and at different GWLs, as simulated with MIKE NAM.

GWLs	Muong Xen	Quy Chau	Dua	Son Diem
		Peak discharge (m3/s)		
Sim. 2018	617	759	5723	71
+1.5°C	886	1725	9441	82
+2.0°C	905	1715	9583	83
+3.0°C	1029	1927	10794	86
+4.0°C	1136	1890	11341	93
		Changes compared to 2018 (%)		
+1.5°C	43.6	127.3	65.0	15.6
+2.0°C	46.7	125.9	67.4	17.0
+3.0°C	66.9	153.9	88.6	20.8
+4.0°C	84.2	149.1	98.2	29.8

4.3.3. Projections of flood changes

Flooding status in downstream areas are represented by the surface of flooded areas and the number of flooded administrative units. These indicators are analyzed from simulation outputs of the MIKE Flood model. Upstream boundaries at hydrological stations and sub-basins are taken from the output of MIKE NAM for the different GWLs, while for the reservoirs (Ban Ve, Ngan Truoi, Song Sao) we use the released discharge in 2018. The results are shown in Tables 11 and 12 and Figure 18.

Table 11. Flooded areas for the 2018 flood event and for different GWLs, as simulated with MIKE Flood.

GWLs	Flooded depth				Total
	0-1.5m	1.5-2.5m	2.5-3m	>3.0m	
	Flooded area (km2)				
Sim. 2018	102.7	46.6	15.1	4.4	168.9
+1.5°C	124.4	65.3	28.0	11.8	229.5
+2.0°C	124.2	65.6	29.1	12.0	230.9
+3.0°C	126.9	67.9	33.4	13.6	241.8
+4.0°C	126.0	69.5	35.7	14.1	245.4
	Changes compared to 2018 (%)				
+1.5°C	21.1	40.2	85.9	165.7	35.9
+2.0°C	20.8	40.8	93.2	171.2	36.8
+3.0°C	23.5	45.6	121.8	207.2	43.2
+4.0°C	22.6	49.1	137.3	218.6	45.3

Table 12: Number of flooded communes during the 2018 flood event and at different GWLs, as simulated with MIKE Flood.

GWLs	Flooded depth				Total
	0-1.5m	1.5-2.5m	2.5-3m	>3.0m	
	Number of flooded communes				
Sim. 2018	119	74	51	27	119
+1.5°C	123	93	67	40	123
+2.0°C	123	93	67	40	123
+3.0°C	125	98	69	41	125
+4.0°C	125	98	69	41	125
	Change comparing to 2018				
+1.5°C	4	19	16	13	4
+2.0°C	4	19	16	13	4
+3.0°C	6	24	18	14	6
+4.0°C	6	24	18	14	6

Figure 17. Flooding maps of the Ca River basin during the 2018 flood event (left) and at 4°C GWL (right), as simulated with MIKE Flood.

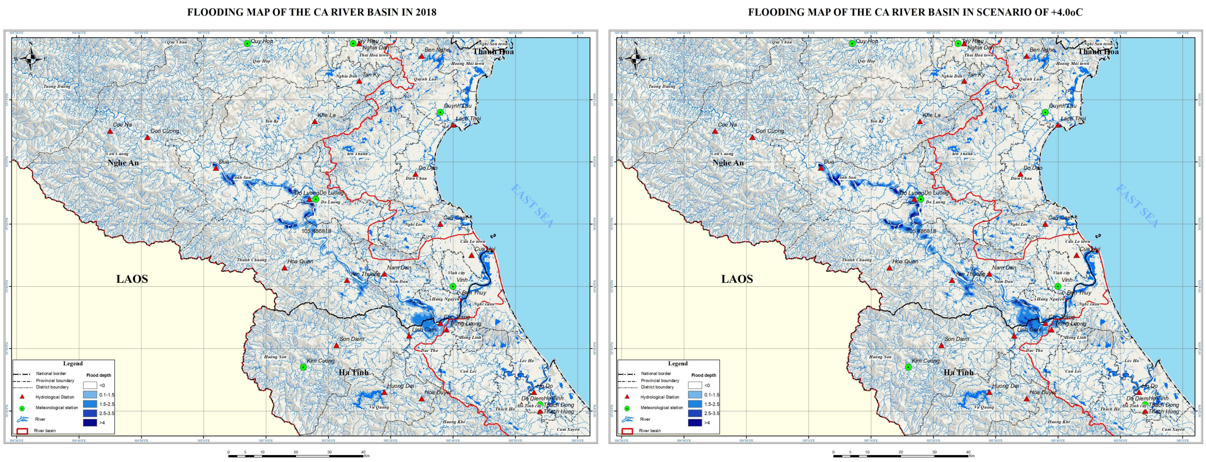


Table 11 shows that the total flooded area under all water levels increases with GWLs, by about 35-45% compared to the 2018 reference simulated flood. However, much larger increases are projected for areas inundated to depths greater than 2.5 meters—approximately the height of a typical house's first floor. This indicates a higher potential for severe flood damage in the future.

Regarding the number of communes affected by flooding, Table 12 illustrates an upward trend at higher GWLs. Notably, the number of communes experiencing flood depths exceeding 1.5 meters—roughly equivalent to human height—shows a significant increase. This trend suggests that downstream flooding is likely to become more extensive and destructive at higher GWLs.

4.4. Impacts of reservoir operations

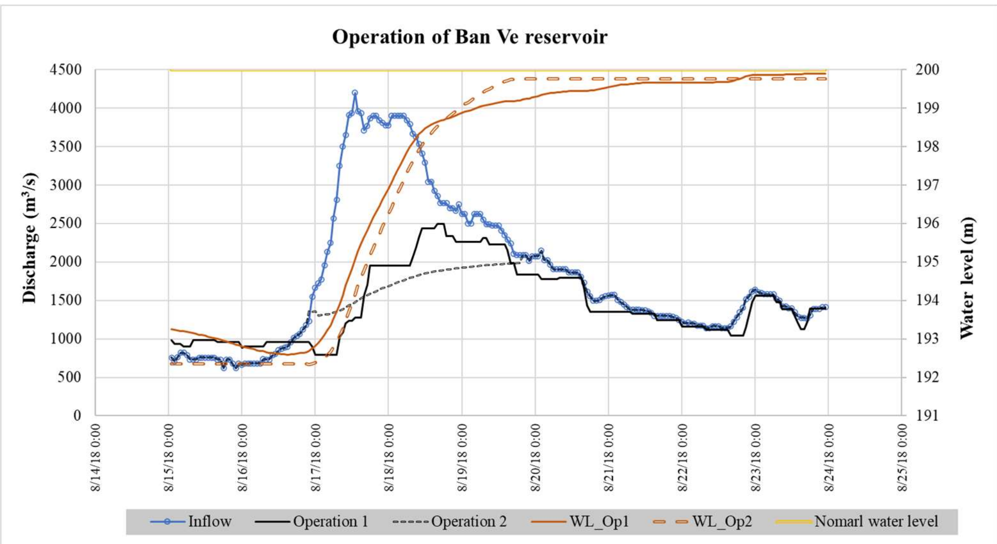
The inflow to major reservoirs in the Ca River basin is projected to increase with GWLs (Table 13). The peak discharge to Ban Ve and Ban Mong reservoir is projected to increase by approximately 40–80% and 110–130%, respectively. In contrast, the changes are much smaller for the Ho Ho reservoir. The total flood volume flowing into the reservoirs under future GWLs also shows a substantial increase — exceeding the flood storage capacities of these reservoirs. This indicates that climate change could have a significant impact on the operational procedures of major reservoirs in the Ca River basin during extreme flood events such as 2018 flood. The increase in flood volume could threaten operational safety of the reservoir and limit their flood regulation capacity.

Table 13. Flood peak and flood volume at 3 reservoirs for the 2018 flood event and for the different GWLs, as simulated with MIKE NAM.

GWLs	Ban Ve	Ban Mong	Ho Ho	Ban Ve	Ban Mong	Ho Ho
		Flood peak (m^3/s)			***Flood Volume ($10^6 m^3$)***	
Sim.2018	1990	1074	5.7	871	501	2.6
+1.5°C	2840	2257	6.3	1153	717	3.0
+2.0°C	2904	2239	6.6	1153	711	3.1
+3.0°C	3303	2511	6.3	1253	759	3.0
+4.0°C	3645	2464	6.9	1319	754	3.2
		Changes in flood peak compared to 2018 (%)			***Changes in flood volume compared to 2018 (%)***	
+1.5°C	42.7	110.2	11.4	32.4	43.1	11.8
+2.0°C	45.9	108.5	15.7	32.4	41.8	16.2
+3.0°C	65.9	133.8	12.0	43.9	51.5	12.4
+4.0°C	83.1	129.4	21.6	51.4	50.6	22.4

The operational scenarios of the Ban Ve reservoir are presented in Figure 18, illustrating the real-time operation during the 2018 flood (Operation 1) and a more optimized alternative (Operation 2). In Operation 1, the peak discharge reached 2491 m³/s, whereas in Operation 2, it was reduced to 2147 m³/s. Additionally, the peak discharge in Operation 2 is delayed by approximately 34 hours compared to Operation 1. This delay helps to prevent the acceleration of downstream flooding.

Figure 18. Operation of the Ban Ve reservoir for the 2018 flood event.



Note: Evolution of: the inflow discharge to the reservoir (blue line); the real-time outflow discharge during the event (black line, Operation 1); the optimized outflow discharge (grey dashed line, Operation 2); the real-time water level in the reservoir (dashed orange line, WL_Op1); the optimized water level in the reservoir (orange line, WL_Op2); the normal water level, i.e. the critical water level in normal operation (yellow line).

Tables 14 and 15 highlight the role of the Ban Ve reservoir in mitigating downstream flooding. While its effectiveness is limited in areas with flood depths less than 2.5 meters, it becomes more significant in regions with flood depths exceeding 2.5 meters. Specifically, the reservoir can reduce the flooded area by 5.7% for depths between 2.5–3.0 meters and by 26.6% for depths greater than 3.0 meters. The total number of flooded communes also decreases when the reservoir is operated according to Operation 2.

However, under increasing GWLs, the effectiveness of the Ban Ve reservoir in reducing downstream flooding diminishes. Both the flooded area and the number of affected communes are projected to rise, with the most substantial increases occurring under the 3.0°C GWL scenario.

The impact of land use changes on flood flow at over 2010-2020 have also been investigated using a hydrological model (see Appendix 2). The results show that land use changes are limited and do not lead to significant changes on flood flow to Quy Chau, Son Diem and Muong Xen sub-basins.

Table 14. Flooded areas for the 2018 flood event under reservoir Operation 1 and Operation 2, and at different GWLs under reservoir Operation 2, as simulated with MIKE Flood.

GWLs	Reservoir operation	Flooded depth				Total
		0-1.5m	1.5-2.5m	2.5-3m	>3.0m	
		Flooded area (km2)				
Sim.2018	Operation 1	102.7	46.6	15.1	4.4	168.9
Sim.2018	Operation 2	115.6	56.9	14.2	3.3	189.9
+1.5°C	Operation 2	112.9	56.3	21.5	7.6	198.3
+2.0°C	Operation 2	122.9	61.8	24.2	9.7	218.7
+3.0°C	Operation 2	123.7	65.2	28.5	11.2	228.6
+4.0°C	Operation 2	116.2	60.6	27.4	9.6	213.9
		Changes compared to 2018 under operation 1 (%)				
Sim.2018	Operation 2	12.5	22.1	-5.7	-26.6	12.5
+1.5°C	Operation 2	9.8	20.9	42.7	71.3	17.4
+2.0°C	Operation 2	19.7	32.6	61.1	118.3	29.5
+3.0°C	Operation 2	20.4	39.8	89.2	152.2	35.4
+4.0°C	Operation 2	13.1	30.1	82.3	116.6	26.7

Table 15. Flooded communes for the 2018 flood event under reservoir Operation 1 and Operation 2, and at different GWLs under reservoir Operation 2, as simulated with MIKE Flood.

GWLs	Reservoir operation	Flooded depth				Total
		0-1.5m	1.5-2.5m	2.5-3m	>3.0m	
Number of flooded communes						
Sim. 2018	Operation 1	119	74	51	27	119
Sim. 2018	Operation 2	116	71	50	23	116
+1.5°C	Operation 2	123	79	58	36	123
+2.0°C	Operation 2	123	90	63	39	123
+3.0°C	Operation 2	125	94	66	39	125
+4.0°C	Operation 2	124	85	63	36	124
Changes compared to 2018 under operation 1						
Sim. 2018	Operation 2	-3	-3	-1	-4	-3
+1.5°C	Operation 2	4	5	7	9	4
+2.0°C	Operation 2	4	16	12	12	4
+3.0°C	Operation 2	6	20	15	12	6
+4.0°C	Operation 2	5	11	12	9	5

5. Discussion

This study assesses changes in flooding patterns in the Ca River basin under four global warming levels (GWLs), from 1.5°C to 4°C above pre-industrial, using hydrological and hydraulic models. Future extreme rainfall scenarios were developed by combining rainfall observations during the flood event of 2018 and an ensemble of 28 climate simulations from 4 regional climate models forced by 9 CMIP5 global climate models under the scenarios RCP4.5 and RCP8.5. The findings reveal a dramatic increase in flood flows to upstream hydrological stations, particularly along the Ca and Hieu Rivers. At Quy Chau station, the simulated inflow flood peak is more than double across all GWL scenarios. In downstream areas, flooding is projected to become more severe and damaging, with the flooded area increasing by up to 45% and 24 additional communes inundated at depths between 1.5 and 2.5 meters.

This study also evaluates the implications of climate change for reservoir operations and the flood control capacity of reservoirs under different GWLs. The substantial increase in inflow to the Ban Ve, Ban Mong, and Ho Ho reservoirs illustrates the significant impact of climate change on future reservoir operations. Although the Ban Ve reservoir currently plays a crucial role in reducing flood peaks downstream, its regulation capacity is projected to decline under intensified hydrometeorological conditions, limiting its effectiveness at higher GWLs.

Our study, however, includes some limitations that should be further investigated in future research:

- **Uncertainties and tail-risks:** the extreme rainfall projections used to build our future scenarios are calculated as the average across all models and RCP scenarios that reach the chosen GWL. But the large inter-model spread in rainfall projections over Vietnam (e.g. Tran-Anh et al., 2025) leads to a high level of uncertainty in future changes of extreme rainfall indices. These uncertainties should be accounted for in future studies to improve the assessment of tail-risks in future floods in the Ca River Basin. More specifically, future studies should select models that perform well over Vietnam and exhibit the most severe extreme rainfall trends to investigate worst-case scenarios. Additionally, our study relies on the projections from dynamically downscaled CMIP5 climate models, which project very large increases in extreme rainfall at higher global warming levels. However, the projections from statistically downscaled CMIP6 models (Tran-Anh et al., 2025) show significantly smaller changes in extreme precipitation. This discrepancy warrants further investigation to reduce uncertainties in extreme precipitation projections and associated flood risks.

- **Return period and frequency analysis:** we have studied the potential changes in flood magnitude using a specific historical event as a baseline. However, climate change can drive changes in both the frequency and intensity of flooding. In addition, some previous studies (e.g. Wasko & Sharma, 2017; Sharma et al., 2018) have shown that extreme precipitation increase does not always lead to more severe flooding. The relationship between heavy rainfall and floods is not linear. In particular, it depends on the river catchment size, the rainfall pattern across the basin and the antecedent soil moisture. The latter depends on both the rainfall regime and the temperature conditions prior the event, both of which will be affected by climate change. For instance, drier soils resulting from warmer conditions and/or increased drought severity during the dry season prior an extreme rainfall event may enhance soil water storage capacity, thereby reducing runoff potential and flood magnitude. On the one hand, climate projections from CMIP6 models suggest that drought intensity over the Ca River Basin may increase above 2°C GWL, but that drought frequency and severity would decrease (Nguyen-Xuan et al., 2025). On the other hand, climate models project an increasing trend in extreme heat events over the basin (Nguyen-Le et al., 2025; Tran-Anh et al., 2025), which would enhance evapo-transpiration. Hence, multi-year hydrological simulations are needed to account for this complexity and assess future changes in 10-, 50-, 100-year flood event at higher global warming levels.
- **Compound flooding:** sea-level at the Ca river estuary is also a critical driver of flood magnitude. On the one hand, global sea-level rise will increase the backwater effect at the river's outlet, decreasing the river flow velocity and potentially increasing flooding risk upstream. On the other hand, extreme rainfall events can combine with storm surge, also increasing flooding risk upstream. Both factors should be further investigated to assess worst-case scenarios.
- **Multi-reservoir operations:** our study focuses on the Ban Ve reservoir. However, multi-reservoir coordination could increase flood regulation capacity in the basin. Quantitative studies testing different operational scenarios for all the major dams would also provide relevant information to revise reservoir operation rules.

6. Conclusion and recommendations

Keeping in mind the aforementioned limitations of our study, we conclude that climate change is likely to amplify flood risks and place increasing pressure on existing hydraulic infrastructure in the Ca River basin. Our findings qualitatively align with the 6th IPCC Assessment Report (AR6), which projects an increase in flood frequency over South-East Asia by the end of the century under all climate scenarios (Caretta et al., 2022). AR6 also states that " *there is high confidence that climate change and projected socioeconomic development would increase exposure in inundation areas resulting in a large increase in direct flood damages*".

Addressing these challenges in Vietnam will require not only technical innovation but also institutional coordination and long-term strategic planning grounded in science. Given these challenges, a number of recommendations are put forward to support adaptive management of water resources in the Ca River basin:

- **Reservoir operation rules should be re-evaluated and revised**, with consideration for climate-induced variability in inflow patterns. Adopting flexible, scenario-based rule curves could improve operational responsiveness during extreme events.
- **Monitoring and early warning systems need to be enhanced**, especially in the upper basin. Incorporating real-time data, satellite observations, and forecasting tools will be essential for timely flood response.
- **Integrated modeling platforms combining physics-based and data-driven methods** should be developed to support both real-time operations and long-term planning. These tools can be embedded in decision support systems to aid in risk-informed management.
- **High-resolution flood hazard mapping under different climate scenarios should be conducted** to inform land-use planning and emergency preparedness, particularly in vulnerable downstream communes. Since there is a large inter-model spread in precipitation projections at higher GWLs, different climate models spanning the full range of projections should be considered, in order to investigate tail risks.
- **Stronger institutional collaboration and data sharing** between hydrometeorological services, dam operators, local governments, and scientific institutions will be critical. Coordinated efforts can help bridge knowledge gaps and support more resilient and informed water management strategies.

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List of acronyms and abbreviations

CMIP	Climate model intercomparison project
DHI	Danish Hydraulic Institute
FAO	Food and Agriculture Organization
GCM	Global climate model
HEC	Hydrologic Engineering Center
IMHEN	The Vietnam Institute of Meteorology Hydrology and Climate change
JAXA	Japan Aerospace Exploration Agency
LULC	Land use/Land cover
MONRE	Vietnam Ministry of Natural Resources and Environment
NRCS	Natural Resources Conservation Service
NCHMF	National centre for hydro-meteorological forecasting
RCM	Regional climate model

Appendix

Appendix A1. Climate models and scenarios

In this study we use the outputs from 5 regional climate models (RCMs) (AGCM/MRI, PRECIS, CCAM, RegCM, and CLWRF), forced by 9 global climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) under Representative Concentration Pathways (RCPs) scenarios RCP4.5 and RCP8.5 (MONRE, 2020). The RCP4.5 corresponds to a medium range global emissions scenario, leading to a global warming of ~3°C by 2100, while the RCP8.5 corresponds to a high emission scenario, leading to ~4.5°C of warming by 2100 compared to 1850-1900 (IPCC, 2014). The list of the 28 GCM-RCM climate simulations is provided on Table A1. This ensemble allows to capture both model variability, scenario and structural uncertainty, critical in monsoon regions.

Table A1. List of the different regional climate models (RCMs) and forcing global climate models (GCM), the RCP scenario available for each model and the 20-year period when the simulated global average temperature reaches the different global warming levels (GWLs).

No.	GCM	RCM	RCP scenario	GWL 1.5°C	GWL 2°C	GWL 3°C	GWL 4°C
1	CCSM4	CCAM	RCP4.5	2008 - 2027	2030 - 2049	-	-
2			RCP8.5	2005 - 2024	2021 - 2040	2048 - 2067	2068 - 2087
3	CNRM-CM5	CCAM	RCP4.5	2028 - 2047	2050 - 2069	-	-
4			RCP8.5	2022 - 2041	2036 - 2055	2058 - 2077	2078 - 2097
5		PRECIS	RCP4.5	2028 - 2047	2050 - 2069	-	-
6			RCP8.5	2022 - 2041	2036 - 2055	2058 - 2077	2078 - 2097
7		RegCM	RCP4.5	2028 - 2047	2050 - 2069	-	-
8			RCP8.5	2022 - 2041	2036 - 2055	2058 - 2077	2078 - 2097
9	GFDL-CM3	PRECIS	RCP4.5	2014 - 2033	2027 - 2046	-	-
10			RCP8.5	2013 - 2032	2025 - 2044	2047 - 2066	2064 - 2083
11		RegCM	RCP4.5	2014 - 2033	2027 - 2046	-	-
12			RCP8.5	2013 - 2032	2025 - 2044	2047 - 2066	2064 - 2083
13		CCAM	RCP4.5	2014 - 2033	2027 - 2046	-	-
14			RCP8.5	2013 - 2032	2025 - 2044	2047 - 2066	2064 - 2083
15	NorESM1-M	CCAM	RCP4.5	2031 - 2050	2065 - 2084	-	-
16			RCP8.5	2024 - 2043	2039 - 2058	2064 - 2083	-
17		CLWRF	RCP4.5	2031 - 2050	2065 - 2084	-	-
18			RCP8.5	2024 - 2043	2039 - 2058	2064 - 2083	-
19	HadGEM2-ES	PRECIS	RCP4.5	2020 - 2039	2036 - 2055	-	-
20			RCP8.5	2015 - 2034	2027 - 2046	2047 - 2066	2064 - 2083

21	EC-EARTH	RegCM	RCP4.5	2012 - 2031	2034 - 2053	-	-
22			RCP8.5	2009 - 2028	2026 - 2045	2052 - 2071	2073 - 2092
23	CSIRO-Mk3-6-0	RegCM	RCP4.5	2026 - 2045	2039 - 2058	-	-
24			RCP8.5	2025 - 2044	2035 - 2054	2056 - 2075	2073 - 2092
25	HadGEM2-AO	RegCM	RCP4.5	2018 - 2037	2035 - 2054	-	-
26			RCP8.5	2024 - 2043	2035 - 2054	2058 - 2077	2075 - 2094
27	MPI-ESM-LR	RegCM	RCP4.5	2012 - 2031	2033 - 2052	-	-
28			RCP8.5	2007 - 2026	2026 - 2045	2052 - 2071	2072 - 2091
							-: GWL not reached

Source: Pham-Thi-Thanh et al. (2025).

All the RCM outputs were bias-corrected using the Cumulative Distribution Function transform (CDFt) method and observed data from 150 meteorological stations within the observation network of the National Hydro-Meteorological Service.The CDFt method adjusts the entire probability distribution of modeled climate variables, such as temperature and precipitation so that they more closely match the observed distribution derived from in-situ meteorological station data.

Appendix A2. Parameters of the MIKE NAM model

Table A1. List of the parameters of the MIKE NAM model.

Parameters	Unit	Descriptions
Umax	mm	Maximum water content in the surface storage
Lmax	mm	Maximum water content in the lower or root zone storage
CQOF	-	Overland flow coefficient
CKIF	hour	Interflow drainage constant
TOF	-	Overland flow threshold
TIF	-	Interflow threshold
TG	-	Groundwater recharge threshold
CK1	hour	Timing constant for overland flow
CK2	hour	Timing constant for interflow
CKBF	hour	Timing constant for base flow

Table A.2: Parameters values for the calibrated MIKE NAM model.

Parameter	Umax	Lmax	CQOF	CKIF	CK1,2	TOF	TIF	TG	CKBF
Quy Chau	12.6	108	0.367	359.7	17.3	0.0587	0.533	0.351	370.1
Son Diem	20	150	0.6	30	20	0.4	0.01	0.01	120

Appendix A3. Impact of LULC changes on flooding

To analyze the impact of land use/land cover changes on flood peaks in the Ca river basin, we use the HEC-HMS hydrological model (HEC, 2022), which includes land use characteristics into its inputs. This model has been selected because of its simplicity and applicability in data requirements and simulation.

HEC-HMS model

The HEC-HMS model is a mathematical and deterministic hydrological model designed to simulate the precipitation-runoff processes in river basins. The HEC-HMS includes event and continuous models, lumped and distributed modules, conceptual and empirical methods. The parameters are determined from both direct measurement and fitting methods. To simulate rainfall-runoff process, HEC-HMS user may choose between six different runoff-volume models, seven direct-runoff models and three baseflow models. Eight different methods for river routing are included (Feldman, 2000). In this study, HEC-HMS is set up to simulate stream flow in the upstream subbasin of the Ca river with the following options:

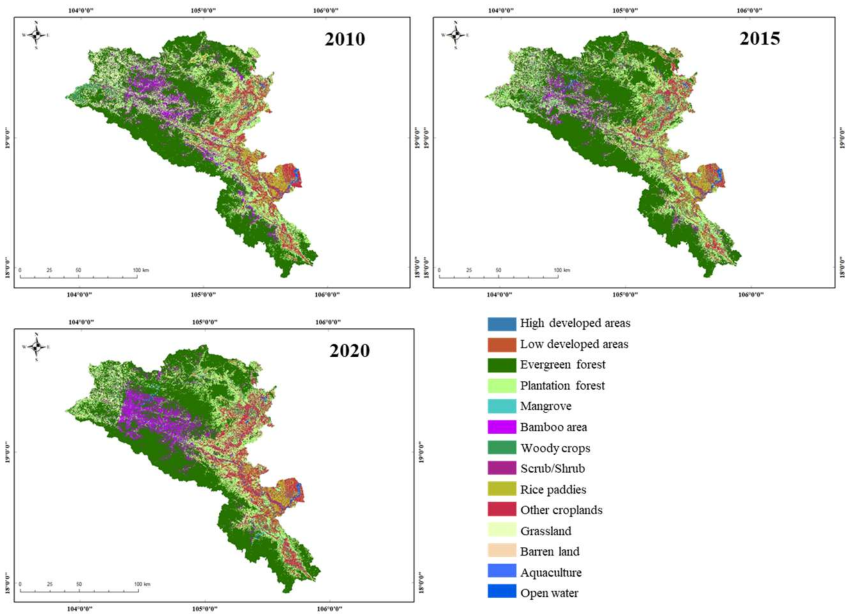
- SCS Curve Number (CN) is used to calculate runoff from rainfall.
- User-specified unit hydrograph (UH) is used to calculate direct runoff.
- Exponential recession is used to simulate base flow.

The hourly river discharge in the subbasin recorded at Muong Xen, Quy Chau and Son Diem hydrological stations are computed based on the hourly rainfall data and CN values. Since there is a lack of data in upstream areas, hourly rainfall data are collected at Muong Xen, Quy Chau and Huong Son meteorological stations, respectively. The CN values represent the water storage capacity and hence runoff potential. It depends on soil type, land use and soil moisture. The Curve Number values range from 30 to 100, depending on land cover and soil permeability, with lower values for permeable soils and higher values for impervious surfaces such as water bodies or urban areas. They can be calculated using a lookup table provided by the Soil Conservation Service (SCS, 1986). In this study, CN values of subbasins are determined from the information of land use and hydrologic soil groups (NRCS, 2007).

Impact assessment on flood peaks

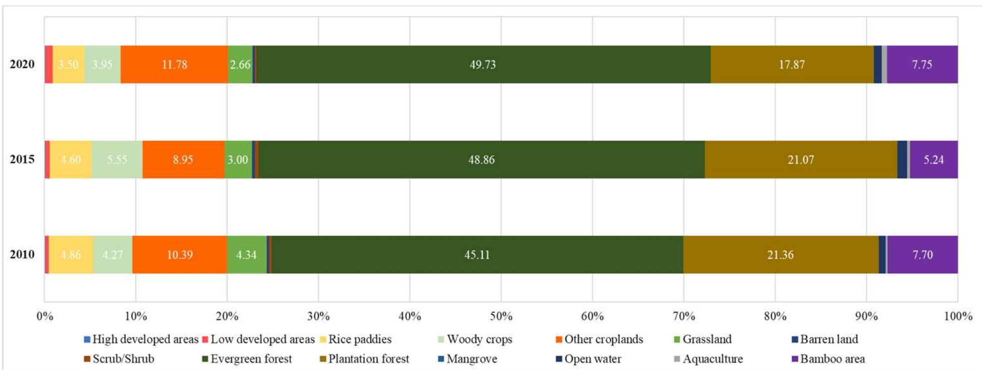
The land use maps for Vietnam at 30m resolution are constructed by JAXA (2021) using Random Forest algorithm with multiple geospatial sources such as Landsat, Sentinel-1 and Sentinel 2. This data consists of 10 primary-dominant land use types at level-1 layer and 18 secondary-dominant land-use type at level-2 layer. The land use classification was validated from field surveys and visual interpretation of data. For the Ca River Basin, we exploited the land use maps in 2010, 2015 and 2020, that is expected to present the reservoir development and urbanization growth of the basin. (Figure A1 and A2). Within the study area, 14 out of the 18 level-2 land use categories are represented, reflecting the specific land use characteristics of the basin.

Figure A1. Land use classification of the Ca River Basin for 2010, 2015 and 2020.



Source: Jaxa (2021)

Figure A2. Land use classification of the Ca River basin for 2010, 2015, and 2020.



Source: Jaxa (2021)

Evergreen forests account for the largest area among land use types in the Ca River basin. From 2010 to 2020, the area of evergreen forests tends to slightly increase, from 45.11% to 49.73% of the basin's total area, while the area of planted forests decreases from 21.36% to 17.87 %. The area of bamboo forests remains stable between 2010 and 2020, after a slight decrease in 2015. The area of rice cultivation also gradually decreases, from 4.27% to 3.50%, while the area of other cultivated land increases. The percentage of residential area increased from 2010 to 2020, but is still sparse, often concentrated around river and stream areas.

The land use maps of the Ca River basin are combined with soil type maps (FAO, 1988) to calculate the CN values (NRCS, 2007). The FAO soil maps are classified into hydrological soil groups (HSGs) representing infiltration rates. The four HSGs are A, B, C and D indicating the proportion of clay, sandy and silt in soil (NRCS, 2007). According to this database, the Ca River basin contains C and D soil groups. The CN values corresponding to the different soil types and land use types are shown in Table A3 in which bamboo land use is categorized as forest land use type.

Table A3. CN table lookup for the Ca River basin

Land use type	**CN values for HSG of Ca River basin**	
	C	**D**
Barren land	91	94
Forest	73	79
Rice paddies	83	87
Woody crops	73	79
Other croplands	83	87
Grassland	79	84
Scrub/Shrub	86	89
High developed areas	90	92
Low developed areas	83	87
Aquaculture	100	100
Open water	100	100

Source: USDA, U. (1986). Urban hydrology for small watersheds. Technical Release (TR-55)

Table A4. CN value of subbasins in the Ca River basin

Subbasin	Mean CN value		
	2010	2015	2020
Muong Xen	75.60	75.23	75.16
Quy Chau	73.42	73.54	73.81
Son Diem	77.60	77.60	76.60

Even if areas of forest, bamboo area and cropland change over time, the mean CN value for the subbasins at upstream hydrological stations (Table A4) are not significantly modified. Indeed, CN values for these land use types over soil groups are very similar. Therefore, the results of the HEC-HMS simulations performed with the different land use type show no significant change in stream flow at the major subbasins. The flood peak differences simulated at Muong Xen, Quy Chau, Dua and Son Diem stations with the land use pattern of 2015 and 2020 are only ~1% compared to results with the land use of 2010 (not shown). We therefore conclude that LULC changes between 2010 and 2020 produced negligible flood impacts, indicating that climate is the dominant flood driver over the period. Since no very large LULC changes are anticipated for future decades, we conclude that climate change will also dominate future flood hazard trajectories.

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