MINISTRY OF NATURAL RESOURCES AND ENVIRONMENT
VIET NAM INSTITUTE OF METEOROLOGY, HYDROLOGY AND CLIMATE CHANGE

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ANALYZE AND ASSESS THE ROLE OF KEY ACTORS IN FLOOD INUNDATION IN DOWN-STREAM OF CA BASIN

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SUMMARY OF DOCTORAL THESIS
IN HYDROLOGY

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The work has been completed at:

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At hour, day, month, year

PREAMBLE

1. The urgency of the Thesis

Flooding is an ancient threat to humankind. According to Jonkman (2005), the total number of people killed and affected by natural disasters in the world from 1975 to 2001 was 2 million and 4,2 billion, respectively. The number of deaths and affected by floods in the period was 175 thousand and 2,2 billion people, respectively. Floods have the most significant impact compared to other natural disasters, even though not the most significant cause of death. The tremendous flooding causing death and terrible destruction in the history of China happened in 1931 that killed approximately 3.700.000 people, which is still circulated for posterity nowadays. Today, the modern update of information shows more clearly that flooding is the ongoing fierce worldwide. The damage caused by floods is enormous. Moreover, under the impact of climate change, flooding is increasingly showing signs of increasing in magnitude and frequency. The task of research and finding solutions to cope with this type of disaster is always scientific, urgent, and practical.

In Vietnam, there were also great floods recorded through the legend of Son Tinh - Thuy Tinh from the age of Hung Vuong. The embankment structure of the Red River is proof of historical flooding prevention. In central Vietnam, severe floods often threaten people's lives. Historic flooding in 1999 devastated many places in the region that killed 645 people and caused damage up to 3.721 billion VND. In the downstream of the Ca River basin, flooding occurs frequently. The historic flood that happened in 1978 inundated a total of 31 communes and killed 37 people. The damage caused by the flood is estimated at approximately 60 billion VND. Recently, the floods that happened in 2019 and 2020 have flooded this area, lasted 10 to 14 days, and caused significant damage to the socio-economic development of the whole region. For the reasons mentioned above, the name of the Thesis, "***Analysis and assessment of the key factors in flooding in the lower Ca basin***" was chosen as the topic of the Thesis.

2. Objectives of the study

- Determine rainfall thresholds causing flooding in the downstream of the Ca river basin; - Quantitative assessment of the effects of rainfall, upstream reservoir system, and storm surge on flooding downstream of Ca river.

3. Object and scope of the study

Research object: Flooding in downstream of Ca river.

Scope in science: - Rainfall and floods in the Ca basin that causes flooding;

- Upstream reservoirs and their role in flooding downstream of the Ca basin;

- Affect of storm surge to flooding in the downstream of the Ca basin.

Study area: The study area focuses mainly on the downstream of the Ca basin, ranging from Nam Dan and Linh Cam stations to Cua Hoi station (18°31'29" to 18°51'41" in latitude and 105°33'13" to 105°45'32" in longitude).

4. New Contribution

- Quantify the threshold of rainfall causing flooding in the inside/outside area of the dyke system of the Ca basin in case of reservoir operation impacts and natural flow in three different flooding phases;

- Determine the relationship of reservoir operations and downstream inundation in the Ca basin;

- Assess the impact of sea-level rise due to storms on flooding in downstream of the Ca basin.

5. Arguments

5.1. Research question

(1) Is there a relationship between the rainfall threshold and the inundated downstream area of Ca basin? Does this relationship change temporally during the flood season? How to quantify the relationship?

(2) How do upstream reservoirs affect the flooding in downstream of the Ca basin?

(3) Does sea level rise due to storms aggravate inundation in downstream of the Ca river? How to quantify the influence?

5.2. New contributions of Thesis

Idea 1: The relationship between rainfall threshold and inundated area in downstream of the Ca basin at different periods during flood season.

Idea 2: Upstream reservoirs have specific roles in flooding in downstream of the Ca basin.

Idea 3: Sea level rise caused by storms poses a danger to inundation the downstream of Ca river.

6. Scientific and practical meaning of research

The results have the following scientific and practical meanings:

Scientific meaning:

- Quantify the influence of several factors on flooding in downstream of the Ca river, including reservoir operation and storm surge through the simulations using mathematical models;

- Determining the role of heavy rainfall on inundation in the downstream of Ca river.

Practical meaning:

- Use in planning and designing the drainage system to minimize flooding;

- Contribute to flood warning and operation of the reservoir system;

- Lay a foundation in proposing solutions for integrated flood management.

7. The structure of the Thesis

In addition to the Table of contents, Introduction, List of acronyms, List of tables, List of figures, Conclusion, References, the Thesis is presented in 3 chapters:

Chapter 1: Overview of the flooding situation in Vietnam and around the world

Chapter 2: Analyze the factors causing flooding and the selection of research methodology

Chapter 3: Assess the influence of key factors on inundation

CHAPTER 1. OVERVIEW OF INUNDATION IN VIETNAM AND AROUND THE WORLD

1.1 Concepts of inundation

Inundation is a phenomenon of rising water caused by heavy rainfall in a low-lying area. This happens when water from rivers overflows into ordinarily dry territory due to a significant flood, the failure of flood prevention structures, and sea-level rise in coastal estuaries.

1.2 Overview of flooding

1.2.1 Flood situation around the world

The global prevalence of natural disasters, especially floods, can be illustrated by the number of significant floods occurring in the world (e. g., Thailand (https://en.wikipedia.org/wiki/2011_Thailand_floods) , China (Chris Courtney, 2019; E. O'Connor, John E. Costa, 2004; https://en.wikipedia.org/wiki/ 1954_Yangtze_floods), Europe

(Rudolf brázdil et al., 2012), USA (https://www.climatesignals.org/ resources/history-mightiest-floods-Mississippi-river, Africa (https://baotainguyenmoitruong.vn/lu-lut-o-phia-nam-chau-phi-lam-hon-700-nguoi-chet-289088.html), and Oceania (https://www.australiangeographic.com.au/ topics / history-culture / 2012/03 / floods-10-of-the-deadliest-ins -Australian-history/).

1.2.2 Flood situation in Vietnam

Approximately 188 floods had broken the dyke system in the Red River basin over 1.000 years, causing severe flooding (e. g., in 1945, 1968, 1969, 1971, 1978, 1984, 1986, and 2010). Annually, the Mekong Delta has about 1.4 million hectares flooded, and the inundation period lasts from 3 to 6 months. In the central region of Vietnam, it is the place that suffers the most severe storms and floods due to its geographical location and topographical characteristics. In the past 20 years, there were four extreme storms causing damage to people and property in 1999, 2007, 2016, and 2017. In the Ca basin, major floods seriously affected the downstream areas in 1954, 1964, 1978, 1983, 1988, 1996, 2002, and 2010. Most devastate effects happened in 1954 and 1978.

1.3 Overview of flood studies

Research on flooding mainly aims to understand, control and minimize the damage caused by it. Scientists in many fields around the world have focused on clarifying the factors that cause flooding.

1.3.1 Flooding factors

1.3.1.1. The influence of hydro-meteorological factors:

Rudolf Brázdil et al. found that flooding by tidal in Western Europe, particularly in Belgium, Denmark, the Netherlands, and part of the UK, is more affected. Bui Duc Long et al. studied the main weather patterns causing heavy rainfall and floods, whereas Ngu Yen Khanh Van et al. (2013) and Tang Van An et al. (2019) studied the causes and patterns of heavy rainfall weather in the Central region of Vietnam.

1.3.1.2. The influence of the surface-related factors:

Nguyen Thanh Son has applied the empirical-numerical model of the permeability formula in the SCS method for the Ve basin and assessed the impact of urbanization on flows in some areas of Central in 2006. Nguyen Van Cu et al. evaluated the current situation and initially searched for the causes of floods in the South-central region, especially in Ho Chi Minh City, which is often affected by flooding. Many studies determine the causes and solutions to prevent flooding for Ho Chi Minh City, such as Le Sam's study in 2010 and Dao Xuan Hoc's study in 2009.

1.3.2 Set-up mathematical models to solve the problem of flooding

Various hydrological-hydraulic modeling has been established due to the rapid advancement of technology. First of all, lumped hydrological models were developed, such as NAM (Denmark), TANK (Japan), SSARR (USA)... Along with the development of data collection on hydro-meteorology, hydrological models (both lumped and distributed) have developed strongly, such as TOPMDEL (USA), DIMOSOP (Italy), HBV (Sweden), WETSPA (Belgium), MARINE (France), and IFAS (Japan). At the same time, hydraulic models also thrived, such as the HEC family (USA), MIKE (Denmark), and ISIS (UK).

1.3.3 Studying the impact of reservoirs on flooding

More and more multi-purpose reservoirs are being built upstream of rivers. In fact, after creating the reservoir system in the Red River basin (e. g., in Son La, Hoa Binh, Thac Ba, Tuyen Quang, Lai Chau, Ban Chat, and Huoi Quang), flooding-control works in downstream has been achieved and improved significantly. Therefore, many domestic and international scientists have studied the operation of reservoirs to achieve the optimum in power generation, water supply, and flood reduction in downstream (e. g., Tran Hong Thai, 2005; Long Ngo Le et al., 2007, K Umar, 2007, Wei el al., 2009, and Hoang Thanh Tung, 2011).

1.4. Study on flooding in the Ca basin

In the Ca basin, there are numerous studies related to flooding. The most notable are: 1. Research to provide water drainage and flood prevention solutions and control for Vinh city and surrounding areas (Nghe An Irrigation Construction and Consulting Company, 2006; Department of Agriculture and Rural Development, 2013); 2. Research on medium-term rainfall and flood forecasting for the operation of reservoirs in the Ca basin (Hoang Thanh Tung, 2011); 3. Research on flood management in Ca basin (Tran Duy Kieu, 2012); 4. Apply optimization algorithm for reservoir operation to reduce the water level in downstream with the lowest value (Nguyen Xuan Tien et al., 2018).

1.1. Research direction:

The research direction has been determined to evaluate the influence of hydro-meteorological factors on flooding in downstream of Ca basin using mathematical models.

1.2. Conclusion on Chapter 1

Through the Research Review, it was found that flooding is a common natural disaster in Vietnam and in the world. This type of natural disaster causes a lot of damage to people and property.

With the characteristics of topography and hydro-meteorology of the Ca basin, the study will analyze and assess the role of some factors that cause the inundation in the downstream area of the Ca basin. Because the MIKE model has been well tested in Vietnam, this model has been selected as a tool to finish the Thesis.

CHAPTER 2. ANALYSE THE FACTORS THAT CAUSES FLOODING AND CHOOSE RESEARCH METHODOLOGY

2.1. Data availability

2.2.1. Hydro-meteorological data

6-hourly rainfall data (from 2005 to 2019) was used in the Thesis. During this period, the total number of floods was 23 events. The data used to simulate the flow discharge at Coc Na station in the NAM model was only available from 1961 to 1976.

2.2.2. Terrain data

The data was inherited from the Ministerial Project "*Detailed research disaster-risk levels caused by flooding in urban areas and coastal plains in the North Central region*" in 2019;

Topographic data (i. e., Digital Elevation Model) with resolution in 1:10.000 was taken from Project "*Building society to adapt to natural disasters, Phase 2 - Nghe An province* " of JICA organization in 2014;

2.2.3. Cross-section data

The cross-section data were obtained from the Federation of Hydro-meteorological Surveys in 2001. In 2016, the study was carried out by the Project "*Development of a program to calculate and predict floods for system operation. Reservoir on Ca river basin"* provided additional 70 cross-sections.

2.2. Factors causing flooding in Ca basin.

Typically, the factors that cause natural disasters are divided into endogenous, exogenous, and anthropogenic.

2.2.1. Endogenous factors

2.2.1.1. Geographical location

Due to its location nearby the East Sea, the basin has very favorable conditions to form heavy rains, causing flooding in the lower part of the basin.

2.2.1.2. Topographic

The high mountain terrain is favorable for causing heavy rain when it encounters a source of moisture from the East Sea in the rainy season, causing floods in the Ca basin. Moreover, low topography in the lowlands with traffic systems, coastal sand dunes, and urbanization are favorable conditions for causing flooding when heavy rainfall prevents the flow from upstream flooding.

2.2.1.3. Soil type

The basin has various types of soil. In hilly areas, the ground is developed on numerous types of lava. Most of the mountainous area lies below 800 to 1.000 m, should be strongly weathered. The ferralic process is primary.

2.2.1.4. Vegetation cover

Although forest cover in the Ca river basin has improved much in recent years, the coverage is still low, limiting the flood regulation process in the basin.

2.2.1.5. River network

The river network is the factor that transports water from upstream to downstream, so it is an essential factor affecting flooding.

2.2.2. Exogenous factors

2.3.2.1. Rainfall

Rainfall is the main factor causing inundation in the Ca basin in general, especially in the downstream area.

2.3.2.2. Floods coming from upstream

The flood season usually occurs from August to November due to weather patterns causing heavy rain. Minor floods can appear around the end of May and the beginning of June.

2.3.2.3. Sea-level rise due to storms

Sea-level rise due to storms is a factor that aggravates flooding in downstream of Ca basin. Every year, the North Central region is often directly affected by 1 to 2 tropical cyclones.

2.2.3. Anthropogenic factors

2.3.3.1. Urbanization

Along with the socio-economic development of the whole country, two provinces located inside the Ca basin (e. g., Nghe An and Ha Tinh) have been developing strongly. Increasing urbanization impacts inundation in the Ca basin, especially in the downstream area.

2.3.3.2. Dike system against floods of Ca river

There are two prominent dikes (e. g., Ta Lam and Huu Lam dikes). The Ta Lam dike divides the lower part of the Ca river into outside and inside parts of the dike.

2.3.3.3. Reservoir system on Ca river

On 13 October 2019, the Prime has released a Multi-reservoir Operating Procedures of the Ca basin including 11 reservoirs, of which three of them (e. g., Ban Ve, Ban Mong, and Ngan Truoi) play an important role in flooding prevention.

2.3. The method of determining the flooding area

2.3.1. Some methods to identify inundation

- Investigation of flood tracks method
- Application of remote sensing method
- Mathematical modeling method

2.3.2. Selection of research method

The following methods are used to solve the objectives of the Thesis: inheritance method, statistical method, investigation of flood tracks method, and mathematical modeling method.

There are various methods to assess the flooding area, such as investigating flooding traces and remote sensing. However, many

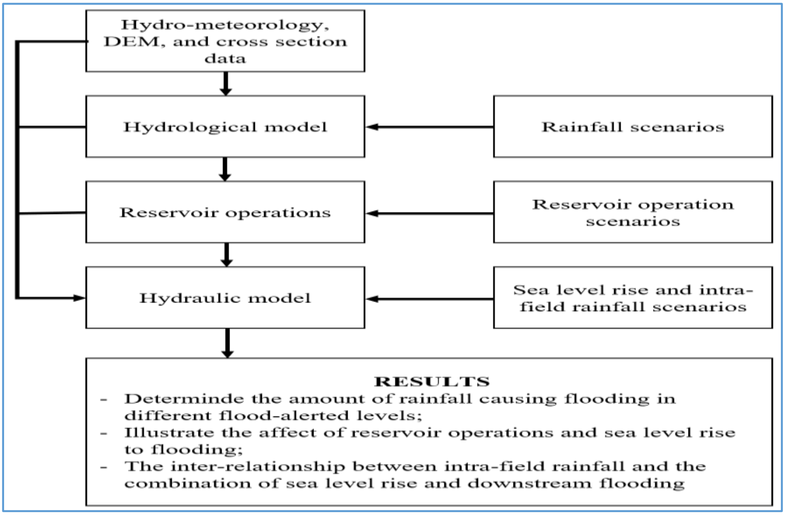

Figure 2.15: Thesis structure

mathematical models can represent the rain-runoff relationship and simulate the inundation in riverbanks and low-lying areas along rivers. Within the framework of this study, we have selected hydrological and hydraulic modules in the MIKE model as a tool to calculate inundation for the Ca basin.

2.4. MIKE models

The MIKE model is commercial software with a compelling interface. This model has excellent integration with GIS software. There are many sub-models, namely rainfall-runoff model (e. g., NAM), 1-D hydraulic model (e. g., MIKE 11), and 2-D hydraulic model (e. g., MIKE 21). These models are used to simulate inundation in watershed scales. The Thesis has selected the MIKE model to implement the goals of the study.

2.5. Conclusion in Chapter 2

The Ca basin has a large area and complicated terrain. The reservoir system in the Ca basin has a significant impact on the flow regime. Sea level rise by storms is also an essential factor affecting inundation in downstream of Ca basin. The MIKE model was selected as the primary computational tool. The structure of the Thesis is shown in Figure 2.15.

CHAPTER 3. ASSESS THE EFFECTS OF FACTORS ON FLOODING IN THE CA BASIN

3.1. Flow simulation using the MIKE model

The study area is classified into two areas, including the outside and inside of dikes.

3.1.1. The outside area of dikes

a. Set-up NAM model: The Ca basin is divided into 57 sub-basins.

b. Set-up MIKE 11 model: Establishing a 1-D hydraulic network for the Ca basin consisting of 17 rivers. The upper boundary includes Muong Xen, Ban Ve, Quy Chau, Thac Muoi, Thanh Huong, Thanh Thuy, Thanh Mai, Cau Om, Son Diem, Ho Ho, Da Han, Ngan Truoi, and Kim Son, whereas the lower boundary is Cua Hoi station.

c. Set-up MIKE 21 model: Constructing a grid for a 2-D domain including floodplains along rivers from upstream locations from Dua, Son Diem, Ho Ho, Da Han, Ngan Troi, and Kim Son to the outlet of the basin. With an area of approximately 3,200 km^2, this region is discretized into 89,861 finite triangular elements.

3.1.1.1. Calibration and validation of the NAM model

The study uses three sub-basins to calibrate and validate the NAM model, including Quy Chau, Son Diem, and Coc Na. The calibration/validation tasks imply a good model.

3.1.1.2. Calibration and validation of the MIKE 11/MIKE 21 models

Calibration and validation results are shown in Tables 3.6 and 3.8.

Table 3.6. Model calibration results

Stations	The Nash-Sutcliffe coefficient	Peak error ΔH (m)	Total volume error (%)
Nam Dan	0,93	-0,11	-1,8
Linh Cam	0,95	- 0,02	+4,7
Cho Trang	0,93	+ 0,3	+1,5

Table 3.8. Model validation results

Stations	The Nash-Sutcliffe coefficient	Peak error ΔH (m)	Total volume error (%)
Nam Dan	0,89	- 0,09	+7,4
Linh Cam	0,93	+ 0,31	+10
Cho Trang	0,91	+ 0,1	+2,6

3.1.2. The inside area of dikes:

a. Set up the NAM model

The area is divided into 15 sub-basins using the GIS software.

b. Set up the MIKE 11 model

The 1-D network is established, including four channels. The upstream boundary is Nam Dan. when a storm occurs, Nam Dan sluice is always closed, so the discharge value equals 0.0 m3/s. The downstream boundaries are at Nghi Quang and Ben Thuy sluices.

c. Set up the MIKE 21model

The study has been conducted to build a grid network for 2D flooding simulation. This region has an area of 550 km ^{2}, which is discretized into 94,832 finite elements. Calibration/validation results are summarized in Table 3.11 and 3.13.

Table 3.11: Model calibration results

Location	The Nash-Sutcliffe coefficient	Peak error ΔH (m)	Total volume error (%)
Ben Thuy	0,96	+1,5	+0,6
Nghi Quang	0,86	-2,5	-5,5

Table 3.13: Model validation results

Location	The Nash-Sutcliffe coefficient	Peak error ΔH (m)	Total volume error (%)
Ben Thuy	0,89	-1,2	+6,0
Nghi Quang	0,90	-3,8	-1,1

3.2. Evaluate the influence of factors on flooding in the downstream of Ca basin

3.2.1. Quantitative calculation of rainfall causing flooding in the area outside the dyke in downstream of Ca basin

The study has divided into various scenarios to calculate the amount of rainfall contributed to downstream flooding, including the natural condition and the reservoir's impact with three different periods. The storm event in October 2010 is used to model the spatial-temporal distribution of rainfall in this Thesis. The initial water level of Ban Ve, Ban Mong, and Ngan Troi reservoirs is determined based on Reservoir Operation Rules in the Ca basin. However, these values of Ban Ang, Ho Ho, Song Sao, and Da Han reservoirs are set as the normal operating level. The results are shown in Table 3.17 and Figure 3.22, and 3.23.

Table 3.17: Amount of rainfall causing flooding in the outside area of the dyke (mm)

Period	Basin conditions	
	Within reservoirs	Without reservoirs
Begin of flood season	200	240
During the flood season	150	210
End of flood season	150	200

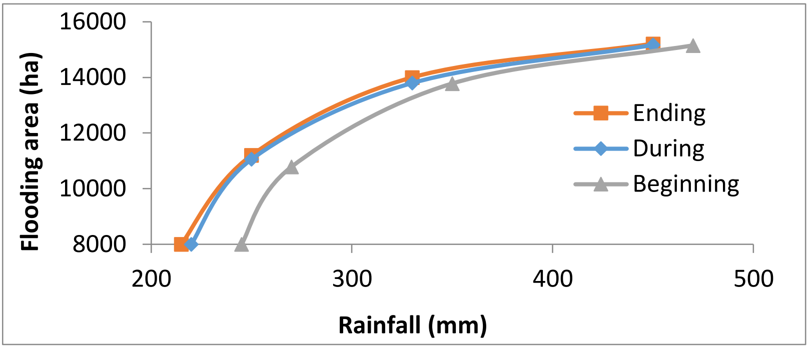

Figure 3.22: Relationship between rainfall and flooded area in the outside of the dyke

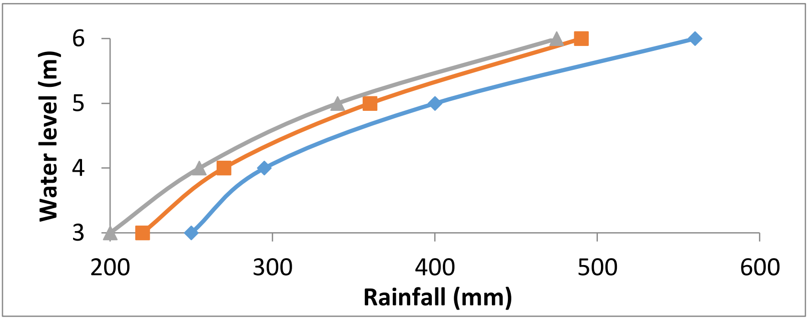

Figure 3.23: Relationship between rainfall and maximum water level at Cho Trang station

Comment: When there is an impact on the reservoir, the rainfall thresholds that causing flooding in downstream tend to increase, showing that the regulation of reservoirs reduces flooding downstream.

In this section, the calculation of downstream inundation considering the impact of reservoir operations. The study focuses on inundation in the lower part of the Ca basin considering single/multiple reservoir operation and the conditions at Cho Trang station in flooding-alerted at levels 1, 2, 3 and, 3+1. Design-flood discharge at reservoirs with the trapezoidal shape is referred from the Ca basin Multiple-reservoir Operation Procedure.

- Individual reservoir flushing operation

Table 3.25: Water level at Cho Trang station with single reservoir operation (m)

Flood-alerted level	Ban Ve	Ban Ang	Ban Mong	Ho Ho	Ngan Truoi
Level 1	4,1	3,7	4,3	3,2	3,2
Level 2	4,7	4,4	5,0	4,1	4,2
Level 3	5,8	5,4	5,9	5,1	5,1
Level 3+1	6,7	6,4	6,7	6,2	6,1

Table 3.27: Flooded area when reservoir design flood discharge

Flood-alerted level	Flooded area (ha)					
	h≥0.2m	h≥0.5m	h≥1.0m	h≥2.0m	h≥3.0m	h≥5.0m
Level 1	10.537	9.482	7.973	3.352	83	
Level 2	13.141	12.488	11.284	7.766	1.227	
Level 3	15.107	14.695	14.135	12.060	7.811	2
Level 3+1	15.650	15.337	14.908	13.901	11.669	1.272

Comment: Ban Mong reservoir had the most significant impact on flooding in downstream in single reservoir operation, whereas Ngan Truoi reservoir had a minor effect.

- Multiple reservoir flushing operations

Table 3.29: Water level at Cho Trang (m) in multiple reservoir operation

Flood-alerted level	Ban Ve and Ban Ang	Ban Ve, Ban Ang, and Ban Mong	Ngan Truoi and Ho Ho	Ban Ve and Ban Mong
Level 1	1,6	2,6	0,4	2,1
Level 2	1,3	2,2	0,3	1,7
Level 3	1,2	1,8	0,2	1,5
Level 3+1	1,2	1,8	0,2	1,5

Comment: The combination of Ban Ve and Ban Mong reservoirs had the most significant impact, whereas the combination of Ho Ho and Ngan Truoi had the most negligible impact. The combination of Ban Ve, Ban Ang, and Ban Mong reservoirs impacted the historic flood in 1978, with the maximum water level corresponding to 7,8 m.

- Individual-storage reservoir

Table 3.31: Water level (m) at Cho Trang station in individual-storage reservoirs

Flood-alerted level	Ban Ve	Ban Mong	Ngan Truoi
Level 2	0,2	0,1	0,0
Level 3	0,3	0,2	0,1
Level 3+1	0,3	0,2	0,1

Table 3.32: Flooded area when reservoirs cut off floods separately

Flood-alerted level	Flooded area (ha)		
	Ban Ve	Ban Mong	Ngan Truoi
Level 2	11.180	11.197	11.241
Level 3	13.950	13.988	13.998
Level 3 +1	15.211	15.264	15.259

- Multiple-storage reservoirs

Table 3.33: Water level (m) at Cho Trang station in multiple-storage reservoirs

Flood-alerted level	Hmax at Cho Trang (m)	Reduction of water level (m)	Reduction of flooded area (ha)
Level 2	3,6	0,4	467
Level 3	4,6	0,4	244
Level 3 +1	5,5	0,5	240

Comment: When there is an impact of the reservoir in reducing the amount of discharge flow downstream, the flooded area in downstream tends to decrease minorly. The Ban Ve reservoir has the most pronounced effect. The water level in Cho Trang station is reduced by 0.3 m, and the flooded area is reduced by 77 ha. The Ngan Truoi reservoir has no contribution to flood reduction. The obtained results can be used to reference natural disaster decision-making and the design of reservoir operation rules.

3.2.2. Assess the impact of sea-level rise to flooding in downstream of Ca basin

Table 3.36: Water level rise at Cho Trang under the influence of storm surge and with/without design flood discharge of the reservoir (m)

Basin conditions		Flooding-alerted level			
		Level 1	Level 2	Level 3	Level 3+1
Without reservoirs		0,9	0,3	0,1	0,1
Within reservoirs	Ban Ve	1,4	0,9	0,9	0,8
	Ban Ang	1,2	0,6	0,5	0,4
	Ban Mong	1,5	1,1	0,9	1,1
	Ngan Truoi	1,1	0,4	0,2	0,2
	Ho Ho	1,1	0,2	0,2	0,3

Table 3.37: Effects of storm surge and design-flood flush discharge from Ban Ve reservoir to inundated area

Flood-alerted level	Flooded area (ha)					
	h≥0.2m	h≥0.5m	h≥1.0m	h≥2.0m	h≥3.0m	h≥5.0m
Level 1	12.167	11.377	10.354	6.541	656	5
Level 2	13.923	13.402	12.490	9.764	2.856	7
Level 3	15.502	15.195	14.728	12.986	9.095	15
Level 3+1	15.915	15.665	15.312	14.365	12.330	1.655

Comment: The flooding water depth in the downstream area increases since the sea level rises due to storms. The trend tends to be higher in the case of low-lying areas. The highest increment occurs when a combined effect of both reservoir operations and the impact of sea-level rise.

3.2.3. Flooding simulation in Vinh city and surrounding areas due to intra-field rainfall

a. Determine the hourly rainfall pattern at Vinh station

Hourly-rainfall events in October 2010 and October 2019 were selected as the rainfall pattern for the study. This study will calculate flooding in Vinh city with total rainfall corresponding to 687, 3 mm (at P = 10%). The study point is the Duoc bridge junction.

b. Determine the water-level boundary at Ben Thuy and Nghi Quang sluices

- The water-level boundary at Ben Thuy sluice is taken from the results of flooding simulation on the Ca basin;
- The water-level boundary at Nghi Quang sluice is taken at Hon Ngu station; in case of water surge at Cua Hoi station in 2010, the value is pluses 2 m.

c. Results:

Table 3.43: Inundated area inside the dike in case of rainfall occurs with 10% frequency

Flood-alerted level	Flooded area (ha)				
	h≥0.2m	h≥0.5m	h≥1.0m	h≥2.0m	h≥3.0m
Level 1	16.099	13.787	7.690	1.341	1.0
Level 2	17.139	15.074	9.493	1.843	1.0
Level 3	17.783	15.866	10.758	2.274	1.9
Level 3+1	18,793	16.826	11.950	2.837	10.5

Table 3.44: Flooded area inside the dike in case of rainfall occurs with 10% frequency and flush discharge from Ban Ve reservoir

Flood-alerted level	Flooded area (ha)				
	h≥0.2m	h≥0.5m	h≥1.0m	h≥2.0m	h≥3.0m
Level 1	17.738	15.765	10.558	2.203	1.3
Level 2	18.887	16.881	11.887	2.742	4.2
Level 3	19.889	17.967	12.737	3.256	22
Level 3+1	19.120	17.081	12.025	2.885	12

Table 3.45: Flooded area inside the dike in case of rainfall occurs with 10% frequency, flush discharge from Ban Ve reservoir, and sea-level rise

Flood level	Flooded area (ha)				
	h≥0.2m	h≥0.5m	h≥1.0m	h≥2.0m	h≥3.0m
Level 1	17.774	15.812	10.633	2.418	2
Level 2	18.925	16.926	11.961	2.972	5
Level 3	19.932	18.021	12.823	3.522	23
Level 3+1	19.166	17.142	12.112	3.117	13

Comment: The change of water level in the Ca basin significantly influences the drainage system of Vinh city. The difference between the highest water level at the Duoc bridge junction varies from 2.9 m up to 3.6 m when the flooding-alerted level in Ben Thuy is at 1 and 4, respectively. The influence of rainfall intensity on flooding in Vinh city is minor since no flood in upstream of Ca basin.

CONCLUSIONS AND RECOMMENDATIONS

❖ CONCLUSIONS

1. Natural disasters happen across the planet from the past to the present. Primarily due to climate change, this type of disaster is increasing in frequency, extent, and scale. Identifying and assessing the role of factors causing inundation are always topical, scientific, and practical. The factors that cause flooding include three groups: endogenous, exogenous, and anthropogenic. The hydro-meteorological factors have a significant influence on flooding in downstream of Ca basin. The Thesis has deeply evaluated the role of

heavy rainfall and flooding in the upstream, individual/multiple reservoir operation, intra-field rainfall, and storm surge.

2. A hydrological-hydraulic model (e. g., the MIKE model) has been selected to simulate inundation in downstream of Ca basin.

3. The hydro-meteorological data, topography, and various types of maps have been collected to analyze floods.

4. The obtained results show:

4.1 The role of the first factor

The study quantified the amount of rainfall causing flooding in downstream of Ca basin at different flooding-alerted levels for three flood periods, within/without reservoir operation. The rainfall values causing flooding in downstream at the beginning, during, and ending of the storm event are 240, 210, and 200 mm, respectively. The relationship between rainfall, flooded area, and the most significant values of water level at Cho Trang station has been established;

4.2 The role of the second factor

The increase/decrease of inundation magnitude downstream of the Ca basin has been determined in individual/multiple reservoir operations with different flood-alerted levels. For example, Ban Mong and Ban Ve reservoirs have the most significant impact with an increase of 1.3 and 1.1 m, respectively, in individual operations with level-1 flood-alerted. Ngan Truoi and Ho Ho reservoirs has a minor effect with an increase of 0.1 and 0.2 m, in case of individual operation with level-3 flood-alerted. The influence of upstream reservoirs in Ngan Sau river (e. g., Ho Ho, Da Han, Ngan Truoi, and Tiem reservoirs) is not significant in causing flooding downstream. When all three reservoirs, including Ban Ve, Ban Ang, and Ban Mong, are combined to operate the flushing, the water level at Cho Trang station can reach 7.8 m. This figure is equivalent to the historical storm event in 1978.

4.3 The role of the third factor

The study identified the change in flooding considering the impact of storms of sea-level rise (+2 m). The increase in flooding magnitude occurs more significantly when the conditions in Cho Trang station at level-1 than at level-3 flood-alerted status. These figures are 0.9 and 0.2, respectively. The study also determined the flooding magnitude in the case of multiple reservoir operations and the effect of storm surge. The water level at Cho Trang station can reach 7.0 m in the case of the combination of Ban Mong's flush discharge and sea-level rise due to storms. The figure is only lower than the water level in 1978 by 0.8 m.

4.4 The role of the fourth factor

The study results conclude that the area inside the dyke begins to flood when the amount of rainfall is 250 mm. In October 2010 (P ≈ 1%), the flooded area was 19,000 ha, and inundation time lasted 14 days. The inundation level of the area inside the dyke has been determined with the frequency P = 10% (X_P = 687.3 mm). An increase in inundation of 0.2 m has been determined in Vinh City and surrounding areas in the case of heavy rainfall with a frequency of P = 10%. Effects of floods at different levels on the Ca river. An increase in inundation in Vinh City and its vicinity has been determined when heavy rainfall is combined with frequency P = 10%, reservoir operations, and high tide.

4.5 Limitations of the study:

Data on the drainage system of Vinh city has not been collected for detailed simulation in the hydraulic model.

❖ REQUEST

Research has not collected data on the drainage system of Vinh city. Thus, the study did not simulate flooding in detail. Therefore, more attention should be paid to this limitation in practical applications.

PUBLICATIONS

1. **Nguyen Xuan Tien**, Le Huu Huan, Phan Thi Toan, Nguyen Van Linh (2018), *Building a flood simulation model and calculating optimal flush discharge for reservoir systems for basins without tidal effects*, Journal of Hydro-Meteorological. No. 687, p. 23-31.

2. **Nguyen Xuan Tien**, Le Huu Huan, Trinh Dang Ba (2018), *Application of IFAS model for flood warning in upstream in Nam Non and Nam Mo Rivers, Nghe An province*, Journal of Hydro-Meteorology. No. 688, p. 52-58.

3. **Nguyen Xuan Tien**, Nguyen Thanh Son, Nguyen Van Linh (2020), *Application of hydrological/ hydraulic model to simulate flooding in downstream of Ca basin*, Journal of Hydro-Meteorology. No. 687, p. 23-31.

4. **Nguyen Xuan Tien**, Nguyen Thanh Son, Nguyen Van Linh (2020), *Application of MIKE model to assess the impact of the reservoir system on downstream flooding of Ca basin,* Journal of Science and Climate Change. No. 13.

5. **Nguyen Xuan Tien**, Nguyen Van Linh, Phan Thi Toan, Pham Tra My (2020), *Application of hydrological/hydraulic models to assess the impact of Ban Ve reservoir on downstream flooding of Lam basin,* Journal of Nghe An Science and Technology. No. 3.

6. Nguyen Thanh Son, Phan Ngoc Thang, **Nguyen Xuan Tien** (2016), *Analysis of flooding situation in downstream of Lam basin*, Journal of VNU. The Earth and Environmental Sciences. Volume 32, No. 3S, 2016167.