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Experimental Study on Coastal Drainage Solutions for Ky Anh Urban Area, Ha Tinh Province, Vietnam

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Abstract

In the Central region of Vietnam, the heavy rains, low land, tidal influence, and rapid urbanization have caused coastal urban flooding to be a major and growing concern. This study focuses on assessing the drainage capacity and proposing flood drainage solutions for the Ky Anh urban area (Ha Tinh Province) through an integrated hydrological-hydraulic modeling approach. The MIKE modeling system was applied to study, including MIKE NAM, MIKE 11, MIKE 21 FM, and MIKE FLOOD. Calculation scenarios were developed based on the historical rainfall event of October 2020, combined with a 10% design tidal range and climate change projections. Simulation results indicate that the existing drainage system in Ky Anh has exceeded its capacity, resulting in severe and prolonged flooding under adverse rainfall–tidal interaction conditions. Unidirectional drainage solutions offer limited effectiveness, whereas diversion schemes and multidirectional combined solutions yield superior results. Analysis shows that peak flood levels were reduced by 0.7–0.9 m, alongside a reduction in inundated areas of over 60% and a significant shortening of flooding duration. The study confirms that a systems-based, inter-regional, and modeling-based drainage approach is a crucial scientific basis for planning and managing coastal urban areas adapted to climate change.

Keywords: Coastal Urban Drainage, Hydrodynamic Modeling, Ky Anh, Vietnam, Tidal, Urban Flooding.

1. Introduction

Urban flooding has become an increasingly critical challenge for coastal cities in Vietnam over recent decades [1]. This area is subject to multiple adverse natural and anthropogenic conditions, including intense and concentrated heavy rainfall, low-lying coastal terrain, short and steep river systems, and direct tidal influence from the East Sea [2]. Thus, rapid urbanization is occurring, accompanied by increasing building density [1], [3]. Regional climate analyses indicate an increasing trend in maximum daily rainfall in Central Vietnam, with numerous storm events exceeding 300–500 mm/day, thereby imposing considerable pressure on urban drainage systems with limited capacity [4].

The Ky Anh urban area (Ha Tinh Province, Vietnam) represents a typical example of these challenges. During the rainy season, the administrative center and its surrounding areas frequently experience deep and prolonged flooding. The most severe flooding occurred in 2020, when heavy rainfall combined with high tides constrained drainage capacity, resulting in flood depths ranging from 0.8 to 1.5 m and durations of 2–5 days [5], [6].

The Ky Anh (Fig. 1) is a coastal commune located near some river estuaries (Cam Nhuong estuary, Rac estuary). Its terrain slopes from west to east, combined with low hills (20m to 100m high), creating numerous small valleys. This results in short periods of water concentration and rapid flood rise. Furthermore, the influence of the East Sea tides hinders natural flood drainage and creates prolonged water retention areas, causing widespread flooding [4], [6], [7].

The Nha Le channel is an artificial channel that was constructed in 983, a waterway system connecting the provinces of Ninh Binh, Thanh Hoa, Nghe An, and Ha Tinh (Vietnam). It has consistently functioned as a crucial element in the region's stormwater management and flood mitigation strategies [8]. Conversely, after years of extensive use and swift urban growth, the Nha Le channel has undergone substantial siltation, a decrease in its cross-sectional area, and disruption of its flow due to the construction of roads and other urban infrastructure.

Thus, its ability to manage floods has been notably compromised, making it unsuitable for current rainfall levels. Moreover, considering the projected intensification of extreme rainfall occurrences and the ongoing increase in sea levels linked to climate change, the effectiveness of Ky Anh's drainage system is likely to further deteriorate [5], [7].

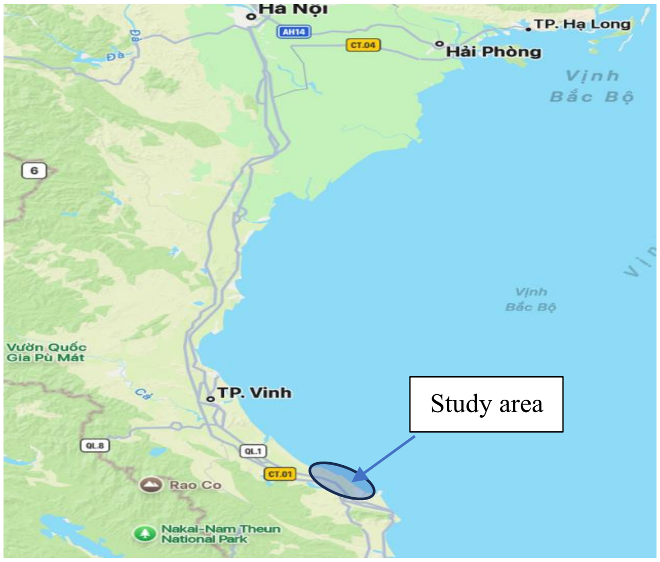

Figure 1. Location of the study area (Ky Anh commune, Ha Tinh Province, Vietnam).

Studies on urban drainage in Vietnam, particularly in coastal cities of central Vietnam, have not adequately addressed hydraulic-based approaches for determining urban ground elevations. In practice, a single ground elevation value is often defined and uniformly applied across the entire city. This approach complicates urban planning, as some areas require extensive embankment construction while others necessitate significant lowering of ground levels, thereby increasing construction and management costs. Therefore, a clear understanding of urban flow characteristics and the causes of urban flooding is essential for determining appropriate ground elevations to support flood mitigation. Therefore, re-evaluating the drainage capacity of the Ky Anh urban area and proposing comprehensive, inter-regional, and climate-adaptive solutions are both scientifically justified and practically urgent for urban planning, management, and disaster risk reduction. This study focuses on three main areas: (1) finding the root causes of flooding; (2) measuring how overloaded the system is; and (3) measuring how well the proposed solutions work. Based on the analysis of flow characteristics, the study develops multiple drainage scenarios, evaluates these scenarios, and proposes sustainable drainage solutions for the Ky Anh urban area.

2. Review of Related Literature

Because of climate change and rising sea levels, which are making coastal urban areas around the world much more likely to flood, it is more important than ever to study how to drain these areas [8], [10]. This is especially important for cities on the coast, where about 13% of the world's urban population lives and where up to 150 million people are expected to be at risk of flooding by 2070 if no effective adaptation measures are taken [11]. This indicates that the urban area is under parallel pressure from increased runoff and rising downstream water levels (due to high tides), resulting in frequent flooding [2].

Climate change leads to an increase in extreme weather events, with increasingly heavy rainfall in coastal cities, but the drainage system remains largely unchanged [10]. This leads to increasingly large flood damage [12], with an estimated 80% of human casualties occurring within 100m of the coastline [13]. Rapid urban development in coastal areas, coupled with inadequate drainage infrastructure, along with global warming and sea level rise, has limited natural drainage capacity, so a drainage plan is needed that takes into account all influencing factors, especially the appropriate drainage direction [14], [15]. Consequently, urban drainage systems are experiencing declining performance, leading to increases in both the frequency and severity of rainfall-induced flooding [8].

In addition, rapid urbanization expands impervious surface coverage, thereby increasing peak surface runoff and shortening runoff concentration time, rendering urban drainage systems susceptible to overload during heavy rainfall events [16]. Meanwhile, global mean sea level has risen steadily over the past century, and projections suggest that the rate of rise could increase by a factor of 2 to 5 times. This trend significantly elevates downstream water levels and reduces the self-drainage efficiency of coastal drainage systems[8], [17]. These trends underscore the urgent need for innovative, integrated, and feasible urban drainage solutions capable of adapting to adverse tidal and rainfall conditions and the long-term impacts of climate change [18].

Currently, floods have become one of the most serious global natural disaster threats, causing significant economic, social, and environmental losses **Error! Reference source not found.**. In particular, global economic losses due to climate disasters, in which floods and storms account for a large proportion, have continuously increased in recent decades, with total losses in the period 2017–2021 frequently exceeding US$100 billion per year [20], which has highlighted the need to find a sustainable drainage solution for coastal cities [21]. To furnish enduring, climate-resilient solutions, modern methodologies necessitate the integration of advanced hydrological-hydraulic modeling, multi-criteria risk analysis, and socio-economic evaluation [20], [22].

In this context, the development of coastal urban drainage solutions based on a systems approach, inter-regional coordination, and hydrological-hydraulic modeling has become an essential research focus for improving the resilience and sustainability of coastal cities [7], [23], [23]. Analysis reveals that there is no all-encompassing plan for modeling the interplay of variables during floods in central Vietnam's coastal cities, particularly the Ky Anh urban area. Thus, evaluating the severity of flooding and comprehending its causes are essential to coastal development.

Therefore, using 1D and 2D hydraulic models in conjunction with flood simulations will yield precise recommendations for drainage design appropriate for coastal urban growth. The application of various mathematical models to simulate hydraulic flow processes provides an integrated perspective on sustainable drainage system planning and urban development orientation. More importantly, determining appropriate urban ground elevations for different areas is essential to ensure that urbanization does not lead to the formation of unintended water-retention "basins".

3. Research Methods

The study was conducted based on the collection of field data (e.g., flood levels, topographic data, flow cross-sections) and observational data (e.g., rainfall and tidal records). These datasets were integrated with mathematical modeling to evaluate drainage solutions and identify the optimal scenario for the coastal urban area. The research workflow is illustrated in the diagram presented in Fig. 2.

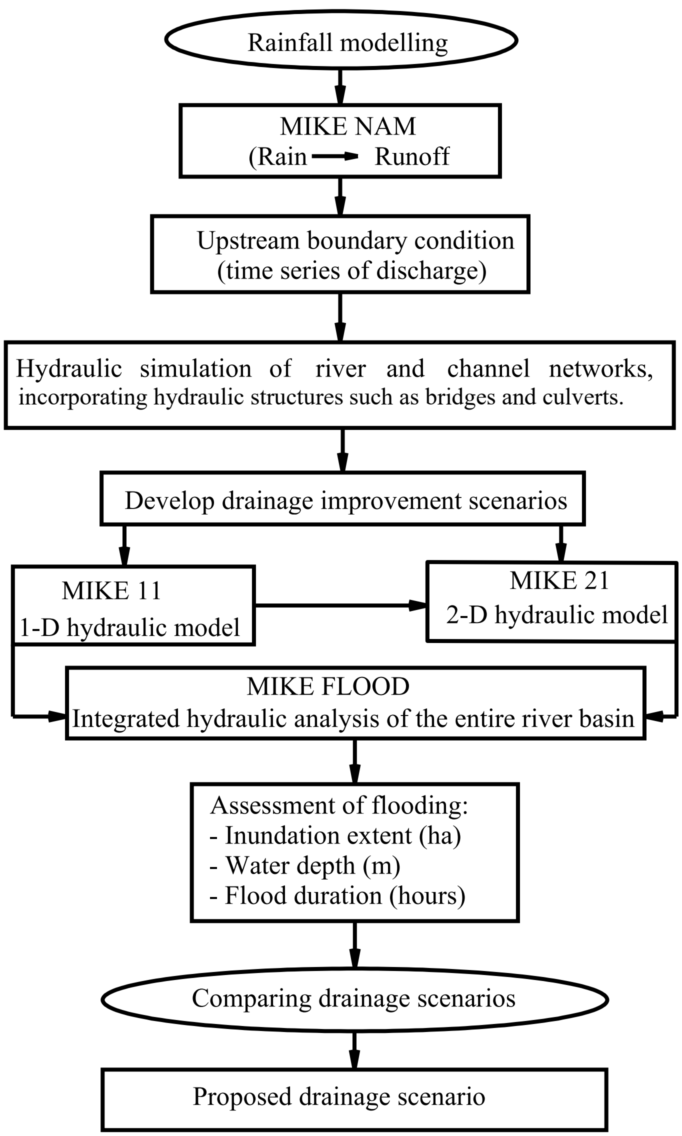

Figure 2. Structure determines the optimal drainage scenario.

Based on the research framework presented in Fig. 1, the study is structured around the following aspects:

- Collecting current situation data: Topographic data, irrigation systems data, flood data, etc.
- Long-term investigations of meteorological and hydrological datasets are essential. This entails the examination of time series data pertaining to precipitation, tidal water elevations, and floodwater levels, alongside the data acquired from automated monitoring stations situated within the designated study area.
- Mathematical Modeling: The MIKE modeling system (MIKE NAM, MIKE 11, MIKE 21, and MIKE FLOOD) was used to model rainfall-runoff, simulate the hydraulics of the river-canal system, and analyze flooding.

Based on the results of the hydraulic analysis, the study determines the optimal capacity of the drainage scenarios and provides guidance for the development of drainage infrastructure in the Ky Anh urban area.

4. Characteristics of the Study Area

The Ky Anh urban area is located along the eastern coast, characterized by a short, sloping terrain and dissected by numerous river and stream systems. This area has significant potential for industrial and maritime transport development. However, drainage issues have been challenging in recent years. Therefore, establishing a sustainable drainage plan will greatly contribute to the economic development of the region.

Table 1 indicates that significant elevation differences within a relatively small area accelerate runoff concentration, thereby shortening the time to peak discharge. As a result, peak flows rapidly propagate toward the urban area. Consequently, the urban area functions as a natural retention zone and becomes highly susceptible to flooding when intense rainfall coincides with high tidal levels.

Table 1. Topographic characteristics and elevation ranges of Ky Anh Urban Area.

Parameters	Characteristic values
Urban ground elevation (m)	0 – 5
Elevation of surrounding hills and mountainous areas (m)	20 – 100
Dominant slope direction	The terrain exhibits a gradual slope from west to east and from northwest to southeast.
Topographic characteristics	Low-lying and poorly drained area

The main roads that connect Ky Anh commune are National Highway 1A, the 70 m road, and the coastal road. The Nha Le channel is the main drainage channel, collecting most of the runoff from upstream sub-basins. The Deng stream, on the other hand, drains the northern urban area. The basin's hydrological features have changed a lot in the last few years because of rapid urbanization. Impervious surfaces now make up 35–40% of the land, up from 10–15%. Natural permeable areas, on the other hand, now make up 35–40% of the land, down from 65–70%. Because of these changes, the peak discharge is higher and the time it takes for surface runoff to concentrate is shorter (Table 2).

Table 2. The urban surface features of Ky Anh commune

Surface type	Before urbanization (%)	Currently (%)
Naturally permeable surfaces	65 – 70	35 – 40
Semi-pervious surfaces	15 – 20	20 – 25
Impervious surfaces	10 – 15	35 – 40

(Source: research team)

Additionally, a lot of roads have been built at heights of 0.5 to 1.5 meters higher than the land around them, but the current drainage system is not good enough to handle the amount of water it needs to. Transportation systems and urbanization have resulted in the formation of "artificial basins" (Table 3). This causes older residential areas to become relatively low-lying, thereby constraining drainage capacity and increasing flood risk.

Table 3. Comparison of Existing Ground Levels and Planned Flood Protection Elevations.

Area	Ground elevation (m)	Control elevation (m)	Risk level
Existing residential area	1.5 – 2.5	≥3.5	High
Newly developed urban area	2.5 – 3.0	≥3.5	Medium
Administrative center	3.0 – 3.5	≥3.5	Medium

From Table 3, it can be seen that the planned flood control elevation is higher than the residential area's ground level, meaning the risk of flooding will occur more frequently. This indicates that a drainage system planning solution based on hydraulic analysis will play a crucial role in urban development planning.

5. Optimization of Drainage Solutions for the Ky Anh Urban Area

5.1. Baseline Scenario (PA0)

The baseline scenario, referred to as PA0, is the starting point for this analysis. The scenario is examined using natural conditions and field data, including information about bridge systems, canal systems, and rivers. This scenario is also used to calibrate the parameters of the hydraulic model. The structure of the PA0 is described in Fig. 3.

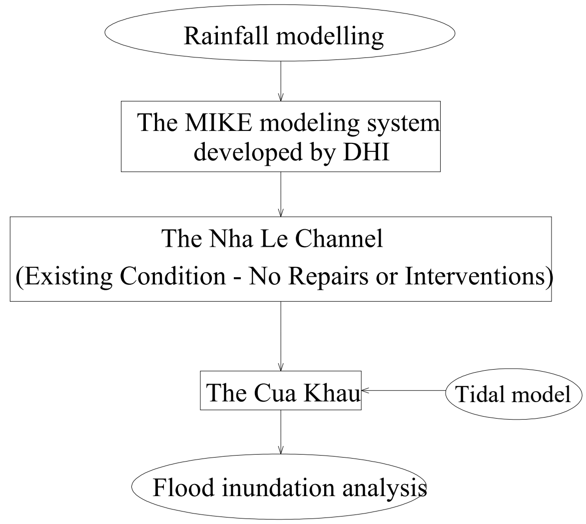

Figure 3. A framework for hydraulic analysis of drainage scenarios in the Ky Anh urban area: Baseline case (PA0).

Fig. 2 depicts the current structure of the drainage system in Ky Anh. The analysis results will be compared with other scenarios to determine the optimal drainage scenario for Ky Anh.

5.2. Scenario PA1

Scenario PA1 is all about using traditional engineering methods to improve flood drainage. The main way to do this is to move all of the floodwater through the Nha Le channel to the Cua Khau estuary. The primary measures include canal dredging, localized channel widening, and the removal or mitigation of hydraulic bottlenecks.

Compared to scenario PA0, scenario PA1 assumes that the channels have been dredged and their dimensions are suitable for the bridge and culvert openings. However, because this solution primarily relies on a single drainage pathway and remains directly influenced by tidal fluctuations, the system still faces a risk of flooding when heavy rainfall coincides with high tides.

5.3. Scenario PA2

Scenario PA2 is predicated on the concept of flood diversion, wherein a segment of the Nha Le channel's discharge is controlled and redirected into the Rac River system. This scenario diverts a portion of the water flow to the Rac River, reducing the burden on the Nha Le channel system leading to the Nhuong estuary (Fig. 4).

Fig. 4 shows scenario PA2, which reallocates water resources to evaluate the effectiveness of drainage zoning compared to PA0.

5.4. Scenario PA3

The PA3 scenario is based on the construction of a new drainage route to Ky Khang beach. PA3 will utilize two drainage routes: one along the Nha Le canal to the Cua Khau estuary, and the other along the new route to Ky Khang beach (Fig. 5).

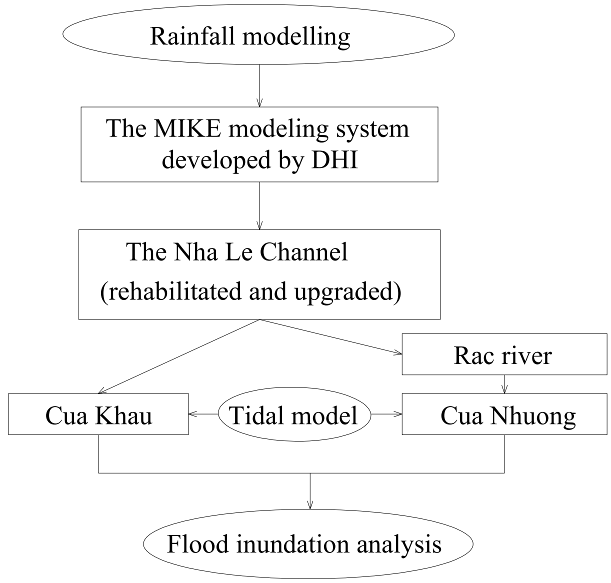

Figure 4. Hydraulic analysis of the structure of scenario PA2

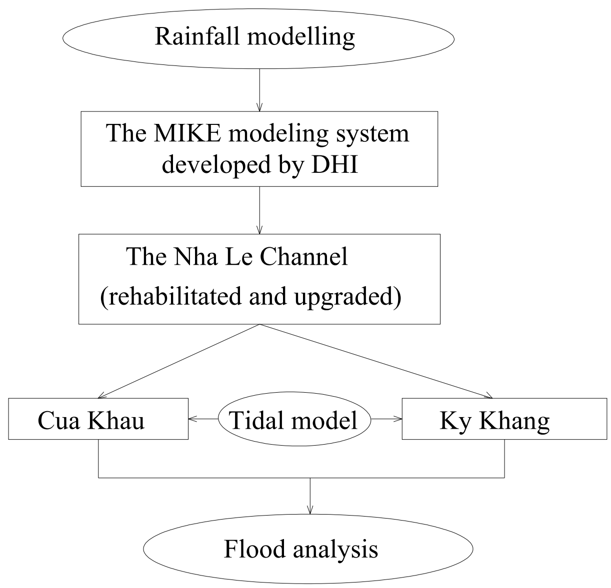

Figure 5. Hydraulic analysis of the structure of scenario PA3.

Fig. 5 illustrates scenario PA3. This scenario has the advantage of a shorter drainage route to Ky Khang beach and faster drainage speed. However, it faces difficulties regarding the cost of investing in a new drainage route, which is expensive and takes a long time to complete.

5.5. Scenario PA4

Scenario PA4 combines all the previous scenarios, using the drainage option based on three main drainage channels. As shown in Fig. 6, this method will allow for more detailed drainage zoning and shorter drainage line lengths.

Fig. 6 shows a way to manage urban coastal drainage that is both systemic and flexible and adapts to the current process of climate change. This multi-directional setup is a varied and useful way to make cities more flood-resistant. The integrated design improves hydraulic redundancy and makes the system less likely to fail when there is both rain and tides.

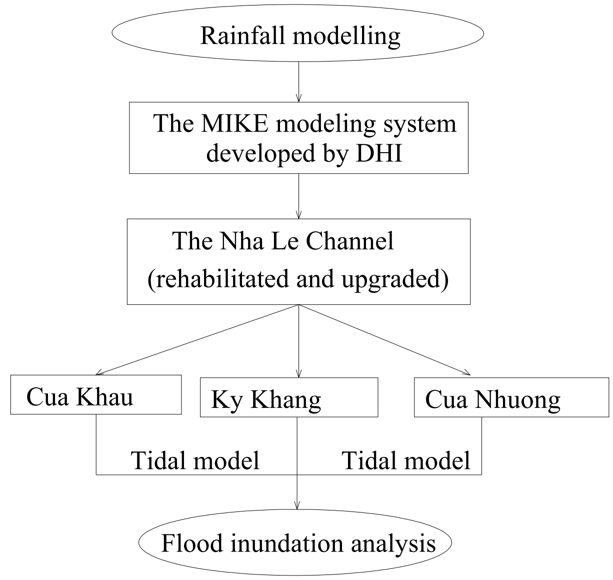

Figure 6. Hydraulic analysis of the structure of scenario PA4

6. Results and Discussion

6.1. Development of the Hydraulic Modeling Framework

The hydraulic computation scheme was constructed based on the flow structure of the river and channel network, including drainage outlets to the sea. This framework provides a basis for evaluating and selecting suitable drainage solutions in urban areas. The modeling framework integrates hydrological inputs, boundary conditions, and 1D–2D coupling methods to ensure the reliability of the simulation results (Fig. 7).

To simulate flood drainage and assess inundation in the administrative center of Ky Anh commune and its surrounding areas, a hydraulic modeling framework was developed, as illustrated in Fig. 8.

6.1.1. Rainfall model

In this study, the selected rainfall event was adjusted to represent a design storm, preserving its key characteristics, including total rainfall depth, event duration, and temporal intensity distribution (Fig. 9). The resulting design storm was then used as input to the rainfall–runoff model to evaluate the flood drainage capacity of the system under adverse real-world conditions, specifically heavy rainfall coinciding with high tide.

The rainfall event used for urban drainage analysis in Ky Anh occurred in October 2020. This high-intensity event caused severe flooding in Ky Anh, and it provides a robust basis for model calibration and scenario evaluation.

The selection of rainfall events for the study was based on field surveys and statistical comparisons. Five rain gauge stations (including Bau Nuoc station, Cam Nhuong station, Kim Son station, Ky Anh station, and Ky Thinh station) were selected for analysis. These stations were strategically distributed around the study area, ensuring spatial representativeness and capturing synchronous rainfall conditions during the selected event.

The event was associated with a tropical depression interacting with a cold air mass, resulting in persistent and heavy precipitation across Central Vietnam. In Ky Anh and its surrounding areas, the cumulative rainfall over 3–5 days typically reaches 600–800 mm, with some locations recording more than 900 mm. These values significantly exceeded the long-term average and approached the design rainfall corresponding to a 5% exceedance probability.

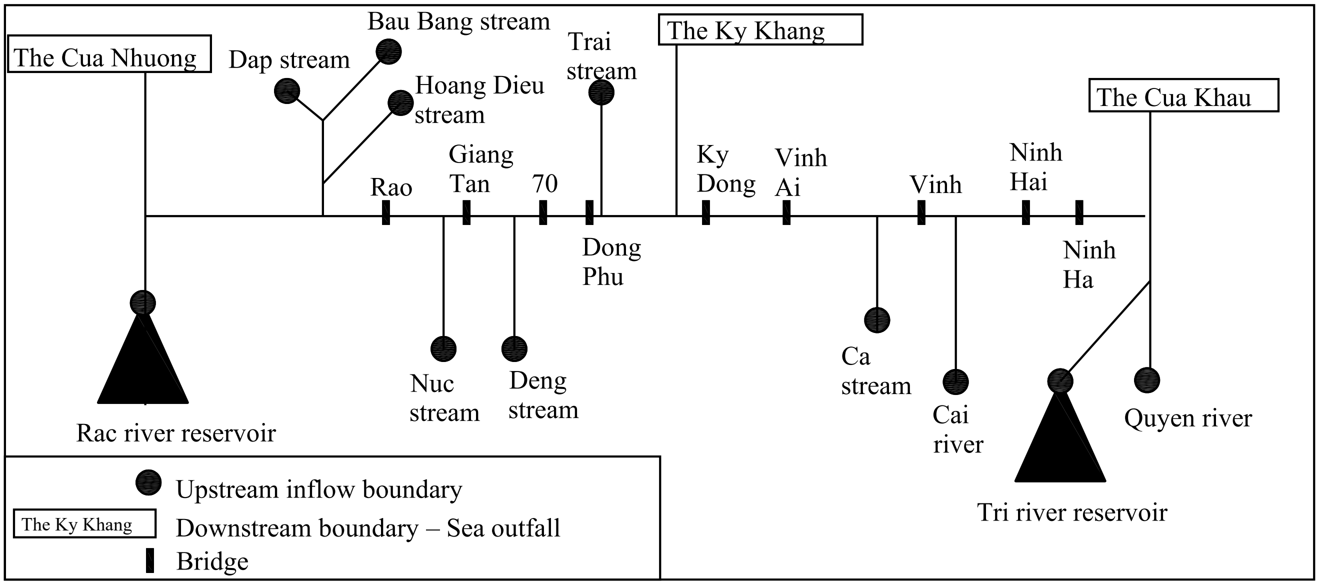

Figure 7. Schematic representation of the river-channel network and bridge structures in the Ky Anh urban area.

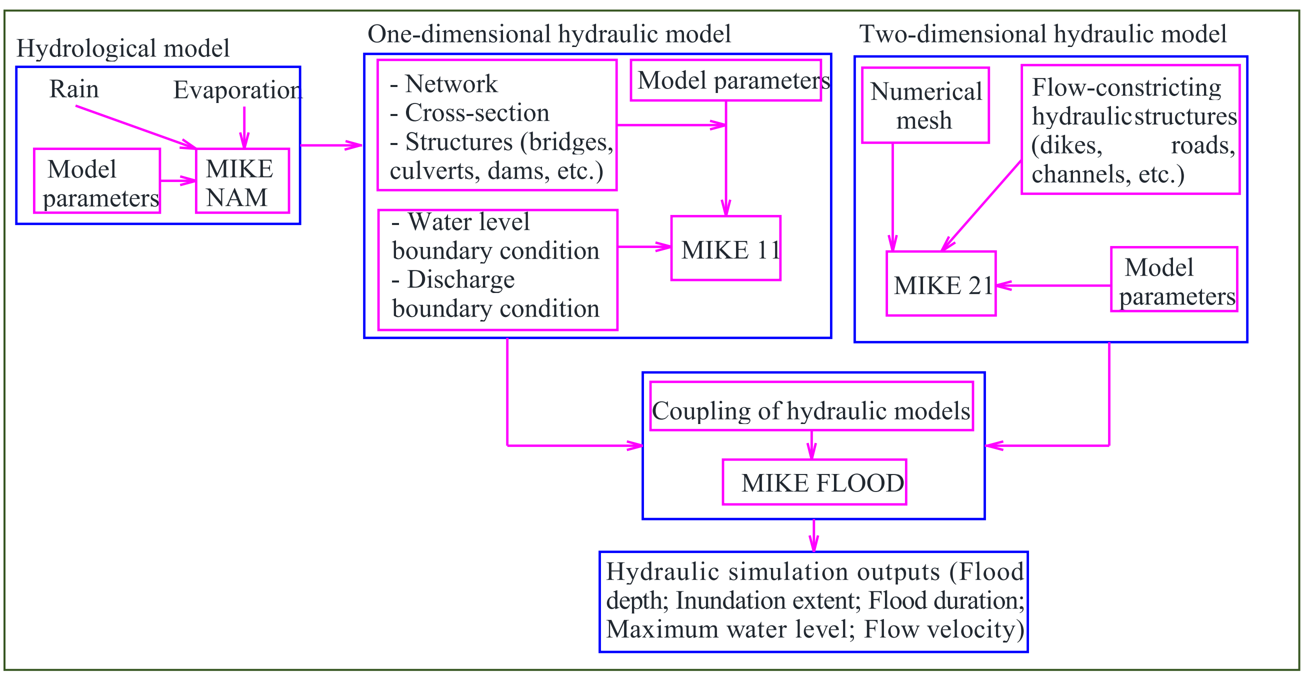

Figure 8. Mathematical modeling framework for flow simulation in the Ky Anh.

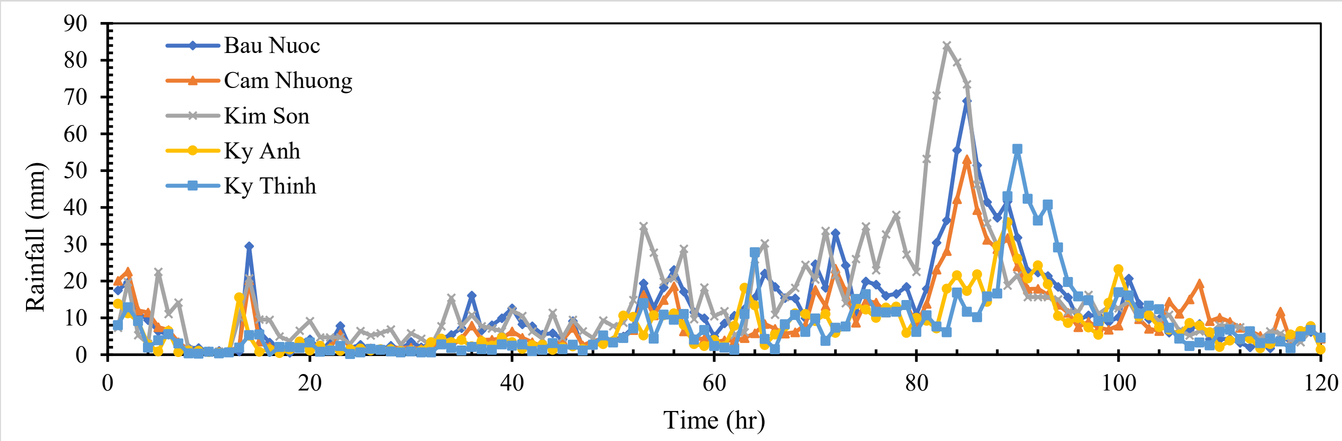

Figure 9. Hourly rainfall hyetograph for the October 2020 event.

6.1.2. Tidal boundary condition modeling

In this study, a design tidal condition corresponding to a 10% exceedance probability was applied as the downstream boundary condition of the drainage system. This tidal scenario occurs frequently in reality, but it is detrimental to drainage capacity. The tidal boundary, as determined by water level data from the Cam Nhuong station (Fig. 10), has high tide peaks. The tidal model in this study was developed based on time series of observed tidal water levels. The dataset was selected according to the design tidal frequency, with a simulation duration of 120 hours, corresponding to the duration of the design rainfall event (120 hours).

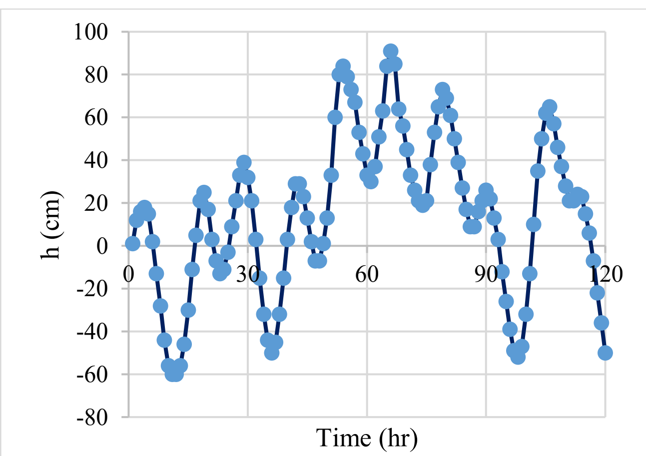

Figure 10. Tidal pattern at Cam Nhuong estuary (August 20–24, 2000).

This approach enables a quantitative assessment of the drainage performance of the Ky Anh urban system under compound rainfall–flood–tide conditions and provides an essential basis for evaluating the safety and effectiveness of the proposed drainage alternatives.

6.1.3. Hydraulic analysis framework

Based on the flow system structure of the Ky Anh urban area, the study develops and integrates multiple research scenarios. The hydrological and hydraulic analysis framework is developed based on the interconnection of hydraulic nodes and contributing watersheds, as illustrated in Fig. 8.

Based on the hydraulic analysis framework presented in Fig. 8, the study performed simulations for multiple scenarios, with the baseline scenario (representing existing drainage conditions) serving as the reference for evaluating the effectiveness of the proposed solutions.

6.1.4. One-dimensional hydraulic modeling using MIKE 11

The MIKE 11 model was applied to simulate flood routing and one-dimensional drainage capacity within the main river and canal network of Ky Anh District, Ha Tinh Province, with particular emphasis on the Nha Le Canal drainage axis and its associated river reaches. A one-dimensional hydraulic network was developed through comprehensive digitization of the main and tributary river–canal systems, combined with field-surveyed cross-sectional data to accurately represent channel morphology and existing flood conveyance capacity. In the modeling framework, sub-basin inflows were derived from the MIKE NAM model (rainfall–runoff model) and incorporated into MIKE 11 as time-varying discharge boundary conditions (Fig. 11).

The MIKE 11 model is used to simulate one-dimensional flow, but it can incorporate tidal surges at estuaries. This investigation provides a scientific basis for evaluating the existing drainage capacity and for assessing the effectiveness of suggested drainage enhancement strategies within Ky Anh Commune.

The model has boundary conditions for the upstream, downstream, and middle parts. Time series data for meteorological, hydrological, water level, and discharge variables are used to define each boundary (Figs. 11 and 12).

- Upstream boundary conditions: Twelve river branches are defined as boundaries for inflow discharge.
- Downstream boundary conditions: Cam Nhuong, Cua Khau, and Ky Khang are the three tidal water level boundaries (three downstream outlets).
- Intermediate boundary conditions: Water-storage rice paddies are represented as lateral storage areas within the system.

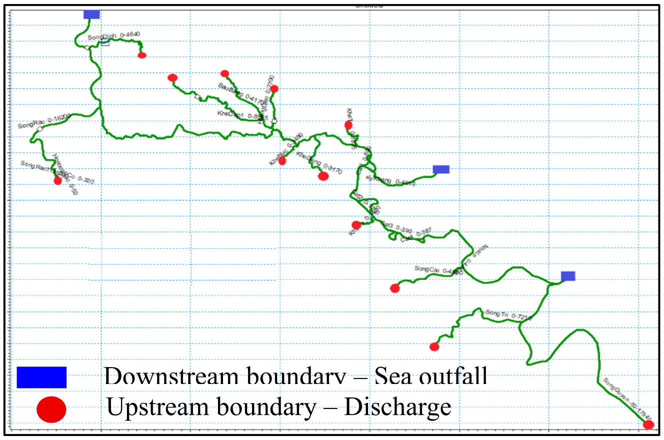

Figure 11. MIKE 11 simulation layout of the river system.

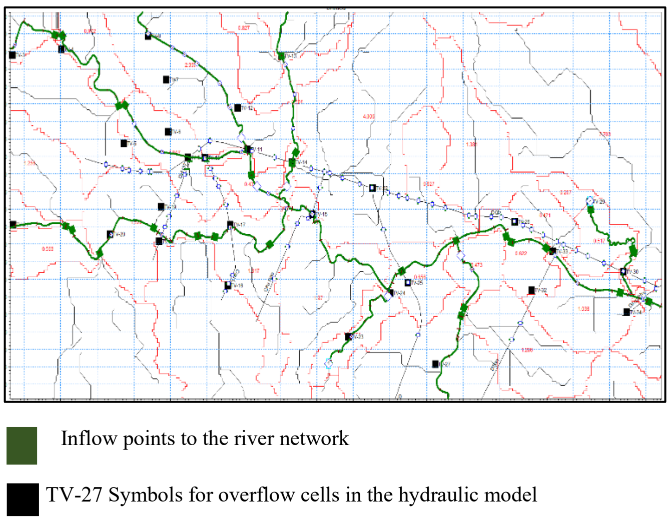

Figure 12. Interface nodes that connect the rainfall-runoff model to the river network model.

6.1.5. Two-dimensional hydraulic analysis by MIKE 21 FM

MIKE 21 FM is a two-dimensional hydrodynamic model used to simulate overland flow and flood propagation in urban and agricultural areas of the Ky Anh under conditions of heavy rainfall, flooding, and tidal influence. The flexible mesh (FM) method lets you use an unstructured grid to show complicated terrain, which lets you accurately show low-lying areas, road networks, and natural drainage corridors that control the direction and extent of floods (Fig. 13). The two-dimensional computational domain was established based on a digital elevation model (DEM) derived from SRTM 30m data, combined with existing topographic maps. The hydraulic computation grid was configured with high resolution in critical areas, including residential zones and low-lying regions, while a coarser resolution was applied in open and relatively flat terrains to optimize computational efficiency. In addition, spatially distributed Manning's roughness coefficients were assigned to accurately represent the variability of flow resistance and energy dissipation across different surface types, including residential areas, agricultural land, water bodies, and vegetation cover.

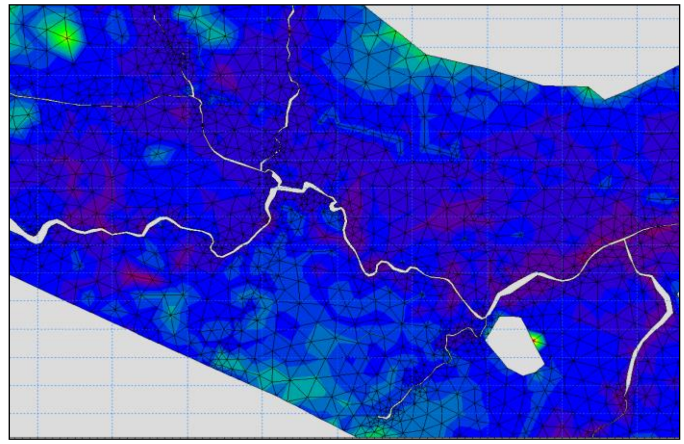

Figure 13. Simulation of two-dimensional hydraulic grid connectivity in the MIKE 21 FM model.

Systems of infrastructure (such as roads, dikes, and canal embankments) as well as flow-obstructing structures were represented in the model as line features or equivalent elevation adjustments within the terrain data to reproduce the "local dike" effect that induces water stagnation in urban areas. The outputs of the MIKE 21 FM model provide key quantitative indicators, including spatial distributions of flood depth, flow velocity, inundation extent, and flood duration. These results form the basis for urban flood risk assessment, identification of vulnerable locations, and support the selection of optimal drainage strategies for Ky Anh.

6.1.6. Hydraulic simulation using MIKE FLOOD

The MIKE 11 hydrodynamic model (one-dimensional) and the MIKE 21 FM model (two-dimensional) were dynamically coupled through link interfaces within the MIKE FLOOD framework (Fig. 14). This coupling mechanism enables bidirectional flow exchange between the 1D river network and the 2D floodplain domain. The integrated setup allows for accurate simulation of in-channel flow as well as overbank flooding and surface runoff across floodplains and rice paddies.

In the coupled flood drainage model for Ky Anh (Fig. 14), flow exchanges between the 1D river network and the 2D floodplain domain were implemented using lateral links. These links represent overbank flow interactions between the river channel and adjacent floodplain areas. Culvert connections between river branches and the 2D domain were represented using standard links within the MIKE FLOOD framework. In total, 165 links were defined in the model, including 37 lateral links and 128 standard links.

6.2. Hydraulic Performance Evaluation of Alternative Drainage Scenarios

6.2.1. Hydraulic computation method

Current condition scenario (PA0): The river and channel system under existing conditions. The model is calibrated and validated using real flood events, and it's also tested under conditions that match the expected design frequencies. It is called "PA0" and is used as a reference case to compare the proposed improvement scenarios and see how well each one drains water from the flood.

Analysis of the PA0 scenario involves parameter calibration, in which the roughness coefficients are adjusted according to existing conditions and the characteristics of each area. The calibrated parameters from the PA0 scenario are subsequently applied to other scenarios. Hydraulic simulations under the PA0 scenario provide baseline data on flood depth, flow direction, and inundation extent. Selected flood analysis results are presented in Fig. 15.

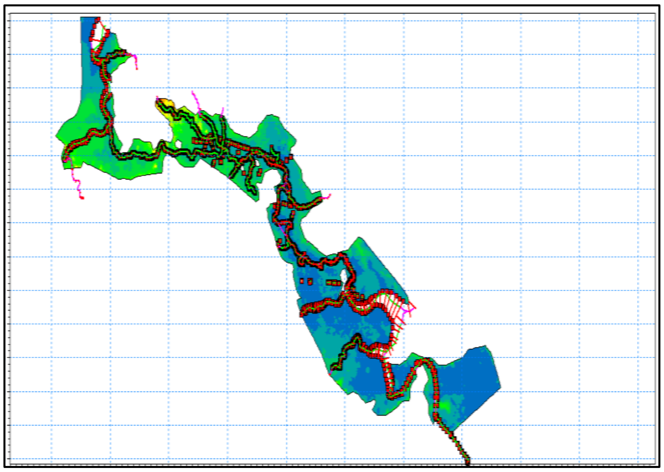

Figure 14. Integrated modeling framework linking MIKE FLOOD with MIKE 11 and MIKE 21

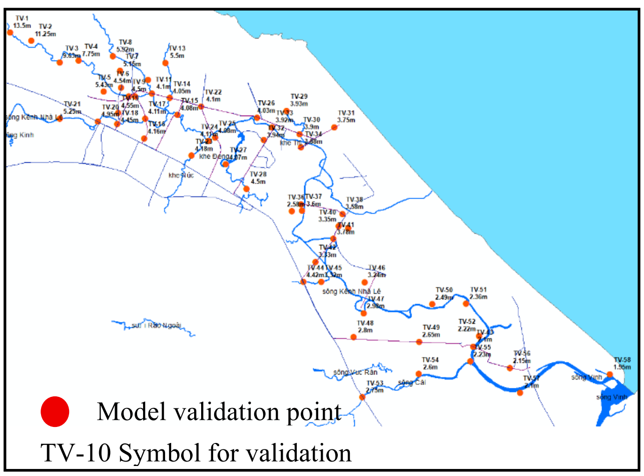

Figure 15. Locations and elevations of the model validation point.

The analysis results at the validation points for the scenario PA0 are summarized and presented in Table 4.

Table 4. Water surface elevations at calculated and observed points based on the Vietnamese national coordinate system.

Values	Nha Le channel		Channel and overland flooding	
	Calculated elevation (m)	Observed elevation (m)	Calculated elevation (m)	Observed elevation (m)
Max	6.066	6.150	6.070	5.92
Min	1.946	1.950	2.254	2.34

Table 4 presents flood data for the Nha Le channel and urban areas. Due to topographical characteristics, particularly low-lying zones formed by surrounding high-elevation structures, flood depths are considerable, and drainage duration is prolonged. Although the Nha Le channel maintains continuous flow, overtopping still occurs, affecting areas adjacent to this primary drainage channel.

Based on the analysis of data in Table 4, the observed and calculated water surface elevations in the study area are presented in Fig. 16.

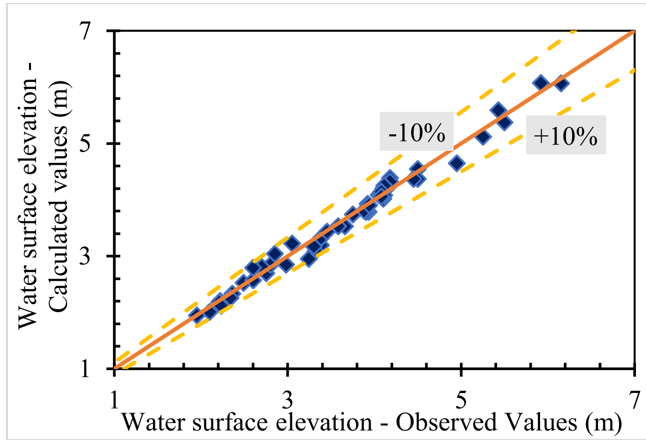

Figure 16. Comparison of flood depth between observed and simulated data under the PA0 scenario.

Fig. 16 indicates that most amplitude errors fall within the ±10% range, with smaller calculation errors observed in the Nha Le Canal compared to urban areas. This can be attributed to the more stable and well-defined hydraulic flow conditions in the canal, in contrast to the complex overland flow processes in low-lying urban regions.

To quantitatively assess model accuracy, statistical indicators were employed to compare simulated results with observed data. These indicators include Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and the coefficient of determination (R^2) [25]. The results are presented in Table 5.

Table 5. Statistical indicators for evaluating the calculation results of the scenario PA0.

Scenario	Statistical indicators of agreement between the calculated and observed data				
	MEA	MSE	RMSE	MAPE (%)	R^2
PA0	0.099	0.015	0.122	2.788	0.985

Evaluation based on Fig. 16 and Table 5 demonstrates a strong correlation between hydraulic simulation results and observed data ($R^2 > 0.98$), with other statistical metrics approaching ideal values. This confirms the reliability of the MIKE modeling system in analyzing urban flood characteristics. Therefore, the calibrated parameters from the PA0 scenario are adopted as the basis for analyzing subsequent proposed scenarios.

Figure 17. Flow directions in drainage system simulations.

Renovation scenario (PA1-4): This option involves figuring out the necessary channel widening and dredging parameters for the Nha Le channel and the Ky Khang channel. The analysis factors for the channel include the bottom width (B), depth (H), bed slope (S), and bed elevation (Z), which are all examples of these. The goal of the Nha Le Canal's reconstruction is to make it easier for floods to flow in three primary directions: toward the Cua Khau estuary, the Rac River, and the Ky Khang coastal outflow (Fig. 17).

The solution for renovating the Nha Le channel is to dredge the canal based on the size of the drainage bottom of the structures along the channel. However, the bridge on the 70 m road will stay the same.

6.2.2. Hydraulic performance results of the drainage scenarios

Based on the analyzed scenarios, together with the specified boundary conditions (design rainfall, tidal boundary, and drainage direction), the hydraulic analysis results for the five scenarios are presented in Tables 6, 7, and 8.

The hydraulic simulation results presented in Table 6 indicate that the Ky Anh urban drainage system is simultaneously influenced by three major adverse factors:

- High-intensity rainfall with large cumulative depth.
- Low-lying terrain coupled with the rapid runoff concentration characteristics of small catchments.
- Significant downstream tidal effects. The interaction of these factors leads to elevated peak water levels in the Nha Le channel system and prolongs inundation duration within the central urban area.

Table 6. Quantitative Evaluation of Hydraulic Performance under Different Drainage Scenarios

Parameters	PA0	PA1	PA2	PA3	PA4
Simulated maximum depth (H_{max}) in the Nha Le channel (m)	4.10-4.30	3.80 – 4.00	3.50 – 3.70	3.45 – 3.70	3.30 – 3.50
Reduction in peak water level relative to PA0 (m)	–	0.20 – 0.30	0.45 – 0.60	0.45 – 0.60	0.70 – 0.90
Compliance with the urban flood protection level (+3.50 m)	Exceeding 0.5–0.7 m	slightly above the standard	approaches standards	Meets requirements/approaches standards	Ensuring safety
Flooded area (ha)	1.200-1.350	900 – 1.000	650 – 750	650 – 720	450 – 550
Percentage reduction in inundation area relative to PA0 (%)	–	20 – 25%	40 – 45%	40 – 45%	55 – 65%
Average flood depth within the urban area (m)	0.8 – 1.2	0.6 – 0.9	0.4 – 0.6	0.4 – 0.6	0.2 – 0.4
Maximum inundation depth (m)	1.8 – 2.0	1.4 – 1.6	1.1 – 1.3	1.1 – 1.3	0.8 – 1.0
Inundation duration (depth > 0.3 m) (hours)	72 – 120	60 – 96	36 – 60	36 – 60	18 – 36
Time to recession after peak water level (hours)	48 – 72	36 – 60	24 – 36	24 – 36	12 – 24
Maximum discharge (Q_{max}) in the Nha Le channel (m^3/s)	90 – 105	100 – 120	75 – 90	70 – 85	60 – 75
Percentage of flow redistributed to secondary outlets (%)	0	<10%	25 – 35%	25 – 30%	40 – 50%
Influence of downstream tidal conditions	Very large	Large	Medium	Medium	Small
Capable of handling urban rainfall with a 2% exceedance probability and a duration of 3 hours	No	Limit	Suitable for certain regions	Suitable for certain regions	Ensure comprehensi ve drainage.
Flood safety level of the drainage system	Small	Low - average	Average	Good	Best

Under the PA0, the peak water level in the Nha Le channel exceeds the urban flood protection level by approximately 0.5–0.7 m under both the 10% design rainfall scenario and the 5% verification scenario. The total inundated area exceeds 1,200 hectares, with a mean flood depth of 0.8–1.2 m in the urban area and a flooding duration of approximately 3 to 5 days. These results indicate a severe hydraulic overload of the existing drainage system and are consistent with field observations recorded during recent major flood events.

The effectiveness of the drainage scenarios in terms of inundation extent and duration is presented in Tables 7 and 8.

Table 7. Relationship between Hydraulic Mechanisms and Simulation Results under Different Scenarios

Scenario	Dominant Hydraulic Mechanism	Maximum water level in the Nha Le channel (m)	Flooded area (ha)	Inundation duration (depth > 0.3 m) (hours)	Mechanistic interpretation
PA0	Drainage flow is governed by natural topography and is predominantly conveyed through the Nha Le channel	4.10 – 4.30	1.200 – 1.350	72 – 120	The flow is compressed → exceeds the carrying capacity → widespread overflow.
PA1	The drainage configuration is unidirectional and highly sensitive to downstream tidal forcing	3.80 – 4.00	900 – 1.000	60 – 96	Faster drainage, but tides hinder the flow → limited flood reduction
PA2	A distributary branch conveys flow toward the Rac River	3.50 – 3.70	650 – 750	36 – 60	Sharing and reducing water flow → reducing flood peaks → shrinking flooded areas.
PA3	The stream branches off towards Ky Khang beach (Figure 20)	3.45 – 3.70	650 – 720	36 – 60	Opening additional independent drainage channels → reduces downstream pressure.
PA4	Multi-directional flow distribution and optimization of drainage pathways	3.30 – 3.50	450 – 550	18 – 36	Distribution of flow in space and time → highest efficiency

Table 8. Comparison of the maximum water level (Hmax) between different options.

Scenarios	Hmax (m)	Reduction relative to PA0 (m)
PA0	4.10–4.30	–
PA1	3.80–4.00	0.2–0.3
PA2	3.50–3.70	0.5–0.6
PA3	3.45–3.70	0.5–0.6
PA4	3.30–3.50	0.7–0.9

Table 7 indicates that, in addition to reducing peak flood levels, scenario PA4 also decreases both the inundation extent and duration. These results demonstrate the effectiveness of drainage zoning in urban planning. The effect of PA4 in reducing maximum water levels is clearly demonstrated in Table 8, and this is highly significant for determining appropriate urban ground elevations across different areas.

6.2.3. Analysis of factors affecting urban flooding

The drainage scenarios in the Ky Anh urban area are illustrated through the following analyses:

** Impact of drainage structures on maximum water levels*

The flood depth across the scenarios enables an assessment of the drainage performance of each option. In particular, the maximum depth in the Nha Le channel varies significantly among the different scenarios (Table 8). The analysis compared with the PA0 shows that the PA1 reduced the water depth by 0.2- 0.3 m, while the PA2 and PA3 reduced the flooding depth by approximately 0.45- 0.6 m. The PA4 showed the largest reduction in flooding depth, ranging from 0.7m to 0.9m. Thus, the PA4 was the most effective in reducing flood depth, demonstrating that the more detailed the flood drainage zoning solution, the better the flood reduction effectiveness.

These results show that the way the drainage pathways are set up is very important for controlling the system's hydraulic state. Coastal cities that are affected by both tidal factors and climate change need to use multi-way drainage solutions.

** The area and depth of flooding*

The factors are two important signs that show how likely it is that an urban area will be flooded. It can be seen from Tables 7 and 8 that the total area that is flooded is about 20–25% less under PA1, 40–45% less under PA2 and PA3, and more than 55–65% less under PA4 compared to PA0.

The average depth of urban flooding decreases from 0.8 to 1.2 meters (PA0) to 0.2 to 0.4 meters (PA4). This large difference has significant effects on society and the economy, as well as on urban development.

** Duration of flooding and the process of water receding*

Coastal cities that are affected by tidal conditions often have long periods of flooding. In scenario PA0, flooding with water depths greater than 0.3 m lasts for about 72 to 120 hours, and the time it takes for the flood to recede after the peak lasts for 48 to 72 hours. The scenario PA1 only makes this situation a little better.

The diversion-based scenarios (PA2 and PA3) cut the time of flooding down to about 36–60 hours. The PA4 cuts it down even more, to 18–36 hours. These results show that how quickly the system can drain and recover after a flood depends a lot on how well it can move water around and how well it can reduce the effects of tidal backwater downstream.

7. Conclusion

The present research examined urban flooding within the coastal zone of Ky Anh commune, located in Ha Tinh Province, Vietnam, employing a detailed hydrological-hydraulic modeling approach. The study identified the optimal drainage model for the Ky Anh urban area based on the MIKE model system (MIKE NAM, MIKE 11, MIKE 21, and MIKE FLOOD). The study analyzed and identified five drainage scenarios (PA 0-4). Scenario PA0 was used to analyze the flooding process under existing conditions, indicating that the system can accommodate rainfall only up to a certain threshold, including both moderate and heavy events.

Analysis of scenarios PA1-4 with different drainage directions showed the effectiveness of drainage zoning. It proposed adding a drainage direction to Ky Khang beach and incorporating it into scenarios PA3 and PA4.

Among the four proposed drainage scenarios, the zoned drainage solution (PA4) demonstrates the highest effectiveness and ensures sustainable drainage for the Ky Anh urban area. These results show that the best way to protect coastal cities from the effects of climate change and tidal forces is to have a drainage plan that is flexible, works across regions, and is part of a larger system.

The results suggest that isolated engineering interventions are inadequate for the effective mitigation of coastal urban flooding. The Ky Anh and similar coastal municipalities must integrate hydraulic modeling, urban spatial planning, and adaptive management approaches in an environmentally sound manner. A hydraulic model should be established for the entire basin or for independent sub-areas. Based on this, appropriate urban planning elevations should be determined for each area to ensure effective drainage and minimize flooding. This integrated approach is particularly crucial given the escalating impacts of climate change and the concomitant rise in sea levels, which are exacerbating urban density in these cities.

This study demonstrates that integrated hydraulic modeling is not only an effective tool for computational simulation but also a critical scientific foundation for evidence-based decision-making in urban planning and management.

The limitations of this study are primarily technical. A more comprehensive determination of drainage scenarios requires the inclusion of economic and social assessments. Quantifying the costs and benefits of different drainage options would enhance the practicality of the proposed solutions and improve their alignment with policy objectives.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Vu Hoang Diep and Le Van Nghi proposed the research problem.

Le Van Nghi, Vu Hoang Diep, and Nguyen Minh Ngoc were responsible for collecting and analyzing data, as well as developing hydraulic models. All authors contributed equally to the preparation of the first manuscript.

Nguyen Minh Ngoc was responsible for finalizing and editing the manuscript; evaluating the research findings and managing the manuscript development process; corresponding author.

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