Kristian van der Lek

Stormwater management inside Vietnam's coastal urban developments

Assessment of the urban drainage system design on Hà Nam island in Quang Ninh province, Vietnam

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By

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To obtain the degree of **Master of Science**
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Thuy Loi University

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This master's thesis report marks the end of my student years, but it also signifies the continuation of my journey in the field of water management. I began my academic pursuit in 2015 with a bachelor in the field of built environment at Utrecht university of applied sciences. The people I encountered during this period played an important role in shaping me professionally. I want to especially thank Judith Sloot, Paul Roeleveld, Romano Wannyn, Erwin Rebergen, Johan van der Woude and Marco van Bijnen for all of your support. Thanks to your encouragement, I gained the confidence to pursue a master's degree at TU Delft.

Throughout my master's program, I worked as an urban water engineering consultant, requiring me to maintain a delicate balance between academic studies and practical application of my knowledge in the field. I want to thank all my colleagues with whom I have worked with for taking into account my study schedule while working together. Paul and Romano, I want to thank you both for your patience and support.

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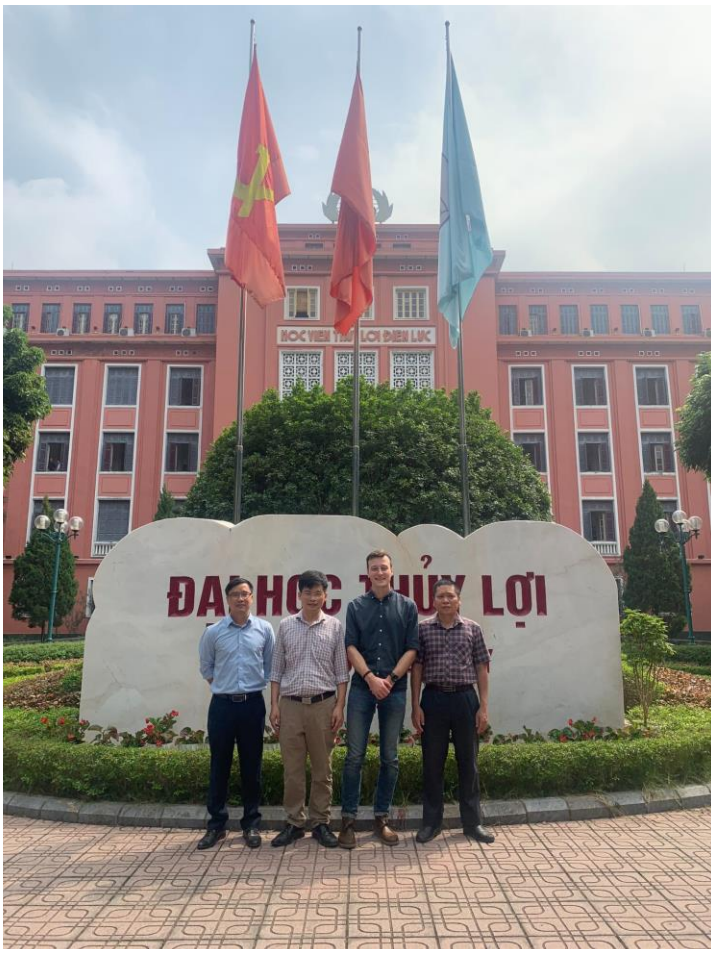

In front of the Thuy Loi University campus building with professors from the water resources department in Hanoi

Ba Vì national park, Hanoi

Summary

Many cities in Vietnam are located at the coast and are exposed to heavy weather events that yearly cause casualties and economic losses. The World bank estimated in 2020 that 12 million people in Vietnam are directly exposed to intense flood risk. At the same time the country is developing rapidly and thus more space is allocated to accommodate urban growth. Studies have shown that within these developments not enough emphasis is given on flood adaptation strategies. Literature study has shown that there are cases in Vietnam were residential expansions have led to an increase in risk of pluvial flooding. This type of flooding is caused by insufficient capacity of the urban drainage system as a result of heavy rainfall. When capacity is insufficient, inundation can occur in the lowest areas in topography as a result of canal overtopping. This type of flooding can also take place more locally in cities when pipes or gutters cannot transport the water fast enough out of the area. Many types of approaches to make these systems more flood resilient exist, like the Water Sensitive Urban Design approach. Or the more globally known one: Sustainable Urban Drainage systems (SUDS).

Keeping in mind the exposure of flooding in Vietnam and the potential of SUDS, it is desirable to set general design guidelines with respect to urban drainage. On top of that, 1D/2D hydrodynamic models have proven to be useful when mapping flood risk at different scales. Therefore, this study aims to show how 1D/2D hydrodynamic models can be put into practice when designing drainage infrastructure and implementing flood adaptation measures. For this research, hydrodynamic modelling tool Delft3D FM (D-HYDRO) was implemented in a case study.

The province of Quang Ninh is working out major development plans for the coastal area between Hải Phòng and Hạ Long. Đảo (island) Hà Nam is one of the areas inside this coastal economic development zone. This 40 km^2 area now mainly consists of rice paddy fields and some communities with a total population of about 50,000 residents. An important characteristic of Hà Nam is that the open canals drain to the surrounding rivers by means of sluice gates. These are operated manually and can only be opened during low tide. This means that if heavy rainfall occurs during high tide, stormwater has to be stored within Hà Nam for a certain amount of time. The modelling study presented in this report, shows that, under current conditions, the flood extent during extreme rainfall inside built-up areas is quite low (<2%).

Hà Nam is projected to have many land use changes over the coming two decades. To cope with these developments, the urban drainage system is being examined by Vietnamese authorities. This study presents possible design solutions that aim to reduce the urban flood extent while considering future development projections, local rainfall statistics and sea level rise predictions. The masterplan of Hà Nam that was approved by the Vietnamese government in 2023, was examined to determine changes in land use and terrain elevation. This analysis shows that 70% of paddy fields will have been replaced by built-up areas to make space for industrial, residential and commercial areas. As part of the development, these plots will be elevated. This means that a large portion of the current built-up areas will shift towards the lower topographic zones in the future scenario.

Analysis of sea level measurements and sea level rise predictions has shown that the probability that no free-gravity flow to the rivers is possible during an arbitrary heavy rain event is currently 25%, and will increase to 40% by 2050. Consequently, this study recommends that future design scenarios assume the sluice gates will remain closed throughout the entire duration of extreme rainfall events.

According to this modelling study, in the future land use scenario, more than half of the existing communities will face pluvial flooding during a T=10 year rain event. A set of pumping stations is recommended to ensure effective drainage during high tide. Incorporating pumping stations reduces the urban flood extent for a T=10 year rain event to 7% and for a T=100 year rain event to 40%. The study concludes that, under current land use projections, the existing communities will face an increased risk of flooding. Moreover, the current design does not comply with the Vietnamese authorities' guideline, which states that no canal overtopping should occur during a T=10 year rain event.

This study proposes the implementation of two types of SUDS to increase local stormwater storage, namely vegetated swales and park overflow zones. The SUDS are implemented within the development plots, and combined with allocated greenspaces to ensure sufficient space for the projected developments. Utilizing SUDS reduces the extent of urban flooding to levels comparable to the current situation for the T=10 years event. However, for more extreme rainfall events, such as a T=100 year event, the flood extents remain higher, with the total urban flood extent reaching 25%.

Despite the implementation of pumping stations and SUDS, the area remains vulnerable to pluvial flooding. This study proposes two solutions: scaling back developments to preserve rural land, or constructing wetlands to maintain storage capacity and improve water quality. Alternatively, subdividing the area into smaller pumping zones could also mitigate flooding but requires detailed planning. Both solutions would necessitate modifications to the already approved masterplan, emphasizing the safety and wellbeing of Hà Nam residents.

This study demonstrates that, if enough information is available, combined with 1D/2D hydrodynamic modelling tools, meaningful insights can be gained into the effects of land use and terrain changes, SUDS and climate change on pluvial flooding. It is recommended to widen the scope to include the mitigating effects of SUDS on water pollution of Hà Nam. Lastly, this research recommends to gain insight in the financial investments and benefits that are involved with flood adaptation measures.

Keywords: Pluvial Flooding, Urban Drainage Systems, Vietnam, Red River Delta, Coastal Development, Polder Systems, SUDS, Delft3D FM, D-HYDRO 1D/2D

Samenvatting

Veel steden in Vietnam liggen aan de kust en worden blootgesteld aan zware weersomstandigheden die jaarlijks slachtoffers en economische schade veroorzaken. De Wereldbank schatte in 2020 dat 12 miljoen mensen in Vietnam rechtstreeks worden blootgesteld aan een verhoogd risico op overstromingen. Tegelijkertijd ontwikkelt het land zich snel en wordt er meer ruimte toegewezen voor stedelijke uitbreidingen. Studies hebben aangetoond dat binnen deze ontwikkelingen niet genoeg nadruk wordt gelegd op strategieën die het risico op overstroming verkleinen. Literatuuronderzoek heeft aangetoond dat er gevallen zijn in Vietnam waarbij stedelijke uitbreidingen hebben geleid tot een verhoogd risico op pluviale overstromingen. Dit type overstroming wordt veroorzaakt door onvoldoende capaciteit van het stedelijk regenwaterafvoersysteem. Wanneer de capaciteit onvoldoende is, kan inundatie optreden als gevolg van het overlopen van kanalen en sloten. Dit type overstroming kan ook lokaal in steden voorkomen wanneer buizen of straatgoten het water niet snel genoeg uit het gebied kunnen afvoeren. Diverse soorten methodes om deze systemen beter bestand te maken tegen extreme neerslag bestaan, zoals de “Water Sensitive Urban Design”. Of de meer wereldwijd gebruikte: Duurzame Stedelijke Afvoersystemen (EN: SUDS).

Met het oog op de gevaren van overstromingen in Vietnam en het potentieel van SUDS, is het wenselijk om algemene ontwerprichtlijnen voor stedelijke regenwaterafvoer op te stellen. Bovendien hebben 1D/2D-hydrodynamische modellen bewezen nuttig te zijn bij het in kaart brengen van overstromingsrisico's voor gebieden op verschillende schaalniveaus. Deze studie beoogt te laten zien hoe 1D/2D-hydrodynamische modellen in de praktijk kunnen worden gebracht bij het ontwerpen van stedelijk water afvoersystemen en het implementeren van maatregelen. Voor dit onderzoek is het hydrodynamische modelleringsinstrument D-HYDRO (EN: Delft3D FM) geïmplementeerd in een casestudie.

De provincie Quang Ninh werkt aan ontwikkelingsplannen voor het kustgebied tussen Hải Phòng en Hạ Long. Đảo (eiland) Hà Nam is een van de gebieden binnen deze kustontwikkelingszone. Dit gebied van 40 km^2 bestaat nu voornamelijk uit rijstvelden en enkele gemeenschappen met een totale bevolking van ongeveer 50.000 inwoners. Een belangrijk kenmerk van Hà Nam is dat de open kanalen via sluizen naar de omliggende rivieren afwateren. Deze sluizen worden handmatig bediend en kunnen alleen bij eb worden geopend. Dit betekent dat bij hevige regenval tijdens vloed het regenwater voor een bepaalde tijd binnen Hà Nam moet worden opgeslagen. De in dit rapport gepresenteerde modelstudie toont aan dat onder de huidige omstandigheden de overstromingsomvang tijdens extreme regenval in bebouwde gebieden laag is (<2%).

Voor Hà Nam worden de komende twee decennia veel veranderingen in landgebruik verwacht. Om deze ontwikkelingen het hoofd te bieden, wordt het stedelijke drainagesysteem door Vietnamese autoriteiten onderzocht. Deze studie presenteert mogelijke ontwerpoplossingen die erop gericht zijn de maximale omvang van stedelijke overstroming (EN: Urban Flood Extent) te verminderen, rekening houdend met toekomstige ontwikkelingsprojecties, lokale neerslagstatistieken en voorspellingen van zeespiegelstijging. Het door de Vietnamese regering in 2023 goedgekeurde masterplan voor Hà Nam is onderzocht om veranderingen in landgebruik en terreinhoogte te bepalen. Het masterplan laat zien dat 70% van de rijstvelden zal zijn vervangen door bebouwde gebieden om ruimte te maken voor industriële, residentiële en commerciële zones. Als onderdeel van de ontwikkeling zullen deze percelen worden opgehoogd. Dit heeft als gevolg dat een groot deel van de huidige bebouwde gebieden in het toekomstige scenario zal verschuiven naar meest lage plekken in de topografie.

Analyse van zeespiegelmetingen in combinatie met voorspellingen van zeespiegelstijging heeft aangetoond dat de kans dat er geen vrij-verval afvoer naar de rivieren mogelijk is tijdens een

zware regenbui momenteel 25% is, en tegen 2050 zal toenemen tot 40%. Daarom is besloten om voor het toekomstscenario aan te nemen dat de sluizen tijdens zware regenval gesloten blijven.

Uit de modelleringsstudie blijkt dat meer dan de helft van de bestaande gemeenschappen in het toekomstig landgebruiksscenario te maken krijgt met pluviale overstroming. Het inzetten van gemalen wordt aanbevolen om ervoor te zorgen dat het gebied neerslag kan afvoeren tijdens hoog tij. Het opnemen van gemalen verlaagt de Urban Flood Extent voor een neerslaggebeurtenis met een terugkeerperiode van 10 jaar tot 7% en met een terugkeerperiode van 100 jaar tot 40%. Deze studie concludeert dat de bestaande gemeenschappen door toekomstige projecties van landgebruik een verhoogd risico op overstromingen zullen hebben. Bovendien voldoet het huidige ontwerp niet aan de richtlijn van de Vietnamese autoriteiten, die stelt dat er geen overstroming in stedelijk gebied mag plaatsvinden tijdens een regenbui van T=10 jaar.

Deze studie stelt de implementatie voor van twee soorten SUDS om de lokale opslag van regenwater te vergroten, namelijk beplante greppels (EN: Vegetated swales) en park overloopzones (EN: Park overflowzones). De SUDS worden geïmplementeerd binnen de ontwikkelingspercelen en gecombineerd met toegewezen groengebieden om voldoende ruimte te garanderen voor de geplande ontwikkelingen. Het gebruik van SUDS vermindert de omvang van stedelijke overstromingen tot niveaus die vergelijkbaar zijn met de huidige situatie voor de neerslaggebeurtenis van T=10 jaar. Echter, voor meer extreme neerslaggebeurtenissen blijven de overstromingsgebieden toenemen ten opzichte van de huidige situatie. Bijvoorbeeld bij een gebeurtenis van T=100 jaar, waarin de Urban Flood Extent een waarde van 25% bereikt.

Ondanks de implementatie van gemalen en SUDS blijft het gebied vatbaar voor overstromingen. Deze studie stelt twee oplossingen voor: het terugschroeven van ontwikkelingen om landelijk gebied te behouden, of het aanleggen van wetlands om opslagcapaciteit te behouden en de waterkwaliteit te verbeteren. Als alternatief zou het onderverdelen van het gebied in kleinere bemalingsgebieden het beschermingsniveau van de meest lage plekken verbeteren, maar dit vereist meer gedetailleerde planning. Beide oplossingen zouden aanpassingen aan het reeds goedgekeurde masterplan vereisen. Deze studie betoogt dat bij het doen van aanpassingen er nadruk moeten worden gelegd op de veiligheid en het welzijn van de huidige inwoners van Hà Nam.

Deze studie laat zien dat met voldoende informatie, in combinatie met 1D/2D-hydrodynamische modelleringstools, inzicht kan worden verkregen in de effecten van veranderingen in grondgebruik en terreinhoogte, SUDS en klimaatverandering op de pluviale overstromingskans. Het wordt aanbevolen om deze studie uit te breiden om ook de effecten van SUDS met betrekking tot waterverontreiniging in Hà Nam op te nemen. Ten slotte wordt aanbevolen om inzicht te krijgen in de financiële investeringen en opbrengsten die gepaard gaan met SUDS.

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Introduction

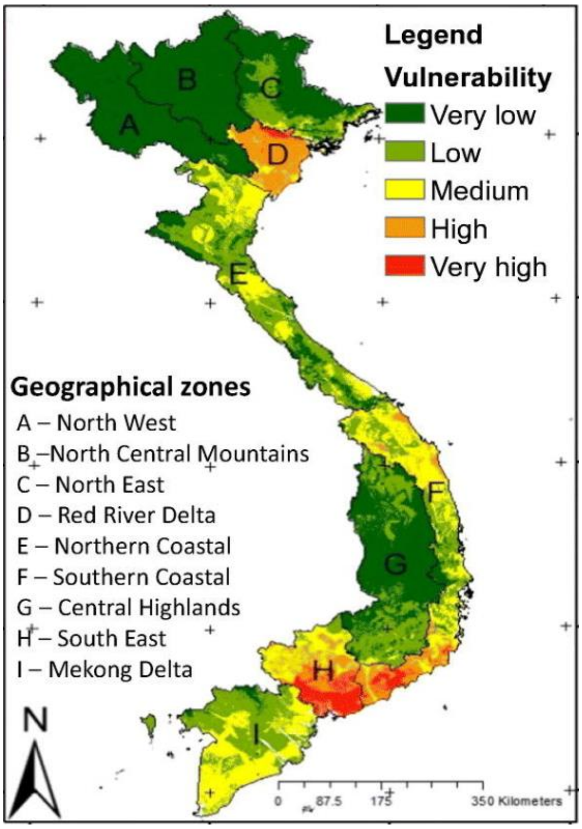
1.1 Flood risk in coastal urban areas in Vietnam

In coastal cities flooding is primarily caused by surface runoff due to inland heavy rainfall and river flooding from extreme high tide and high river discharge (Shen et al., 2019; Lian et al., 2017, Apel et al., 2016, Huong, Pathirana, 2013). Especially coastal cities with low topographical gradient are prone to flooding because of storm surges (Apel et al., 2016). Typhoons are known for creating storm surges and heavy precipitation. In gravity-flow systems the discharge capacity is greatly reduced during high tide. This means that in the situation of a storm surge in combination with heavy rainfall, there is an increased risk of flooding in these systems. Furthermore, sea level rise (SLR) will increase the risk of flooding in coastal areas (Shen et al., 2019; Scussolini et al., 2017; Neumann et al., 2015). In addition, land subsidence also proposes a direct threat for coastal areas. Research in the Mekong delta shows that land subsidence is directly related to human activities and will lead to problems over the long term (de Wit et al., 2021; Minderhoud et al., 2020; Thoang et al., 2015; Erban et al., 2014).

For 2020 it was estimated by the World bank that 12 million people in Vietnam are directly exposed to intense flood risk (World Bank, 2022). Vietnam is a rapidly developing country with a large population. The country has an average of 10 tropical storms landing every year along with high-intensity rainfall (Tran et al., 2016). Most cities in Vietnam are located along the coastline and in river deltas. This means that many highly populated areas and economic assets are exposed to sea-level rise, storm surges and typhoons (Bangalore et al., 2017). Flooding already frequently causes severe casualties and economic losses in Vietnam (Luu et al., 2019). Therefore, protection from urban flooding is a great challenge for the sustainable development of many cities. According to (Kim-Anh Nguyen et al., 2019) the Red River delta and Ho Chi Minh City (HCMC) are the most vulnerable to storm surge induced flooding (see Figure 1.1). Both regions play an important role in the agricultural, industrial and economic development of the country (Minh, Orange et al., 2014).

As Vietnam is a rapid developing country, there is a continuous need to expand urban areas for residential and economical purposes. In (Phan et al., 2018) a study was performed on the flood vulnerability of new development areas in HCMC. They found that three new emerging districts are highly vulnerable to floods, but the local government still implements the plan to invest in housing. The main concern mentioned in their paper is that urban expansions are increasing over lowlying former wetlands. According to (Phan et al., 2018) this pattern can be seen in many coastal cities in Southeast Asia. In (Huong, Pathirana, 2013) it is mentioned that poor land use practices like building in flood-prone areas has contributed to the increase of flooding in Vietnamese cities. Inundation happens in these areas even when the local rainfall is not too heavy.

Figure 1.1 Vulnerability distribution to typhoons across Vietnam (Kim-Anh Nguyen et al., 2019)



1.2 Flood adaptation measures

The Vietnam Country Climate and Development Report states that there is currently insufficient focus on flood adaptation strategies (World Bank, 2022). In order for resilient shores and cities the World Bank recommends to develop an integrated coastal resilience investment program and a more systematic approach to using nature-based solutions. With regard to urban drainage these solutions are often referred to as Sustainable Urban Drainage Systems (SUDS). These target to increase local stormwater storage which leads to the reduction of flood peaks. A publication of the Asian Development Bank called “Nature-Based Solutions for Cities in Vietnam” (2019) describes this by the name of Water sensitive urban design (WSUD). This design approach includes a wide variety of measures like wetlands, vegetated swales, bioretention basins, rain gardens, green roofs, permeable pavements, infiltration wells, and cleansing biotopes. However, to this day the application of SUDS in Vietnam remains limited (Nguyen, Bhuiyan et al., 2020).

The World Bank mentions in its 2022 Development Report that there is a need to regulate urban development that takes place in flood sensitive areas. One way of regulation is by imposing flood adaptation measures that mitigate flood risk. For new developments there is an opportunity to test the efficiency of adaptation strategies by focusing on flood risk reduction. According to (Haasnoot et al., 2019) governments in urban coastal areas can choose to increase flood proofing, increase protection or do a planned retreat from flood sensitive areas. Examples of these types of strategies in South-East Asia have already been studied in literature. In (Scussolini et al., 2017) the dryproofing of houses in HCMC was studied and marked as a cost-effective measure. They mention that dryproofing could be implemented relatively fast and at a low cost. Implementation success depends on the government providing citizens with financial resources. Another way of flood proofing is to increase the capacity of the drainage systems and to install pumps. The effectiveness of pumps was studied by (Pham et al., 2021) in Vietnam and by (Lian et al., 2017) in China. Both concluded that this measure can be very effective for flood reduction in areas that are mainly affected by sea tide. A way to increase the drainage system capacity is by building retention ponds. In (Lian et al., 2017; Nguyen, Phuoc Vo et al., 2021) it is concluded that this measure is effective in areas where rainfall is the main driver for inundation. Protecting areas at risk can be done with flood gates, break waters, wetlands and dikes. Another protection measure is land raising. This measure was studied for HCMC by (Scussolini et al., 2017) and they concluded it is effective for flood risk reduction. Though, this paper expresses concern that areas with higher property value could be prioritized, which leads to more exposure to less developed areas.

For an arbitrary coastal urban area it is not obvious which of these adaptation pathways should be considered. Therefore a modelling study can be performed which aims to map current flood risk.

1.3 Modelling coastal urban pluvial flooding

A modelling study by (Shen et al., 2019) assessed flood risk in a US coastal city using a so-called 1D pipe/2D overland flow model. This is a physically-based model in which the urban drainage network is schematized in 1 dimension. This model enables the simulation of flooding that is induced by surcharging of drainage pipes and open channels. Due to surcharging the water will end up on the surface and can flow based on the elevations in the ground model. This complexity is needed because urban areas have a complex and irregular topography (Guo et al., 2021). A 2D flow model can also incorporate the locations of buildings. This is relevant because buildings will affect flow directions and this also enables to assess the vulnerability of an area.

Several studies have been found in which the potential benefits of SUDS in Vietnam and surrounding countries have been simulated (Le Dung et al., 2021; Nguyen, Bhuiyan et al., 2020; Majidi et al., 2019; Loc et al., 2015). All these model studies have in common that they test the effects of SUDS in areas that are only affected by heavy precipitation. In (Pham et al., 2021) the tidal fluctuations were considered while assessing the performance of various measures in HCMC. However, the results of this paper only show the use of a 1D pipe model, without incorporation of 2D surface flow. Other flood risk studies that were found in Vietnam all focus on existing urban areas (Scheiber et al., 2023; Le Binh et al., 2019; Scussolini et al., 2017; Apel et al., 2016). They assume the urban drainage network to be overloaded due to a combination of storm tide and heavy precipitation. Therefore they do not include flow dynamics in pipes, open channels and flow regulating structures in flood risk calculations. According to (Guo et al., 2021) the neglection of urban drainage network dynamics may result in miscalculations of inundation depths and duration, particularly at a localised scale.

In addition, the modelling studies that were found in Vietnam use a 2D flow model resolution of 15m up to 100m. This is either done because a higher resolution digital elevation model was not available or because the calculation time with fine-resolution grids becomes too large. In addition, most studies focused on fluvial flooding. However, due to new developments higher resolution digital elevation models become more widely available. Simulation of pluvial flooding is very dependent on the resolution of the 2D flow model. Not only to determine at which locations inundation originates, but also how it continues to flow on the surface. A leading example is the research of (Shen et al., 2019) where a resolution of 5m was used.

1.4 Research gap

During urban development in the coastal areas of Vietnam there is an opportunity to improve the capacity of existing drainage networks and build new drainage systems that have increased resilience to pluvial flooding. Currently there is no evidence in literature on how to assess flood risk in coastal urban areas in Vietnam during the design of new urban drainage networks. Studies performed in the US (Shen et al., 2019) and China (Lian et al., 2017) show that the effect of adaptation measures within the urban drainage network on inundation reduction can be simulated using a 1D pipe/ 2D overland flow model. Therefore this type of model can play a crucial role during the design of new urban drainage infrastructure in the course of Vietnam's future coastal development. However, this specific role has not yet been addressed in literature.

1.5 Report outline

This report is divided into the following chapters:
- In chapter 2 the study area for this research is described.
- Chapter 3 discusses the research questions.
- In chapter 4 the methods to come up with an answer for each research question are described in detail.
- Chapter 5 gives a description of the research results.
- Chapter 6 will delve into the interpretation, implications and limitations of the results and offers suggestions for future research.
- Chapter 7 ends this report with the conclusion.

2

Study area: Hà Nam island

2.1 Context

The province of Quang Ninh is currently working out the plans to transform the island Hà Nam and surrounding areas into a coastal economic zone. Hà Nam is located next to the seaport city Haiphong, which lies about 100 km to the west of Hanoi. Hà Nam is surrounded by Chanh river on the north side and Rút river on the south. These two rivers are both tributaries of the Bach Dang river that is part of the Red river delta. At the east side Hà Nam is bounded by the sea. The study area is surrounded by a dike system and has a total surface area of 4000 hectares. Hà Nam will be used as a case study for assessing flood risk and calculating the effects of adaptation measures using the 1D pipe/ 2D overland flow model approach.

Figure 2.1 Map overview of Hà Nam island

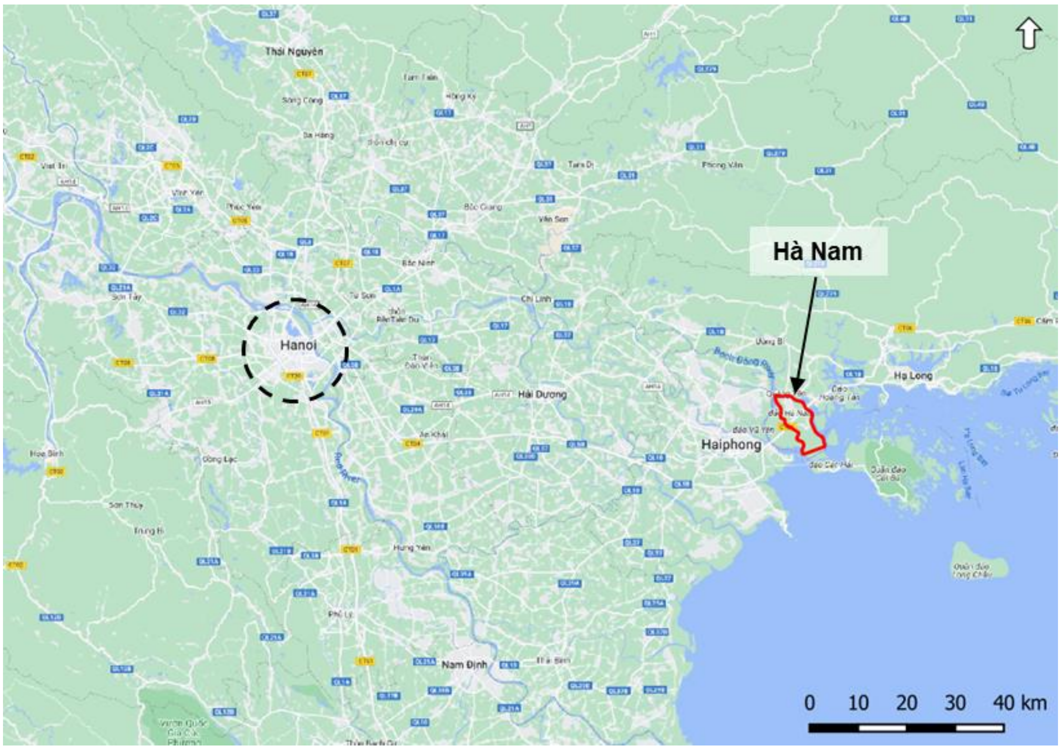
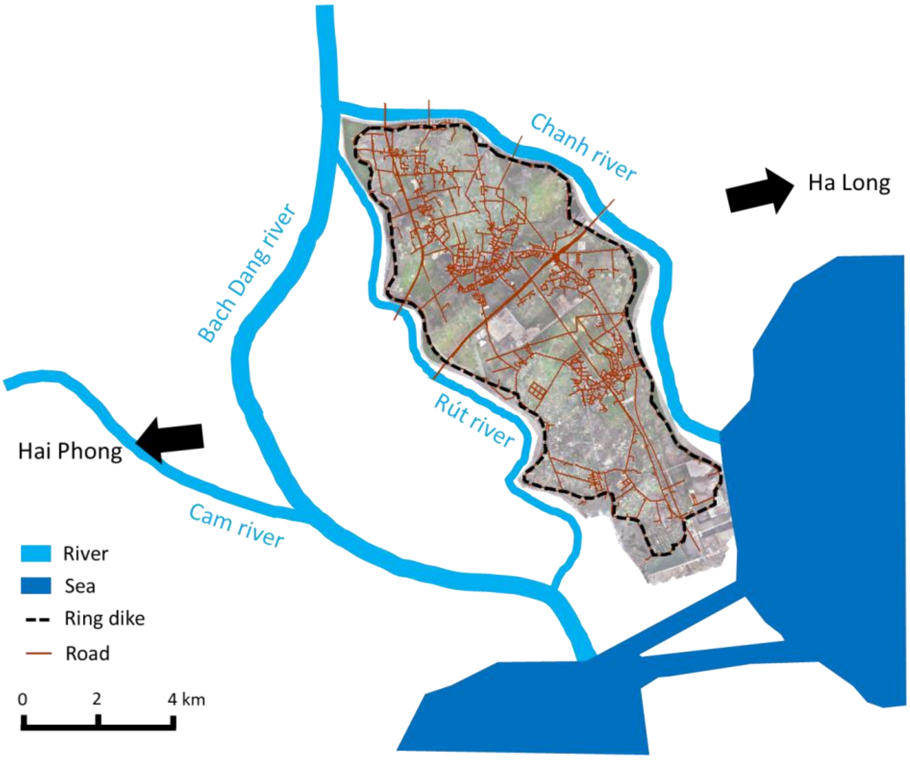


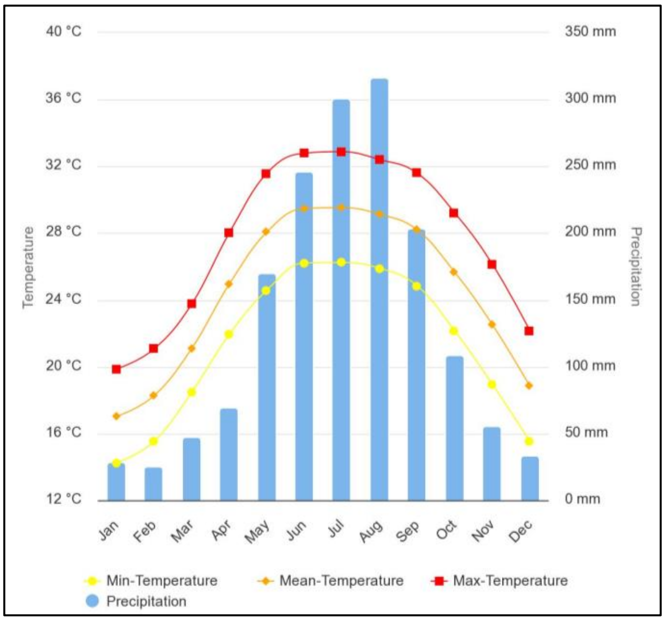
Figure 2.2 Overview of Hà Nam and surrounding rivers



2.2 Climatology and sea tide

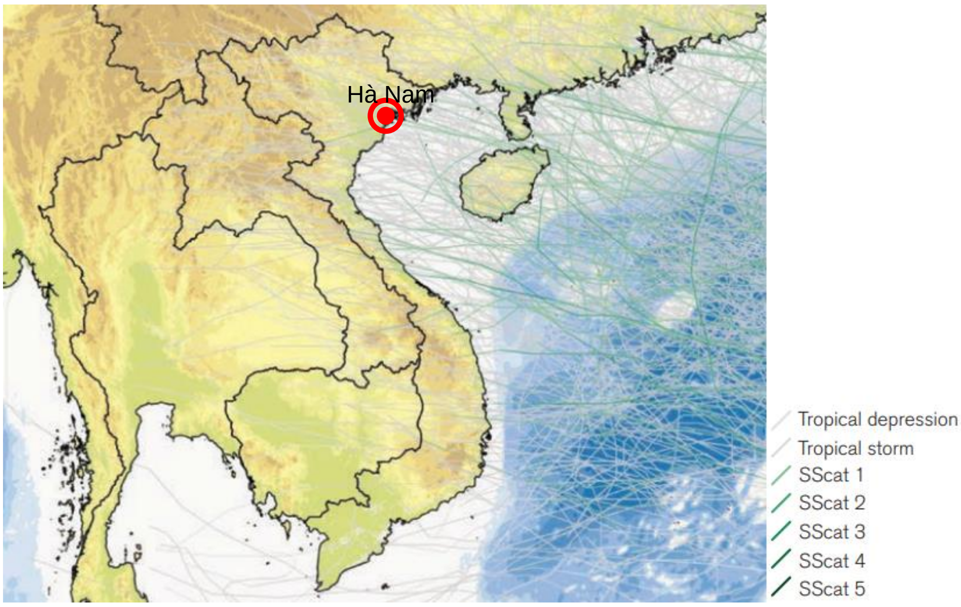
The seasonal variation of rainfall and temperature in the area is shown in Figure 2.3. The Vietnamese climate is influenced by the annual monsoon, which brings heavy rainfall from May to October. The average annual rainfall (1991-2020) for the area is about 1600 mm. According to the Köppen-Geiger classifications the north of Vietnam is classified as a Cwa climate, that is mild temperate with a dry winter and hot summer. On a local scale the climate can vary a lot, resulting in yearly precipitation that exceeds 2000 mm for some areas in Vietnam (Kim-Anh Nguyen et al., 2019).

Figure 2.3 Average rainfall and temperature (1991-2020) in Hai Phong City (source: climateknowledgeportal.worldbank.org)



The water levels inside the rivers are heavily influenced by the sea tide. The Vietnamese coastline experiences diurnal tides, which means one high and low tide each day. The Vietnamese coastline experiences five to six typhoons each year that occur mostly in August and September (Almar et al., 2017). Most typhoons that make landfall in the north move in from the South China Sea and first cross the mountainous island of Hainan (china), which weakens them (Kim-Anh Nguyen et al., 2019). Figure 2.4 shows the historical cyclone tracks over Vietnam.

Figure 2.4 Historical cyclone tracks over Vietnam (1970–2015) (source: Global Risk Data Platform)



2.3 Characteristics of Hà Nam

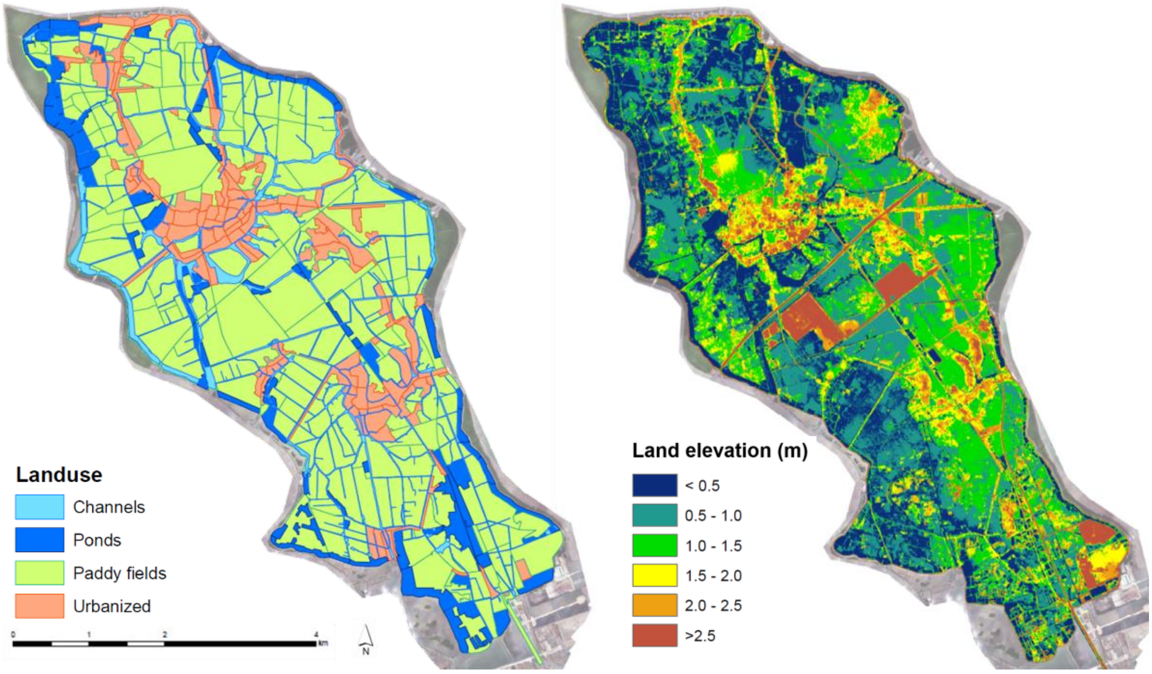
Hà Nam currently has a population of about 53,000 residents. There are two villages and several smaller communities. About 15% of the total area is currently urbanized. Most of Hà Nam is used for rice cultivation and fish breeding. Table 2.1 shows an overview of the different land use areas. In Figure 2.5 the land use classes are shown in a map.

Table 2.1 Land use areas in Hà Nam

Type	Area (ha)	Percentage (%)
Open channels	265	6
Ponds	432	11
Rural	2,746	68
Urbanized	605	15
Total	4,047	100

The land surface in Hà Nam lies between 0.5 and 2.5 m AMSL. Lowest elevations can be found in the north and southwest. The soils in Hà Nam can be classified as alluvial, which means they were deposited by rivers. This is commonly found in floodplains and deltas.

Figure 2.5 Current land use and surface elevation of Hà Nam



Hà Nam transports its water into the Rút and Chanh rivers by means of nine culverts that are operated by sluice gates. There are no pumping stations. This means that the drainage network of Hà Nam flows to the rivers by gravity. The culverts are operated with gates to prevent backwater flow from the rivers during high tide. During regular operation the sluice gates are closed off. Currently there are no indications of regular flooding that negatively affects the local population. Inside Hà Nam most stormwater is not collected through collection sewers but drains into canals and ponds via surface runoff. Inside the villages there are collection sewers present that transport the water into the surrounding canals. Domestic wastewater from residential areas is discharged directly into the canals without treatment. The amount of untreated domestic wastewater that stays in the open channels for a long time has seriously degraded the water quality.

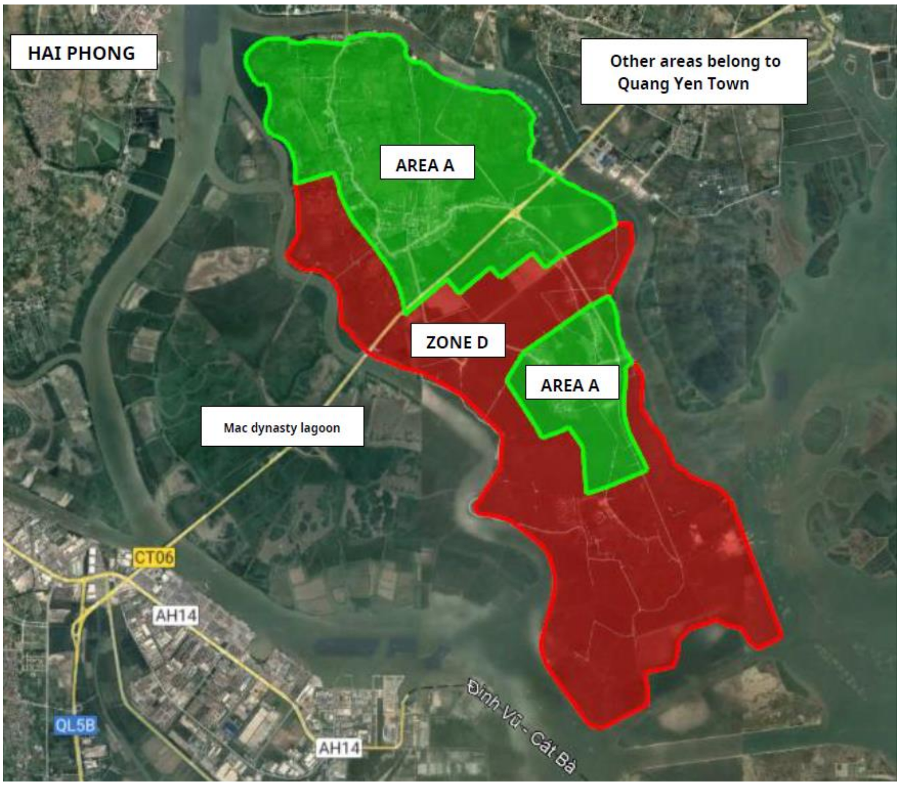
2.4 Future developments

The island Hà Nam will be part of the coastal economic zone of Quang Ninh province. Most of the current agriculture and aquaculture in the area will disappear within the next 20 years. The total population is forecasted to increase from 53,000 to about 89,000 inhabitants (see Table 2.2). The developments have been divided into two zones by Vietnamese authorities (
Figure 2.6). Zone A consist of residential expansions, green urban spaces and other public service areas. Area D will contain multi-industry industrial spaces, logistic systems, warehouses and seaports.

Table 2.2 Population growth forecast (based on Vietnamese planning document)

	Population 2022	Population 2030	Population 2040
Zone A		58,507	61,586
Zone D		9,685	27,253
Total	52,899	68,192	88,839

Figure 2.6 Development zones of Hà Nam



3

Research questions

3.1 Research objectives

This master thesis has the following objectives:

1. The first goal is to evaluate existing models for assessing flood risk in coastal urban areas that are vulnerable to extreme rainfall in combination with high river levels. These models involve hydrodynamic calculations that incorporate system behaviour of urban drainage networks as well as flooding mechanisms on the surface. Inundation due to pluvial flooding is the main hazard that will be taken into account during the flood risk analysis.
2. Hà Nam will act as a case study in order to apply flood risk methods for pluvial flooding. In addition, flood risk mitigation measures will be recommended for Hà Nam. Therefore, this thesis aims to create a stronger basis for decision making and future development of Hà Nam.

3.2 Research questions

The problem definition and research objectives were combined to formulate the following research questions:

1. What is the current interaction through the main culverts between Hà Nam drainage system and the rivers surrounding it that are under tidal influence?

2. How does a concept design of the urban drainage network of Hà Nam look like after implementation of future projections of urban development?

3. What are the inundation level reductions in 2040 by applying SUDS for local water retention and flood peak attenuation?

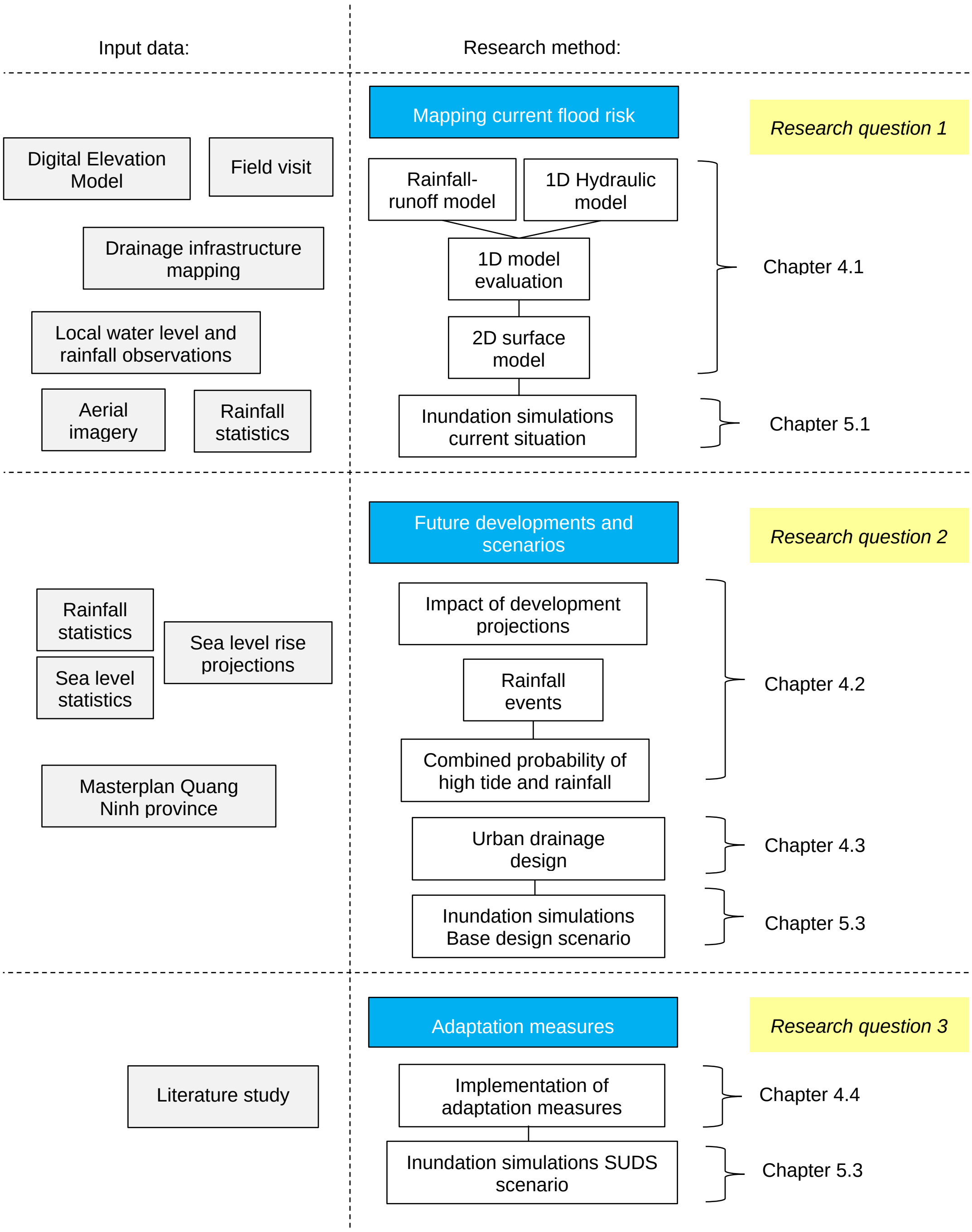
Main research question *How can the interaction between urban drainage networks and rivers under tidal influence be taken into account while assessing pluvial flood risk during the design of developing coastal urban areas using a 1D pipe/2D overland flow model?*

4

Methods

A summary of the research framework is given in Figure 4.1. The following paragraphs describe the methods that will be applied to answer the research questions in more detail.

Figure 4.1 Scheme of the thesis research set-up



4.1 Mapping current flood risk

This paragraph describes the methods that were used to map flood risk for the current situation. The method involves building the 1D model based on survey data obtained from Vietnamese authorities. Subsequently, hydraulic loads and boundary conditions for the model were defined. Different values for model parameters were evaluated based on one recorded rainfall event and data from three water level measurement stations. Finally, the 1D model was expanded to incorporate 2D surface flow. All steps will be discussed in more detail in the following paragraphs.

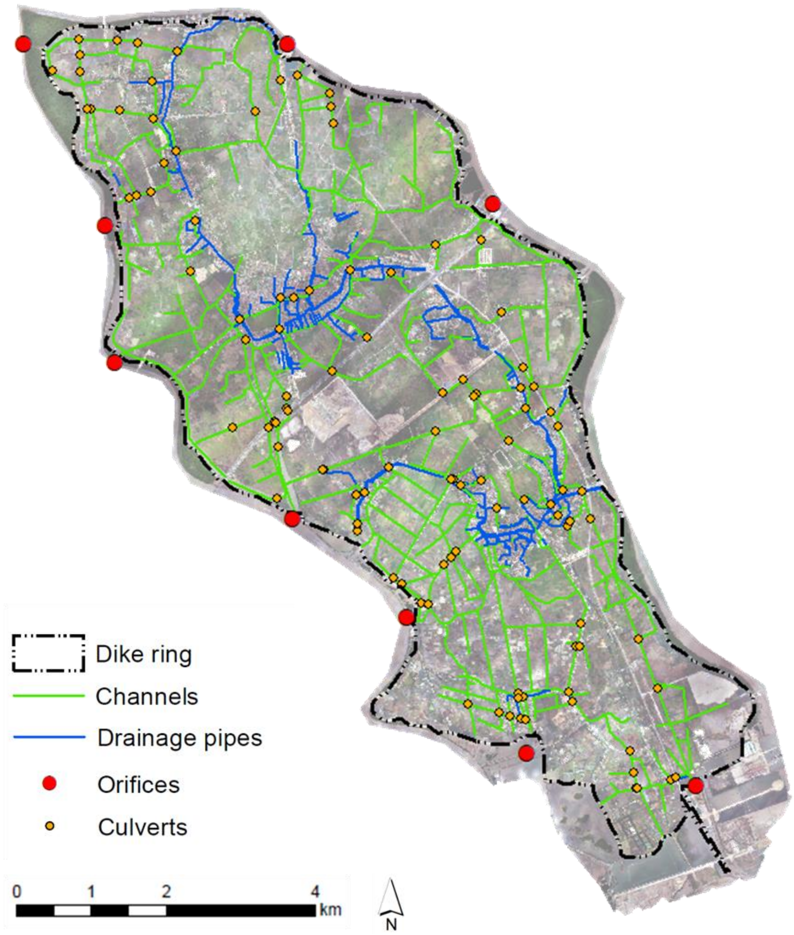
4.1.1 1D-model

For this research the software Delft3D FM version 2023.03 was used. Delft3D FM allows for combinations of 1D flow in closed conduits, open channels, rivers and 2D overland flows. The urban drainage network was made available by Thuyloi University in the form of a SWMM model that was built based on field inspections. The channel cross sections, pipe invert levels and pipe dimensions were retrieved from extensive field inspections that were performed from March until June 2023 by a Vietnamese contractor. The subcatchments were manually drawn based on topographic elements like roads and land elevation. To determine the outlet location for subcatchments, Thuyloi University performed a survey under the local residents that manage the smaller channels and ponds. A summary of all model components is shown in Table 4.1. A map overview of the drainage network of Hà Nam is shown in Figure 4.2.

Table 4.1 Summary of 1D-model components

Model components	Number of components	Total length (km)
Nodes	1124	-
Channels	809	152
Cross sections	525	-
Drainage pipes	326	51
Culverts	99	<1
Orifices	9	-
Subcatchments	522	-

Figure 4.2 Overview of the drainage network of Hà Nam



One of the model parameters to consider for flow calculations is the roughness of the open channel sides and drainage pipes. The roughness is determined by the material, but also by the maintenance state of the infrastructure. Figure 4.3 shows that there is a high variation in how the open channels are maintained. Pictures [1] and [2] in Figure 4.3 show that some channels are overgrown with vegetation. This will lead to a serious decline in the local discharging capacity. Picture [3] shows part of the irrigation system that crosses a channel. At these locations there is an increased risk of clogging of the channel. Lastly, picture [4] showcases that some of the larger channels, that are crucial for draining large parts of the area, are in fact maintained properly. This research does not focus on the effect of various failure modes, like obstruction of flow by vegetation. The roughness of pipes and open channels has been defined as uniform values and are given in Table 4.2.

Table 4.2 Roughness parameters used in 1D model

Roughness types	Manning's n
1D pipes	0.014
1D channels	0.025

Figure 4.3 Different physical conditions of open channels that were recorded Hà Nam

Distinctive for the area is the extensive water supply network that was built to supplement rice fields with water from the rivers without using any of the drainage channels (Figure 4.4). These structures do not interact with the urban drainage network, but do influence the water balance inside the area when river water is let in. Therefore the drainage network is distinguished from the water supply network in the model.

Figure 4.4 Water supply system in Hà Nam

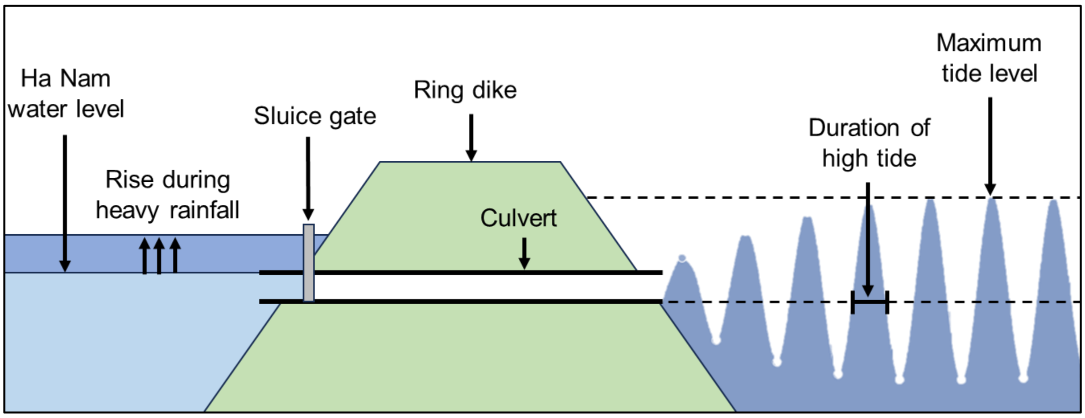
Boundary conditions

During high tide the water level inside Hà Nam lies below the river level. Consequently, sluice gates (as shown in Figure 4.5) are employed to isolate the Hà Nam drainage system from the rivers. High tide duration serves as one of the system's boundary conditions. The second boundary condition is rainfall within the area. When the water level inside Hà Nam increases due to rainfall, the sluice gates are manually opened, provided the river level remains low enough. Subsequently, the local water authority actively manages the sluice gate operation to prevent inflow from the river.

Figure 4.5 Hà Nam sluice gate

Figure 4.6 showcases the two boundary conditions and sluice gate operation. The culverts form the connection between Hà Nam and the outside rivers. Their operation has a large influence on the water levels inside Hà Nam. Subsequently, the water level in the rivers is the boundary condition governing the culvert's operation.

Figure 4.6 Hà Nam culvert operation and boundary conditions

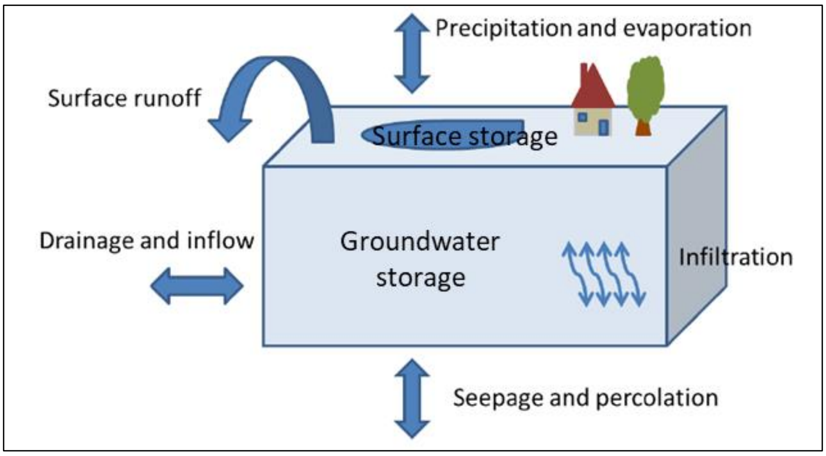


Rainfall-runoff model

The inflow of water to the urban drainage network was simulated using a rainfall-runoff model. The different land use types and hydrological processes that take place in the area were defined. Hà Nam can be divided into rural and urban zones, from which the rural zones take up about 70% of the total area. Inside the rural zone the main land use class is paddy fields. Figure 4.8 gives an impression of the urban and rural environment in Hà Nam. Especially along the outside ring dike there are many basins that are used for fish breeding (see Figure 4.9). These ponds are generally not connected to the drainage network.

During normal operation the sluice gates are closed off, which means that all the water will be contained inside Hà Nam. Figure 4.7 gives an overview of the main hydrological processes in polder catchments. The most important processes that have been identified for the rural zones are surface storage and surface runoff. In the case of Hà Nam most of the rural area is comprised of paddy fields that are surrounded by small dikes. These dikes make sure that the rice fields can be inundated for longer periods to sustain crop growth. In the event of rainfall these paddy fields will function as large storage basins. Only when the maximum storage on the surface has been reached, will there be surface runoff to the open channels. Some of the precipitation will infiltrate into the soil and stored in groundwater. Through subsurface flow some of this groundwater will end up in the drainage channels. However, because of low gradients in terrain the amount of subsurface flow to the main drainage channels will be relatively low. When mapping flood risk the rainfall duration is relatively short (hours to some days) and rainfall intensities relatively high. As a result, the model neglects evaporation and seepage from the rivers.

Figure 4.7 Overview of the hydrological process that occur in any given polder catchment (Deltares, 2023)



Inside the rainfall-runoff model the whole catchment of Hà Nam has been divided into smaller subcatchments. It is assumed that all subcatchments are in direct connection to an open channel or pipe. In practice many areas in Hà Nam are disconnected from the main drainage system because of local ponds, disconnected channels and blockages. Over the years the local people have changed the system which lead to fragmentation. For instance, the local people block of certain culverts to supplement their rice fields with stormwater. Some local channels have silted up, creating local retention ponds that store the water and only empty through infiltration and evaporation (see Figure 4.10).

Figure 4.8 Impression of the urban and rural environment in Hà Nam

Figure 4.9 Fishery ponds in Hà Nam

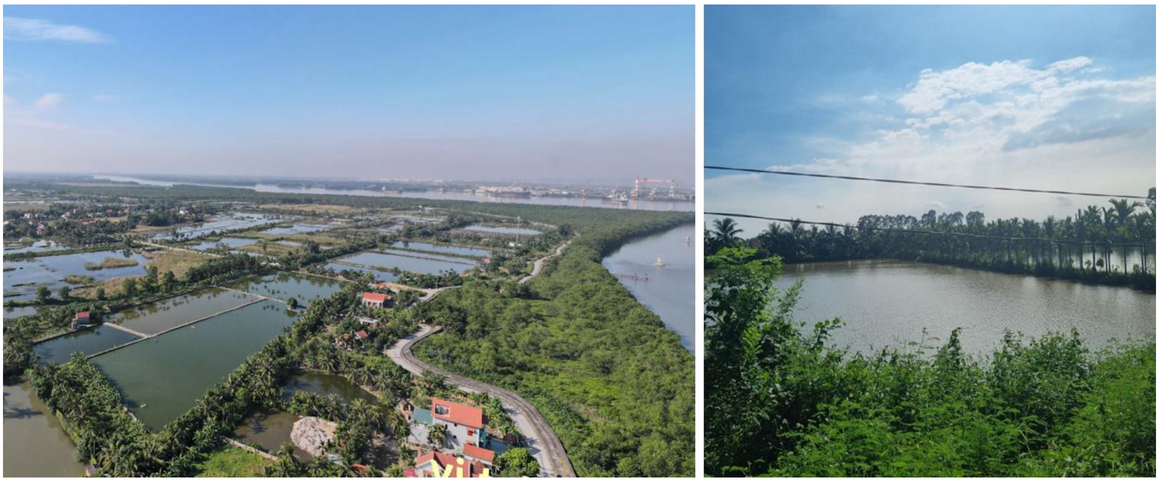
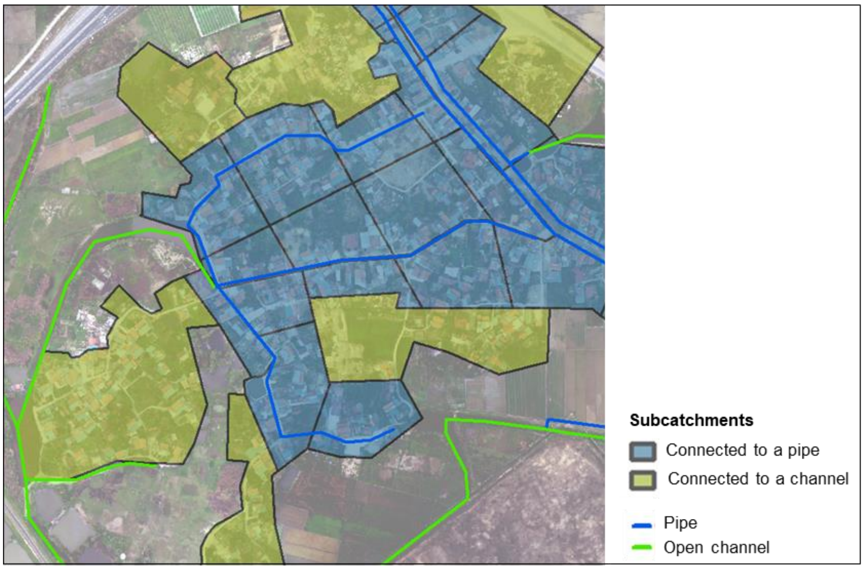


Figure 4.10 Local ponds that formed due to silting up or blockages of local channels

For the urban zones the subcatchments were manually divided over neighbouring drainage pipes and channels (Figure 4.11). Due to dense urbanisation and no information on private connections it is impossible to accurately determine the amount of pavement for each pipe section. Therefore, the pavements were equally divided over the drainage pipes and channels using aerial imagery.

Figure 4.11 Division of subcatchments inside urban areas



The main parameter values inside the rainfall-runoff model are summarized in Table 4.3. The values were chosen based on model evaluation that will be discussed in the next paragraph.

Table 4.3 Rainfall-runoff parameters

Catchment type	**Parameter**	**Value**	**Unit**
Urban	Surface storage	0	mm
	Infiltration	0	mm/hr
	Surface runoff factor	100	1/day
	Evaporation	0	mm/day
Rural	Surface storage	80	mm
	Infiltration	20	mm/hr
	Surface runoff factor	3	1/day
	Seepage	0	mm/hr
	Percolation	1	mm/hr
	Groundwater storage coefficient	0.1	-
	Groundwater reaction factor	0.5	1/day
Fishery ponds	Storage	∞	mm
	Infiltration	0	mm/hr
	Seepage	0	mm/day

For the urban catchment type it was assumed that rainfall will directly lead to surface runoff. In reality there will be some infiltration and surface storage. However, it was assumed that this is only a tiny fraction of the total flow, especially considering that this model will be used to asses flood risk during extreme rain events.

Rainfall that lands on the rural areas will be stored on land and simultaneously infiltrated into the soil. When the maximum land storage has been reached the water will flow towards the connected channel as surface runoff. The surface runoff factor of the rural areas was estimated based on model evaluation and will be discussed in the next paragraph. It is very important to not overestimate this factor. Especially when relatively large subcatchments are connected to one point of the drainage network.

The initial groundwater table in the catchments is equal to the water level in the adjacent channel. When the equilibrium moisture content of the root zone is reached, infiltration becomes equal to the percolation rate towards groundwater. The percolation rate will limit infiltration and thus more rainfall will be stored on the surface or will flow to the channels as surface runoff. The initial model condition is that the soil moisture water content of the root zone is at a minimum. This means that at the start of rainfall the infiltration rate is in effect. For the root zone a reference soil type of peat was chosen. There is no evaporation in the model, so after saturation the root zone will stay saturated throughout the whole calculation. The storage coefficient determines how much water can be stored inside the soil.

To calculate subsurface flow towards the channels, Delft3D FM employs an equation of "De Zeeuw-Hellinga", see below:

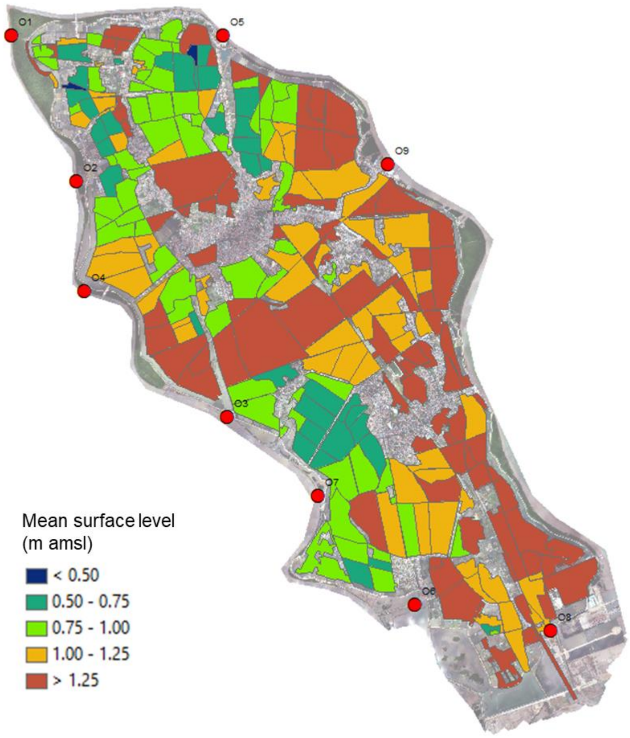
$$Q_{t,average} = \frac{A\alpha\mu\Delta h - A(I)}{\alpha\Delta t}(1 - e^{-\alpha\Delta t}) + A(I + S)$$

With:

$Q_{t,average}$=	average discharge per time step
A =	area (m^2)
α =	reaction coefficient (1/time step)
μ =	storage coefficient (-)
Δh =	difference in pressure head (m)
I =	infiltration (m/time step)
Δt =	time step

The surface level of each rural subcatchment was calculated based on the average surface height within each catchment boundary (see Figure 4.12). The pressure head Δh is calculated per time step as the difference between the groundwater level and the water level inside the channel to which the subcatchment is connected to. The groundwater reaction factor can range from 0.3-0.7 for well-drained agricultural soils (Vademecum, 1988). Based on the model evaluation a value of 0.5 was chosen for all unpaved areas in the rural zones.

Figure 4.12 Mean surface level for the rural subcatchments



4.1.2 1D-model performance

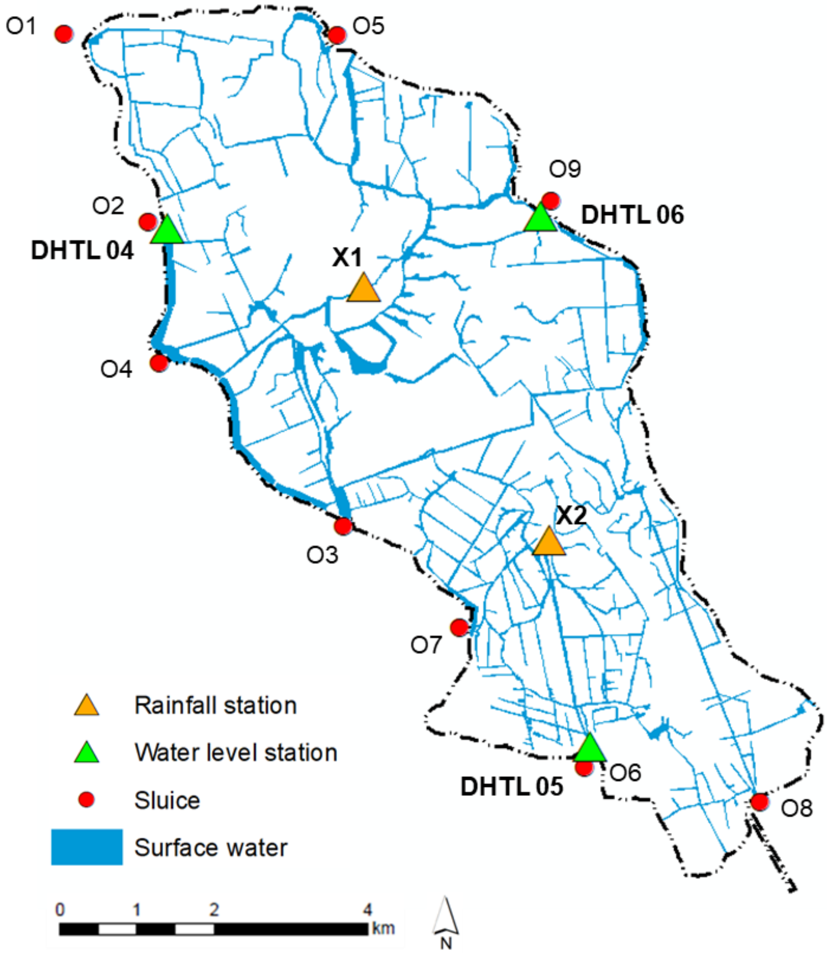
In order to assess the predictability of the model it was evaluated using data from a recorded rainfall event. This involved investigating the operation of the culverts during the event. Subsequently, the calculated water levels were compared with actual measurements.

Measurements

There are two rainfall stations and three water level stations present inside the area (see Figure 4.13 and Figure 4.14). Water levels were measured in the vicinity of three sluice gates. Measurements were recorded every 10 minutes from March to June 2023, capturing only a portion of the rainy season.

Figure 4.13 Installation location DHTL 06

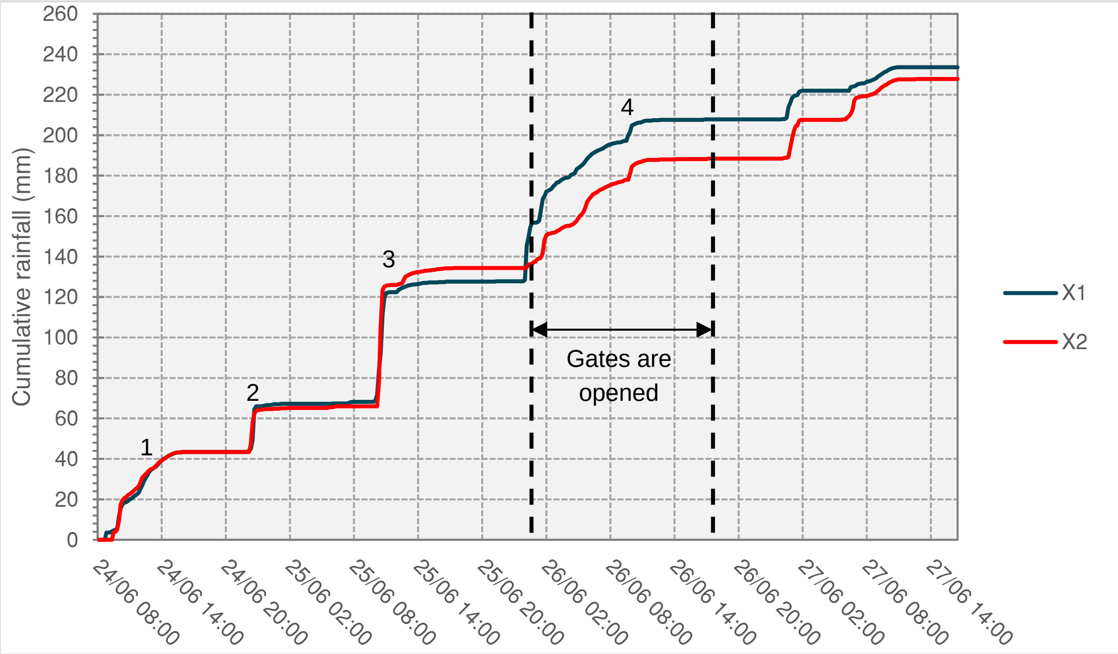
Figure 4.14 Measurement stations in Hà Nam



Model evaluation event

During the measurement period there was one recorded event that has led to a significant rise in water levels inside Hà Nam. The total rainfall amounts to roughly 200 mm in two days. Figure 4.15 shows the cumulative rainfall during the event and also marks at which point in time the sluice gates were being operated. Before the first sluice gate was opened a total rainfall of 130 mm was measured in the area. During this event a total of 4 rainfall peaks can be distinguished. The most significant peak has an amount of 65 mm in 1 hour.

Figure 4.15 Cumulative rainfall measured at the two rainfall stations during the evaluation period



A summary of the rainfall event is given in Table 4.4.

Table 4.4 Characteristics of the 4 recorded rainfall peaks during the recorded event

Rainfall peak	Total amount (mm)	Duration (hr)	Max recorded intensity (mm/hr)
1	43	7	50
2	31	1	90
3	62 - 68	1	170
4	54 - 80	11	100

During the measurement period there were no other recorded rainfall events that have led to significant rise in water level in Hà Nam. Therefore this was the only event that was used to check model performance.

Culvert operation

The sluice gates are operated manually by the local water authority. The operation is done based on the personal experience of the operator. There is no scientific or general operation scheme present. Table 4.5 shows how the sluice gates were being operated during the evaluation event on June 26th 2023. Note that two sluice gates remained closed.

Table 4.5 Culvert operation during evaluation event (26-06-2023)

Nr.	Name	Opening time	Closing time	Measurement station	Gates opened	Gate opening (m)
O1	Đong Coc	03:00	16:30		2	1.50
O2	Cong Hai Yen	02:00	15:00	DHTL 04	2	1.00
O3	Cong Coc	Not opened				
O4	Cong Yên Đông	02:00	15:00		2	1.00
O5	Cong Vông	07:00	15:00		unknown	unknown

O6	Cong Liên Vi 1	02:00	14:00	DTHL 05	2	1.60
O7	Cong Liên Vi 2	Not opened				
O8	Cong Luu Khuê	01:00	14:30		2	1.60
O9	Cong Muong	00:30	17:30	DTHL 06	1	1.65

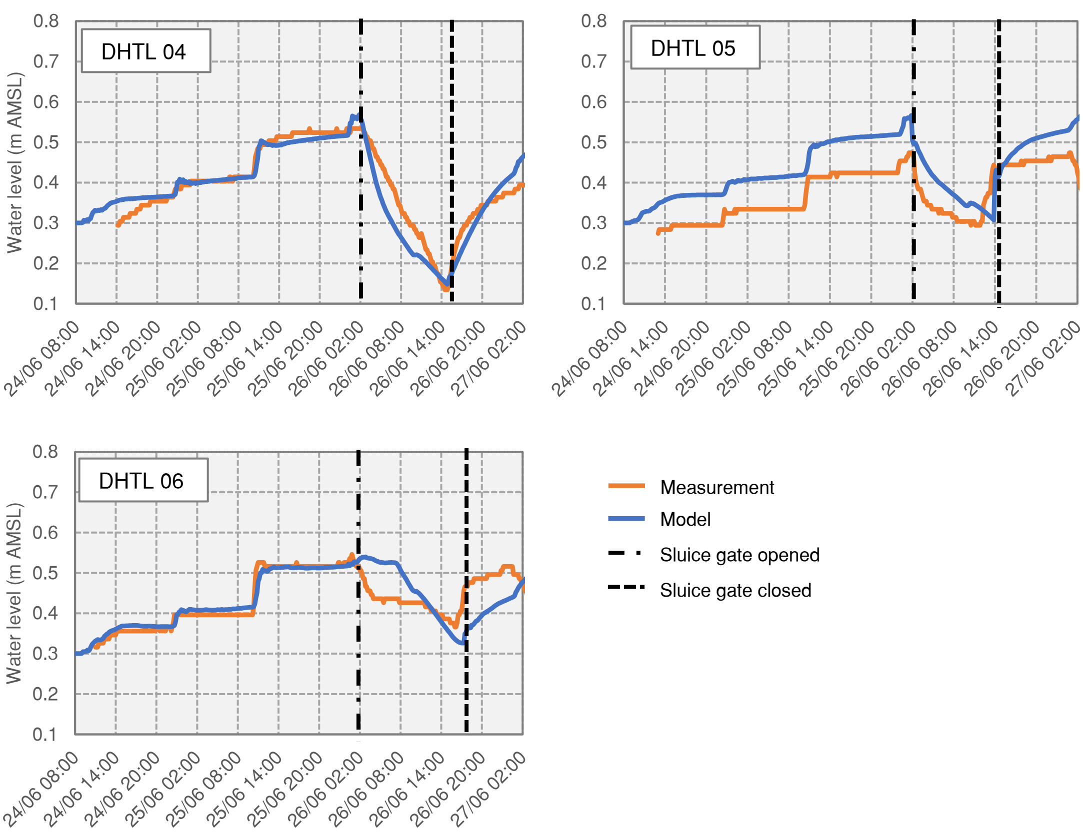
Model evaluation results

The model simulation settings are summarized in Table 4.6. The comparison between simulated and observed water levels is shown in Figure 4.16.

Table 4.6 Simulation settings

Simulation setting	Value	Unit
Time step	10	Minutes
Duration	80	hours
Initial water depth	0.3	m AMSL

Figure 4.16 Simulated and observed water depths during evaluation event

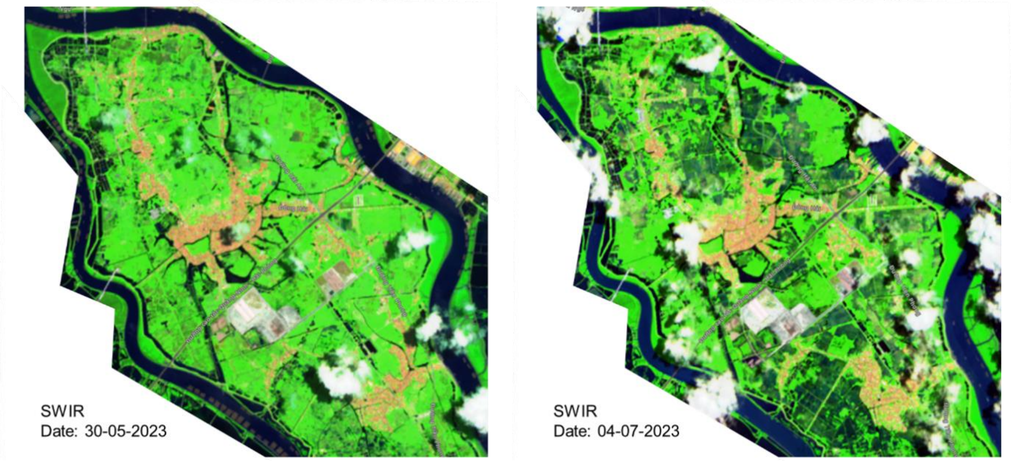


It was found that during the first two rainfall peaks, amounting to about 75 mm, the rural zones do not contribute to channel inflow. This was supported by evaluating the model in which only the urban subcatchment type was connected to the channels. After the first two rainfall peaks the water level has risen 10 cm at DHTL 04 and DHTL 06 and only 3 cm at DHTL 05. This difference suggests that the drainage system in the south of Hà Nam was separated from the north during the rainfall event. There are no known structures that could cause this effect, so this might be the effect of blockages of culverts. Furthermore, the rise in water level is quite abrupt and does not rise after rainfall has occurred. This suggests that groundwater flow has negligible impact on filling of the channels. After opening of the sluice gates, the system starts draining. During sluice gate opening a total of 50 to 80 mm of rainfall was recorded. At this point the maximum storage on land in the rural zones is exceeded in the model and surface runoff takes place.

Initial wetness conditions

One point of attention is the initial wetness condition of the system. The initial state can vary a lot during the year. This can also have an effect on the chosen set of parameters for each event. In the case of Hà Nam the initial storage on land is important to consider. In Figure 4.17 the Short wave infrared (SWIR) measurements received from Sentinel-2 in May and July 2023 are shown. As water absorbs SWIR wavelengths this will appear darker in the image. Built-up areas are visible in various shades of brown. Figure 4.17 showcases that at the start of July there is more water present on the surface compared to the end of May. This is directly linked to the amount of available storage on the surface. Analysing the available SWIR measurements showcases that the initial wetness of the area prior to the evaluation event is similar to the state that was captured on July 4th 2023. Therefore the values for the rainfall-runoff model given in Table 4.3 are representable for a system that is relatively wet at the start of the rainfall event.

Figure 4.17 Short wave infrared (SWIR) measurements at two dates in Hà Nam, source: Copernicus



4.1.3 2D-surface model

In this study the inundation depth will be the main flood hazard component during flood risk analysis. It should be mentioned that inundation has several characteristics. It can be separated into flood area, flood volume, flood depth, flow velocity and flood duration. In theory a 2D-surface model linked to a 1D urban drainage model can be used to accurately predict the exposure of buildings and assets to inundation depths and flooding velocities. The consequences of this exposure can then be expressed into direct- and indirect damages. Direct damage of properties and critical infrastructure can be directly linked to inundation depths. Indirect damages are for example loss of productivity and business opportunities (Barredo et al., 2012). In addition, flooding can have negative consequences on public health and can even lead to casualties.

In Delft3D FM and in other similar software licenses on the market a 2D-surface that is able to simulate flood depths can be made quite fast and efficient. However, it's crucial to critically evaluate the usability of the 2D surface model results. A significant portion of the methodology involved in constructing a 2D surface model should be dedicated to assessing model errors and the impact of model assumptions.

In 2023, the area of Hà Nam underwent an aerial survey to obtain a Digital Surface Model (DSM) with a resolution of 0.5 meters. This dataset served as the foundation for constructing the 2D surface model in Delft3D FM.

The following paragraphs will further explain how the usability of the 2D-surface model was evaluated.

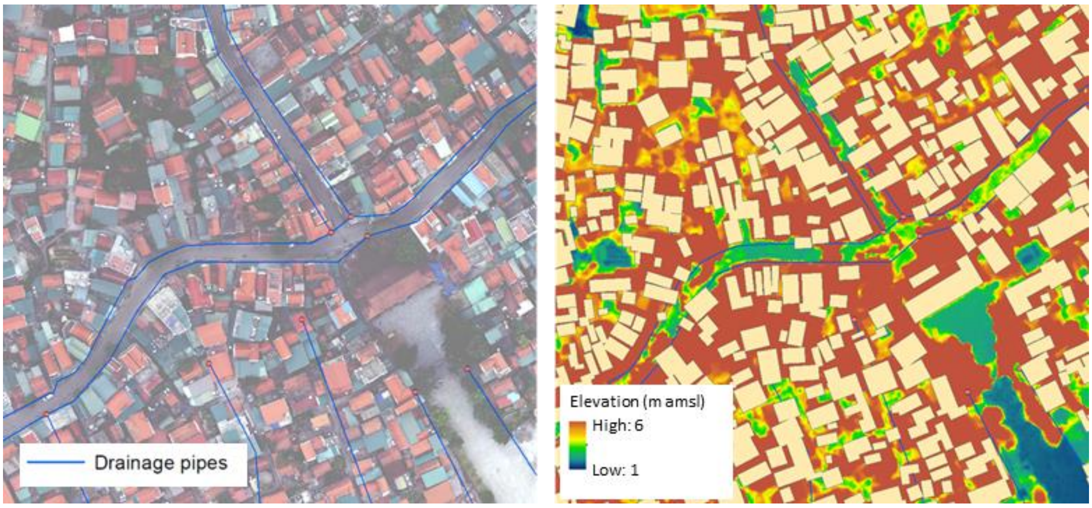
- Firstly, the representability of the urban zones by the 2D grid will be discussed.
- This is followed by an evaluation of the grid size.
- Subsequently, errors due to double storage are addressed.
- This chapter ends by discussing the grid roughness.

In chapter 5.4 some of the above topics will be further discussed in the model sensitivity analysis.

Elevation model representing urban areas

Even though the aerial survey of Hà Nam provided a DSM with a high resolution, it does not necessarily lead to a good representation of the actual terrain within the urban zones. Due to the fact that buildings are densely built, there is a low contribution of actual terrain measurements in these areas (see Figure 4.18). Other objects like trees and cars also cover the real terrain. This is already well documented in literature and many interpolation techniques can be applied to transform the surface model to a so-called Digital Terrain Model (DTM). Within the dense urban environments of Hà Nam the used interpolation techniques for acquiring the DTM lead to errors due to lack of real ground terrain measurements. Therefore, the 2D grid has to be manually improved to limit these errors.

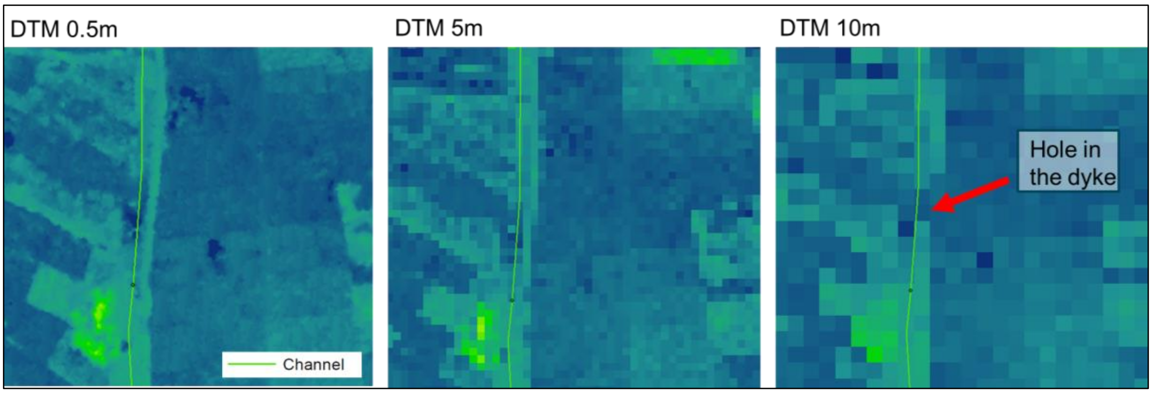
Figure 4.18 Part of an urban area in Hà Nam (left), digital surface model with a resolution of 0.5m (right)



Grid cell size

In selecting the cell size for the 2D grid representing the surface, it's essential to strike a balance between model accuracy and computational efficiency. Ground surface elevations were surveyed in Hà Nam with a resolution of 0.5m. In terms of model accuracy this would also be an appropriate model grid size. However, due to limitations in computer hardware this leads to too long calculation times. For this research a grid size of 5m was chosen. This decision was made to ensure that most crucial topographic features are adequately represented while maintaining manageable computation times. Figure 4.19 demonstrates that using a grid size of 10 meters distorts the elevation model significantly. Local dikes are poorly represented after resampling to 10 meters.

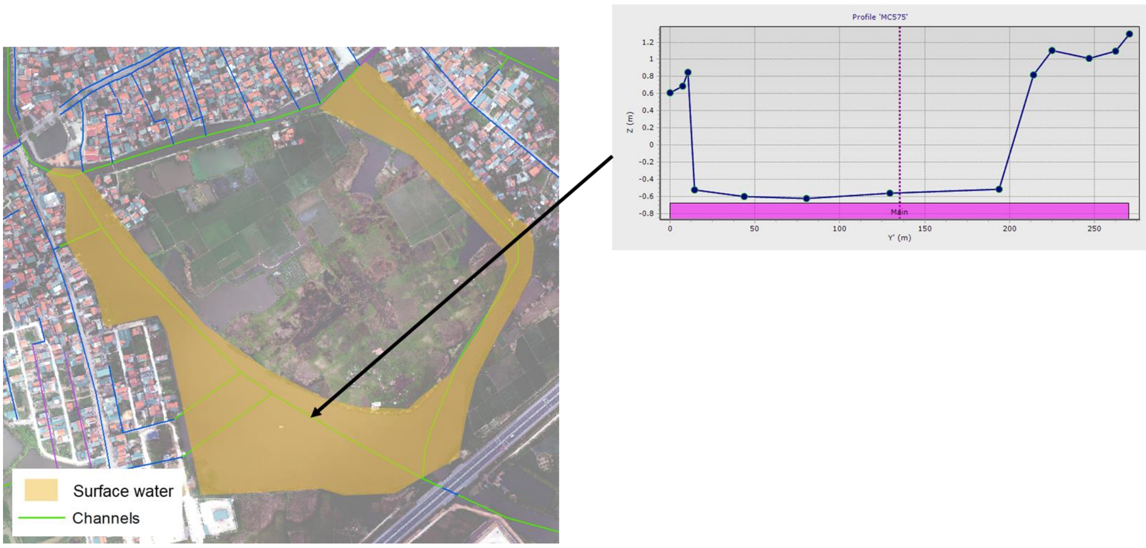
Figure 4.19 Grid representing the channel dike becomes insufficient after resampling



1D/2D double storage

A well-known problem related to 1D flow models that are connected to 2D-surface models is the effect of double storage on the model results. To illustrate this problem, Figure 4.20 shows a large surface water body inside Hà Nam. In the 1D flow model, a cross-section is included to represent this water body. However, on top of this channel lies the 2D surface grid. Consequently, inundation volumes calculated on this grid will also be accounted for within the 1D flow model, potentially leading to duplication of flood volumes.

Figure 4.20 Visualisation of double storage in the 1D model and 2D-surface model



Grid roughness in urban areas

Given the selection of a 5-meter grid size, the finer details such as smaller pathways and open spaces between buildings cannot be captured by the model. To ensure that surface flow within urban zones isn't restricted solely to main roads, a decision was made to enhance surface roughness in built-up areas rather than eliminating the grid over buildings. Building outlines were retrieved from the Google Open Buildings dataset (3rd version), as depicted in Figure 4.21. The roughness values for the 2D-surface grid are outlined in Table 4.7.

Table 4.7 Roughness parameters used in 1D/2D model

Roughness types	Manning's n	Comment
2D roads, unpaved areas	0.023	
2D buildings	0.5	Based on (Apel et al., 2016)

Figure 4.21 Building outlines from Open Buildings Google, 3rd version (left), Roughness surface values (right)

4.2 Future developments and scenarios

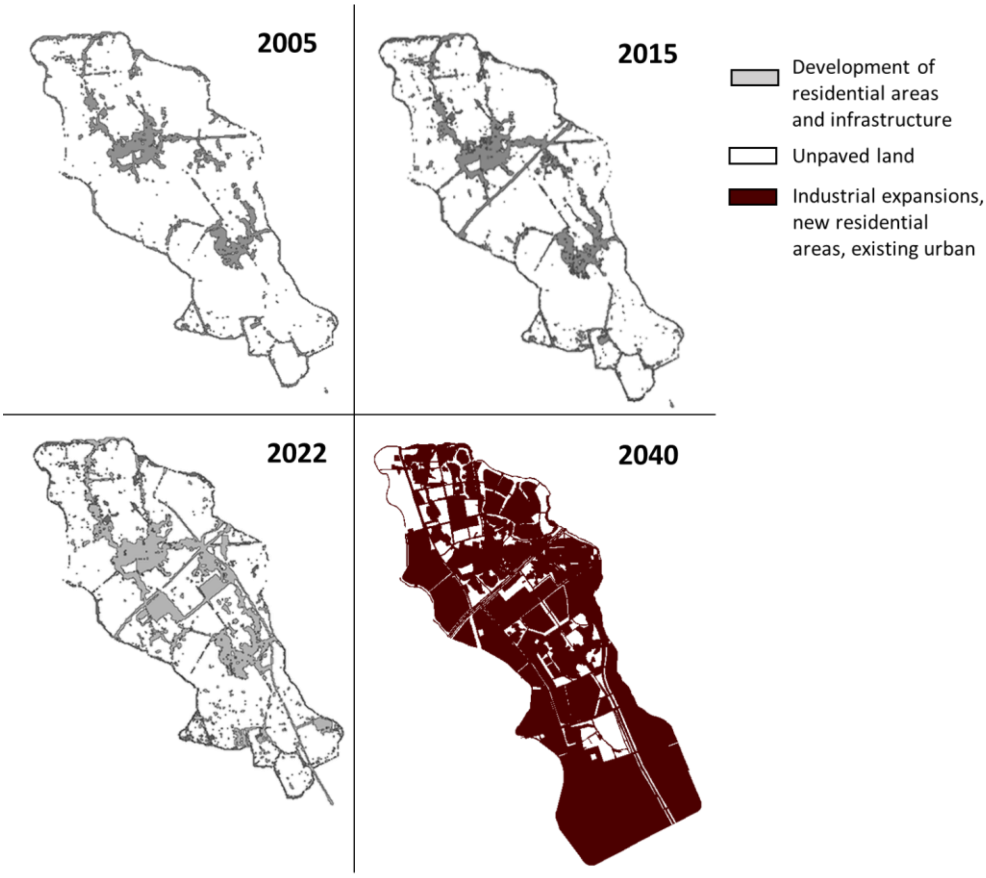
This paragraph lays the groundwork for developing the conceptual design of the future urban drainage system. It begins with an overview of the projected developments, followed by a discussion on the rainfall statistics employed. Lastly, the chapter delves into the tidal characteristics and the impacts of sea level rise.

4.2.1 Development projections

Change in landuse

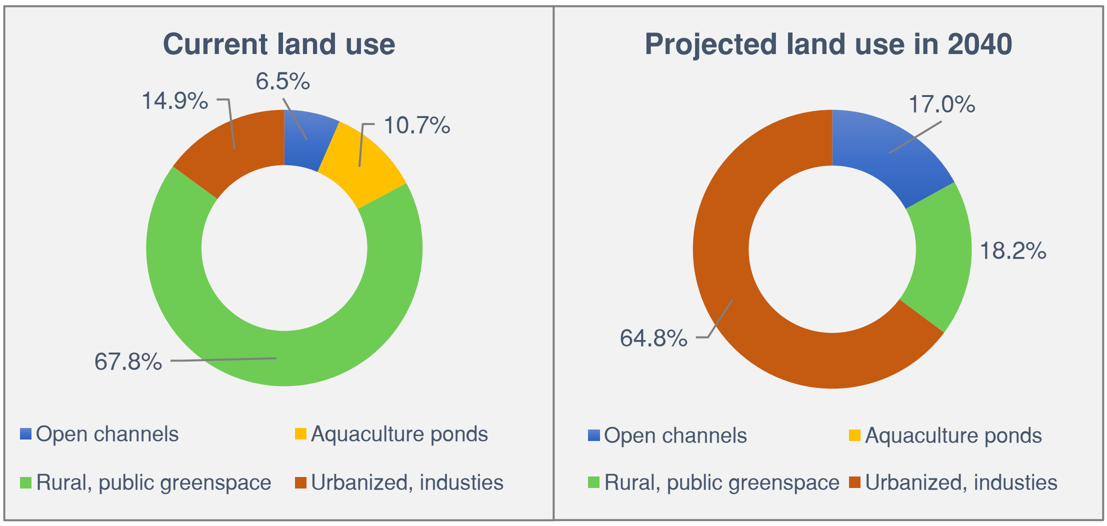
Figure 4.22 shows an impression of the urban development inside Hà Nam until 2040. The projected developments for Hà Nam were extracted from the masterplan of Quang Ninh province, which received approval from the national government in 2023. The region has been undergoing development over the past several decades. Following 2005, the construction of a new highway connecting Hai Phong to the coastal region of Quang Ninh was completed. While newly developed areas began to emerge in 2022, further expansion is anticipated in the coming decades. Notice that in 2040 the area will have been expanded in the south.

Figure 4.22 Urban development projection of Hà Nam until 2040



The projected change in land use from the masterplan will have many implications for stormwater management in the area. Urban and industrial expansions will lead to a significant increase in the amount of paved surfaces. Within the current dike section, the rural area shrinks 70% in size and will have been replaced by residential and industrial development. Figure 4.23 illustrates the total change in land use between 2023 and 2040, which includes the expansion on the south side. The urbanized area, including industrial developments, is projected to encompass 65% of Hà Nam, a significant increase from the current 15%. Based on the masterplan the amount of surface water is estimated to be 17% of the total area. This aligns closely with the combined area currently occupied by open channels and aquaculture ponds

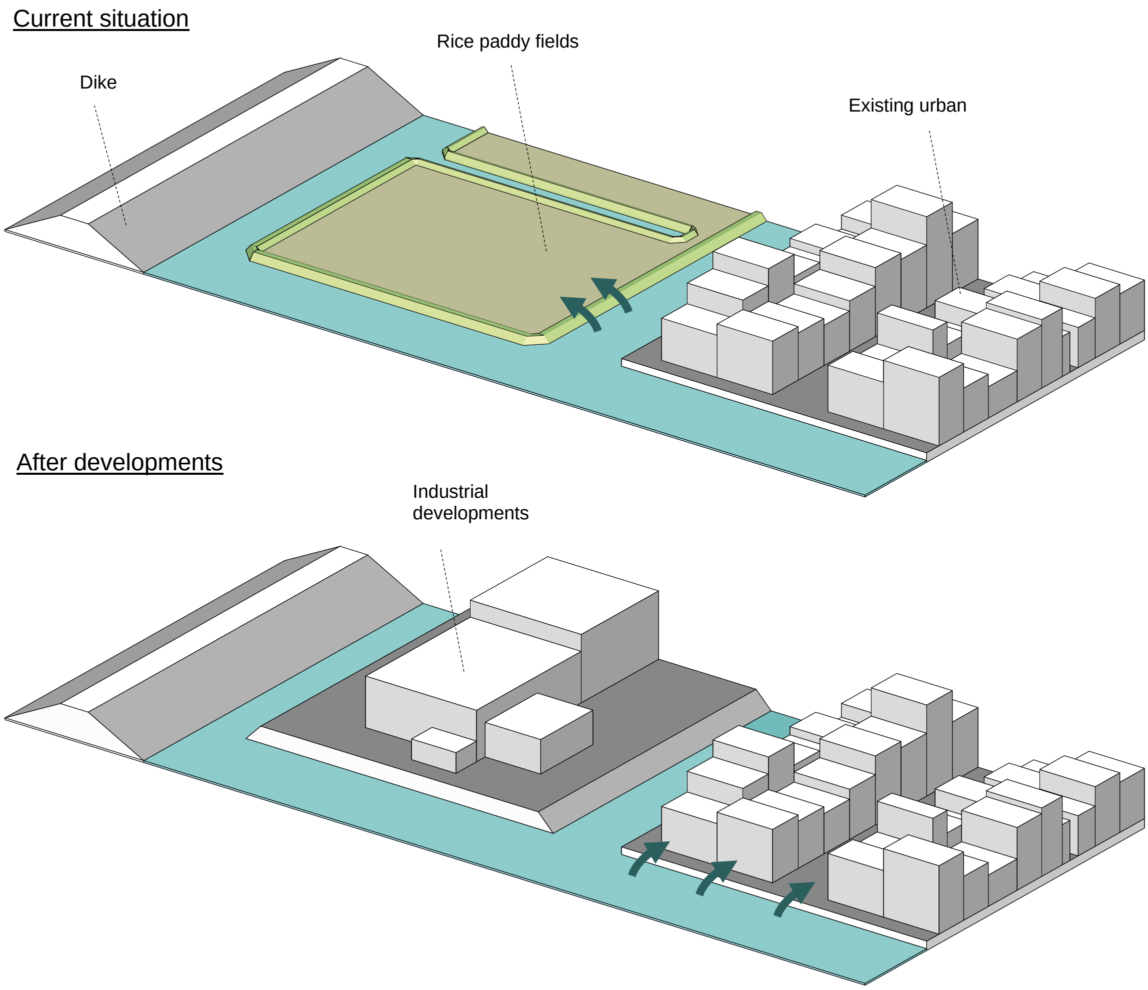
Figure 4.23 Shift in land use in Hà Nam



Change in land elevation

Figure 4.24 illustrates the change in surface elevation. Many of the rural zones will be replaced by industrial parks and residential areas. The new developments are projected to have an increased elevation of +3.00 m AMSL. Presently, urban areas range between +1.50 and +2.50 m AMSL. As a result of this shift, the lowest points in topography will transition from rural zones to the existing urbanized areas. Consequently, in the future, the existing urban areas will face significantly heightened exposure to rising water levels.

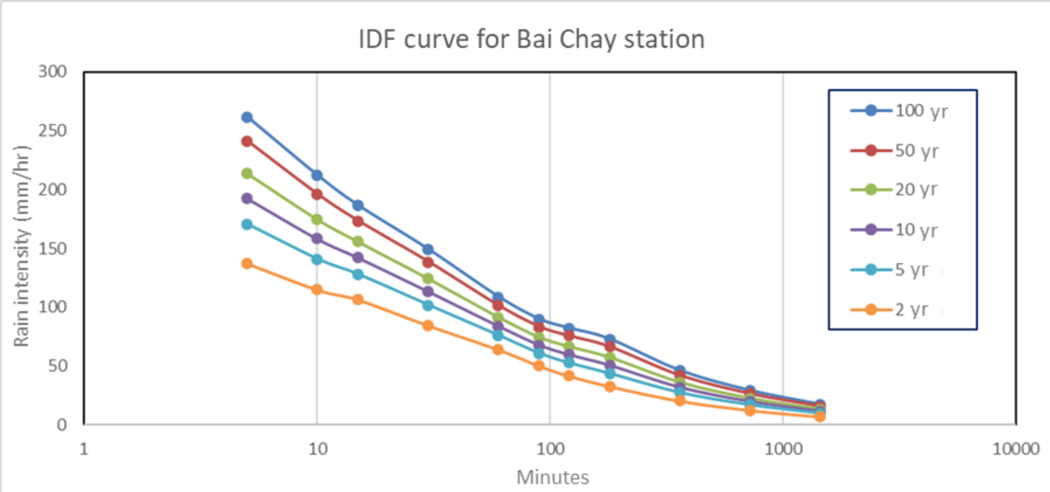
Figure 4.24 Change in terrain elevation



4.2.2 Heavy rainfall

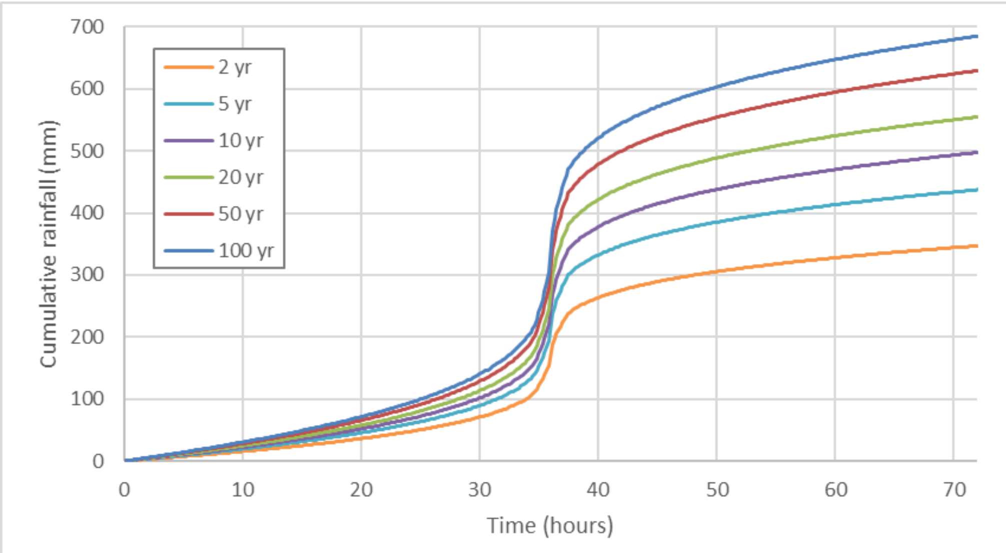
There is no long-term rain measurement data available within Hà Nam. The closest rainfall station is located in Bai Chay, Ha Long, and lies about 20 km north of Hà Nam. The measurement period ranges from 1970 to 2022. Intensity-duration-frequency (IDF) curves for this station (Figure 4.25) were provided for this study. The IDF curves are based on Gumbel extreme value analysis.

Figure 4.25 Rainfall intensity-duration-frequency curve for Bai Chay station (current climate)



The daily rainfall values have been transformed to short-term rainfall using the Simple Proportional Method. Design rain events were constructed using the alternating block method (Figure 4.26).

Figure 4.26 Rainfall design events based on the alternating block method (current climate)



4.2.3 High tide

The duration of river levels exceeding the Hà Nam water level is an important boundary condition to consider in this study. Furthermore, storm tide triggered by tropical storms can prolong periods of elevated river water levels, impeding the potential for gravity-induced drainage.

Sea level rise

The ongoing urban development within Hà Nam is anticipated to persist until at least 2040. Hence, it is crucial to account for the current projected sea level rise (SLR) scenarios along the Vietnamese coast for the forthcoming decades. SLR will extend the periods of time in which the river level exceeds the water level inside Hà Nam, limiting the possibility to discharge by means of gravity. The most recent data regarding SLR predictions from the Ministry of Natural Resources and Enviornment (MoNRE) dates back to 2020 and incorporates climate trends and developments updated to 2018. These predictions are currently being used by Vietnamese authorities. The SLR predictions for the coastline adjacent to Hà Nam are shown in Table 4.8.

Table 4.8 Sea level rise scenarios for the coast from Mong Cai to Hon Dau (cm)

Scenario	2030	2040	2050	2100
RCP 4.5	12	17	22	52
RCP 8.5	13	19	26	72

Combination of heavy rainfall and high tide

Hà Nam is being operated with sluice gates, and therefore the maximum amount of time these gates cannot be opened should be normative for the design. Therefore the worst-case scenario is to consider a rain event in which there is no sluice gate flow possible. The question that arises is what is the probability for a high river level during an arbitrary extreme rainfall event. (Shen et al., 2019) discussed that there is a dependence between both events. In this case study there is insufficient data to perform combined probability analysis. It was chosen to investigate the probability of coincidence. The probability of occurrence of heavy rainfall will be denoted with P(*RF*). Probability of high tide is denoted as P(*HT*). The difference between storm tide and high tide is that the former is the direct consequence of the atmospheric pressure differences during a tropical storm. High tide is the maximum water level during the normal tidal-cycle.

The probability of high tide and heavy rainfall is assumed to be independent:

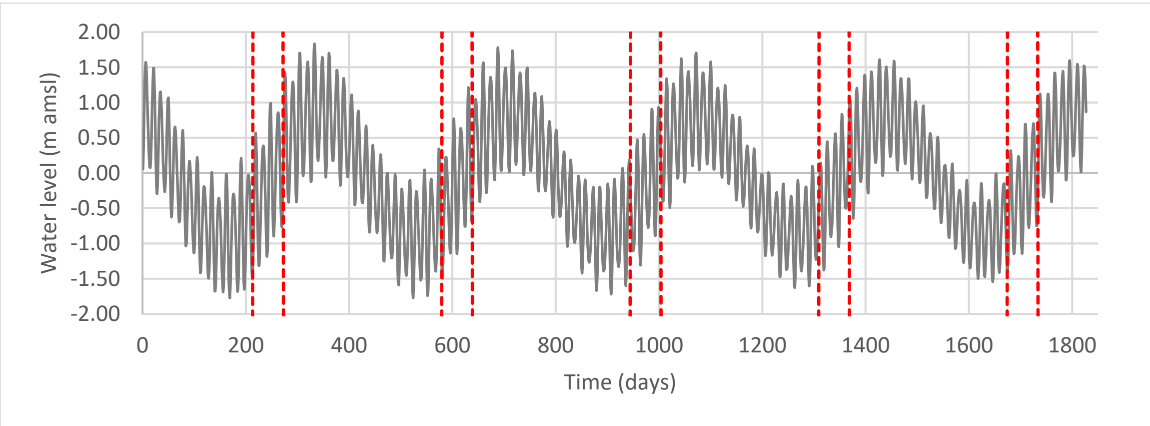
$$P(HT \mid RF) = P(HT)$$

This means that the probability of both events occurring at the same time is:

$$P(RF \cap HT) = P(RF) \cdot P(HT)$$

According to (Almar et al., 2017) there are 5 to 6 tropical storms that make landfall on the Vietnamese coastline each year. This study assumes that during every typhoon season, one storm with significant rainfall makes landfall in Quang Yen province. At Hon Dau station (20 km from Hà Nam), daily measurements of sea level that were collected in the period 2011-2016 were retrieved for this research. Figure 4.27 shows the daily measurements. The storm season period (August-September) is marked with the dotted lines.

Figure 4.27 Daily water level at Hon Dau station, period 2011-2016. Red lines mark months August-September (storm season)



In Table 4.9 the percentage of days during the storm season when the tide exceeds the Hà Nam water level of +0.3 m AMSL is calculated. Table 4.9 reveals that, under current climatic conditions, the sea level rises above the polder level for about 25% of the time during the flood season. Consequently, if one tropical storm strikes the province of Quang Yen per flood season, there is a 25% chance it will coincide with high tide. However, if two tropical storms hit the area, this probability will increase to 50%. With a SLR of 30 cm, the probability of coincidence rises to 40% with one tropical storm and 80% with two tropical storms.

Table 4.9 Percentage of days with tide above polder level (+0,3 m AMSL)

	Current climate	SLR 30cm	SLR 50cm	SLR 70cm
Average high tide duration per event (days)	5	7	8	9
Average days with high tide (days)	16	26	30	36
Percentage of days with tide above polder level	26.7%	43.3%	50.0%	60.0%

4.3 Conceptual drainage design

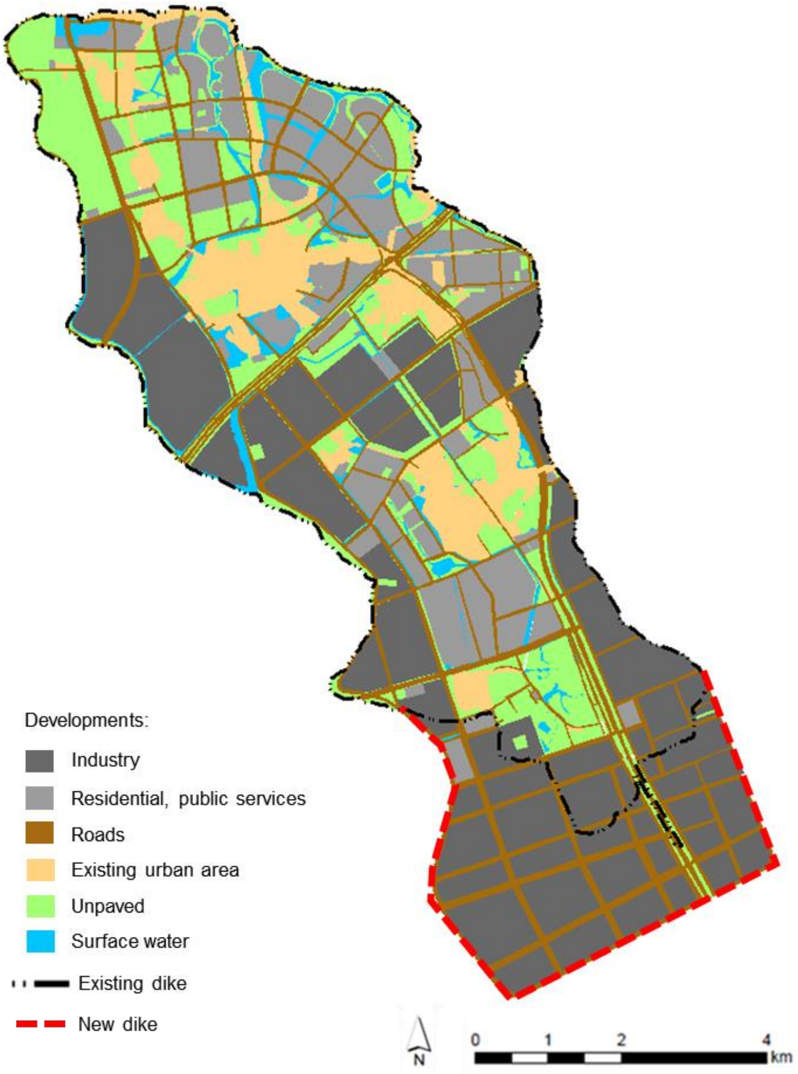
This chapter aims to outline the principal characteristics of the drainage design, taking into careful consideration all envisioned development projections for Hà Nam.

4.3.1 Basic outline

Masterplan

Figure 4.28 gives an overview of the projected development areas. The development consist of large residential and industrial zones that will replace current rural land. On the south side a new dike will be built to accommodate more development. The south expansion leads to an increase in total area of 900 ha.

Figure 4.28 Overview development areas in the masterplan



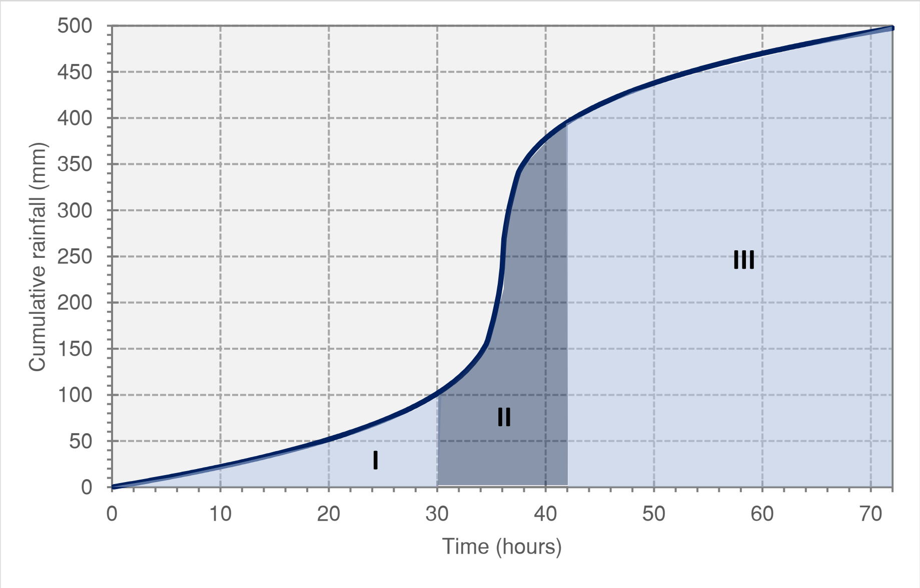
Future water level

An agreement has yet to be reached regarding the future water level, a decision dependent on the desired freeboard and storage requirements. The required freeboard varies depending on the type of land use. Paddy fields require no specific freeboard during the growing season due to their waterlogged nature. To ensure that there will be no significant subsidence, it is not desired to lower the water level too much compared to the current situation. Additionally, attention must be paid to seepage from the river into the canals, as it could adversely affect water quality. This concern is particularly pronounced during periods of low river flow, when saltwater intrusion may occur, potentially exacerbated by sea level rise. For this research there were no local groundwater measurements available. Also, there is no insight in soil compositions. To avoid increasing the risk of subsidence and deteriorating water quality, it has been decided to maintain the water level at +0.30 m AMSL.

Design storm

The Vietnamese authorities have stated that the drainage canals may not be overtopped during a rain event with a return interval of 10 years. There are no further guidelines for stormwater collection and transportation available. Figure 4.29 shows the design event.

Figure 4.29 Design rainfall event T=10 years



The total rainfall for this event is equal to 500 mm in 3 days. This amount is not equally spread over time. In the first 30 hours the accumulated rainfall amounts to 100 mm. During the rainfall peak, the rainfall amounts to 200 mm in just 3.5 hours.

Low- and high tide scenario

Analysis of sea level measurements and sea level rise predictions has shown that the probability that no free-gravity flow to the rivers is possible during an arbitrary heavy rain event is currently 25%, and will increase to 40% by 2050. Hence, this study supposes that forthcoming design scenarios should anticipate that sluice gates remain closed throughout the duration of rainfall events.

4.3.2 Polder sections

This section establishes the plan for Hà Nam to divide the area into smaller separated areas. To begin, the surface elevations of buildings within the existing communities are summarized in Figure 4.30.

Figure 4.30 Building percentages below elevation for each community

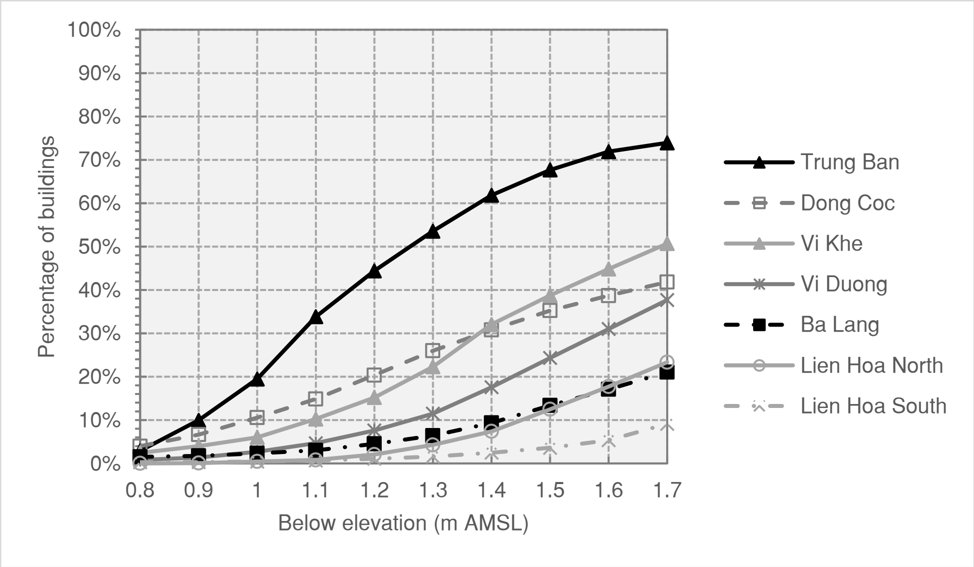
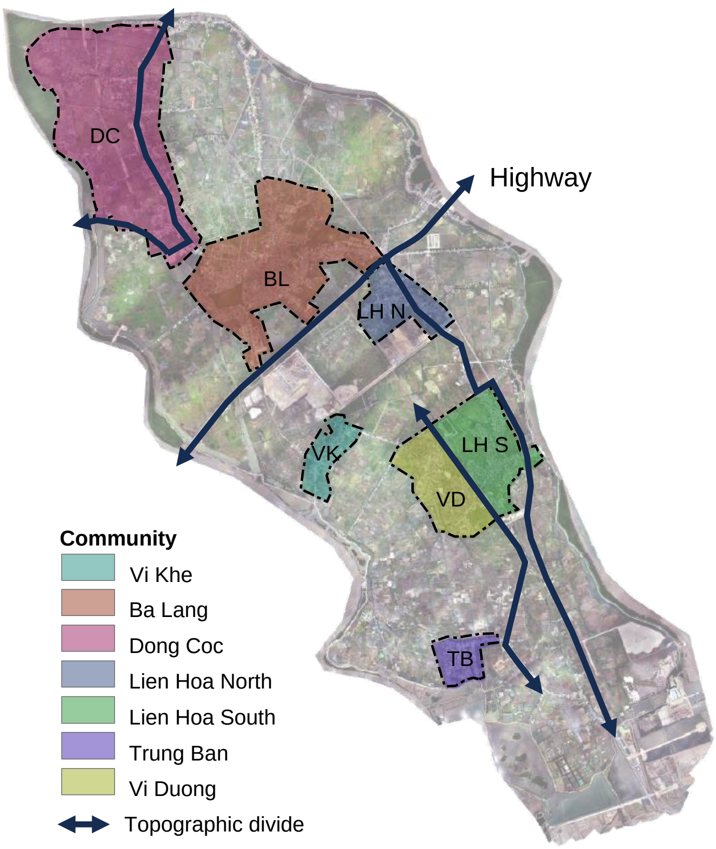


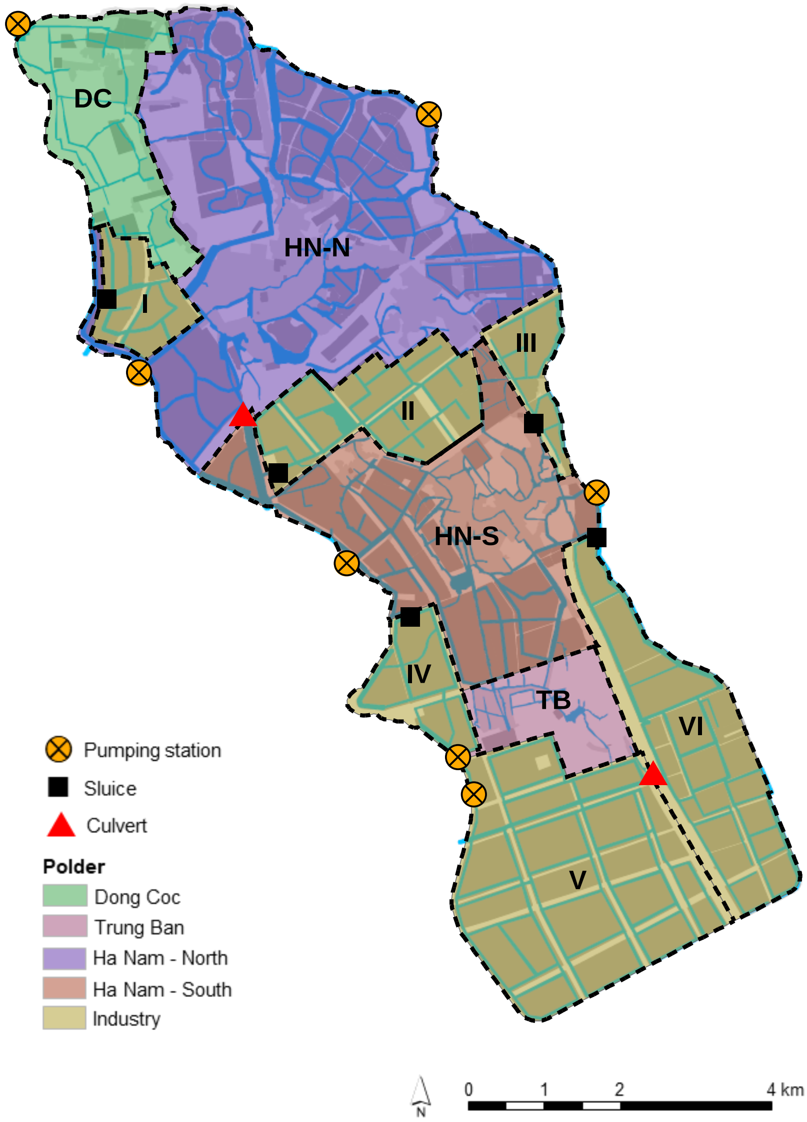
Figure 4.30 highlights significant differences in land elevations between residential settlements, while Figure 4.31 provides a map overview of the existing communities. Considering the varying elevations of these communities, it is logical to partition Hà Nam into distinct polder sections.

Figure 4.31 Overview existing communities and topographic water divides



The division of Hà Nam into different polder sections has been made based on the location of topographic elements and future developments. The result is shown in Figure 4.32.

Figure 4.32 Polder areas design, additional pumping stations and internal sluices



The different polder sections are summarized in Table 4.10 and explained below:

1. **Dong Coc**: This area is already separated from the drainage system of Hà Nam. Future projections indicate that the existing agricultural fields will remain. The buildings and paddy fields in Dong Coc are relatively low compared to the nearby town of Ba Lang. To prevent frequent flooding, Dong Coc community will remain isolated from the main drainage system.
2. **Trung Ban**: The majority of houses in Trung Ban are at a lower elevation compared to those in other communities. Consequently, if connected to the entire polder system of Hà Nam, Trung Ban would be the first to experience widespread flooding. Therefore, maintaining its separation is essential for flood prevention.
3. **Hà Nam (North and South)**: The canals within Ba Lang, Lien Hoa, Vi Duong, Vi Khe, and most future developments will be part of the main polder of Hà Nam. This polder is divided into a northern and southern section, with the highway acting as the dividing line. Ba Lang is located on the north side, while Vi Duong, Lien Hoa, and Vi Khe are situated

on the south side. The north and south sections are connected by a series of culverts that passes under the highway.

4. **Industrial areas I to VI** will be linked to the Hà Nam polder area via sluices. These structures will maintain the water level at +0.30 m AMSL under normal conditions, while allowing the water level within the industrial zones to rise to a maximum of +2.50 m AMSL during design events. Further elaboration on this will be provided in paragraph 4.3.3.
5. **Industrial area V** is designated to have its own pumping station. The distance to the nearest pumping station in Hà Nam polder is too large, which would result in excessively high water levels in the most upstream areas.

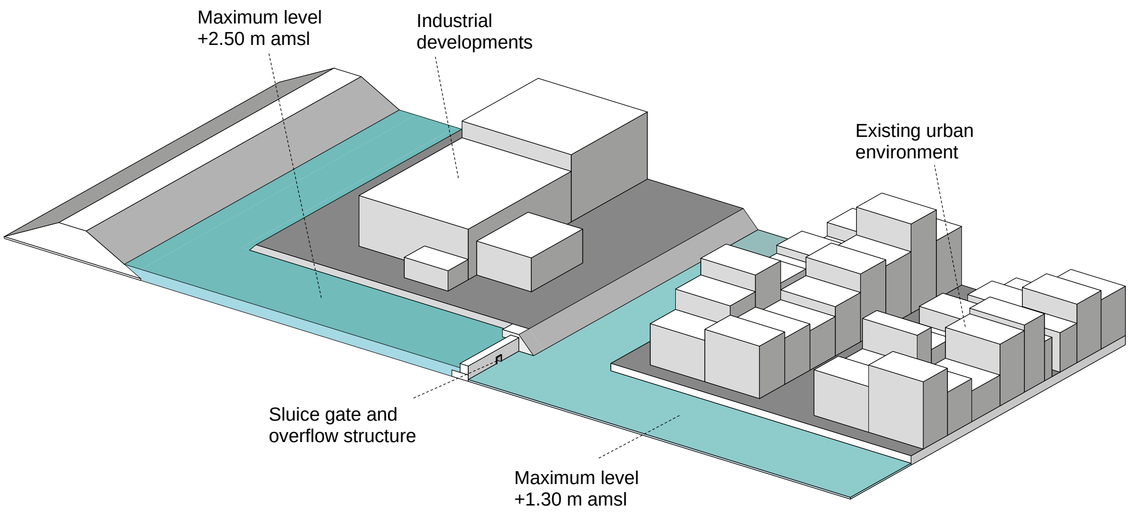
Table 4.10 Summary of all polder sections

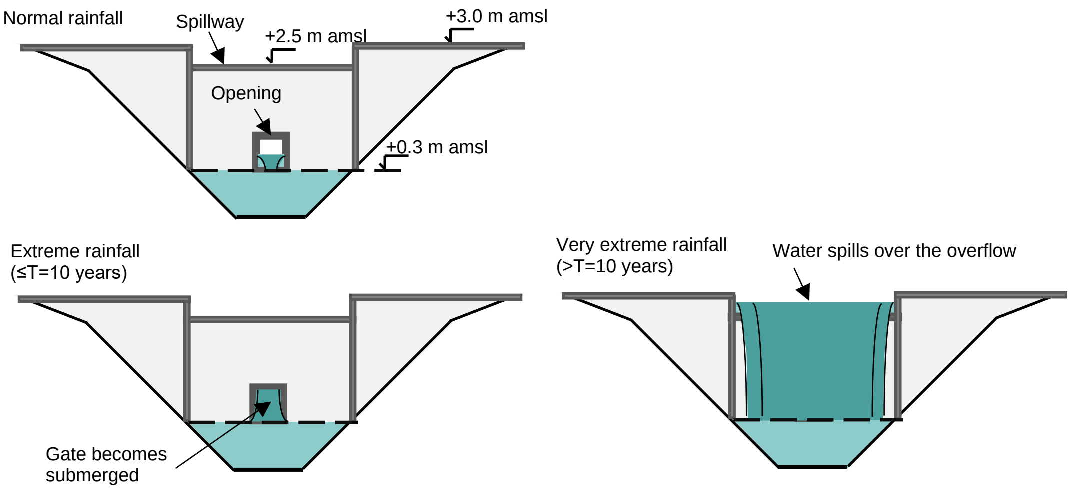
Nr	Polder section	Communities	Industries	Total area (ha)	Total area, including industries (ha)
1	Dong Coc	Dong Coc	-	368	-
2	Trung Ban	Trung Ban	-	199	-
3	Hà Nam South	Lien Hoa South, Vi Duong, Vi Khe	II, III, IV, VI	894	1,886
4	Hà Nam North	Lien Hoa North, Ba Lang	I	1,565	1,722
5	Industry V	-	V	791	791
Total					4,966

4.3.3 Industry gates

The industrial polders will be connected to Hà Nam polder by means of a sluice. The sluices are designed such that the water level inside the industrial polder will reach the maximum level of +2.50 m AMSL, but not exceed this level. The industry polder design is illustrated in Figure 4.33. During small rain events the sluice will operate as a weir. During heavy rain events the sluice becomes submerged. For rainfall events that exceed the design event (T=10 years), the sluice gate will discharge to the downstream area through the gate and over the spillway.

Figure 4.33 Industry polder design





The sluice gate dimensions have been designed using hydrodynamic calculations conducted in Delft3D FM. The dimensions are based on the upstream area and storage within the industrial zones.

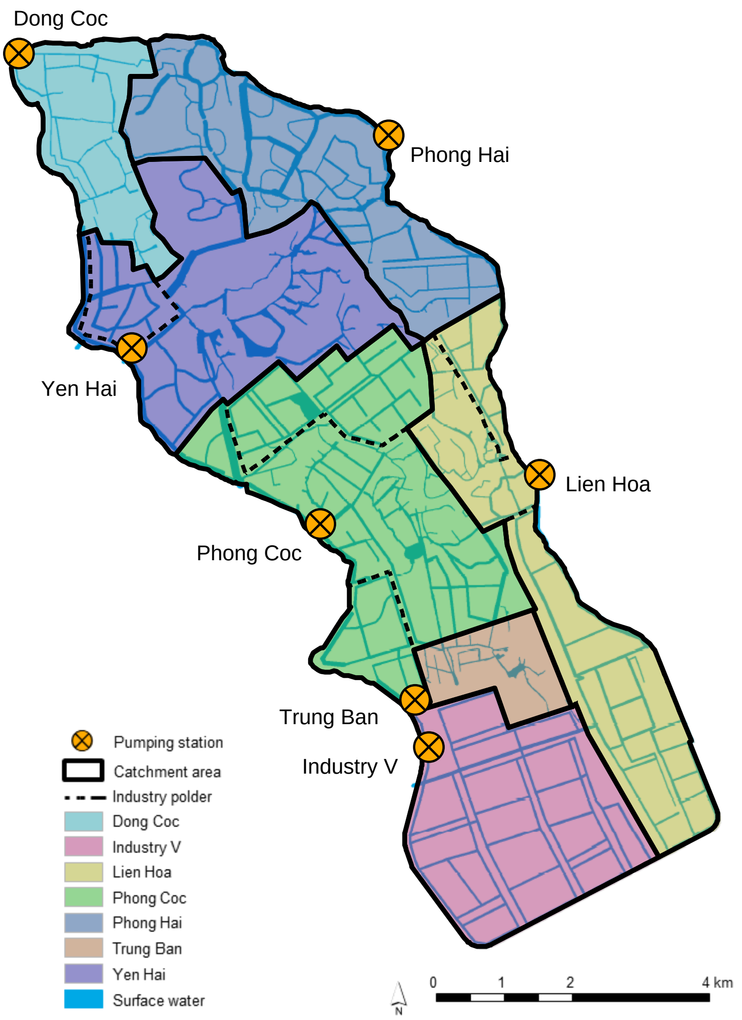
4.3.4 Pumping stations

Vietnamese authorities have already established plans for the construction of four pumping stations. Due to segregation of Hà Nam into smaller polder sections, this study proposes to extend this amount to a total of seven pumping stations. Figure 4.34 gives an overview of the estimated catchment area of each pumping station, while Table 4.11 presents their respective capacities.

Table 4.11 Pumping station capacities for Hà Nam in 2040

Pumping station	**Capacity (mm/day)**	**Area (ha)**	**Capacity (m^3/min)**
Yen Hai	100	935	650
Phong Coc	100	1,110	771
Industry V	100	791	549
Lien Hoa	100	776	539
Phong Hai	100	787	547
Trung Ban	100	199	139
Dong Coc	100	368	256

Figure 4.34 Catchment area for each pumping station



4.3.5 Open canals and culverts

The flow through open canals and culverts is calculated using hydrodynamic calculations in Delft3D FM. The software utilizes the Navier-Stokes equations to describe the conservation of momentum, mass, and energy. For open canals, Delft3D FM employs numerical techniques such as the finite element methods to discretize the governing equations over the computational domain. These equations consider factors like channel geometry, bed roughness and boundary conditions to compute water flow velocities, depths, and other hydraulic parameters.

Cross sections of open canals in the development zones are designed as such to keep flow velocities below 0.30 m/s. This is to prevent erosion of the canal bed. The channels are dimensioned to accommodate the transportation of water according to the pumping capacity of 100 mm/day. In line with the masterplan, the open water area should comprise 17% of the total area. Consequently, channels have been widened and retention ponds have been added to the model. Figure 4.35 shows how open canals and culverts are implemented for a part of the masterplan.

Figure 4.35 Design model structure of stormwater system

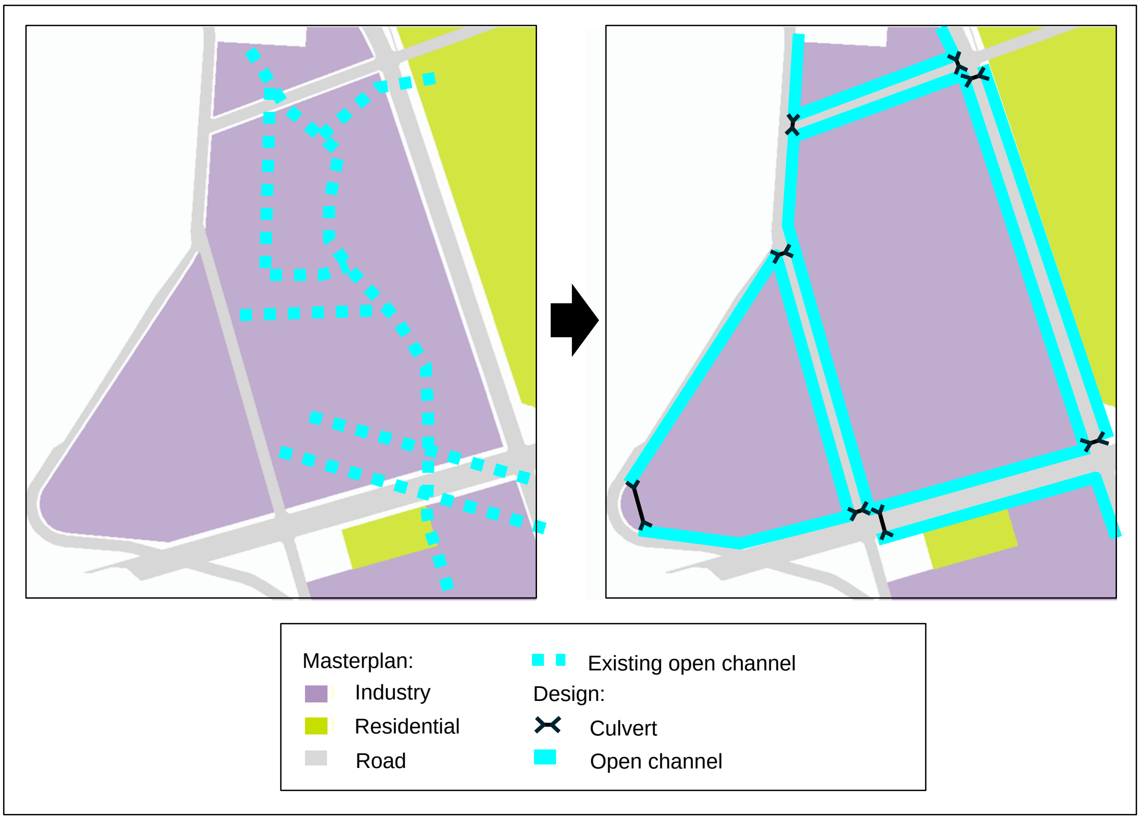


Table 4.12 presents a summary detailing the lengths of both widened and newly constructed canals, alongside the total number of culverts incorporated into the design.

Table 4.12 Summary design of open canals and culverts

Length of existing canals	**km**	**60**
Length of existing canals widened/deepened	km	65
Length of new canals	km	130
Number of designed culverts	-	200

4.3.6 Storage in Hà Nam polder north and south

Adequate stormwater storage is essential in a drainage system to effectively manage and mitigate the impacts of heavy rainfall events. In urban environments, where impervious surfaces are prevalent, the need for ample stormwater storage is critical to protect properties, infrastructure, and public health from the adverse effects of stormwater runoff. The Vietnamese authorities have established the construction of pumping stations in the masterplan. It has been agreed upon to design the pumping station capacities at 100 mm/day. The discharge of stormwater by means of pumping stations influences the amount of storage that is required.

Storage can be realized by different means, like detention basins and open canals. When evaluating storage within open canals, the primary parameter influencing this capacity is the maximum increase in water level, denoted by dHmax (see Figure 4.36). This parameter is related to the elevation of streets and buildings adjacent to the canals. As illustrated in chapter 4.3.2, building elevations vary throughout Hà Nam. Consequently, the maximum allowable increase in water level will differ for each community.

Figure 4.36 dHmax

This study will mainly focus on the main polder of Hà Nam that is divided into a north and south section (see Figure 4.32). Therefore the protection against pluvial flooding will be considered for the following communities: Lien Hoa S., Vi Duong, Vi Khe (Hà Nam South) and Lien Hoa N., Ba Lang (Hà Nam North).

The complete polder design has been put into the Delft3D FM software. The fluxes that are calculated in the hydrodynamic model are used to calculate the required storage for the main polder of Hà Nam. The complete storage calculation is summarized below:

$$S_t = Q_{runoff,t} - Q_{pump\rightarrow river,t} + Q_{sluice,industry,t} - Q_{sluice\rightarrow river,t}$$

$S_t =$	storage at timestep t (m^3)
$Q_{runoff,t} =$	total runoff at timestep t (m^3)
$Q_{pump\rightarrow river,t} =$	pump discharge to the river at timestep t (m^3)
$Q_{sluice\rightarrow river,t} =$	sluice discharge to the river at timestep t (m^3)
$Q_{sluice,industry,t} =$	sluice discharge from industrial zones to Hà Nam polder (m^3)

Runoff from unpaved surfaces is based on the Zeeuw-Hellinga drainage formula:

$$q_{unp,t} = q_{unp,t-1}e^{-\alpha\Delta t} + P_t(1 - e^{-\alpha\Delta t})$$

With:

$$Q_{runoff,unp,t} = q_t \cdot A_{unp}$$

$P_t =$	precipitation at timestep t (m)	
$q_{unp,t} =$	unpaved runoff at timestep t (m)	
$\alpha =$	unpaved runoff factor (1/day)	$= 0.5$
$\Delta t =$	timestep (day)	
$A_{unp} =$	unpaved area (m^2)	
$Q_{runoff,unp,t} =$	unpaved runoff at timestep t (m^3)	

The total surface runoff at timestep t becomes:

$$Q_{runoff,t} = Q_{unp,t} + Q_{paved,t}$$

The total required storage is calculated as follows:

$$S_{tot,t} = \sum_{t=0}^{t=3\ days} S_{t-1} + S_t$$

And:

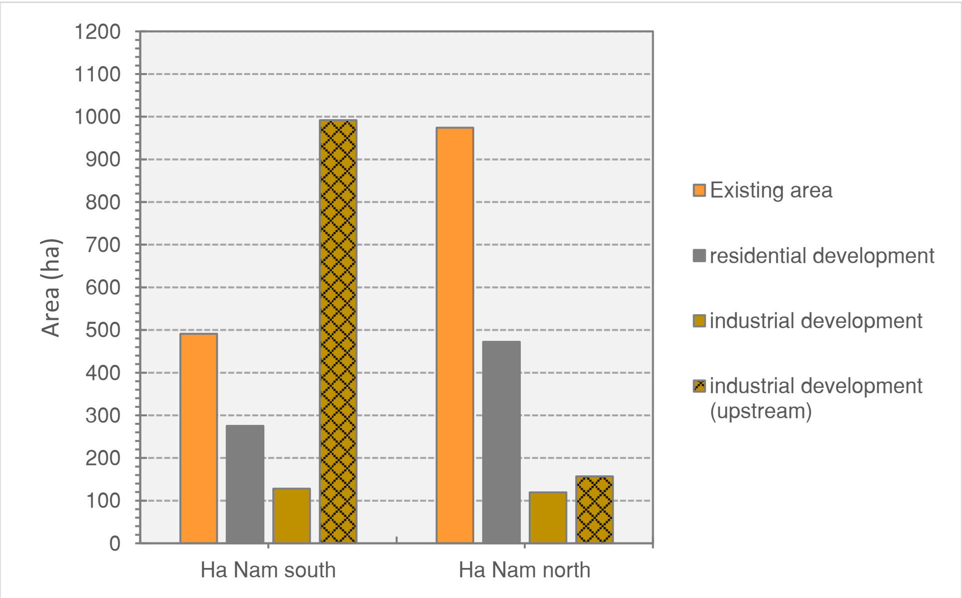
$$S_{max} = \text{Max}\ (S_{tot,0}, S_{tot,1}, \dots, S_{tot,t=3\ days})$$

$S_{tot,t}$ = storage at timestep t [m^3]
S_{max} = maximum storage during event [m^3]

4.3.7 Land use in Hà Nam polder north and south

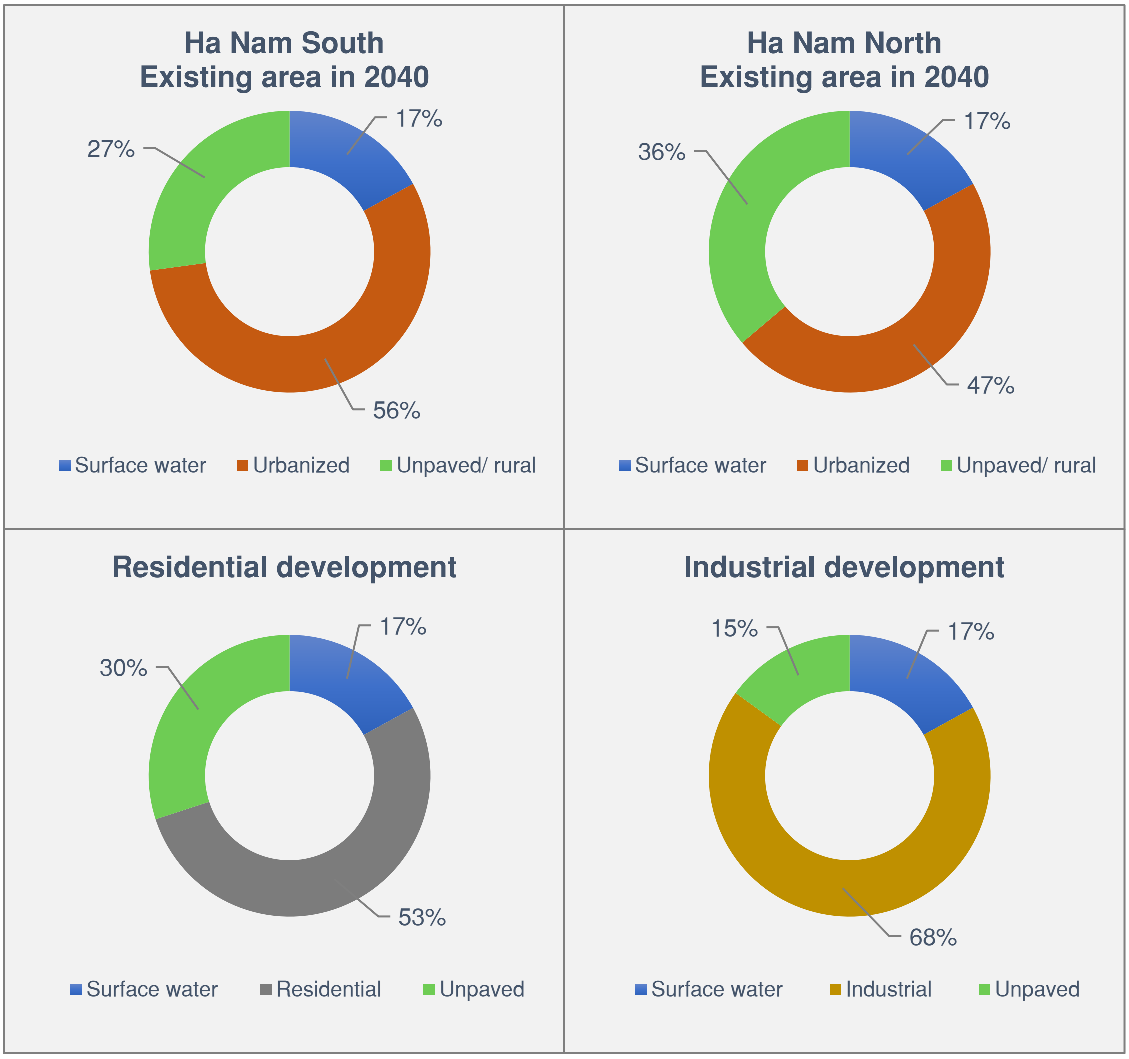
This chapter discusses the future land use distribution in the main polder of Hà Nam. The area is divided into existing urban and rural zones and designated development zones. The development zones are further categorized into residential and industrial lots. Additionally, there are several industrial lots connected to the main polder by sluices, referred to as upstream industrial developments. Figure 4.37 provides an overview of the total area allocated to each category.

Figure 4.37 Total areas in the main polder of Hà Nam



According to the master plan, the percentage of open water is 17%. Within the existing area, the proportion of unpaved and urbanized land varies between the northern and southern polder section of Hà Nam. Figure 4.38 provides an overview of the percentages of urbanized and unpaved surfaces within the existing areas. The same figure also presents the division between paved and unpaved surfaces within the two types of developments. It should be noted that these figures were not provided in the master plan and are assumed for this study.

Figure 4.38 Land use percentages within the existing areas of Hà Nam polder North and South in the future scenario



4.4 Adaptation measures

In this design approach several types of SUDS were studied based on literature in the context of Southeast Asia. Their potential effectiveness in terms of stormwater storage and flood peak reduction was studied. For this research it was concluded to analyse the flood risk reduction effect of vegetated swales and park floodzones. These measures offer several advantages, including their relative ease of implementation on a large scale within public areas. Another benefit is that these type of measures can also fulfil other objectives. For instance, both show great potential to improve quality of stormwater runoff before entering the groundwater and surface water. Additionally, they create opportunities for ecological systems to flourish. Finally, they can be integrated with public parks, providing valuable recreational space for local residents.

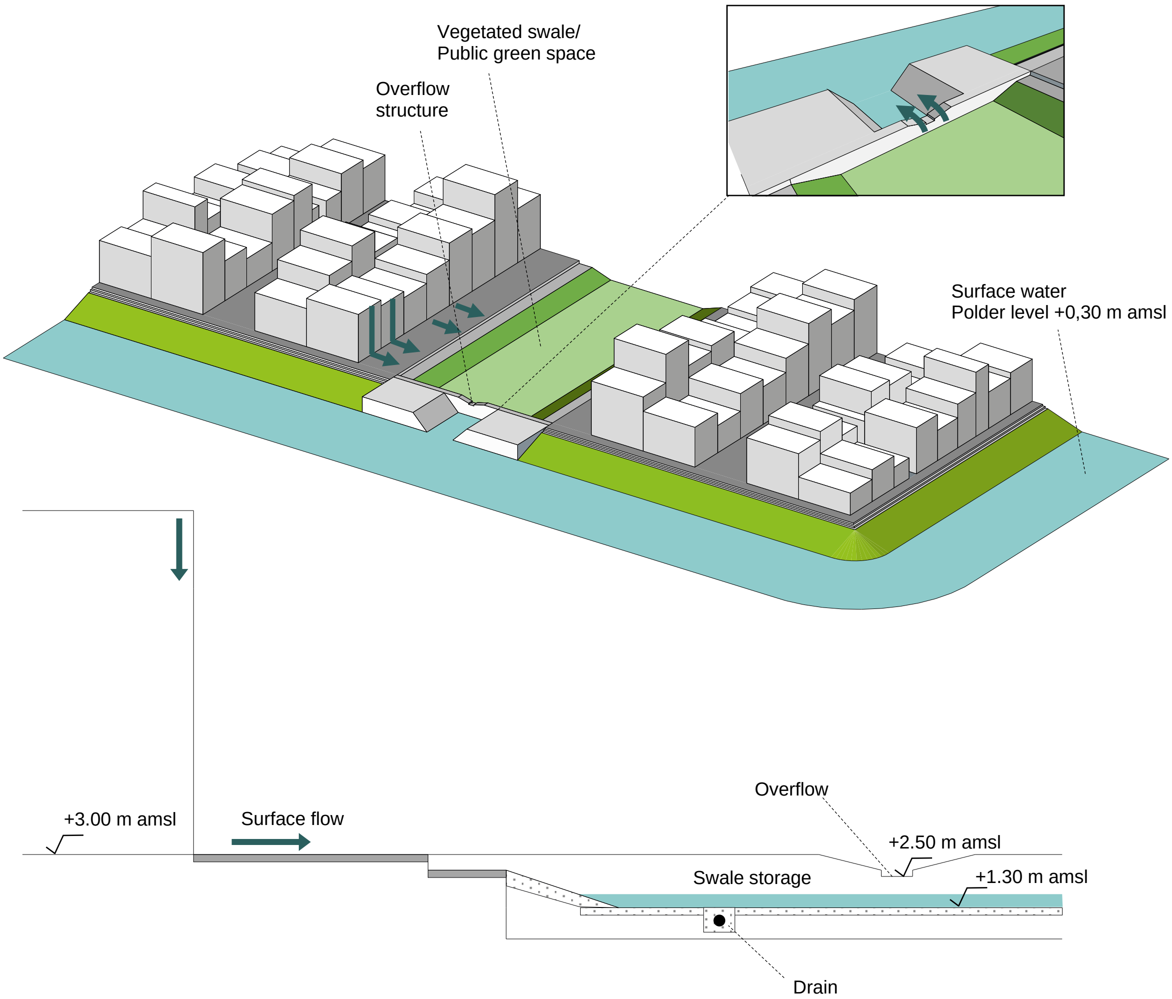
4.4.1 Vegetated swales

The first adaptation measure is the addition of vegetated swales within the new residential development plots. This type of measure can be applied at a very localized level, such as small plots along roadsides. Moreover, it offers scalability, with the potential to expand to the size of public parks, as illustrated in Figure 4.39.

Figure 4.39 Example of vegetated swales in the Netherlands (left) and Singapore (right), source: (ABC Singapore, 2018)

The implementation of the vegetated swales inside the Hà Nam residential expansions is shown in Figure 4.40. Throughout the inhabited areas the swales will form large green corridors. The elevation of these green corridors is lower compared to the build-up areas. Stormwater drains will discharge stormwater to the swales. Streets and buildings adjacent to the swales will runoff via the surface. The soil of the swales is improved as such that stormwater is able to infiltrate. To enhance this infiltration process the swales will be supplemented with drains that discharge into the open canals. Overflows are constructed that enable transport of water to the canals in case of extreme rainfall.

Figure 4.40 Vegetated swale design



To include the rainfall peak reduction effect of the vegetated swales, the surface runoff coming from paved surfaces is reduced. The flood peak reduction is calculated as follows:

$$\begin{cases} Q_{paved,t} = P_t\left(A_{paved} - A_{residential}\right) & if\ P_{tot,t} \leq S_{swale} \\ Q_{paved,t} = P_t\left(A_{paved}\right) & if\ P_{tot,t} > S_{swale} \end{cases}$$

$A_{paved} =$	total paved area (m^2)
$A_{residential} =$	area of projected residential zones (m^2)
$S_{swale} =$	storage of the bioretention swales (m)
$P_{tot,t}=$	cumulative rainfall at timestep t (m)

with:

$$P_{tot,t} = \int_{t=0\ days}^{T=3\ days} P_{t-1} + P_t\, dt$$

The volume inside the bioretention swales is calculated as follows:

$$V_{swale} = A_{residential} \cdot r \cdot d$$

$d =$	depth of the swale (m)
$r =$	bioretention area relative to residential plot (%)
$V_{swale}=$	volume inside the swales (m^3)

Then the swale storage becomes:

$$S_{swale} = \frac{V_{swale}}{A_{tot}}$$

The rainfall peak in the design storm starts at day 2. Prior to this, the swales will already be partially filled. The flood peak reduction is dependent on the initial storage in the swale. The storage that is still available at the start of the rainfall peak is a function of the infiltration rate and amount of rainfall prior to the rainfall peak:

$$S_{swale,t=1\ day} = \int_{t=0\ days}^{T=1\ day} P_t - I_t\, dt$$

Assumed is that the soil is fully saturated and no drainage flow is present, so that infiltration becomes:

$$I_t = I = 0 \text{ [m/day]}$$

The effective storage of the swales during the peak rainfall becomes:

$$SE_{swale} = S_{swale} - S_{swale,t=1day}$$

The vegetated swale parameters are summarized for Hà Nam polder south and north in Table 4.13.

Table 4.13 Vegetated swale design parameters

		Polder		
Description	**Unit**	**Ha Nam South**	**Ha Nam North**	**Symbol**
Total area	ha	894.3	1565.5	A_{tot}
Residential area	ha	275.3	472.2	$A_{residential}$
Bioretention area	%	15	15	r
Depth of the swale	m	1.20	1.20	d
Infiltration	m/day	0.0	0.0	I
Total storage	m^3	$4.96 \cdot 10^5$	$8.50 \cdot 10^5$	
Total storage	mm	55.4	54.3	S_{swale}
Storage at t=1 day	mm	30.8	30.2	$S_{swale,t=1\ day}$
Effective storage	mm	24.6	24.1	SE_{swale}

4.4.2 Park floodzones

In addition to incorporating vegetated swales within residential areas, this study explores the potential implementation of public parks as flood zones along the main drainage canals for flood risk reduction. These flood zones, designed to mitigate flooding during extreme rain events, also serve as accessible recreational areas for local residents on most days throughout the year. As an example, Figure 4.41 shows the Erchong floodway in Taipei.

Figure 4.41 Erchong floodway riverside park (New Taipei Travel, 2023)

In Figure 4.42 an image from the Nature-based solutions design program in Vietnam is given that illustrates a similar principle.

Figure 4.42 Example of a floodable area, source: Water Sensitive Urban Design (Asian Development Bank, 2019)

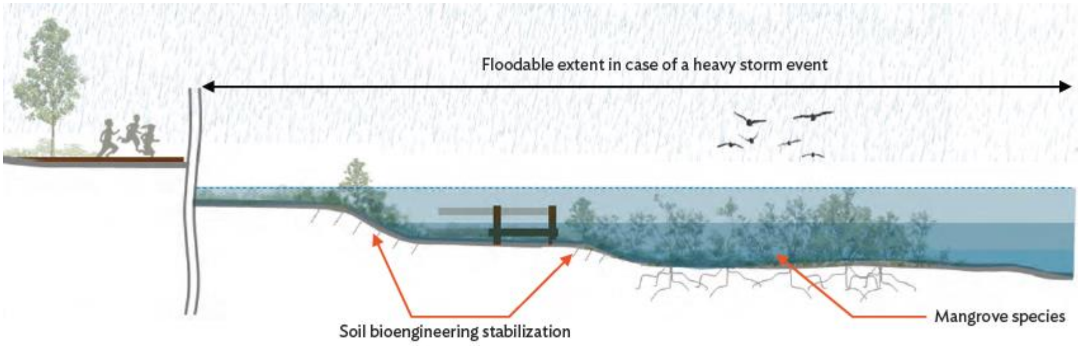
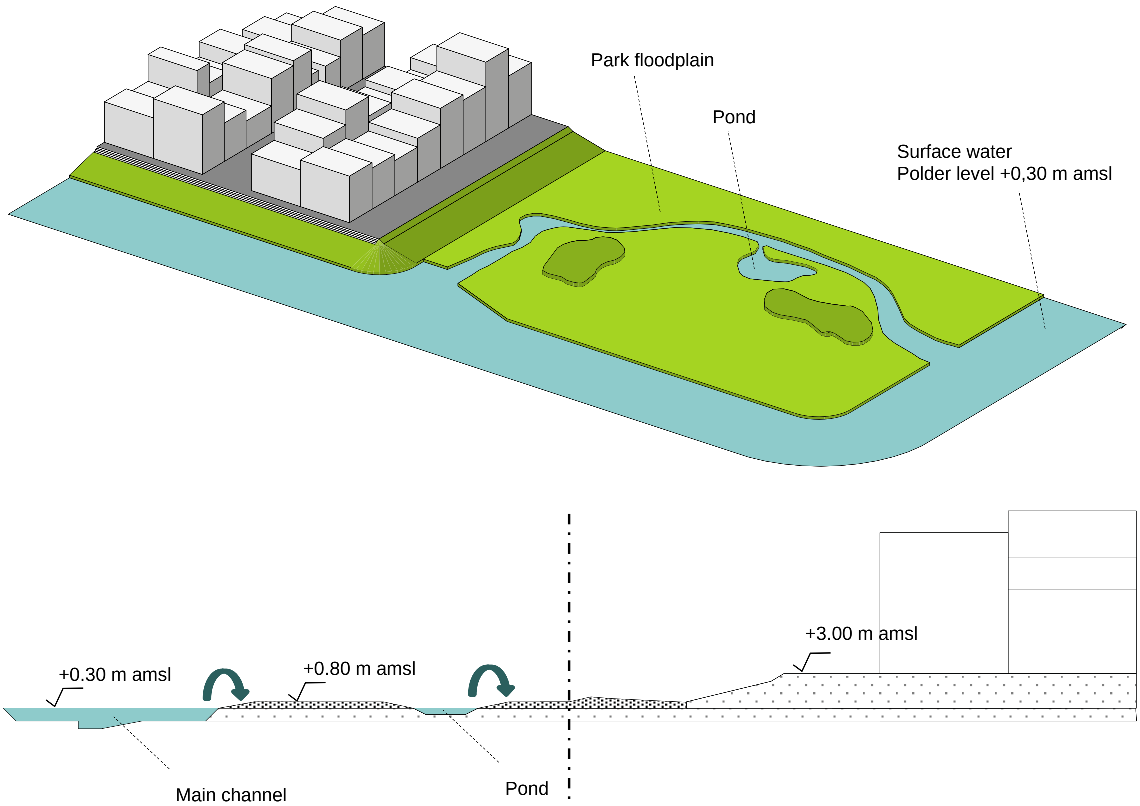


Figure 4.43 gives an illustration that shows how the park floodzones are implemented in the design of Hà Nam.

Figure 4.43 Park floodzones design



The volume on top of the park floodplains is calculated as follows:

$$V_{FloodPlain} = A_{FloodPlain} \cdot d_{FloodPlain}$$

$V_{FloodPlain} =$ effective storage volume on top of the flood plains (m^3)
$d_{FloodPlain} =$ depth of the floodplain w.r.t. maximum water level (m)
$A_{FloodPlain} =$ floodplain area (m^2)

With:

$$d_{FloodPlain} = h_{max} - z_{FloodPlain}$$

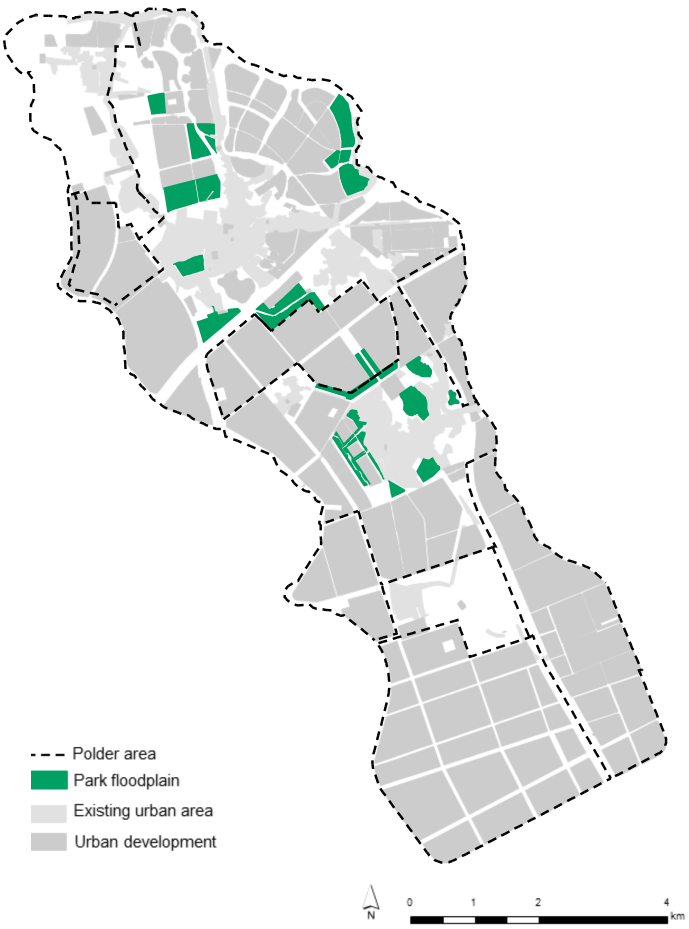
$h_{max}=$ maximum water level (m AMSL)
$z_{FloodPlain}=$ flood plain elevation (m AMSL)

Then the storage inside park floodplains becomes:

$$S_{FloodPlain} = \frac{V_{FloodPlain}}{A_{tot}}$$

Figure 4.44 highlights the park floodplain areas integrated into the public greenspaces outlined in the Hà Nam masterplan.

Figure 4.44 Park floodzone locations



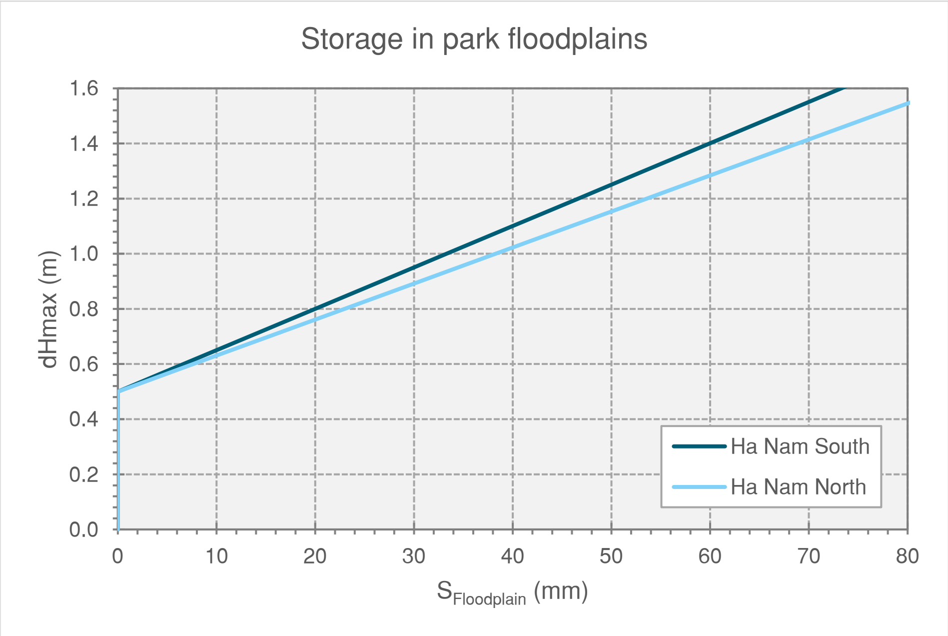
The design parameters which outline key features and dimensions of the park overflow zones are given in Table 4.14.

Table 4.14 Park floodzones design parameters

		Polder		
Description	**Unit**	**Ha Nam South**	**Ha Nam North**	**Symbol**
Total area	ha	894.3	1565.5	A_{tot}
Park floodzones area	ha	59.6	119.8	$A_{FloodPlain}$
Flood plain elevation	m AMSL	+0.80	+0.80	$z_{FloodPlain}$
Canal water level	m AMSL	+0.30	+0.30	

The amount of storage inside the park floodplains is determined by the increase in water level in the adjacent canals. The available storage inside the park floodplains is a function of the maximum increase in canal water level, denoted by dHmax, as depicted in Figure 4.45.

Figure 4.45 Park floodzones design

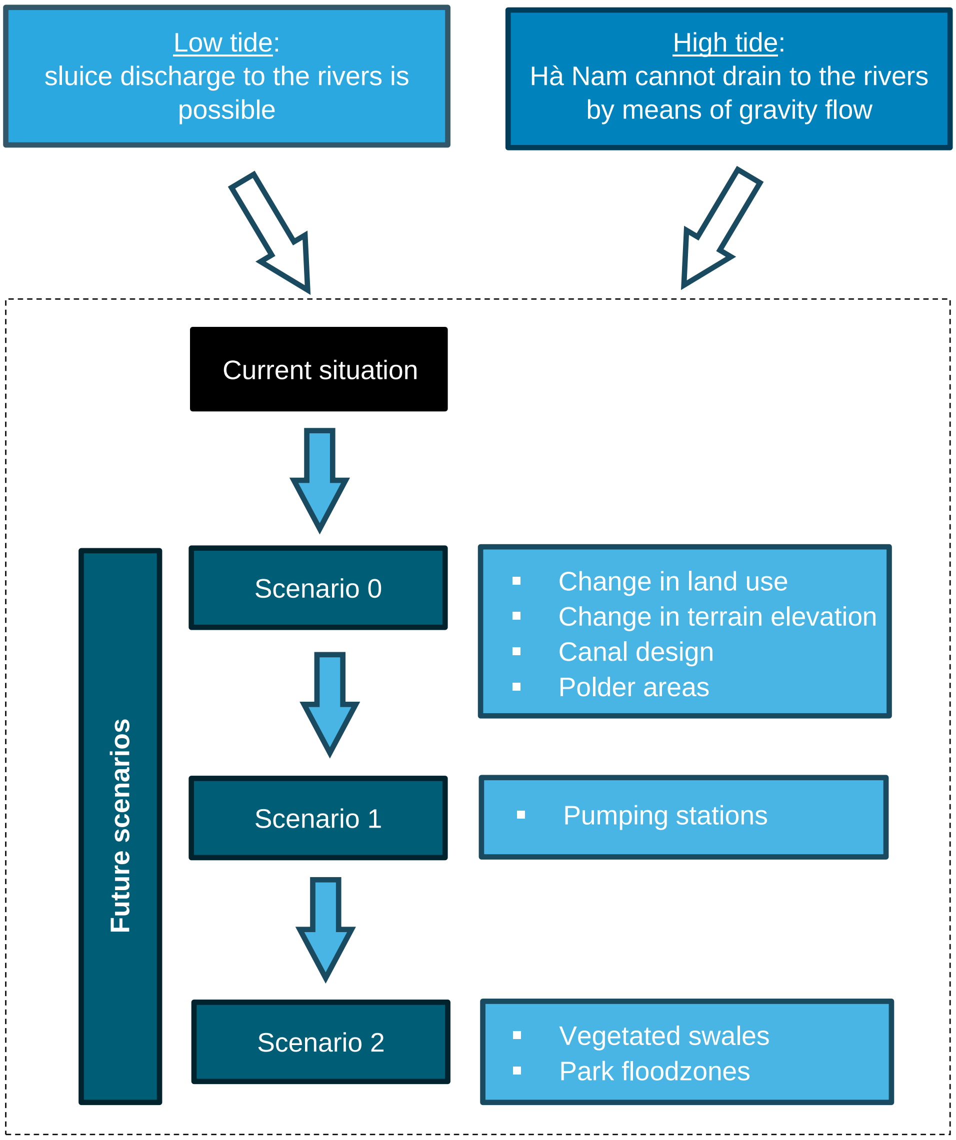


4.5 Design scenarios

The following scenarios with respect to the design have been simulated:

- Scenario 0: This scenario acts as a baseline to show how flood risk in the area is affected by the new developments. Future projections of land use and terrain elevation have been incorporated into the 1D/2D model. Additionally, canals have been designed to facilitate stormwater drainage for the new developments, and the area has been divided into different polder sections.
- Scenario 1: Building upon the base scenario, the proposed pumping stations are added to the base scenario. The pumping stations serve as the only means of discharging stormwater during the high tide scenario.
- Scenario 2: In this scenario, sustainable urban drainage systems are implemented to further enhance flood resilience. Vegetated swales and park floodzones are integrated into the 1D/2D model to augment stormwater adaptation strategies. Vegetated swales lead to reduced runoff and alleviate pressure on the drainage system. Park floodzones serve as designated flood retention areas during extreme rainfall events.

Figure 4.46 Overview scenarios



4.6 Calculating Urban Flood Extent

The hydrodynamic model results provide the inundation depth for each 2D grid cell within the elevation model. To quantitatively assess the performance of each design scenario, the inundation depths will be translated into an Urban Flood Extent indicator (UFE). This indicator represents the percentage of buildings affected by flooding in each community. The level of exposure is determined by the water depth. Table 4.15 categorizes the UFE into three distinct classes.

Table 4.15 Classes for the Urban Flood Extent (UFE)

Class	Exposure	Water depth	Exposure
1	Affected	>10 – 30 cm	Affected: Nuisance is to be expected, but damages stay limited
2	Heavily affected	>30 – 100 cm	Heavily affected: damage to household items, flooring and walls. Risk of negative health effects.
3	Extremely affected	>100 cm	Extremely affected: non-repairable damages to building structure and household items. Very high risk of negative health effects.

The Urban Flood Extent is calculated for each community individually and is the sum of all classes:

$$UFE = \frac{C1 + C2 + C3}{TB}$$

with:

$UFE =$ Urban flood extent
$C1 =$ Number of buildings in class 1
$C2 =$ Number of buildings in class 2
$C3 =$ Number of buildings in class 3
$TB =$ Total number of buildings

5

Results

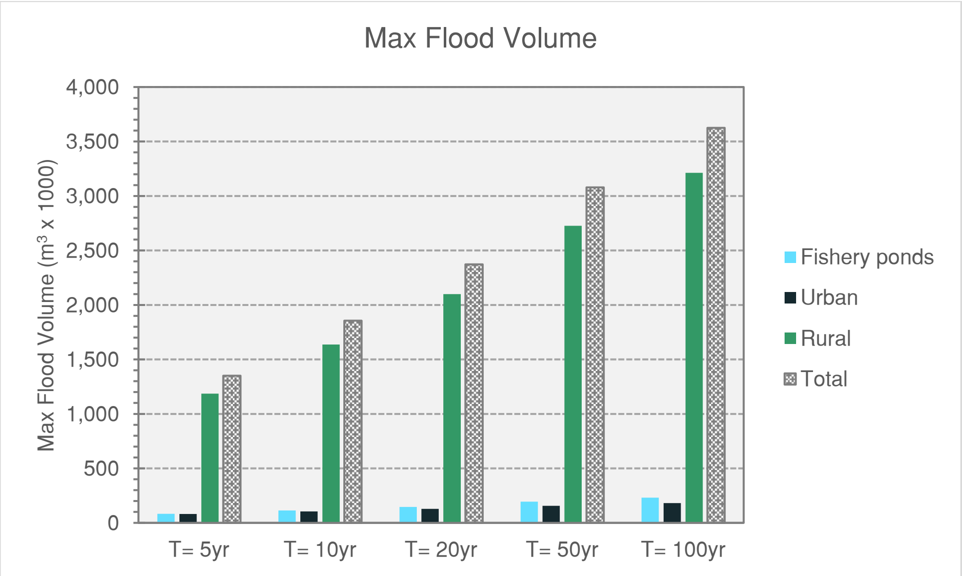
5.1 Current flood risk during high tide

This chapter discusses the inundation results for the current situation that were gained from the hydrodynamic 1D/2D model. The results are shown for the high tide scenario, thus indicating that no discharge through the rivers is possible during the whole extent of the rainfall events.

5.1.1 Flood volumes

The maximum flood volumes for the rainfall events with different return intervals are given in Figure 5.1.

Figure 5.1 Maximum flood volume for different land uses



The graph shows the maximum flood volume on top of the surface for each landuse type. It is evident from the figure that the majority of the flood volume is concentrated within rural zones, with over 85% of the flooded waters accumulating in the rice paddy fields.

5.1.2 Inundation areas

Figure 5.2 gives further insight in the amount of flooded area for each landuse type.

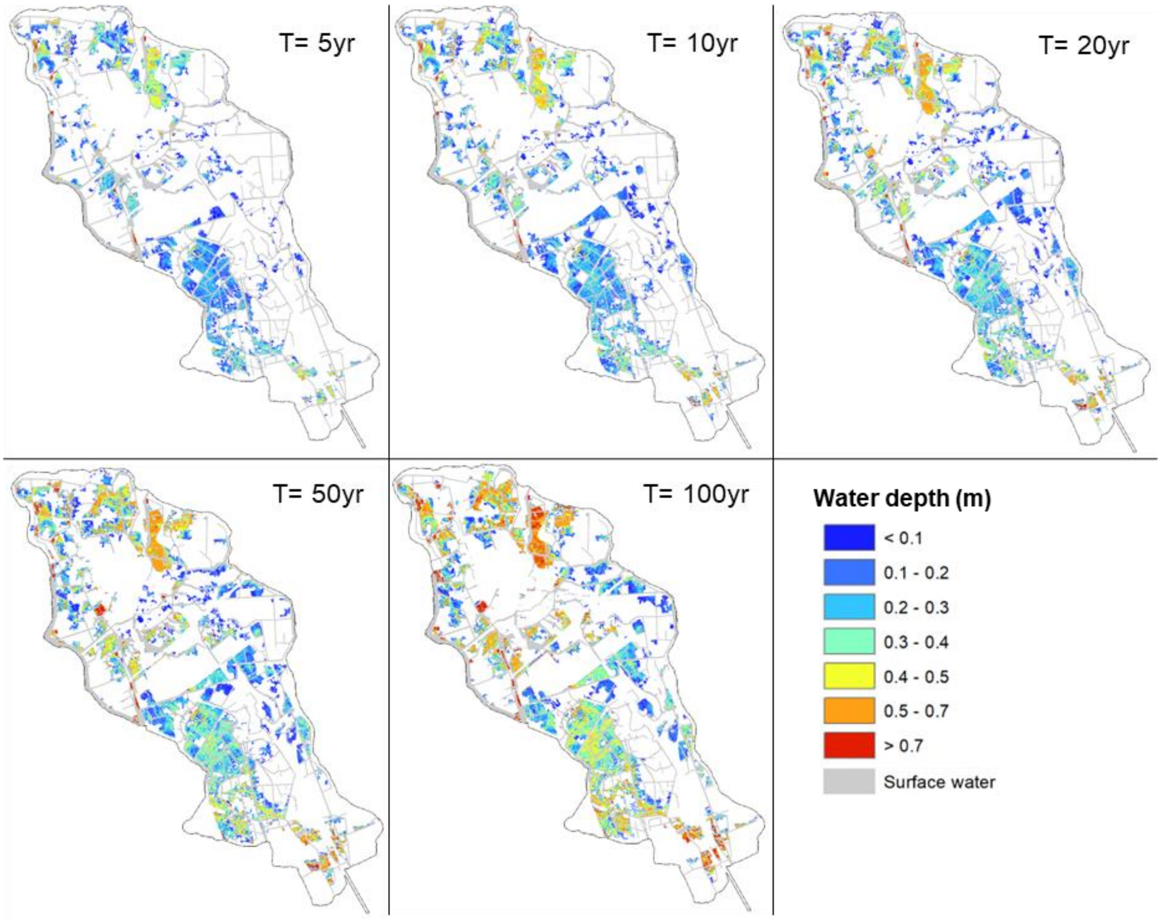
Figure 5.2 Maximum inundation area in percentage of surface area for each land use class

Figure 5.2 shows that during a T=10 year rainfall event, roughly 25% of the rural land is inundated, while 10% of urban areas experience flooding. It is important to note that this analysis encompasses all surfaces within urban environments. The Urban Flood Extent, which will be discussed later, specifically focuses on flooded buildings. Furthermore, in Figure 5.2 it can be seen that a T=100 year rainfall event causes the total flood area inside rural areas to increase by 15%, whereas flooding in urban areas experiences a lesser rise of 7%.

5.1.3 Flood depths

The inundation depths for each design storm are shown in Figure 5.3.

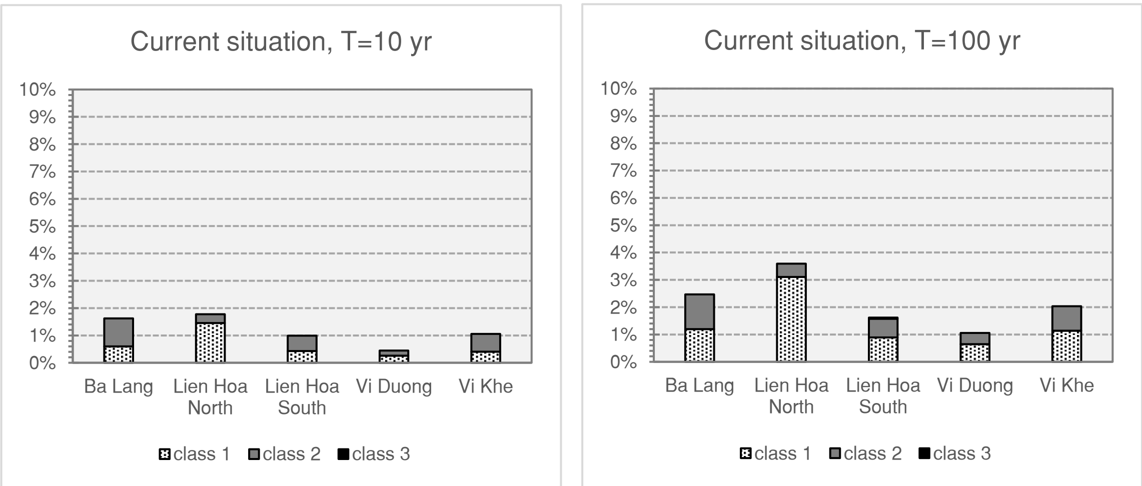
Figure 5.3 Maximum ponding depths in the current situation (high tide scenario)



5.1.4 Urban Flood Extent

The Urban Flood Extent (UFE) for the current situation is presented in Figure 5.4. The model results indicate that the UFE currently ranges between 1% and 2% for a T=10 year rainfall event. For a T=100 year rainfall event, the extent of urban flooding approximately doubles.

Figure 5.4 Urban Flood Extent in the current situation (high tide scenario)



5.2 Required storage in design scenarios

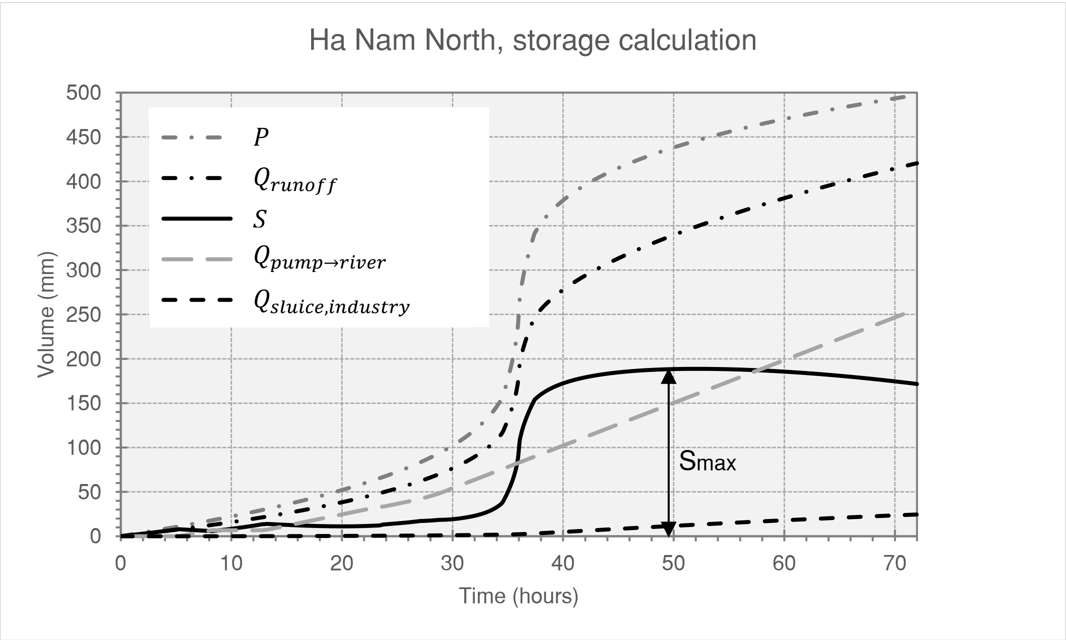
The projected developments result in an increase in paved surfaces, leading to more and faster runoff to the open channels. This necessitates a reassessment of the existing urban drainage system to handle the increased runoff effectively. Chapter 4.3 and 4.4 discuss the design principles and criteria for the urban drainage system, including the incorporation of sustainable urban drainage solutions. This chapter will go into the implications for urban flooding by calculating the required storage capacity to manage the rainfall generated by the design storm. This is done by utilizing the detailed hydrodynamic model.

5.2.1 Scenario 1

The first design scenario considers the future drainage system including the projected pumping stations. The storage that is necessary in the northern section of Hà Nam polder to prevent urban flooding is calculated in Figure 5.5. The contents of this graph are explained below:

- The flows coming into the Hà Nam canal system are: Q_{runoff} and $Q_{sluice,industry}$, the latter is the sum of all flows coming into this polder section through the industrial sluices
- $Q_{pump \rightarrow river}$ is the outgoing flow through the pumping stations.
- The storage S is the sum of all inflows and outflows for each timestep.
- The maximum storage value S_{max} during the event is the storage that is needed to fulfil the design requirements.

Figure 5.5 Storage calculation for Hà Nam North in design scenario 1



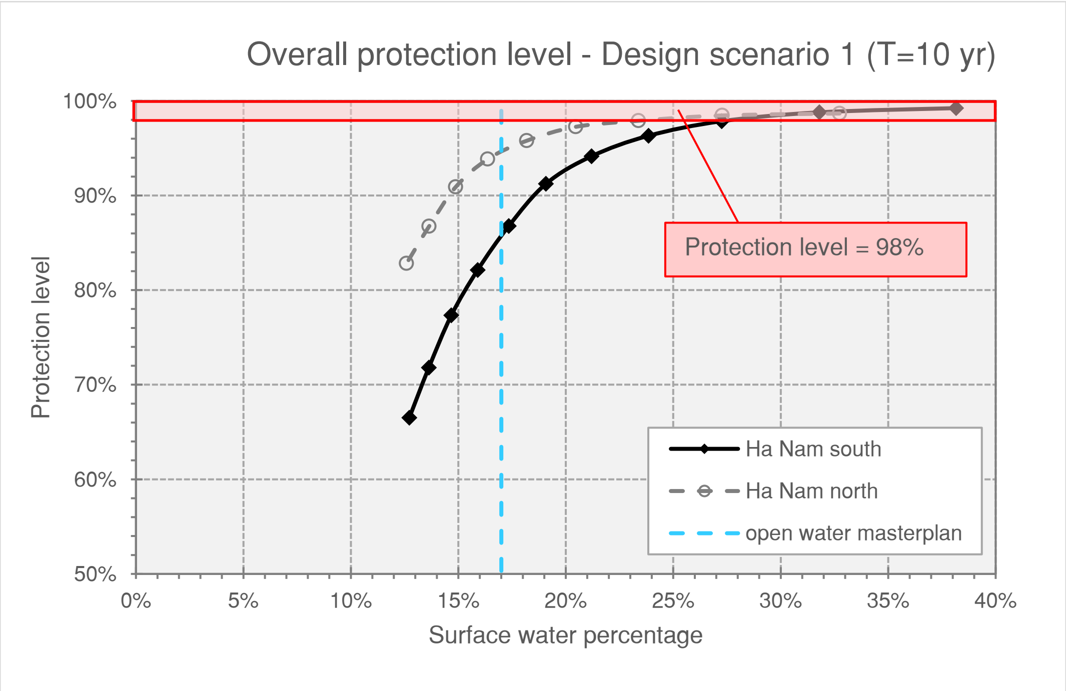
The required storage in the two main polder sections of Hà Nam in design scenario 1 is given in Table 5.1.

Table 5.1 Storage results for design scenario 1

		Polder		
Description	**Unit**	**Ha Nam South**	**Ha Nam North**	**Symbol**
Total area	ha	894.3	1565.5	A_{tot}
Maximum storage	mm	215.8	188.7	S_{max}
	m^3	$1.93 \cdot 10^6$	$2.95 \cdot 10^6$	

According to the masterplan, the anticipated open water percentage in the future scenario is set at 17%. The maximum increase in water level, denoted by dHmax, is a critical factor influencing the probability of urban flooding. Given the varying elevations of buildings in Hà Nam, the protection levels will differ for each community. To align with current flood extents, a minimum protection level of 98% is desired, ensuring that no more than 2% of buildings in each community are flooded during the design storm. Figure 5.6 shows the amount of protection as a function of the open water percentage for all communities in the northern and southern section of the main polder Hà Nam.

Figure 5.6 Protection level as a function of the open water percentage for design scenario 1



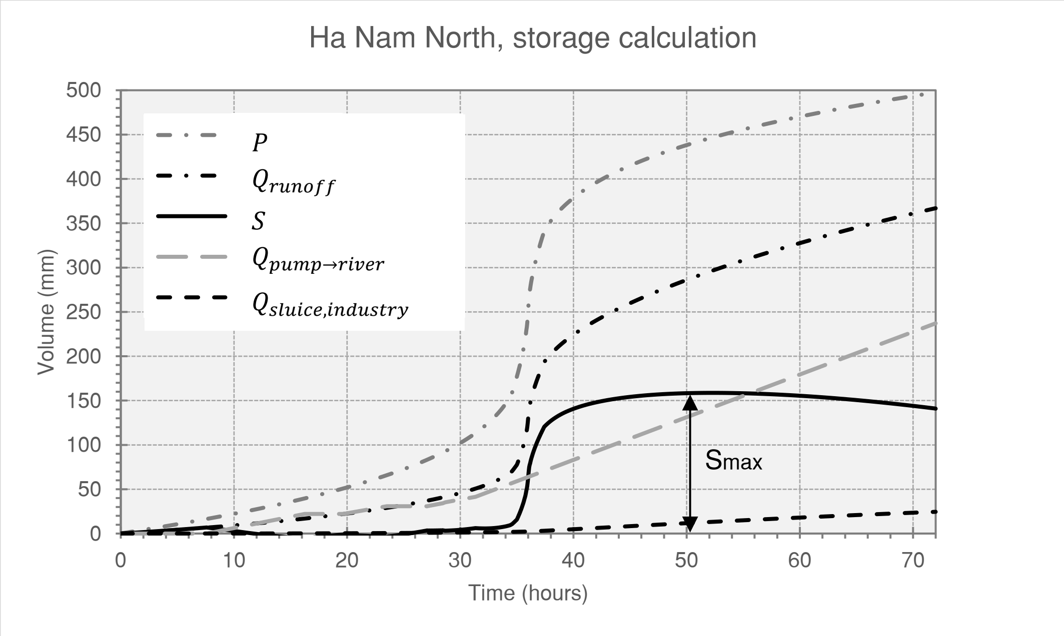
With an open water percentage of 17%, the anticipated protection levels in Hà Nam polder are estimated to reach approximately 85% and 95% for the southern and northern sections respectively. Chapter 5.3 will delve further into the calculated urban flood extents that are derived from the 1D/2D calculations.

5.2.2 Scenario 2 (SUDS)

This chapter examines the effects of adaptation measures on the drainage design of the Hà Nam polder. In design scenario 2, the amount of rainfall entering the canal system is reduced due to vegetated swales within the residential development zones, leading to decreased surface runoff

Q_{runoff}. Excess water in the open canals can overflow into designated park floodzones instead of spilling directly into built-up areas. Consequently, the maximum storage S_{max} refers to the total storage capacity required within both the open canals and park floodzones that is required to prevent urban flooding. The dynamic storage calculation result is shown in Figure 5.7.

Figure 5.7 Storage calculation for Hà Nam North in design scenario 2



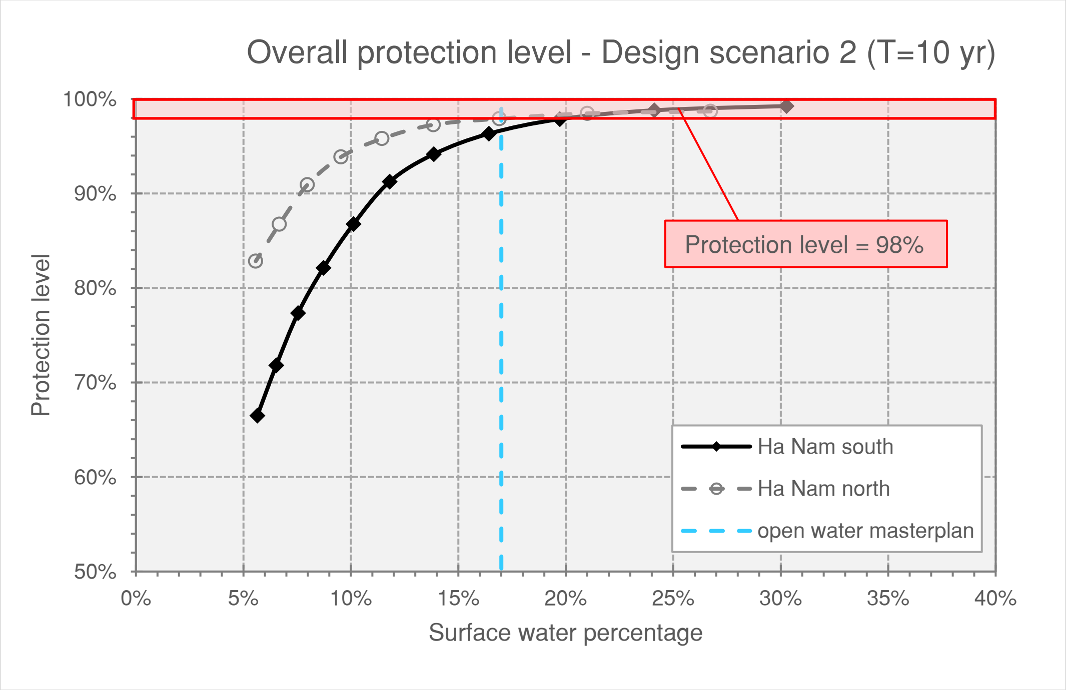
The storage calculation for the open channels and adaptation measures is summarized in Table 5.2.

Table 5.2 Improved storage calculation for Hà Nam polder

		Polder		
Description	**Unit**	**Ha Nam South**	**Ha Nam North**	**Symbol**
Total area	ha	894.3	1565.5	A_{tot}
Maximum storage	mm	176.4	158.7	S_{max}
	m^3	$1.58 \cdot 10^6$	$2.48 \cdot 10^6$	
Vegetated swales				
-Total storage	mm	55.4	54.3	S_{swale}
-Effective storage	mm	24.6	24.1	SE_{swale}
Total storage	mm	231.8	213.0	$S_{max} + S_{swale}$

The required storage capacity within the open canals and park floodzones is 176.4 mm for Hà Nam South and 158.7 mm for Hà Nam North. Considering an open water percentage of 17% and the implementation of park floodzones, the overall protection level for both sections of the polder is calculated. The results are shown in Figure 5.8.

Figure 5.8 Protection level as a function of the open water percentage for design scenario 2



In design scenario 2, the overall protection levels in Hà Nam approach the desired level of 98%. This means that the calculated flood extents resulting from the 1D/2D model should roughly approach 2%. In chapter 5.3 the calculated urban flood extents will be discussed.

5.3 Flood risk design scenarios

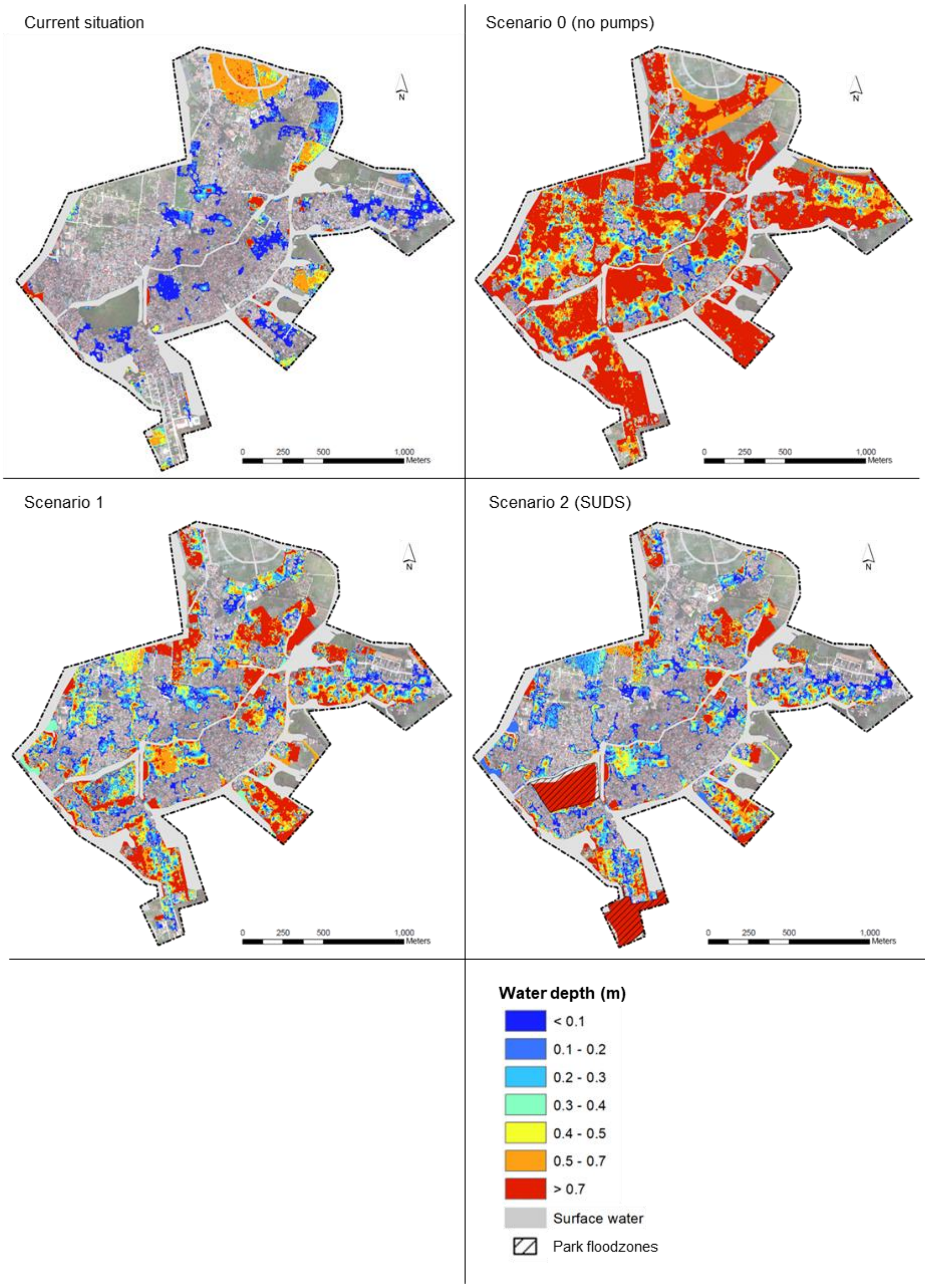
In this chapter the results of flood risk analysis for the future development plan are presented.

5.3.1 Flood risk during high tide

Figure 5.9 presents the inundation depths in the Ba Lang community during a T=100 year rainfall event. The figure illustrates that inundation depths increase significantly in scenario 0 compared to the current situation. This underscores that existing communities will face a significantly higher risk in the future scenario. In Scenario 1, flood depths decrease due to the presence of pumping stations. In Scenario 2, flood depths reduce further as a result of the implemented adaptation measures.

All inundation maps can be found in Appendix A.

Figure 5.9 Maximum inundation levels in Ba Lang during rainfall T=100



T=10 year rainfall event

The following text discusses the Urban Flood Extent (UFE) for the T=10 years design storm. Figure 5.10 starts off by showing the increase in UFE for the future scenario in which no additional measures inside the drainage system have been undertaken. The overall UFE for Hà Nam increases from 1% to 56%. This result underlines how sensitive the existing communities are to the projected changes in topography and landuse.

Figure 5.10 Urban Flood Extent during rain event T=10 for scenario 0

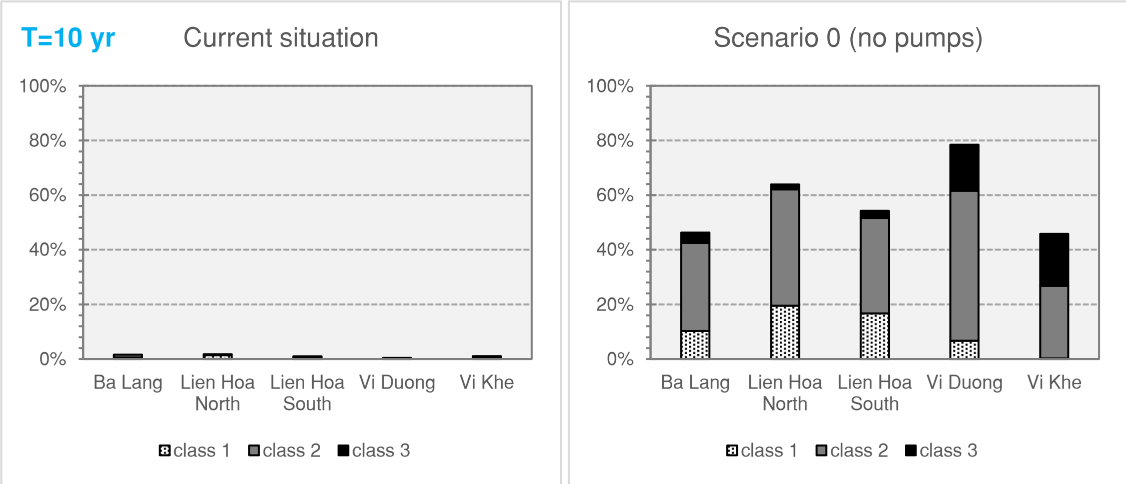
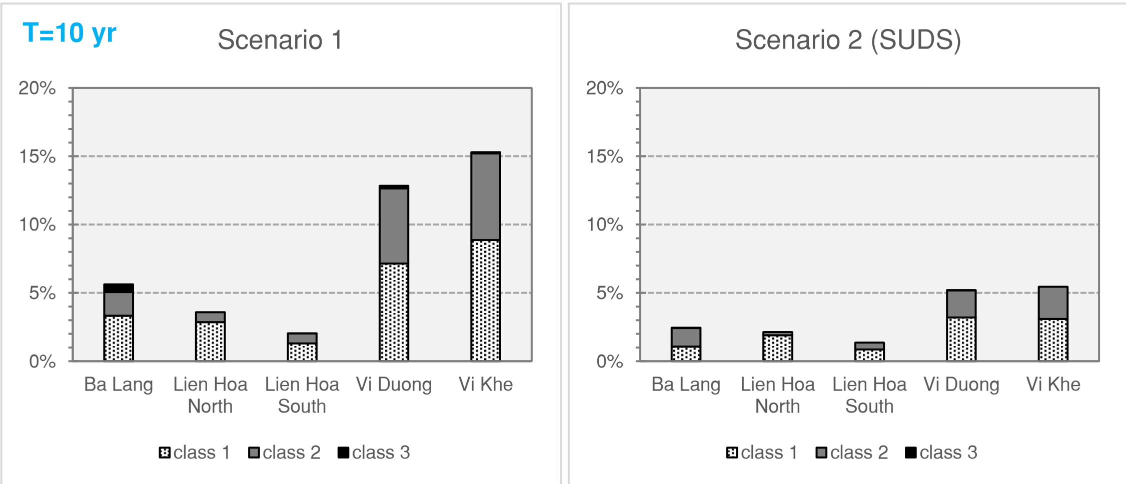


Figure 5.11 continues by showing the UFE for design scenarios 1 and 2. Applying the recommended pumping stations to the future scenario reduces the flood extents tremendously. The UFE per community decreases from 40-80% to 3-15%. The communities Vi Duong and Vi Khe are most vulnerable, and experience urban flood extents of 13 and 15% respectively. After applying the vegetated swales and park floodzones (scenario 2) the UFE decrease to 5% for Vi Duong and Vi Khe. The overall UFE decreases from 7% to 3%.

Figure 5.11 Urban Flood Extent during rain event T=10 for scenario 1 and 2



T=100 year rainfall event

The following text discusses the results for the T=100 year rainfall event. Figure 5.12 presents the Urban Flood Extents (UFE) for both the current situation and after implementing future developments in the 1D/2D model. The UFE per community increases from less than 4% to between 50% and 90%. Compared to the T=10 year rainfall event, the number of extremely affected buildings (class 3) increases significantly.

Figure 5.12 Urban Flood Extent during rain event T=100 for scenario 0

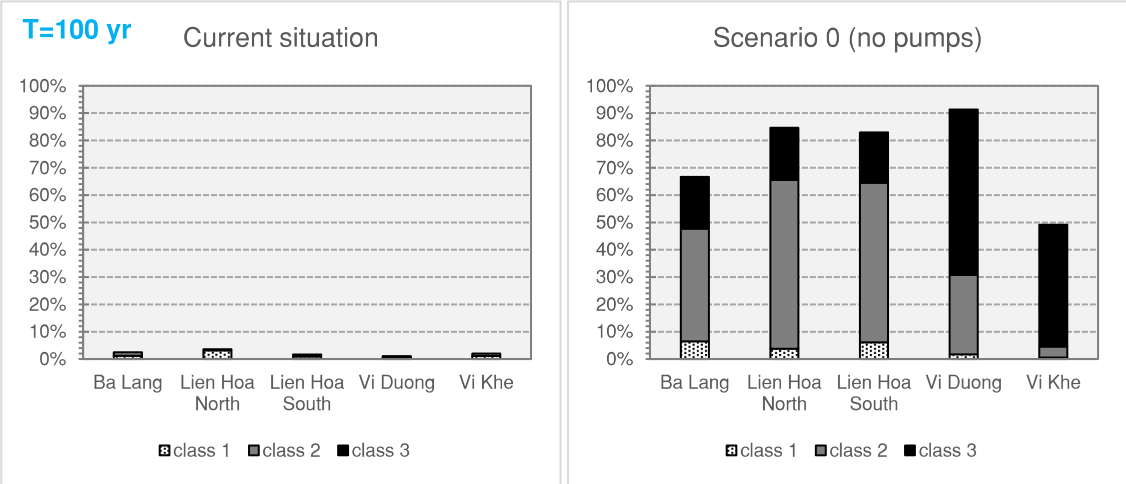
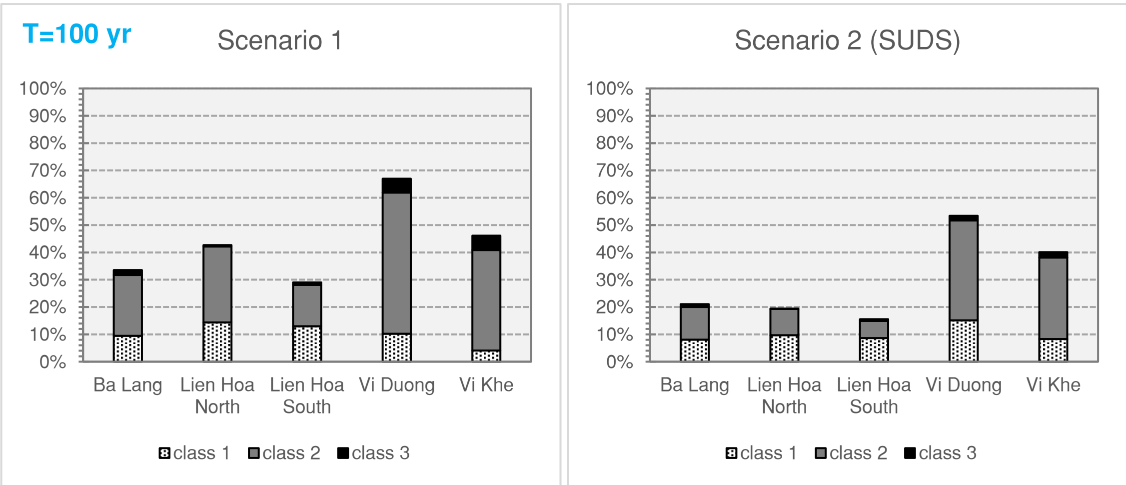


Figure 5.13 shows the UFE for scenario 1 and 2 for the T=100 year rainfall event. The findings are summarized below:

- Scenario 1: The implementation of pumping stations reduces the extent of urban flooding, particularly for the number of severely affected (class 3) buildings. The UFE decreases from 50-90% to 30-70%. However, the impact of pumping stations on urban flooding is less pronounced compared to a T=10 year rainfall event.
- Scenario 2: The results indicate that the Urban Flood Extent (UFE) decreases further after the implementation of adaptation measures. In Hà Nam, the overall UFE decreases from 41% in scenario 1 to 28% in scenario 2. This means that even after implementation of SUDS, there remains a substantial flood risk during the T=100 year rainfall event.

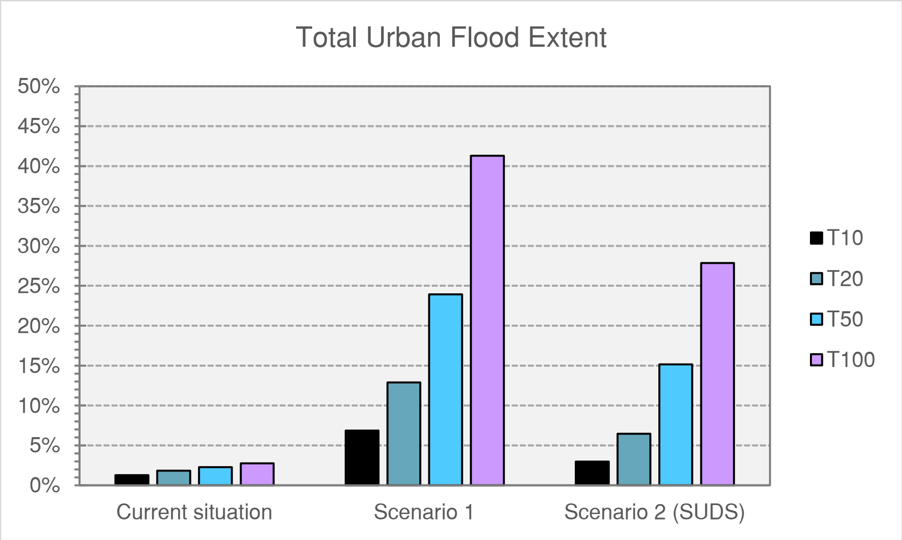
Figure 5.13 Urban Flood Extent during rain event T=100 for scenario 1 and 2



Total UFE for all design storms

Figure 5.14 summarizes the results of the design scenarios by showing the total UFE for each design storm. The results indicate that both scenario 1 and scenario 2 result in larger flood extents compared to the current situation during the design storms. In the SUDS scenario, the total UFE reaches 3% during the T=10 year rainfall event, whereas in scenario 1, the UFE is 7%. The impact of SUDS on the urban flood extent remains evident during more extreme rainfall events. However, the total UFE in the SUDS scenario is still significantly higher compared to the current situation.

Figure 5.14 Summary total Urban Flood Extents for each design storm

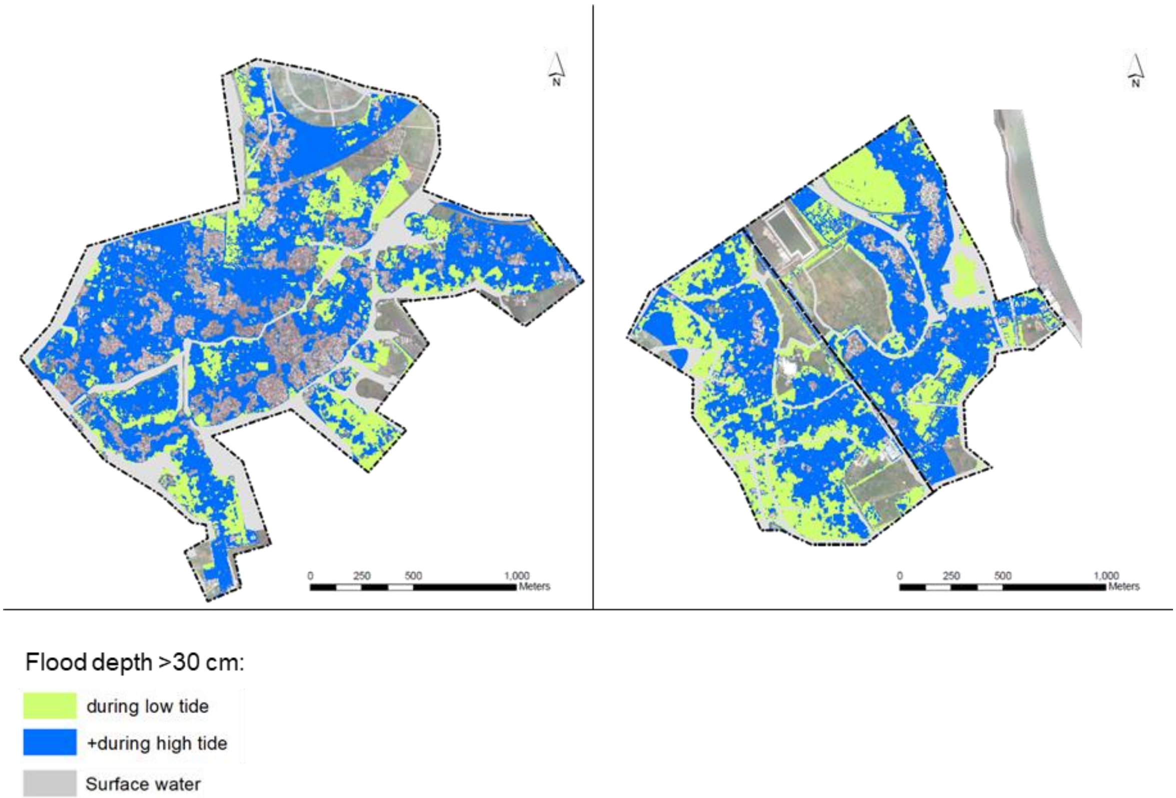


5.3.2 Flood risk during low tide

This paragraph discusses the Urban Flood Extent (UFE) in the event of heavy rainfall during low tide. In this case, the sluices that connect the Hà Nam canals to the rivers are opened during the rainfall peak.

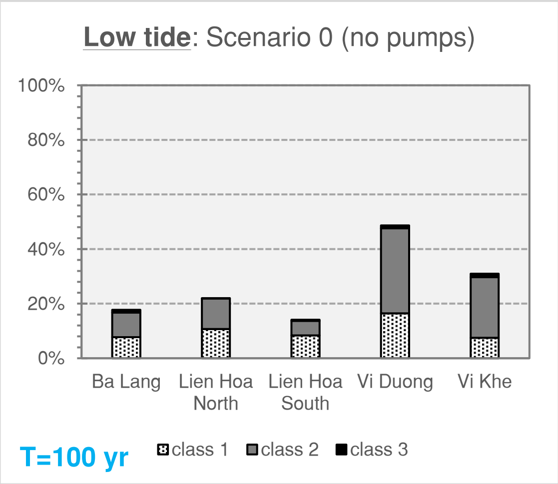
Figure 5.15 illustrates the difference in flood depths between the high tide and low tide case for scenario 0 (projected developments without pumping stations). The figure highlights areas in which the flood depth of 30 cm is exceeded.

Figure 5.15 Inundation depths at low tide versus high tide for T=100 year rainfall event for scenario 0



Based on the flood depths in Figure 5.15, the Urban Flood Extent was calculated for the low tide and high scenario. The total UFE in Hà Nam reduces in scenario 0 from 75% to 30% when sluice discharge is possible. The results for each community are summarized in Figure 5.16.

Figure 5.16 Urban Flood Extent during rain event T=100 for scenario 0 (low and high tide)



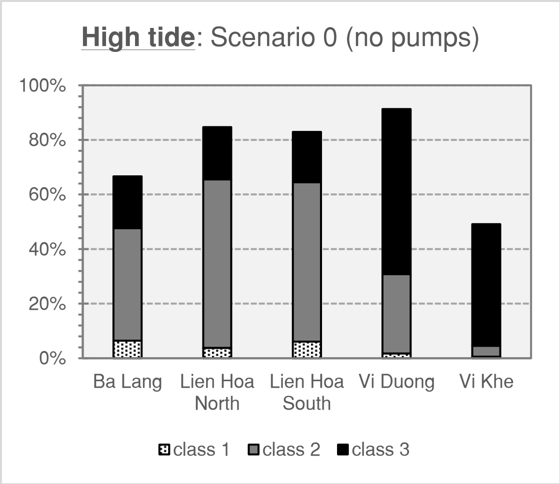
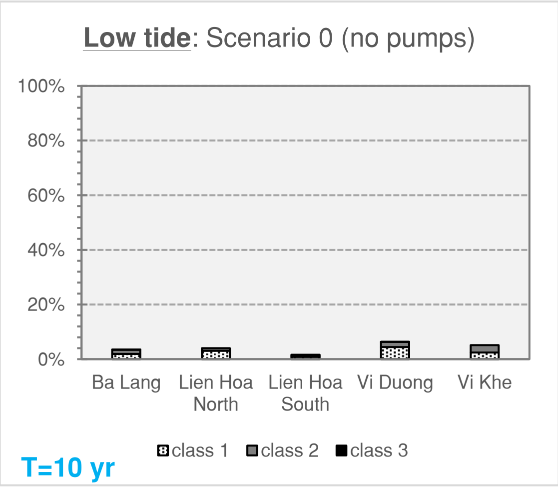
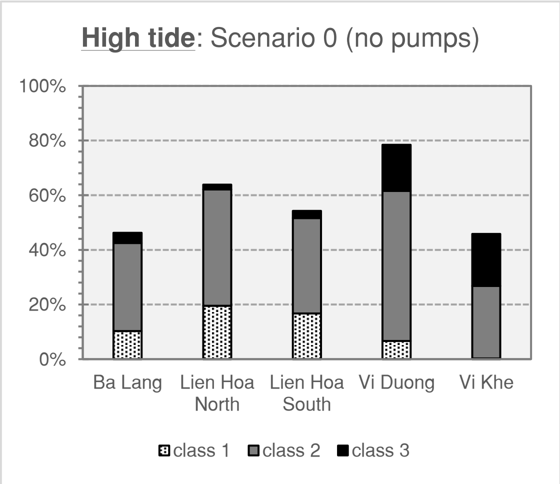


Figure 5.17 presents the UFE for each individual community during the T=10 year storm. The overall UFE is 4% during low tide, compared to 56% in the high tide scenario.

Figure 5.17 Urban Flood Extent during rain event T=10 for scenario 0 (low and high tide)





5.4 Model sensitivity analysis

Model sensitivity analysis involves changing the input parameters of the model to see if there is any change in the model's results. This study clarifies the effect of grid cell size on maximum flood volumes and inundation areas. Additionally, results are shown that illustrate the amount of 1D/2D double storage that leads to underestimation of the calculated flood volumes. Finally, the study investigates the effect of the rainfall-runoff definition on the Urban Flood Extent, particularly in relation to the parametrization of unpaved surfaces.

5.4.1 Grid cell size

As was shown in Figure 4.19 a grid size of 10 m will lead to model errors due to blurring of channel dikes. To illustrate the effect of this error the maximum flood volume and inundation area has been calculated for two cell sizes: 5 m and 10 m. Figure 5.18 contains the results.

Figure 5.18 Effect of mesh grid size on flood risk calculations

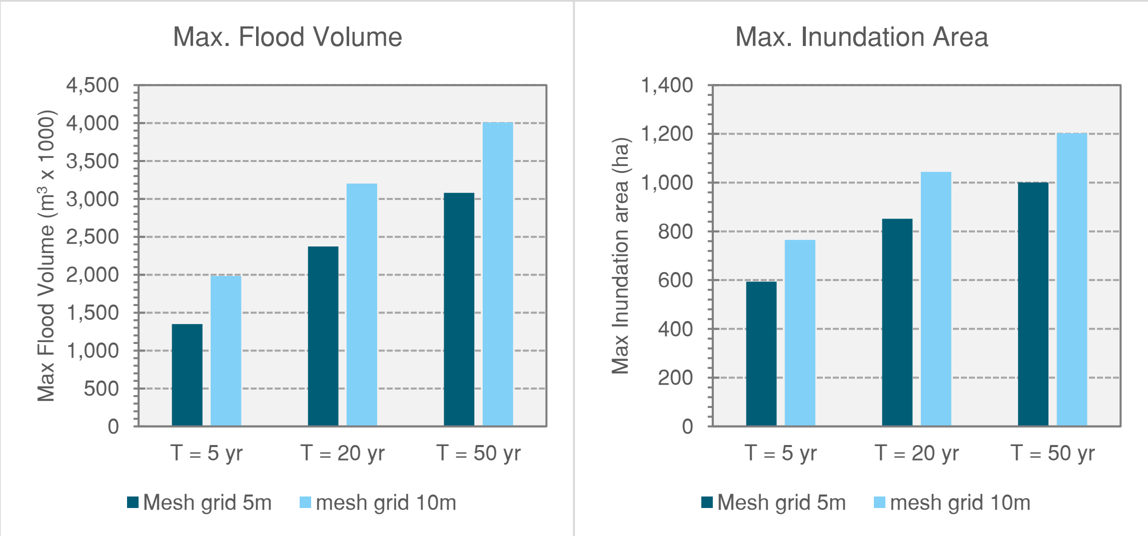
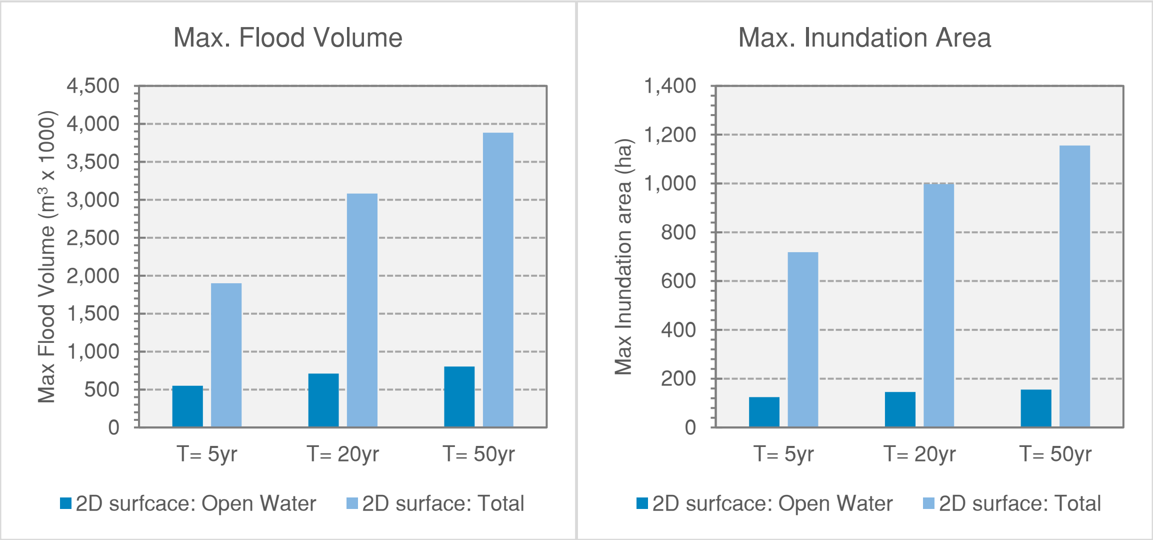


Figure 5.18 illustrates that flood volumes increase as the grid size of the 2D surface model becomes larger. This finding aligns with the observations in Chapter 4.1.3, which demonstrated that reducing grid resolution introduces model errors, particularly in accurately representing local elevations around open channels. One advantage of the 10 m grid is reduced computation time, with calculations taking approximately 1 hour, compared to around 6 hours when using a 5 m grid.

5.4.2 1D/2D double storage

In Figure 5.19 the effect of 1D/2D double storage is shown for three rainfall events within the model that represents the current situation. The graphs show the amount of water that is stored within the channels on top of the 2D-surface grid. This same value is also stored inside the 1D model. The total volume amounts to 20-30% of the total flood volume. Though, this is regarded as a significant contribution, it has not been solved due to software limitations. Solving this model error will not change the relative values of inundation volumes between different scenarios. In the model that is used to calculate the future scenarios the amount of double storage has been reduced to 10-15%, depending on the rain event.

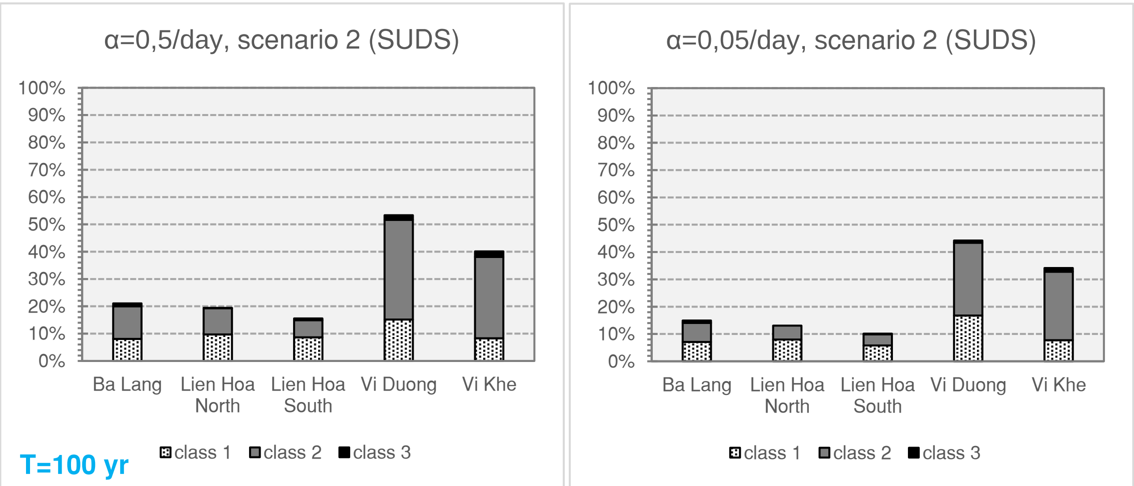
Figure 5.19 Effect of 1D/2D double storage on flood risk calculations (applicable to current situation)



5.4.3 Unpaved rainfall-runoff definition

In the design scenario the runoff contribution originated from unpaved surfaces is simplified using the "De Zeeuw-Hellinga" drainage formula. A reaction factor of 0.5/day was chosen. For grasslands that are not well drained, this value lies in the range 0.03-0.07/day. Choosing a lower reaction factor of 0.05/day decreases the maximum flood volumes, and thus the Urban Flood Extent (UFE), see Figure 5.20. The total UFE during the T=100 year design storm reduces in design scenario 2 from 28% to 21%.

Figure 5.20 Effect of unpaved reaction factor on the UFE



6

Discussion

6.1 Interpretation of the results

Current flood risk

Literature suggests that the combination of storm tide and heavy rain poses an additional threat concerning flood risk in coastal urban areas. Given this premise, it was hypothesized that pluvial flooding is occurring in Hà Nam under present conditions, and that the combined occurrence of heavy rainfall and elevated river levels intensifies the risk of pluvial flooding. The findings of this study revealed that the current urban flood extent in Hà Nam is less than 2%. Most stormwater in the existing towns is collected by means of large U-shaped gutters (see Figure 6.1). This type of structure is implemented to facilitate easy maintenance to prevent blockages. The implication of this is that it leads to discharge capacities that often exceed rainfall intensities during the design storms. The modelling study results also indicate that, in the present scenario, high rivers levels do not contribute to an increase in pluvial flood risk in Hà Nam. This can be explained by the fact that majority of the towns are situated at higher elevations. Canal overtopping does not pose a significant risk to many buildings, as the rice paddy fields will initially absorb the excess water. This suggests that even during a T=100 year rain event coinciding with high tide, the extent of pluvial flooding does not pose significant flood risks to the existing towns.

Literature suggests that sea level rise will result in an increased risk of flooding in coastal urban areas. This study offers insight into the probability of the event where the design storm coincides with the river level exceeding the polder level. This is critical because, in such an event, the area can only be drained by pumping stations, which have not yet been built. For the analysis, it was assumed that there is no dependence between heavy rainfall and high tide. Therefore the resulting probabilities show the probability of coincidence rather than the combined probability. The effect of sea level rise has been incorporated into this method, highlighting that the probability of both events occurring simultaneously is significant and cannot be ignored. This study has shown that the combined probability of high river levels and heavy rainfall will increase from 25% to 40% according to sea level rise predictions until 2050. For Hà Nam, sea level rise does not influence the probability of pluvial flooding in the built-up areas under current conditions. Furthermore, literature suggests that land subsidence will further increase the vulnerability of coastal regions to flooding. However, this study did not provide results to substantiate this statement.

Figure 6.1 Example of an U-shaped gutter in Hà Nam

Future flood risk scenarios

The problem statement emphasized that urban expansions in Vietnam and other regions in South-East Asia often occur in coastal zones already susceptible to flooding. The development of Hà Nam exemplifies this phenomenon. According to the Vietnam Country Climate and Development Report of 2022, there is insufficient emphasis on flood adaptation strategies. This research does not offer direct evidence to support this claim. The current state of the masterplan of Hà Nam offers information about future land use and terrain elevation on the neighbourhood scale. The masterplan does not outline plans for future stormwater management practices beyond the installation of pumping stations. According to (Haasnoot et al., 2019), three approaches can be taken to adopt flood adaption strategies for new developments: increased flood proofing, increased protection or planned retreat. Based on the masterplan, it is evident that Vietnamese authorities have chosen to enhance protection levels for the new development plots through land raising.

From the problem statement, this study expresses as a concern that no adaptation strategies will be implemented that benefit the existing communities. To address this issue, flood depths for future scenarios were calculated. Scenario 0 represents the condition where no floodproofing measures are implemented. The results of this scenario indicate that over 50% of the current population will face significant flood risk as a consequence of future development. Following the definitions outlined in (Haasnoot et al., 2019), this study proposes solutions in terms of floodproofing, which involve augmenting drainage storage capacity and installing pumping stations. In scenario 1, the effects of pumping stations on flood risk has been assessed for both low and high tide scenarios. In two of the five main communities, the urban flood extent reaches 15% in the high tide scenario. This underscores the necessity for additional measures to mitigate flood risk to levels comparable to the current situation. Scenario 2 addresses the lack of flood adaptation strategies and the utilization of Sustainable Urban Drainage Systems (SUDS). Scenario 2 considers the impact of floodable parks and vegetated swales on the remaining flood risk present in scenario 1. The measures are integrated with public green spaces to minimize losses in areas that generate financial revenue for the region. The results of scenario 2 indicate that flood risk in the existing communities remains higher compared to the current situation. Particularly during more extreme rainfall events, the urban flood extent increases significantly, reaching up to 25% for a T=100 year rainfall event. To increase the protection level to its current value would necessitate allocating more space for stormwater storage. This would however lead to conflicts with the proposed development plans.

6.2 Research implications

Implications for the current masterplan

The model results indicate that urban flood extents will be greater in future scenarios, especially during extreme rainfall events that occur less frequently than the T=10 year design storm. This implies that current residents of Hà Nam will face a higher risk of flooding, even after implementation of pumping stations and SUDS. This study propose two potential solutions to mitigate flood risk to current levels.

The first and most robust approach involves scaling back the projected developments. By preserving more rural land, the landscape can help absorb and manage stormwater, thereby reducing urban flooding during extreme rainfall events. Alternatively, instead of retaining rural land, constructing wetlands could be considered. Wetlands can replicate the current storage capacity while also enhancing water quality and supporting local ecology. These natural systems provide a sustainable and multifunctional approach to managing stormwater and improving the resilience of urban areas. These wetlands can be strategically located in areas prone to flooding, thus providing a natural buffer that can absorb excess water during heavy rainfall events.

A more intricate strategy would involve subdividing the area into smaller pumping zones. This would help prevent flooding in low-lying communities located by ensuring that each zone is managed according to its specific needs. However, this approach would require a more detailed design and extensive urban planning efforts to be effectively implemented.

Implementing any of these solutions would necessitate modifications to the masterplan. Given these considerations, this study suggests a careful reassessment of the masterplan, prioritizing the safety and well-being of current residents of Hà Nam. Additionally, the reassessment should account for the increasing frequency and intensity of extreme rainfall events to ensure long-term resilience and sustainability.

Implications on 1D/2D modelling

This study enhances the understanding of the utility of 1D/2D surface models in designing urban drainage systems for Vietnamese coastal areas. While previous research has mainly focused on the impacts of fluvial flooding, the findings presented here highlight the crucial need to consider the effects of new developments on pluvial flooding.

The complete polder design was implemented in the Delft3D FM software to calculate the required storage for the main polder of Hà Nam. There are several reasons why the use of a hydrodynamic model is crucial when considering the necessary storage in this study:

1. Time of concentration. This represents the duration it takes for runoff to travel from the furthest point in the catchment to the outlet. In urban environments, stormwater must be transported via drains before entering open canals, introducing a delay between precipitation and flow into the canals. After entering the canals, stormwater is conveyed to pumping stations. However, friction within the channels and culverts limits discharge capacity during peak flows. Consequently, the pumping stations cannot immediately drain the entire area. With respect to the design storm this causes the system to be partially loaded at the peak of the rainfall.
2. Storage and delayed runoff within unpaved areas. Due to the area's gentle slopes, unpaved surfaces are able to effectively retain water and gradually release it into the open canals. This delayed runoff can significantly alter the overall hydrological balance by providing natural storage and reducing peak flow rates during heavy rainfall events.
3. Unsteady flow through sluices. In addition to local rainfall, the main polder of Hà Nam receives stormwater from the industrial polders that are connected by means of sluices. The discharge through these sluices is dictated by the total head difference between the upstream and downstream channel. As this head difference varies over time, the model can account for these fluctuations, providing a more accurate representation of the system's behaviour.

Other flood modelling studies in Vietnam have revealed a lack of sufficiently detailed information necessary for conducting pluvial flood risk analysis. Simulating pluvial flooding requires the incorporation of drainage infrastructure data, including cross-sectional data of canals, street gutters and pipes and information about the operation of flow-regulating structures. According to the model sensitivity analysis in this study, employing a low resolution for the 2D grid implies that topographic features, such as elevated roads are not accurately represented. This study demonstrates that the 2D grid size should ideally be 5 meters or smaller, a finding consistent with (Shen et al., 2019). This does however implicate that topographic surveys with a similar resolution should be available for these type of modelling studies.

In addition to drainage infrastructure data, incorporating water level monitoring data can significantly enhance the accuracy of pluvial flood modelling. In Hà Nam, monitoring of the local water system commenced just before the start of this study. During the monitoring period there was only one rainfall event recorded that lead to significant rise in water levels. This means that model performance could only be evaluated for a single rainfall event. In the case of Hà Nam more than half of the area will see a change in land use, which does mean that less focus is needed on current system behaviour. For other studies this might not be the case. As far as this research extends, it is unclear to what degree the hydraulic performance of urban water systems is currently being monitored in other areas of Vietnam.

6.3 Research limitations

This chapter addresses the limitations of the 1D/2D hydrodynamic modelling study. Uncertainty was encountered in parameterizing the rainfall-runoff processes. Additionally, application of the 2D surface model presented several challenges. This chapter also examines some limitations of the design methodology and discusses the selection of the flood risk indicator.

6.3.1 Rainfall-runoff model

Current scenario

The rainfall-runoff model describes the processes that occur from the moment rainwater hits the surface until it enters the canals. To check the validity of this model, the calculated water levels at three of the exit points of the system were compared with field measurements during a single 3-day rainfall event. It is concluded that during this event the increase in canal water level is mostly caused by runoff from the built-up areas. The canals also receive water from the rural land through a combination of groundwater flow and overland flow. Relying on a single evaluation event makes it challenging to identify a reliable set of parameters for the rainfall-runoff model. This challenge is compounded by seasonal variations that influence the runoff processes. For instance, seasonal variations influence the inundation extent in rice fields, which in turn affects the volume of runoff flowing into the drainage canals. Runoff coming from the rural land was simplified by lumping all runoff process into one generalized delay factor. The uncertainty surrounding rainfall-runoff parameterization of the rural land does not diminish the finding that the risk of pluvial flooding in built-up areas is currently minimal.

Future scenarios

Similar to the current scenario, the rainfall-runoff processes within the future land use scenario of Hà Nam have been simplified. The “De Zeeuw-Hellinga” drainage formula was used to simplify runoff processes in unpaved areas. This methodology, commonly utilized in the Netherlands for estimating runoff in polder areas serviced by pumps, was adopted in this study with a reaction factor of 0.5/day. This factor is deemed suitable for well-drained unpaved areas served by drainage pipes or canals. Conversely, unpaved surfaces lacking adequate drainage can feature a reaction coefficient ten times lower. Sensitivity analysis shows that using a reaction factor of 0.05/day reduces the urban flood extent. This implies that the results in the design scenario could indicate an overestimation of flood risk. It was determined that this finding does not impact the overarching conclusions of this study.

The effect of vegetated swales on flood risk reduction was calculated as part of the adaptation measures design. These swales serve to capture stormwater and gradually releasing it into the canal system by means of drainage pipes. However, the design assumed no infiltration within the vegetated swales during the 3-day rainfall design event. In reality, some rainfall does infiltrate in the swales and is transported to the canals via drainage pipes. Neglecting this flux results in a loss of storage, as the swales become partially filled before the rainfall peak. Consequently, the flood peak reduction provided by vegetated swales is underestimated in this modelling study.

6.3.2 2D surface model

2D grid considerations

The 1D model, which encompasses all objects within the urban drainage system, was integrated with a 2D surface model to compute the inundation levels in the urban areas. Sensitivity analysis revealed the significance of the cell size in the 2D surface grid. While excessively detailed cell sizes are unnecessary for the predominantly flat terrain of Hà Nam, the grid must accurately capture critical features such as dikes and elevated roads to estimate flood areas correctly. In urban settings, streets and building perimeters influence floodwater flow, necessitating a finer 2D grid. When considering the size of the 2D grid, it is important to take into account computational time as well. In this study a trade-off between topographic accuracy and computational time was found by selecting an uniform grid cell size of 5 meters. Although employing a more detailed grid in areas with significant elevation differences and less detailed grids in extensive flat areas could potentially enhance calculation times, software limitations prevented its implementation. This constraint does not compromise the conclusions drawn from this research.

This study utilized a high-resolution topographic survey, yielding a digital elevation model with a resolution of 0.5 meters. It was anticipated that such detailed information would enhance the accuracy of the 2D-surface flow simulations within the built-up areas. However, Vietnamese urban areas are characterized by dense building clusters, obscuring much of the actual terrain in aerial topographic survey data of Hà Nam. Due to lack of real-terrain measurements inside the towns, it was decided to exclude buildings from the 2D grid. Consequently, the flow dynamics are not influenced by the geometry of streets and alleyways, leading to a margin of error since, in reality, the flow would be affected by building edges. Utilizing ground-level topographic surveys would provide more dependable terrain elevation data. While incorporating buildings into the 2D grid is estimated to enhance the reliability of the results, it is anticipated that the relative difference in urban flood extent between each scenario would remain consistent.

Double storage

To facilitate the spillage of water from the 1D canals onto the 2D surface grid, the open water bodies were incorporated into the grid. Consequently, water accumulates on top of the grid that represents the canals. This results in the retention of the same volume of water within both the 1D channel and the corresponding location on the grid, a phenomenon termed "double storage" in this study. During the T=10 years rain event, this leads to a 10% underestimation of flood volumes. The proportion of double storage increases to 15% in the T=100 years rain event, which is deemed to be significant. Eliminating this model error would cause the urban flood extent to become larger. This error is consistent across all model scenarios, ensuring that the relative difference in flood volume between each scenario remains valid.

6.3.3 Design method

Design storm

Arguably, the most crucial input for the design process is the selection of the design storm event. Rainfall amounts are derived from Gumbel extreme value analysis conducted on 50 years of measurement data in Bai Chay, Ha Long. The T=10 years event, spanning a duration of 3 days, served as the basis for determining necessary storage and calculating urban flood extents. The key assumption is that the return period of this rainfall event is equal to the return period of the calculated water levels. This is actually not the case. An improved method would be to perform a continuous simulation using hourly rainfall measurement data that is available for at least 50 years. This would yield a continuous set of required storage over time. Extreme value analysis can be performed on the calculated volumes necessitated within the system throughout the chosen timeframe. It's important to acknowledge that such an analysis would be feasible solely in a 1D modelling framework, owing to computational constraints. Consequently, this study opted against conducting this analysis.

Polder water levels

The normal water level in the canals was selected to closely match current management practices. Lowering this water level would inevitably impact groundwater levels, potentially leading to undesirable outcomes such as increased subsidence and seepage, thereby increasing vulnerability to flooding and compromising water quality. Setting the maximum water levels in the canals is critical, as it directly impacts the available storage capacity before water overflows onto the surface. Rather than stating the maximum water level, this study presents the overall protection level of buildings with respect to projected open water percentage. To match with current flood risk it was decided to pursue an overall protection level of 98%. However, it's crucial to emphasize that the determination of maximum water levels should be a collaborative effort involving local stakeholders. This same principal also applies to selecting the normal water level, ensuring accurate alignment with the specific requirements and dynamics of the area.

Socio-economic context

The applicability of the design presented in this research is constrained by the lack of insight regarding current maintenance and operational practices in Vietnam. This relates to the long-term effectiveness of flood reduction measures, such as vegetated swales, recommended in this study. Understanding how these measures perform over their lifecycle is vital for sustainable development. Their performance is influenced by how they are managed by local water authorities and the behaviours of the local community toward these facilities. For instance, the effectiveness of vegetated swales relies on maintaining sufficient infiltration capacity to ensure rainfall is effectively transported to the ground. Any alteration by the local population, such as construction of buildings or pavements, could significantly diminish performance. It is therefore crucial that the local population recognizes the importance of these measures and treats them with care. Similarly, flow-control sluices, designed to separate industrial expansions from residential areas, are designed for operation without the need for active control. This research acknowledges the difficulty of performing active sluice control, which would involve regularly opening the sluice gates and closing them prior to heavy rainfall. However, passive operation does not absolve the need for maintenance. To ensure optimal functionality, local engineers should actively monitor the performance and physical condition of these sluices.

In summary, while this research proposes flood risk reduction solutions with maximum performance, considering socio-economic factors, as illustrated, is essential for long-term benefits to the area. Although this study does not delve into the socio-economic context, it recognizes its importance in sustainable flood management.

6.3.4 Choice of flood risk indicators

In this research, the effectiveness of design measures is evaluated by assessing the extent of inundation and its impact on buildings, referred to as the “Urban Flood Extent” in this study. While other potential indicators exist, their incorporation varies based on the specific context. Other possible indicators involve the addition of flood duration (Scheiber et al., 2023), flood velocities (Le Binh et al., 2019) and economic damage (Kefi et al., 2018; Scussolini et al., 2017; Van Dau et al., 2017; Lasage et al., 2014; Giang et al., 2009). Firstly, flood duration is an important factor determining damage and nuisance. In the case of Hà Nam, flood duration is influenced by factors such as pumping capacity, river sluice discharge, and storage. However, it was decided not to include flood duration in the analysis, as it remains relatively consistent across different scenarios due to the unchanging operation of river sluice gates and pumping stations. Additionally, high flow velocities can result in increased damage to objects, underscoring the importance of their consideration in flash flood studies. In the case of Hà Nam the flow velocities on the surface are relatively low, rendering this indicator less applicable for consideration. Finally, economic damage is a complex indicator because it is influenced by various factors including the type of object affected, water level, flood duration, and flood velocity. Due to the complexity involved, estimating economic damages fell beyond the scope of this study. However, subsequent recommendations in the following paragraph aim to address this aspect.

6.4 Recommendations for future research

Cost-benefits of flood mitigation measures

This research has shown that adopting adaptation measures can decrease urban flood extents. However, such measures necessitate financial investment. Over its lifetime, this investment could be recouped through reduced damage during severe weather events compared to a scenario lacking adaptation measures. The relationship between the costs and benefits regarding this matter has not been calculated and could be part of future research. To initiate this analysis, a depth-damage curve can serve as a useful tool. This is a function that relates flood depth to expected damage:

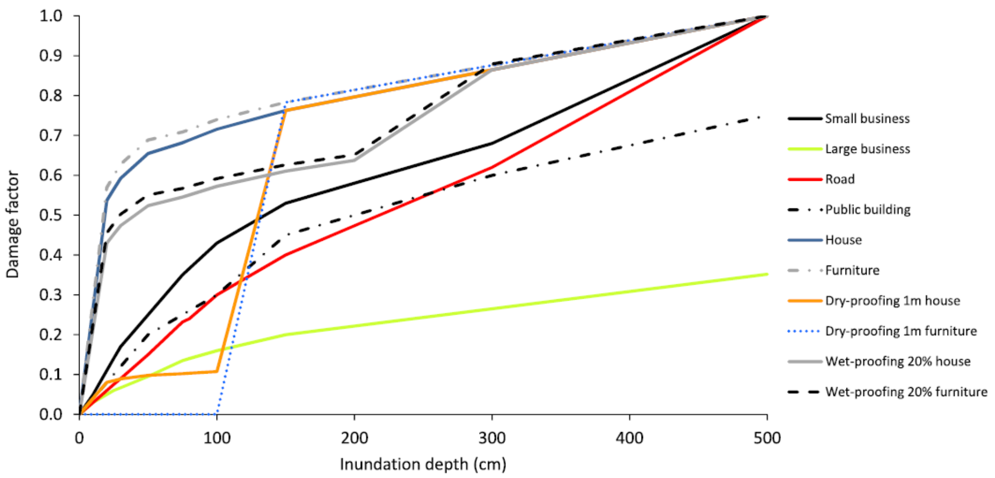
$$\mathrm{ED} = \alpha(\mathrm{d}) \cdot D_{max}$$

$$\mathrm{ED} = \text{Economic damage (USD\$/m}^2\text{)}$$
$$\alpha(\mathrm{d}) = \text{damage factor (-)}$$
$$\mathrm{D}_{\mathrm{max}} = \text{maximum damage value (USD\$/m}^2\text{)}$$

Figure 6.2 shows a set of depth-damage curves developed by (Lasage et al., 2014) for HCMC by means of a household survey in districts that were exposed to flooding in 2011. Other depth-damage curves were made or adopted from literature in Vietnamese case-studies:

- (Scussolini et al., 2017) used a damage function for flood analysis in HCMC that was developed by (Klijn et al., 2007) for Dutch design guidelines. (Chen, 2007; Giang et al., 2009; Van Dau et al., 2017) performed flood risk analysis in Central Vietnam and used similar depth-damage curves.
- (Kefi et al., 2018) constructed a depth-damage function for Hanoi based on interviews regarding extreme pluvial flooding in 2008. This function looks at the damages on the neighbourhood scale, rather than for individual houses.

Figure 6.2 Depth-damage curves applicable to areas in HCMC (Lasage et al., 2014)



Adopting an established depth-damage curve to Hà Nam could show which measures are most effective in mitigating damages resulting from pluvial flooding. However, it's important to acknowledge that household conditions in Hà Nam may differ significantly from those used in other studies, necessitating careful consideration. Furthermore, for a comprehensive analysis, the construction and maintenance costs associated with each measure must also be factored in.

Water quality effects of flood mitigation measures

Throughout 2023, water samples have been taken in Hà Nam that show high levels of organic matter and suspended solids. Many canals are considered to be heavily polluted. Figure 6.3 illustrates examples of poor water quality observed during the field visit. Vietnamese authorities have recognized the urgency of separating wastewater from drainage canals wherever feasible. Inside the new development plots, wastewater will be collected by a separate wastewater system and transported to one of the planned treatment plants. For the existing towns the drainage system will generally be kept in place, however altered to minimize wastewater entering the open canals by constructing combined sewer overflows. The existing network will be connected to the new wastewater transportation system by either gravity-flow pipes or pumping stations. Small-scale treatment facilities will be installed in houses that are far away from built-up areas.

An additional study should be done on how to implement these design principles in practice. Combined with a modelling study, the effects of these measures on the surface water quality should be simulated to find the best optimal design solutions regarding the wastewater transportation system. This extended water quality study should also take into consideration the adaptation measures that have been suggested in this study.

Figure 6.3 Examples of poor water quality that were observed in Hà Nam during a field visit

7

Conclusion

The objective of this research is to explore the integration of pluvial flood risk assessment into urban development strategies, with a specific focus on coastal regions in Vietnam. This study investigates the urban drainage infrastructure and development projections within Hà Nam Island using a 1D/2D hydrodynamic model. Situated entirely amidst rivers affected by tidal influence, Hà Nam is shielded from high river levels by a dike system. The drainage canals within Hà Nam are linked to the rivers through gated sluices. During high tide, river water would flow into the canal system. Consequently, the sluice gates are typically shut and are manually opened to discharge excess water following rainfall events. Therefore, precipitation must be retained within Hà Nam during high tide. This research reveals that the probability of heavy rainfall coinciding with high tide is expected to increase due to rising sea levels. At present, this does not elevate the risk of pluvial flooding within Hà Nam. The primary reason is that the storage capacity of the rural land, predominantly comprising rice paddy fields and fishery ponds, is sufficient to prevent canal water from overtopping in the urban areas.

Analysis of the projected masterplan of Hà Nam reveals that 70% of the rural land will have been replaced by residential and industrial plots by 2040. Furthermore, there are plans to expand the area to accommodate industrial zones, which will contribute to increased runoff. According to the findings of the modelling study, it is concluded that in the high tide scenario, the projected developments put more than half of the existing communities at significant risk of pluvial flooding. Government officials aim to mitigate this flood risk by constructing several pumping stations. In addition, they supplied that the drainage system should be designed as such that canals will not overtop during a T=10 year rainfall event. The masterplan provides that roughly 17% of the developed areas will be allocated for surface water. Additionally, this modelling study takes into account that a large part of the industrial development plots will be segregated by means of passively-controlled sluices. This strategy increases stormwater storage capacity while maintaining the desired level of development. Despite the implementation of these measures, including the projected pumping stations, approximately 7% of buildings in Hà Nam remain susceptible to inundation during the design event. This indicates that the current design falls short of meeting the design requirements. Moreover, the total urban flood extent reaches 40% during the T=100 year rainfall event, significantly higher than the current condition where it remains below 2%. Consequently, residents in Hà Nam may face more frequent flooding than they currently experience.

To mitigate flood risk, this study concentrated on integrating flood mitigation measures into the Hà Nam masterplan, drawing insights from the Water Sensitive Urban Design program of the Asian Development Bank and the ABC-water program from Singapore. As a result, part of public greenspaces that are established in the masterplan have been designated as inundation zones. Half of the greenspaces within the residential development plots have been reserved for vegetated swales. The modelling study demonstrates that vegetated swales are effective in reducing the flood peak by intercepting rainfall before it enters the canal system. Park floodzones serve as an effective means of enhancing storage capacity. These measures help to reduce the urban flood extent to levels comparable to the current situation during the T=10 year design storm. However, calculations show that their effect diminish as rainfall events get more extreme. For example, 25% of Hà Nam will still be vulnerable to flooding during a T=100 year rainfall event. While this represents an improvement over the base scenario, it still means that current residents of Hà Nam will continue to experience increased flooding in the future, even with additional adaptation measures implemented within the constraints of the current masterplan.

The area remains vulnerable even after implementation of pumping stations, SUDS and segregated industrial zones. This study proposes two potential solutions to reduce flood risk to current levels. The most robust approach involves scaling back the projected developments, thereby preserving more rural land to help mitigate urban flooding during extreme rainfall events. Alternatively, instead of retaining rural land, constructing wetlands could be considered to replicate current storage capacity while also providing benefits for water quality and ecology. A more intricate strategy would involve further subdividing the area into smaller pumping zones to mitigate flooding in communities situated in low-lying topographic conditions. However, this approach would require a more detailed design and extensive urban planning efforts. Implementing either solution would necessitate modifications to the masterplan, which was already approved in 2023. This study suggests a careful reassessment of the masterplan, prioritizing the safety and wellbeing of current residents of Hà Nam.

Before commencing this study, the utility of 1D/2D surface models in the design of urban drainage systems in Vietnamese coastal areas was still uncertain. This study demonstrates that they can play a crucial role in delineating spatial distribution of pluvial flood risk and assessing the impact of mitigation measures. However, the use of these models do present some challenges that need to be addressed. Firstly, the availability of high-resolution topographic data and information on drainage infrastructure is crucial for generating pluvial flood maps with adequate accuracy. Secondly, incorporating water level monitoring data is important, as it enables the modeller to validate how well hydrological processes and the operation of existing flow-regulating structures are represented by the model.

8

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Appendices

Appendix A: Inundation maps

Ba Lang

Figure A.1 Maximum inundation levels in Ba Lang during rainfall T=10

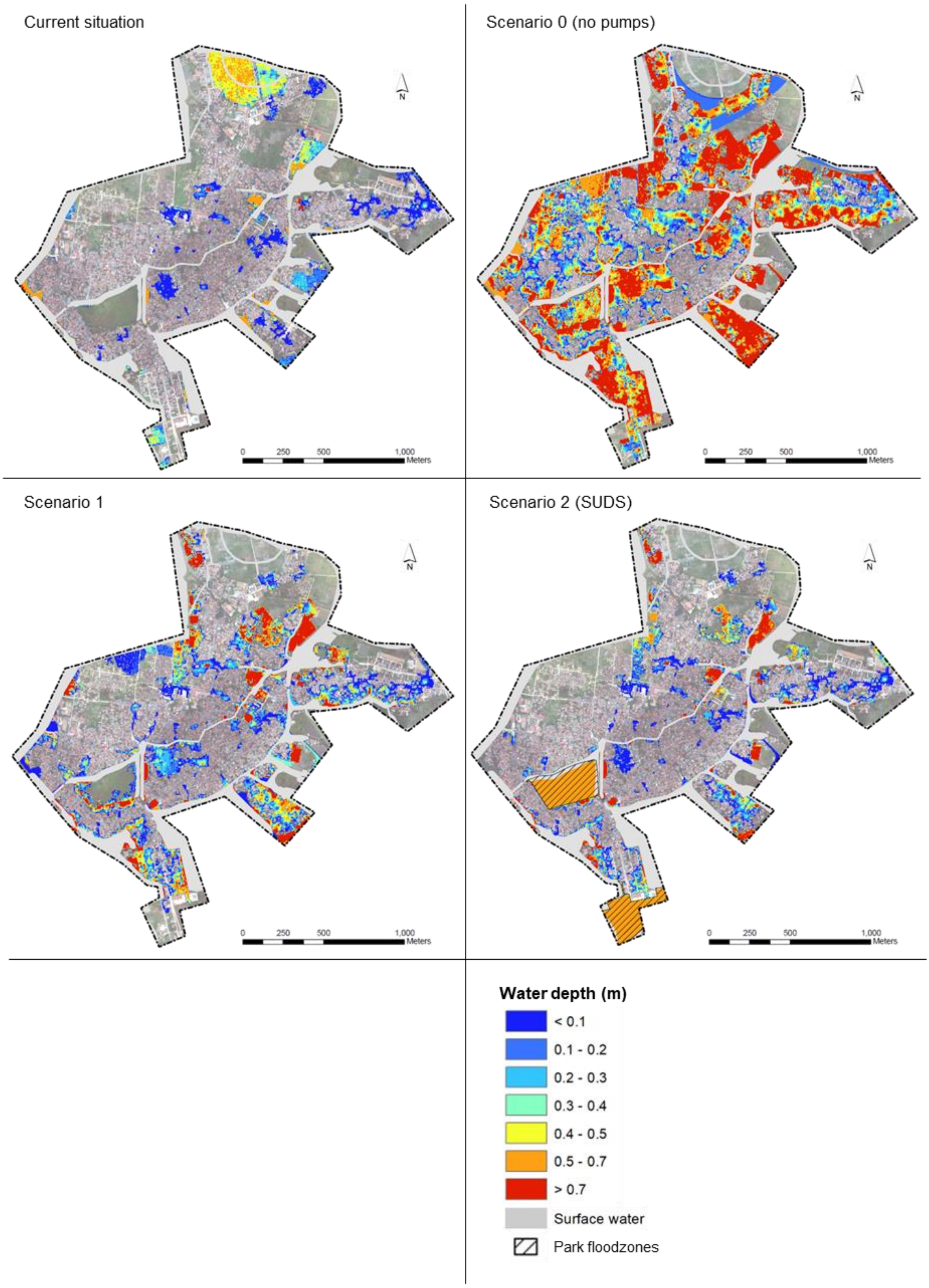
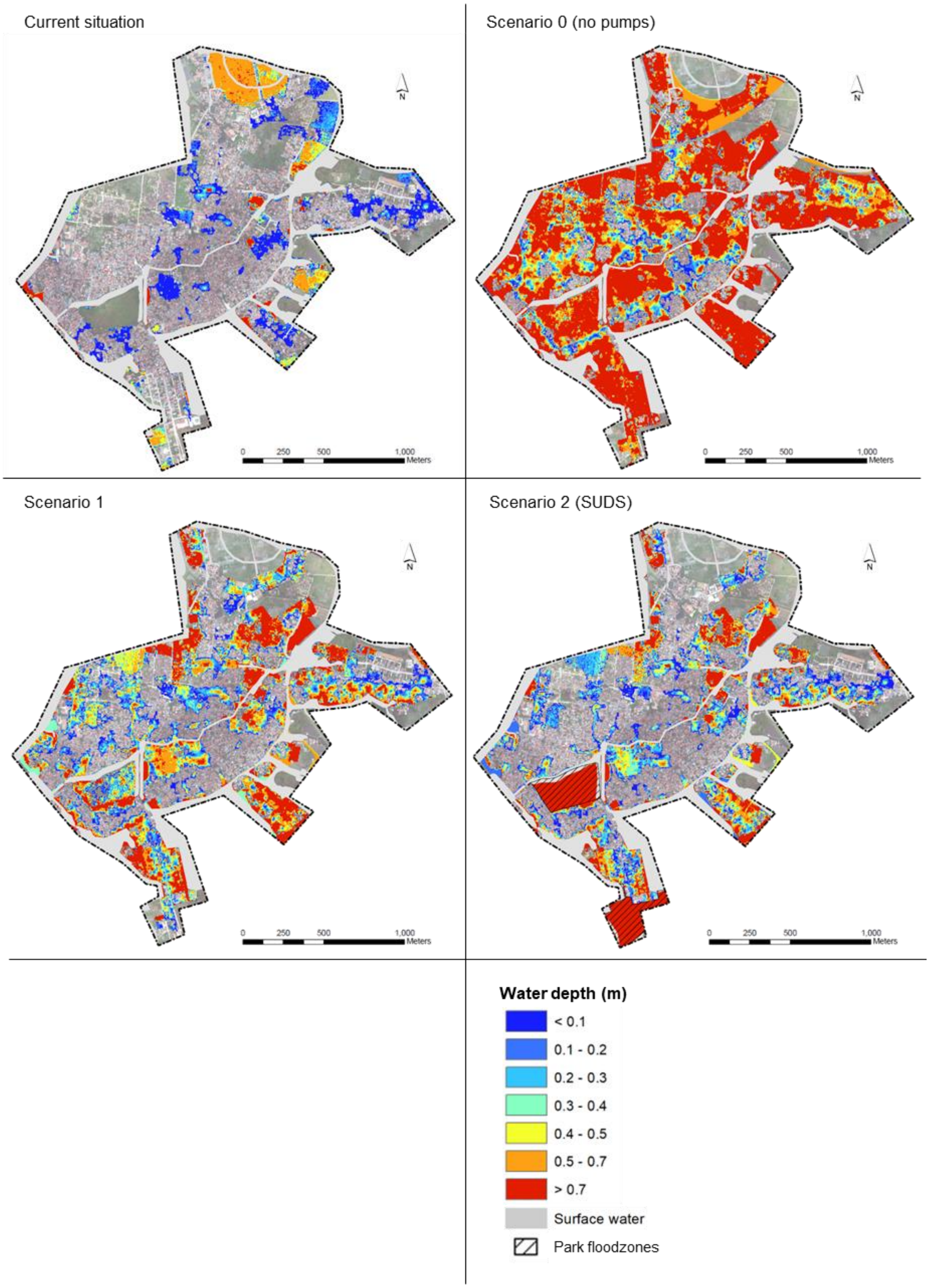


Figure A.2 Maximum inundation levels in Ba Lang during rainfall T=100



Vi Duong/ Lien Hoa South

Figure A.3 Maximum inundation levels in Vi Duong/ Lien Hoa South during rainfall T=10

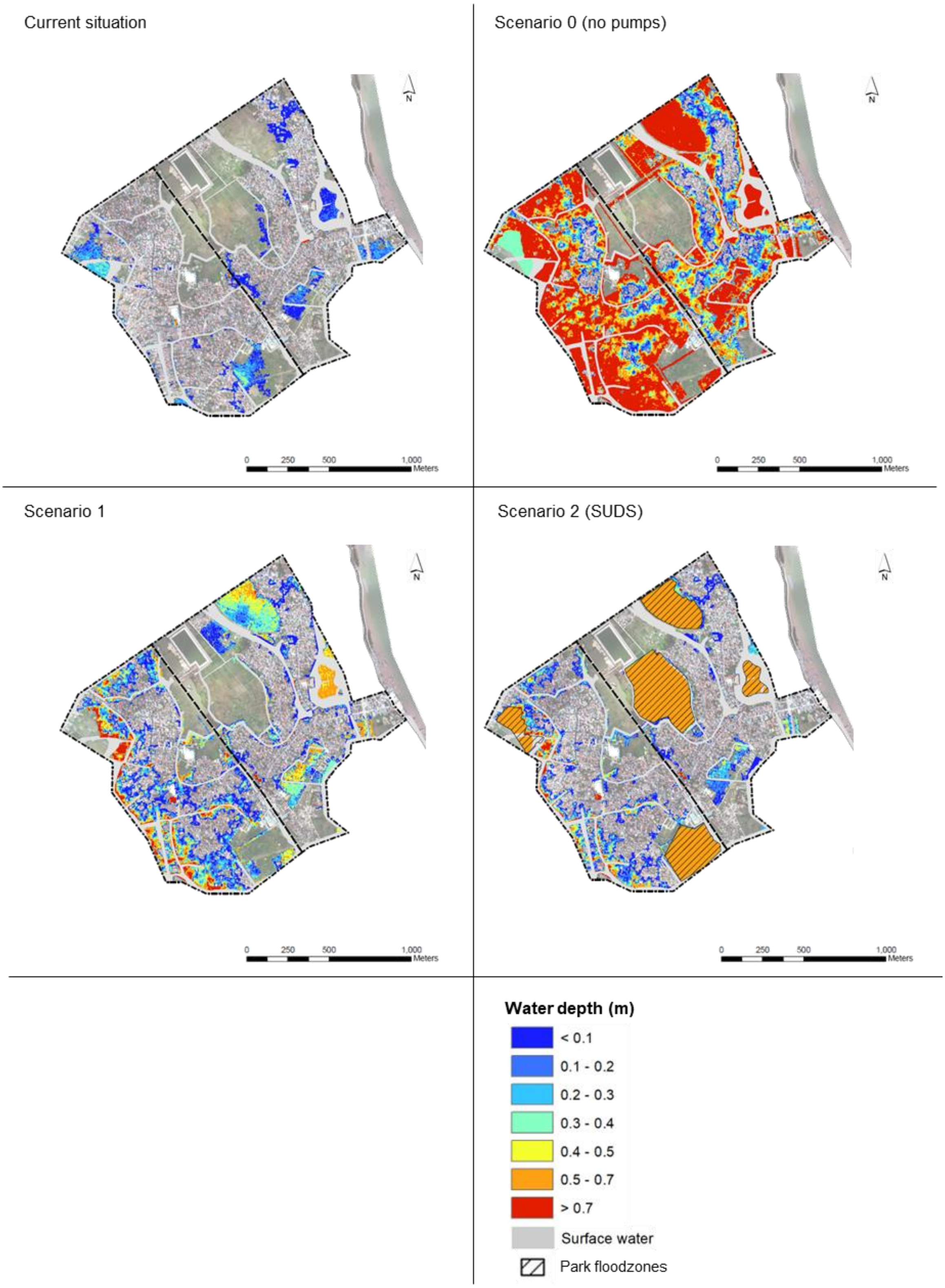


Figure A.4 Maximum inundation levels in Vi Duong/ Lien Hoa South during rainfall T=100