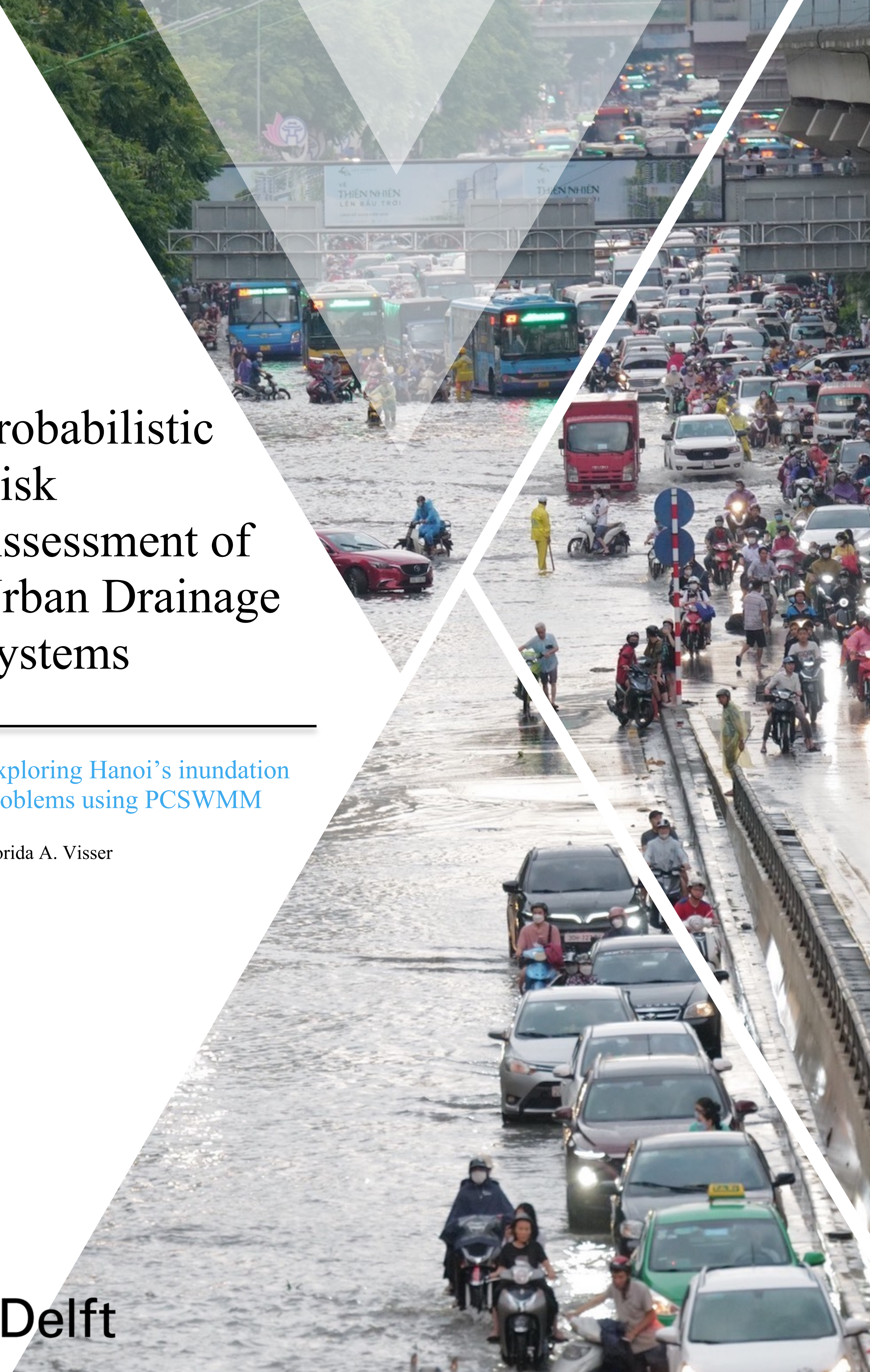
Probabilistic Risk Assessment of Urban Drainage Systems

Exploring Hanoi's inundation problems using PCSWMM

Florida A. Visser



The cover of this report shows an image of the Nguyễn Trãi Street, Hanoi, during an inundation event on May 29, 2022. Nguyễn Trãi Street lies at the heart of the study area of this research in Thanh Xuân district. Credit: VNExpress

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by

Florida A. Visser

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Abstract

This research explores the frequent urban flooding problems typically experienced in South-East Asian cities. Heavy rainfall during the monsoon period in combination with rapid urbanisation in the past decades causes an increasing amount of inundation events in the case study area Hanoi. The damage caused by these floods results in major economic losses that affect local citizens as well as governmental authorities. Flood waters are often heavily polluted with sewer water, threatening public health and reducing the overall livability of Hanoi. In addition, inundated streets are difficult to navigate, and waves induced by vehicles can lead to dangerous situations for pedestrians and other road users. This research aims to have a better understanding of the failure mechanisms of Hanoi's drainage system, and the risks associated with each mechanism. Since there is no standard methodology for probabilistic risk assessment of urban drainage systems, the methodology for levee assessment was adopted and adjusted to the field of urban drainage. This straight-forward method is transferable to other study areas and results in clear and comprehensive fault trees which are easily interpreted by drainage authorities.

A combination of expert judgement, qualitative fieldwork and analysis of newspapers was used to obtain an overview of all failure mechanisms and presented in the form of a fault tree. To investigate the potential damage that could be done by each failure mechanism, a probabilistic risk assessment was done using the urban drainage modelling software PCSWMM, and the potential risk of each mechanism was quantified. For the mechanisms with an unacceptably high risk, potential solutions were proposed. Four failure mechanisms were found that pose an unacceptably high risk on the drainage system: increased catchment size, pipeline blockage, inaccessible drains, and design inaccuracies. Potential solutions are to incorporate Low Impact Development (LID) in the urban area such as green and blue roofs, infiltration trenches and rain barrels. This type of infrastructure reduces the hydraulic load on the drainage system by reducing the runoff peak. In this way, urbanisation goes hand in hand with preserving the natural flows. Other recommended solutions are to revise the cleaning schedule to make it more efficient, and raise awareness among local inhabitants to enlarge their role in the functioning of Hanoi's drainage system.

Keywords: Urban flooding, Hanoi, probabilistic risk assessment, fault tree analysis, PCSWMM, integrated 1D-2D modelling, LID

Preface

When I started this research a year ago, I did not expect that it would turn out to be such an inspiring journey. The project started out as a desk study, and for months I had been staring at Google Streetview to get a grasp of area around the Nguyễn Trãi street, which is depicted on the cover page. With the ongoing pandemic I never expected to have the opportunity to actually visit the place that I had been looking at so much.

I would like to thank my thesis committee for all of their contributions and encouragement with which they have guided me through this process. In particular my supervisor Martine for her creative ideas, her patience and for always making time for me and being empathetic in times when it was difficult to carry on. Jeroen, thank you for the critical comments that helped me improve my thesis up to an academic level. I am thankful that Cong joined my thesis committee as soon as he joined the faculty; your input and knowledge of probabilistic risk assessment and the study area were invaluable. Lastly, I would like to thank Juliette for giving me the opportunity to be part of the project Climate Proof Vietnam, for helping me shape the project especially in the beginning phases, and for her enthusiasm throughout the year.

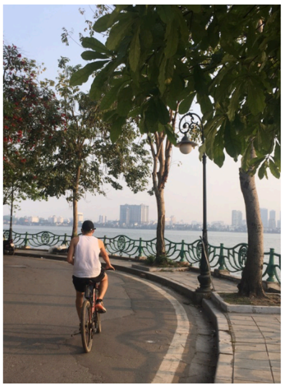
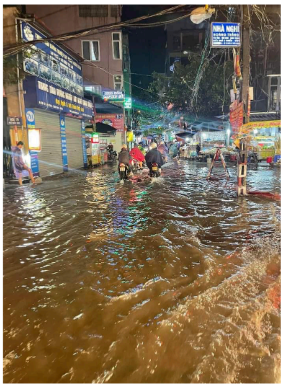
In addition, I would like to thank some Vietnamese colleagues for their helpfulness, especially Chi for welcoming me at HUNRE university and for helping me with interviews and translation. Tung, thank your for all the translations you have done during and after the focus group, and for enabling me to connect your colleagues at HUNRE. A big thanks to Thu Ha for making me feel so welcome in Hanoi, and teaching me to overcome my fear of the roadways of Hanoi on the first day. It was such an inspiring journey and I met the kindest people in the most random places. Thanks to Binh and Huyen for their interesting ideas and Manh for the daily journals you provided about the ongoing inundation problems in Hanoi. The real flood season started the day I left Hanoi for some sightseeing, and everyone I met started sending me pictures and videos of their homes and flooded basements. My apologies for being the weird tourist that took snapshots of every raindrop and every drain.

My background is in another discipline than civil engineering and when I first started the the master Water Management, it was quite complicated to adjust to the Delft ways of studying, researching and reporting. However, I never hesitated to quit, and I am proud that I finally completed my versatile student career with this research. I believe you can recognise that in this work as it is a multidisciplinary approach to a very actual and practical problem. In the beginning, especially the modelling was a big challenge for me, but after 5 months I almost knew the CHI documentation by heart and I can call myself an acquintance of PCSWMM - I even had the opportunity to give a PCSWMM workshop at the university of Thủy lợi.

A special gratitude goes to my fiancé Henk, who always wanted to listen to my ideas even flew across the world to enjoy the beautiful culture and country of Vietnam with me. Finally I would like to thank my fellow students from *afstudeerhok 1* for reviewing my work, the motivation, and for the numerous breaks we took on the fourth floor.

Một, hai, ba, dzô!

Florida A. Visser
Delft, September 2022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List of Abbreviations

DWF	= Dry weather flow
IDF	= Intensity-Duration-Frequency
DEM	= Digital Elevation Model
FTA	= Fault Tree Analysis
WWTP	= Wastewater treatment plant
FORM	= First order reliability method
MC	= Monte Carlo
SADCO	= Sewerage and Drainage Company
HSDC	= Hanoi's Sewerage and Drainage Company
PCSWMM	= Personal Computer Storm Water Management Model
PRA	= Probabilistic risk assessment
HUNRE	= Hanoi University of Natural Resources & Environment
SRTC	= Sensitivity-based Radio Tuning Calibration
CHI	= Computational Hydraulics International
SQL	= Standard Query Language
CUR 190	= Civieltechnisch Centrum Uitvoering Research en Regelgeving: Publication 190
LID	= Low Impact Development
HGL	= Hydraulic Grade Line
IDW	= Inverse distance weighting
TIN	= Triangulated irregular network
CRS	= Coordinate reference system

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1 Introduction

Urban flooding is an issue that more and more South-East Asian metropolises face. Especially during the rainy season, torrential rains induce large quantities of stormwater that the urban drainage system is not always prepared for (Hung et al., 2007; Kefi et al., 2018; Luo et al., 2018; Scaparra et al., 2019). Common issues associated with urban flooding are economic losses such as damaged infrastructure and private property, hampered traffic that prevents people from commuting. There is also intangible damage, such as the loss of livability and the adverse effects on public health through polluted surface waters (Kefi et al., 2018). Large cities are particularly vulnerable to flooding because urbanisation is generally associated with an increase of streets and buildings, and a decrease of green areas and surface waters (Kefi et al., 2018; Kuroda et al., 2017). As a result, less storm water infiltrates into the ground and ends up as runoff over the streets, causing frequent flash floods. Previous research shows that urbanisation unquestionably leads to an increase in urban flood risk, especially in areas affected by high-intensity precipitation (Dammalage & Jayasinghe, 2019; Feng et al., 2021).

One of the cities in which rainfall frequently leads to inundation is Hanoi, the fast-growing capital of Vietnam. The current population of the city is more than 8 million, and it has doubled in only 15 years (Q. Anh, 2019; General Statistics Office of Vietnam, 2019). Flood events take place multiple times per year and sometimes even weekly, inundating Hanoi's streets for multiple hours or days (An, 2021; Khanh, 2021; Thanh & Chinh, 2022). In this research, Hanoi is taken as a case study because it faces this specific combination of circumstances: rapid urbanisation and heavy monsoon rainfall. A particular extreme case of flooding due to rainfall occurred in October and November 2008, affecting a large region in Northern Vietnam. In a time span of three days, 563 mm precipitation fell over Hanoi's urban area, which is nearly a third of the average annual precipitation. The model in Figure 1.1 shows all parts of the city that were inundated during the 2008 floods. As can be seen in the figure, many parts of city were inundated up to one or two metres high.

The frequent inundation problems in the city of Hanoi indicate that the drainage system is facing major challenges. Hanoi's original drainage system was built by the French during the colonisation period from 1874 to 1954 and has deteriorated since then (Cau et al., n.d.; Ngoc Bao et al., 2013). As the city expanded severely since 1954, the load on the drainage system increased, making the older parts of the system obsolete (V.-A. Nguyen et al., 2005). Hence, to keep up with the pace of the city's expansion, the drainage system needs to be renovated and improved.

1.1. Problem statement

It is clear from the frequency of inundation problems that the drainage system is not functioning as it was once designed. In order to make targeted adjustments to the system to enhance its functioning, it is important to know how, when and where failure of the drainage system is taking place. As this not well documented yet, it is necessary to have a clear view of the causes that lead to inundation, also known as *failure mechanisms*. This enables authorities to identify adequate investment opportunities and to improve the drainage system in such a way that the probability of flooding is lowered. Based on knowledge of all potential causes of failure and their mutual relations, solutions can be proposed to

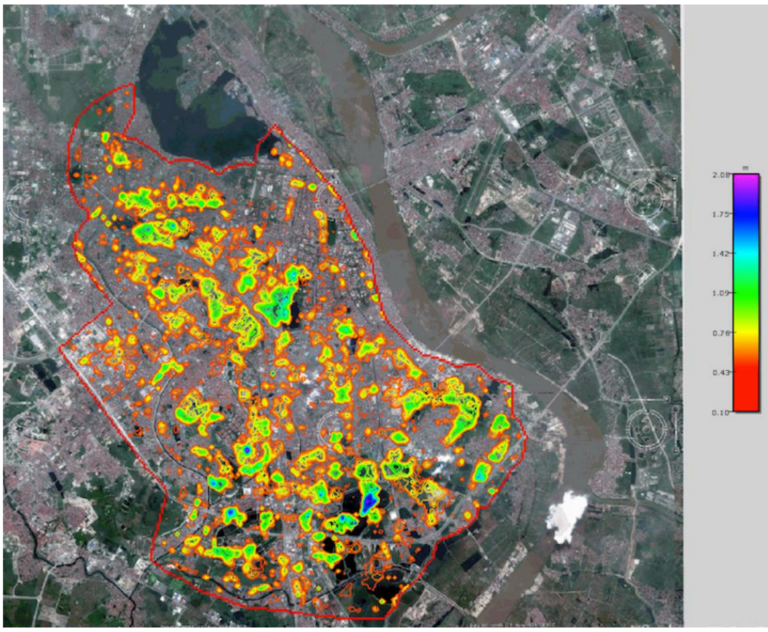


Figure 1.1: Modelled inundation of Hanoi after the 2008 floods. Original image is provided by Pingping Luo (2018)

mitigate the inundation problems.

One of the problems that arises here is that there are many types of uncertainty involved, which makes it complicated to estimate the effects of each failure mechanism. Sources of uncertainty are either inherently random, such as the natural variability of precipitation, or arise due to a lack of knowledge such as the unknown condition of the underground pipeline system (Jongejan et al., 2021). A promising tool to account of these uncertainties is probabilistic *fault tree analysis*. This type of probabilistic risk assessment (PRA) provides a clear and understandable overview of all potential causes of failure in a drainage system. This is important, because urban drainage is an interdisciplinary field, where urban planners, engineers, municipalities etc. have to work together and need a common language that aids in knowledge sharing among different expertises. Fault tree analysis has been widely applied to many engineering practices such as coastal engineering (e.g. Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997; Jongejan et al., 2021; Mai Van et al., 2007). However, the application to urban drainage remains limited, such that there is no unifying framework that prescribes a methodology to apply PRA urban drainage systems. This research functions to explore the applicability and the usefulness of fault tree analysis on urban drainage systems with Hanoi as a case study.

To summarise, there is a societal and a scientific problem to be addressed:

Societal problem:	Hanoi suffers frequent inundation problems and the underlying causes are unknown
Scientific problem:	There is no standard methodology to perform a probabilistic risk assessment of urban drainage systems

1.2. Research questions

Four research questions were set up following the problem statements. The first three refer to the societal problem, and the fourth one refers to the scientific problem. To allow for a study that provides recommendations as accurate as possible, the geographic scope is targeted at Thanh Xuân district in the city centre of Hanoi.

The definition of risk that is used in this research is: risk = severity × likelihood. The likelihood of an event equals the probability of occurrence. Furthermore, the modelling component of this study is carried out using the urban drainage modelling software PCSWMM. An introduction of PCSWMM is given in Section 3.3. The three research questions that address the societal problem are:

1. What mechanisms lead to inundation in Thanh Xuân district and how do they relate to each other?
2. What is the risk in terms of severity and likelihood of each failure mechanism?
3. How can the probability of failure mechanisms with an unacceptably high risk be lowered?

The fourth research question that addresses the scientific problem is:

4. To what extent can fault tree analysis in combination with PCSWMM be applied in a probabilistic risk assessment framework for urban drainage systems?

1.3. Research setup

The following approach was taken to answer the four research questions. First, an overview was made of all potential causes of failure in cooperation with local experts that have site-specific knowledge. A cause-effect analysis on the results lead to a concise fault tree, which constitutes the answer to the first question. Next, a modelling study was done to quantitatively estimate the consequences of these causes, in terms of inundation depth and total flood volume. A probabilistic model was set up that allows to set uncertain parameter distributions, such that uncertainty was taken into account and the sensitivity of different failure mechanisms with respect to underlying parameters could be analysed. This answers the second research question. The results from the first two research questions were combined to identify the cause(s) that pose the highest risk on Hanoi's urban drainage system. This was used as input for the third question: for each cause with an unacceptably high risk, a solution was formulated. Where applicable, these solutions were implemented in the probabilistic drainage model to assess the effects on the total flood volume [m^3]. The fourth research question is addressed by evaluating the effectiveness of the methodology used in this study. It is not described in the methodology, but the methodology is reviewed in the discussion to answer the fourth research question.

1.4. Reading guide

Chapter 2 provides a description of the study area in Hanoi. It includes the nature and frequency of precipitation and inundation events, as well as the governmental organisation of the city's drainage system. **Chapter 3** gives an overview of the theoretical background of this study. A literature study was conducted to find the research gap and to set the demarcations of this research. The chapter has three main focus points: (1) urban drainage in general, (2) probabilistic design in engineering practices, and (3) probabilistic modelling techniques. Chapter 3 concludes with a demarcation of the research gap that was found in the literature. The methodology entails the previously stated research questions and is presented in **Chapter 4**. The results are presented in **Chapter 5**, provided with an interpretation. The applicability developed methodology is critically evaluated in the discussion in **Chapter 6** by addressing the main limitations. Additionally, Chapter 6 reviews the research gap that was identified in the literature study and discusses to what extent it has been addressed. Last, the conclusion in **Chapter 7** answers the four research questions and gives recommendations for future research and for the agencies that are responsible for Hanoi's drainage system.

2
Study Area

This chapter gives an overview of different aspects of the study area of this research, including the population of Hanoi, average climate, and a description of the inundation problems. The drainage system and the affiliated parties and organisations are addressed in Section 2.4. As this study aims to propose solutions to reduce the inundation problems, it is important to know who is responsible and whom to interview. Since Hanoi is a large city with different land use types and inundation problems, it is not feasible to consider every district of the city. Section 2.5 further explains the geographic scope of the study, which is limited to Thanh Xuân district.

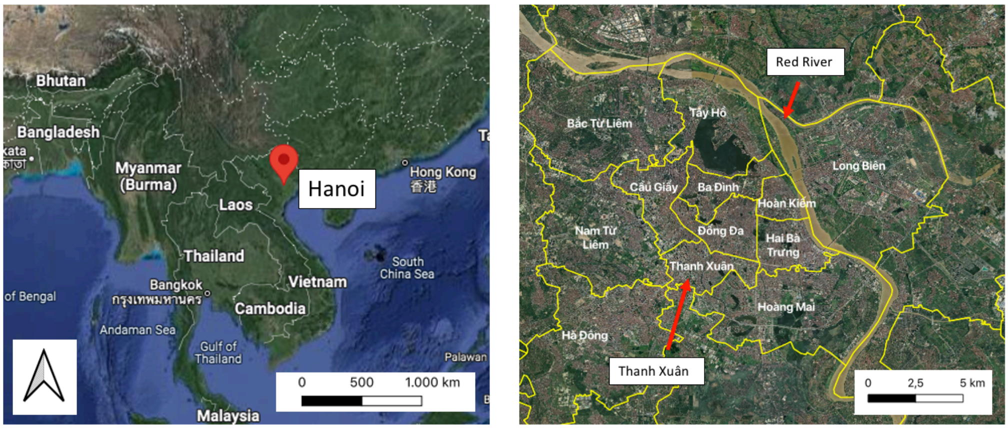


Figure 2.1: Location of Vietnam and Hanoi, which is divided into districts. The districts are demarcated by the yellow lines.

2.1. Population

The total population of Hanoi's entire municipality is 8.3 million. However, population density is heavily heterogeneous, as shown in Figure 2.2. The population of the urban area is currently 5.1 million (General Statistics Office of Vietnam, 2019). Prognoses of the General Statistics Office of Vietnam show that this number is likely to increase for the coming 20 years.

2.2. Climate

Hanoi is located northwest of the Red River delta; this river can be seen at the right in Figure 2.1. The Red River delta is characterised by a humid tropical climate with an average annual rainfall of approximately 1,760 mm ("Climate Hanoi, Vietnam", 2022). The southwest monsoon often causes typhoons and tropical low pressures, leading to heavy storms and precipitation, especially in the months June to September (T. A. Nguyen et al., 2008). The strong variation in precipitation throughout the year can be seen in Figure 2.2. Although the frequency of the inundation problems is increasing in Hanoi (Hung et al., 2007), this is presumably not due to changing weather patterns. Average annual precipitation in

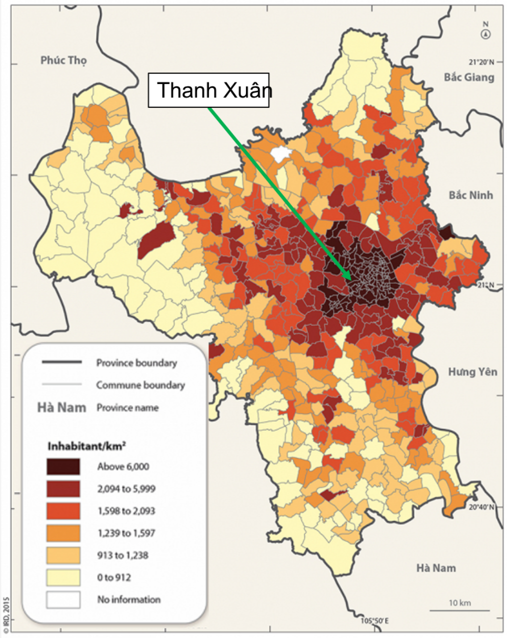


Figure 2.2: Distribution of Hanoi's population. Source: Cerise et al., 2016

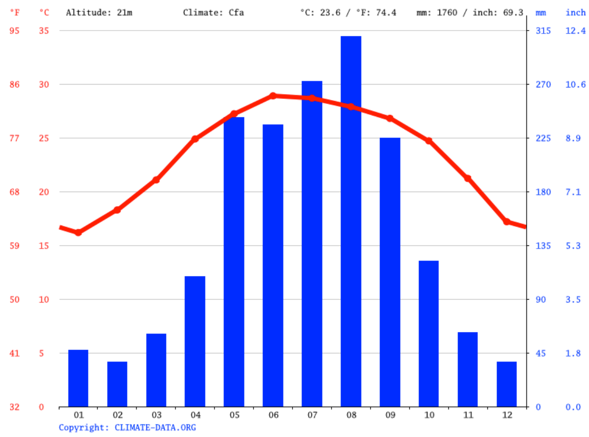


Figure 2.3: Average climate of Hanoi. The blue bars indicate the average rainfall in mm for each month, and the red line indicates the average temperature in °C. Source: Climate Data Hanoi from climate-data.org

Hanoi has decreased in the last 40 years. This can be seen in Figure 2.4, which shows the precipitation trend and annual anomalies for 1979 to 2022.

For urban drainage it is in fact more relevant to look at rainfall intensities and especially the peaks, rather than annual averages. A report published by the Asia-Pacific Network for Global Change Research developed a prognosis for the peak rainfall in Hanoi with different climate scenarios (Mishra et al., 2015). In this work, it was calculated that based on current precipitation data, a precipitation event with a duration of 2 hours and a return period of 2 years has an intensity of 40 mm/hour. However, with an RCP4.5 scenario, in 2070-2099, the same event would have an intensity of 45 mm/hour (IPCC definition). This is a considerable increase, but it should be noted that this increase is expected in the next 50-70 years, and the increase in the coming decade is expected to be minimal. Different methods to analyse precipitation in Hanoi exist and are presented in literature. These are discussed in Section 3.2.1.

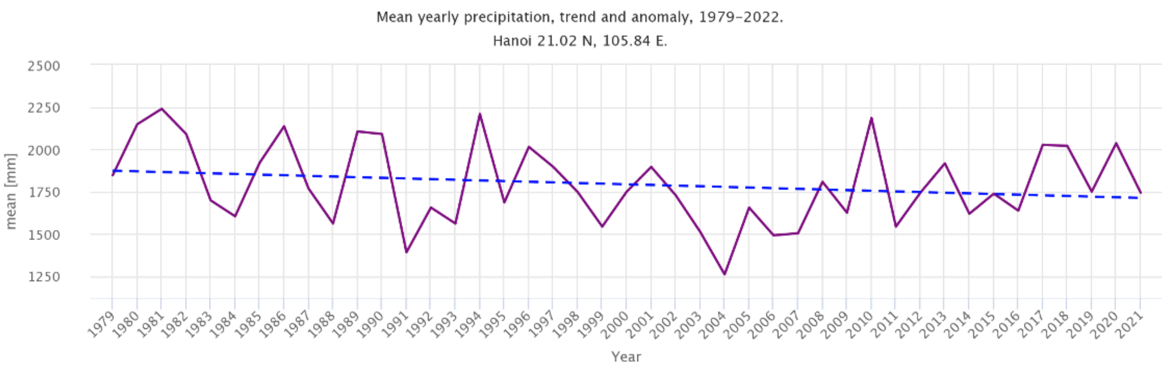


Figure 2.4: Trends and yearly anomalies in precipitation in Hanoi for the years 1979-2022. Source: Meteoblue, 2022

Figure 2.5: Pictures taken during a recent inundation event end May 2022. In some areas, the water level went up to 80 cm, and inhabitants had trouble navigating. Source: Van Phuc, 2022

2.3. Inundation problems

Typical durations of inundation events in Hanoi lie between an hour and two days. This was observed using live webcams available via the application HSDC maps, made publicly available by the drainage company (SADCO, n.d.). This application is further addressed in the next section. Additionally, it was testified by inhabitants during personal communication that Hanoi's streets usually inundate after heavy rainfall. During the monsoon season, it can happen multiple times per week that the streets inundate, depending on the rainfall intensity and duration. Whenever inundation starts to occur, the drainage company (further addressed in subsection 2.4) is notified and dispatched to the affected site to remove blockages and install emergency pumps, among other things. Figure 2.5 gives an impression of the inundation extent.

Scaparra et al. researched the community perceptions regarding the social, economic and environmental impacts associated with flooding of Hanoi's streets. This was done by carrying out interviews and focus-group discussions with two groups of people: residents and visitors. The second group includes mainly street vendors and taxi-drivers. Multiple problems were identified by the researchers, of which a few are briefly addressed in this section. First, the water makes it is difficult to navigate the streets. Because of this, people are unable or hardly able to commute, which negatively affects local economy. In personal communication with inhabitants affected by inundation, it turned out that this is the most important consequence of inundation. It can sometimes even be dangerous to enter the traffic as a pedestrian or on a motorbike. Whenever a car passes the street, it creates waves that easily knock over bikes and pedestrians (Khoa & Do, 2022). These waves are also shown in the right picture in Figure 2.5. Second, the water damages buildings and houses, which is associated with a high economic cost for both resident households and for visiting traders. In practice, the responsibility for these costs usually come down to the personal and household level. There is little or no support from government or non-government institutions (Scaparra et al., 2019). Third, the water that inundates the streets is often heavily polluted. Scaparra et al. found that especially the local residents were affected by this, rather than the visitors. This is mainly due to the fact that residents' homes are threatened by overflow of wastewater from canals and streams, which carries garbage and foul smells. Besides, often children and elderly people get sick from the pathogens that are carried by the flood waters (Scaparra et al., 2019). In other words, urban flooding negatively affects public health.

2.4. Hanoi's drainage system

In principle, urban drainage systems function to drain excess water away to avoid inundation of the streets. That is, when they are designed properly and are maintained well. As stated in the introduction, Hanoi's major drainage system was built between 1874 and 1954, and has become outdated in many parts (Cau et al., n.d.). Figure 2.6 gives a broad overview of the drainage system of Hanoi's city centre. As can be seen from the figure, the city has a combined sewer system, meaning that wastewater and stormwater are collected by the same pipelines. Consequently, the two flows are discharged together via a combined sewer overflow (CSO). Wastewater comes from households and industry, and

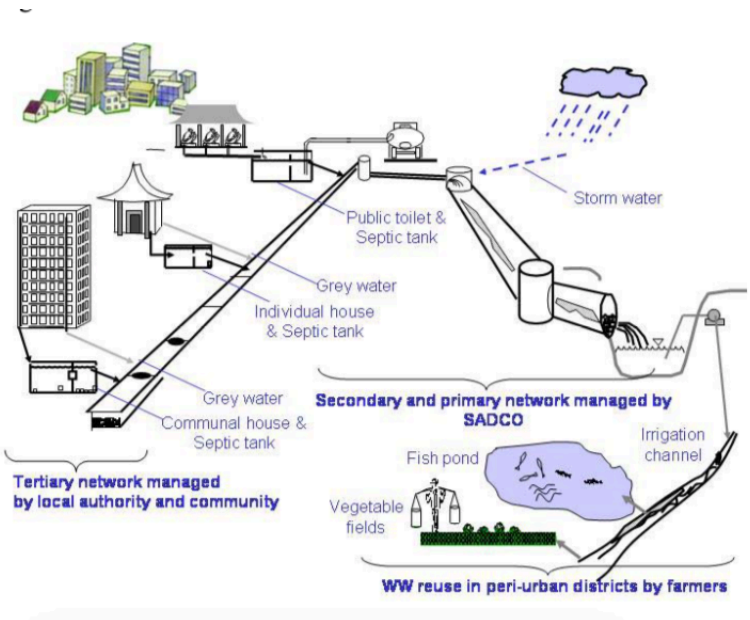


Figure 2.6: Wastewater flows in Hanoi. Source: V.-A. Nguyen et al., 2005

consists mainly of polluted water. Stormwater comes from precipitation that falls on the urban surface and needs to be collected by drains. The discharge capacity of the whole system is said to be 100mm in 2 hours. This value was suggested by Prof. Dr. Vu Trong Hong, former Deputy Minister of Agriculture and Rural Development, former President of Vietnam Irrigation Association, in a public interview (An, 2021). This rainfall amount is associated with a return period of $\pm$ 2 years, which would mean that Hanoi's drainage system is designed to flood once every two years (A. T. Nguyen, 2009). However, inundation occurs multiple times per year, which suggests that the drainage system experiences frequent failure.

Besides quantitative problems, Hanoi's drainage system also faces challenges with the water quality. Only 6.2 % of the water is treated before it is being discharged via the CSO into the receiving waters. For Hanoi's city centre, these waters are the rivers To Lich, Nhuệ, and the Red River, and they are heavily polluted due to this practice (Hoan et al., 2015; V.-A. Nguyen et al., 2005). Furthermore, Figure 2.6 shows that there is a distinction between the primary, secondary and tertiary network. The primary and secondary networks consist of the main sewers, channels, rivers, discharge gates and pump stations. The tertiary network consists of small ditches and sewers in alleys and residential areas V.-A. Nguyen et al., 2005. Along the whole network, manholes are built that can be entered if necessary. They are placed when e.g. the sewer changes in direction, size or gradient, and also every 90-200 metres to facilitate access (p.126 Butler et al., 2018).

When new system components are designed, the Vietnamese design norms should be used. They are laid down in a report called "NATIONAL STANDARD TCVN 7957:2008". The design norms are written by the Ministry of Construction, inspected by Directorate for Standards, Metrology, and Quality, and published by the Ministry of Science and Technology. Henceforth this report is referred to as 'Vietnamese design norms'. It includes many topics, ranging from characteristic parameter values for the Vietnamese landscape and precipitation statistics, to requirements for pumping stations and water quality.

2.4.1. Institutional framework

There are several Vietnamese governmental agencies that have separate responsibilities in the wastewater management sector, of which three relate to Hanoi's drainage system. First, The Ministry of Science and Technology (MOSTE) is responsible for wastewater discharge quality standards. Second, the Ministry of Natural Resources and Environment (MONRE) is responsible for natural water resources

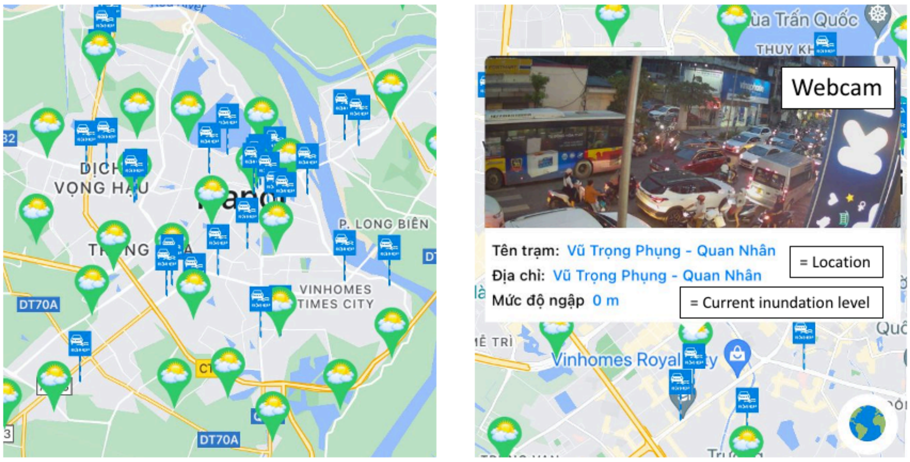


Figure 2.7: Screenshots of the application HSDC Maps, developed by Hanoi's drainage company SADCO (July 7th, 2022). Left: overview of Hanoi the locations of rain gauges (green) and webcams (blue). Right: image from one webcam showing no inundation or precipitation at the moment when the screenshot was taken.

management and wastewater discharge control. Third, the Ministry of Construction (MOC) is responsible for the urban water supply, as well as urban drainage and sanitation (N. V. Anh, 2005). Whereas the State is officially responsible for the management of Vietnam's water resources, the operation and maintenance of the urban drainage system is decentralised. The specific responsibilities can vary depending on the region, province and individual cities. In Hanoi, the City People's Committee (City PC) designates the institutions that are responsible for specific tasks. The secondary and primary network are managed by the Sewerage and Drainage Company (SADCO). This company is a public utility enterprise under the Department of Transport and Urban Public Works Service. However, SADCO does not have the resources or capacity to manage the entire network, which is why the tertiary network is outsourced to local authorities, such as ward People's Committees (N. V. Anh, 2005). The responsible parties for distinct parts of Hanoi's drainage system are indicated in Figure 2.6.

The main task of SADCO is to maintain the drainage system throughout the year, and to clean it before the rainy season. The larger parts of the system are cleaned using high-pressure sprayers and vacuum trucks, whereas the smaller pipelines are cleaned manually (V.-A. Nguyen et al., 2005). During heavy rainfall, SADCO must be ready to quickly reach places where the drainage system is flooded. In a personal interview with SADCO's senior employee Nguyen Huu Trong, who has more than 10 years experience with Hanoi's drainage system, it was mentioned that it is common to clean the sewers during a precipitation event (Nguyen Huu Trong, 2022).

Besides maintenance, SADCO also has the responsibility to inform citizens when inundation occurs. And since one of the most important problems associated with inundation is hindered traffic, SADCO developed an application that communicates which streets still navigable and which not. This application was developed in 2018 and is called HSDC Maps. The app has been referred to in the previous paragraph as well. This application is freely available for both IOS and Android devices. For this application, the company installed 31 cameras at locations that are frequently inundated, and users can see the inundation at these locations in millimetres in real-time (SADCO, n.d.). It is also possible that users of the app upload pictures of inundation, to warn other users. Besides the current inundation, the precipitation from 42 rain gauges is shown in the app. A screenshot of HSDC maps is shown in Figure 2.7. HSDC Maps is useful for citizens when they are planning their route and want to avoid flooded streets.

2.5. Geographic scope

Since the aim of this study is to provide relevant recommendations to reduce the flood incidences in Hanoi in a certain timeframe, it is necessary to consider a demarcated study area. The metropolitan

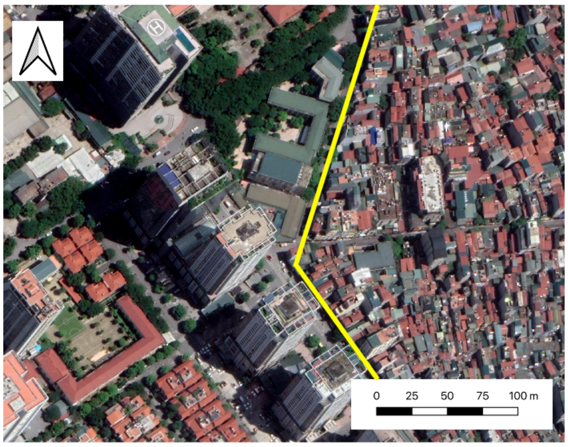


Figure 2.8: Two types of land use that are clearly distinguishable. Left: newly built high-rise buildings. Right: older and densely packed residential area.

area of Hanoi has a large variety of landscapes, including areas with lots of green spaces and agriculture, but also areas with skyscrapers and concrete surface. It is not feasible to consider the entire city for this study, and a smaller, *normative* area of Hanoi is demarcated. Three criteria were used to select an appropriate area, which are described below.

1. **Dense population:** the appropriate study area for this research should be densely populated, such that the consequences of urbanisation can be studied [1]. Areas with a high population were found by visually analysing satellite imagery and focusing on residential areas. Areas including parks were not considered as highly urbanised. The focus lied on older and densely populated residential areas, including newly built high-rise buildings.

2. **Frequent inundation:** As this research aims to address the causes of inundation in Hanoi, the study area should be subject to these problems and thus an overview of flood-prone locations is required. As stated before, SADCO's application HSDC indicates 31 flood-prone locations in Hanoi's city centre. The appropriate study area should be one of these locations.

3. **Mixed land use:** To examine the consequences of every potential failure mechanism, it is essential that as many failure mechanisms are present in the study area as possible. That is why the study area was selected such that multiple land use types are present. These two land-use types are expected to affect the drainage system in different manners. Satellite imagery was used to distinguish land use types. Figure 2.8 shows a satellite image of two land use types: An older and densely populated residential area and an area consisting mainly of newly built high-rise buildings.

The selected study area is Thanh Xuân district (*quận*) in Hanoi. This area meets the three criteria, which makes it an appropriate area for this research. First, Thanh Xuân district has a population density of ±32,000 inhabitants per square kilometre, with a total of 293,524 inhabitants as of 2019 (General Statistics Office of Vietnam, 2019). Second, the area deals with frequent inundation problems. Vũ Trọng Phụng street in the Thanh Xuân district is designated as one of the 31 flood-prone areas according to the app HSDC maps (The Smart Local, 2021). A recent event occurred at the end of May 2022, when 110mm precipitation fell in the Thanh Xuân district. This caused inundation on many locations, which led to severe traffic jams and damaged infrastructure and buildings (Thanh & Chinh, 2022). Third, this street is located at the border of a newly built area with a lot of high-rise buildings on one side, and older residential areas on the other side. Hence, the third requirement of mixed land use is also fulfilled in this study area.

[1] Inundation problems also occur in less populated areas, such as floodplains or rural areas, but this is not within the scope of the present research.

3
Theoretical Background

This chapter outlines the theoretical background of the study. It starts with an introduction of general definitions and key concepts. Next, an introduction of urban drainage systems is given, including the design approach in Hanoi, state-of-the-art mitigation strategies. This is followed by addressing existing urban drainage models and an overview of modelling studies of Hanoi's drainage system. Section 3.4 presents the standard methodology of probabilistic risk assessment (PRA) in general, and Section 3.5 reviews to what extent PRA has been applied to urban drainage in the past. The chapter concludes with the research gap that is found by studying the literature.

3.1. Definitions and key concepts

3.1.1. Types of flooding

There are three common types of flooding that exist: pluvial, fluvial and coastal flooding. This classification is based on how they are generated. The first type, which is the only type considered in this research, is pluvial flooding. Pluvial flooding is induced by (extreme) rainfall and occurs in rural areas as well as urban areas. Usually, drainage systems have the function of draining rainwater, but they can become overwhelmed or fail, leading to pluvial flooding. The second type is fluvial flooding, which occurs when high water levels in a river or stream overflow their banks, or when a river levee fails. The third type is coastal flooding, which occurs when land areas along the coast inundate. Fluvial and coastal flooding are outside of the scope of this study. Coastal flooding does not occur in Hanoi because it is not located alongside the coast, and fluvial flooding in Hanoi only occurs once every 20-30 years (Pham et al., 2013)

3.1.2. Flood, inundation and nuisance

Not every flood incident is a deadly disaster. There are different degrees of severity and it is important to distinguish between these degrees to understand the problems in Hanoi. Three levels are: flooding, inundation and nuisance, but there are other classifications conceivable. Flooding is generally referred to when dangerous situations occur due to flood waters and is considered the most severe of the three. Inundation refers to the situation of water being in areas that would otherwise remain dry, and can be considered the second most severe of the three. This is a more neutral term than flooding. Inundation can also be deliberately induced, for example for irrigation purposes of e.g. rice fields. Last, water nuisance is another word for hinder induced by water. Nuisance refers to low levels of inundation that do not pose significant threats to public safety or cause major property damage, but can disrupt routine day-to-day activities (Moftakhari et al., 2018). Nuisance exists when there is nuisance if, for example, a basement is flooded and is considered the least severe of the three.

The severity of flooding in Hanoi can best be characterised by the term inundation, because the floodwaters are not life-threatening, but pose more serious problems than mere nuisance would do. In this thesis, the words flood and inundation are both used, just like the cited literature and newspaper articles do. Some articles use the phrase ”flood inundation” (Luo et al., 2018), but it is important to keep in mind that this refers to *inundation*.

3.1.3. Failure

The definitions described in this section were derived from Cur 190 ’Kansen in de Civiele Techniek’ (Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997). This document is referred to as ”Cur 190”. This publication describes the principles of probabilistic design in civil engineering in general. This publication is also used as a guideline for the standard method of PRA, which is addressed in Section 3.4. The definitions of failure, failure mechanisms, and limit states as presented in the Cur 190, are:

> [Translated] Failure occurs when a system or part of it no longer fulfils one or more desired functions. The state of failure can be reached in several ways. A particular way that leads to failure is called a failure mechanism. The state in which no failure occurs just yet is called a limit state.

As the definition of failure above indicates, the essence of failure depends on the function of the construction. In urban drainage engineering, the function of e.g. an underground conduit is to keep the surface clean from runoff or stormwater. Failure of an urban drainage system thus leads inundation of the streets. In this research, the following definition formulated by Ten Veldhuis (2010) is employed:

> ”Failure of the drainage system is defined as the occurrence of a pool of water on the surface somewhere in an urban area, lasting long enough to be detected [by inhabitants] and cause disturbance” (Ten Veldhuis, 2010).

3.2. Urban drainage and flooding

This section outlines general concepts related to urban drainage systems, including characteristics of Hanoi’s drainage system. This includes rainfall analysis, the effect of urbanisation on drainage, and recent developments in green-blue urban infrastructure. An overview of the system components of Thanh Xuân’s drainage system was already given in the study area description in Chapter 2. The principles urban drainage systems discussed in this section are derived from the book *Urban Drainage* (Butler et al., 2018). This book contains fundamental principles of the design, maintenance and modelling of urban drainage systems. A few core principles of Urban Drainage are discussed in this section, see the book by Butler and Davies for further insights.

3.2.1. Rainfall analysis

In the initial design phase, precipitation is the most important flow to consider. Rainfall analysis enables to set up design storms, which are used to determine the required dimensions of the drainage system. Using historical precipitation data from nearby weather stations, rainfall analysis is done to classify precipitation events. This classification is done by linking the intensity to the duration and the frequency. In general, the duration of rainfall is inversely related to the intensity: the longer the event, the lower the intensity. The same holds for frequency and intensity: the higher the intensity for a set duration, the lower the frequency. These relations are visualised by means of intensity-duration-frequency (IDF) curves. The main advantage of using IDF curves is that, given a certain return period and duration, the expected amount of precipitation can directly be read from the graph. IDF curves contain parameters that are characteristic for specific catchments and specific circumstances. The mathematical functions that describe the IDF curves are statistical distributions that are fitted to the extreme values, e.g. log-normal, Gumbel or Pareto distributions.

Hyetographs

Hyetographs describe the precise course of design storms, such as the height and duration of the peak intensity. For each time unit, the rainfall intensity is presented in a graph. Typically, hyetographs show a high peak and lower values around the peak. There are several methods of calculating a hyetograph described in literature. Common methods to construct hyetographs are the alternating block method, which is frequently used in urban areas, and the SCS storm distribution, frequently used in agricultural watersheds (Keifer & Chu, 1957; “SCS Standard Rainfall Distributions”, 2011; Soulis & Valiantzas, 2012).

Vietnamese design norms and rainfall analysis

The Vietnamese design norms propose three different methods to define a design storm for Hanoi, and recommend to compare all three methods for high accuracy (Ministry of Construction, 2008). The first method states that an IDF diagram should be used, which is specifically derived for the area at hand. The document does not provide IDF coefficients for Hanoi itself, so external publications should consulted to this end. A few publications are addressed in the next paragraph. The other two methods are briefly described in paragraph 4.2.2. However, the descriptions are very concise, and no official references are given such that the methods could not be verified. One of the two methods is using Wenzel's formula, but the equation given in in the document does not match equations that other publications refer to as Wenzel's equation (e.g. Zapata-Sierra et al., 2009). The design norms do not explain how certain coefficients ought to be determined. It should also be noted that the original document of the Vietnamese design norms is written in Vietnamese, and the translated English version is of limited quality. Therefore, due to the language barrier, it is not possible to ascertain the definitions of each parameter without proper references. The two methods proposed by the design norms are thus not reliable and should not be used in this study.

IDF-curves derived for Hanoi

Four publications were found that present design storms and IDF curves developed for Hanoi, each slightly different from each other. Potential reasons for these differences are that they use different (lengths of) precipitation data sets, different interpolation techniques, or different extreme value statistics. The first publication is the Climate Change Adaptation report mentioned already in Section 2.2. It contains graphs with IDF-curves for return periods of 2, 5, 10, 20, 50 and 100 years. There are no equations provided, and it cannot be read from the graph what the intensity of a precipitation event with a return period of 1 year is. The three other publications contain equations that describe the IDF-curves, each developed by Associate Professor Ph.D Nguyen Tuan Anh from Thủy lợi University, Hanoi (N. T. V. Hong & Nguyen, 2020; Ministry of Construction, 2008; Mishra et al., 2015). The IDF curves presented in all three papers are applicable to the Northern Delta of Vietnam and suitable for urban as well as rural applications. The papers published in 2008 and 2020 contain equations for which the parameters are only published for return periods of 5, 10, or 20 years (N. T. V. Hong & Nguyen, 2020; T. A. Nguyen et al., 2008). Therefore, these cannot be used to calculate a design storm with a return period of 1 or 2 years. Tuan Anh's paper from 2009 contains equations where the return period is a variable, such that IDF curves for a range of return periods can be defined. Equations 3.1a and 3.1b describe these IDF curves (A. T. Nguyen, 2009).

$$H_d = (b_1 * log(T) + c_1) * d^{e_1 * log(T) + f_1} \ (d \leq \alpha * T * \beta) \tag{3.1a}$$

$$H_d = (b_2 * log(T) + c_2) * d^{e_2 * log(T) + f_2} \ (d > \alpha * T * \beta) \tag{3.1b}$$

In these equations, H_d is the rainfall depth [mm], d duration [hours], and T is the return period [years]. All other parameters are coefficients that belong to the nearest weather station. For the Lang station in Hanoi, these are presented in the article. The resulting IDF curves are shown in Figure 3.1.

3.2.2. Runoff generation

Not all rainfall ends up as runoff but is lost due to depression storage, evapotranspiration, and infiltration losses (Butler et al., 2018). Depression storage refers to the rainwater that got trapped in small depressions and depends on the surface type and slope of the catchment. Rainfall retention on vegetation cover is known as interception. Evapotranspiration is the evaporation of water from water bodies and plants, and therefore reduces the amount of runoff. In short, high-intensity rainfall events, the effects of evapotranspiration are negligible (Butler et al., 2018). Infiltration happens through the pores of the soil in pervious areas, and the rate depends on the soil type. In highly urbanised areas, pervious areas such as grass or woodlands make room for infrastructure and buildings, thereby reducing the infiltration capacity. The impact of urbanisation on infiltration and the runoff peak is schematically represented in Figure 3.2.

The amount of water that remains after the initial losses have been subtracted is also known as the *effective* rainfall. This part ends up as runoff on the streets and must be collected by the drainage

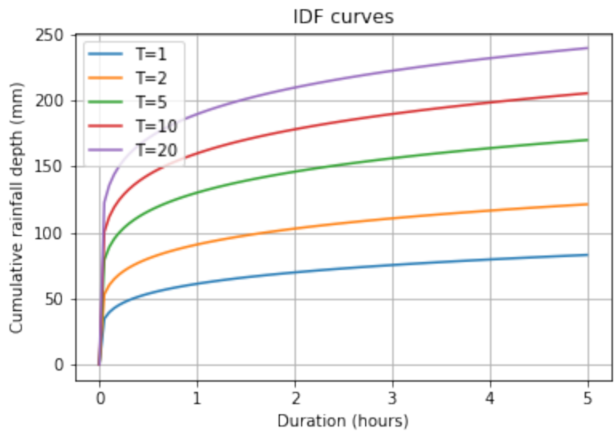


Figure 3.1: IDF curves developed by Tuan Anh Nguyen (2009) for T = 1, 2, 5, 10 and 20 years. Described by Equations 3.1a and 3.1b

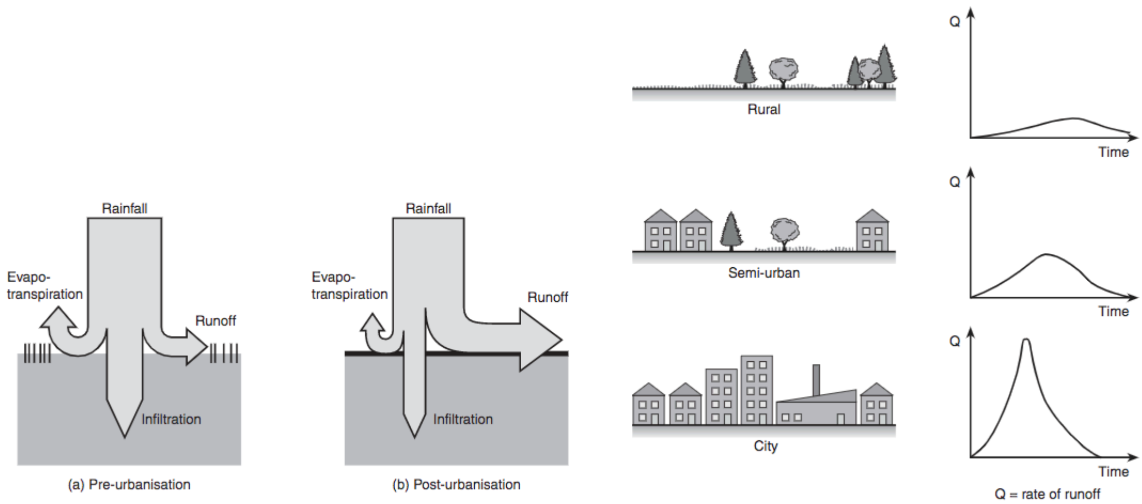


Figure 3.2: Effect of urbanisation on peak rate of runoff: a higher degree of urbanisation results in a higher runoff peak. (Source: Butler et al., 2018)

system. The fraction of effective rainfall is determined by the *runoff coefficient* of the catchment:

$$i_e = Ci_n \tag{3.2}$$

Herein, i_e is the effective rainfall intensity [mm/h], C is the runoff coefficient [-], and i_n is the net rainfall intensity [mm/h]. The runoff coefficient depends essentially on the surface roughness, soil type, land use and slope. Estimates for the runoff coefficient can be found in literature (Bizier, 2007; Butler et al., 2018; Nicklow et al., 2004, 2006), but guidelines have also been drawn up for specific areas. For Vietnam, guidelines for the roughness coefficient are given in Table 6 of the Vietnamese design norms (Ministry of Construction, 2008).

Besides the effective rainfall, another important process in drainage system design is the time it takes for runoff to travel from the most remote location to the drainage system. This is also known as the *time of concentration*, and it plays a crucial role in estimating the peak flow through the drainage system. The time of concentration can be calculated using the Rational Method (Butler et al., 2018). This is an intuitive approach in which the rainfall intensity is multiplied by the catchment area, such that the total volume of water for each node can be calculated using Equation 3.3. An important parameter used in the Rational Method is the surface roughness, which determines the potential velocity of the runoff.

$$t = \frac{6.94(Ln^*)^{0.6}}{I^{0.4}S^{0.3}} \quad (3.3)$$

Where:

t = overland flow time [min]
L = flow path length [m]
n^* = a surface roughness or retardance coefficient [-]
I = rainfall intensity [mm/h]
S = slope [m/m]

The initial losses as described above are negligible for typical precipitation events in Hanoi's city centre, such that virtually all precipitation ends up as runoff and must be collected by the drainage system. Because Hanoi's city centre is highly urbanised, there is little pervious area and thus little infiltration into the soil is possible. Depression storage and evapotranspiration occur, but the rates at which it happens is minimal compared to the high rainfall intensities in Hanoi. The Vietnamese design norms recommend to use the Rational Method with values for the surface roughness in the range 0.15-0.24 for urban areas [$m^{1/3}$/s] (Table 6 of the design norms).

3.2.3. Recent developments

As illustrated in Figure 3.2, growing cities interrupt natural water flows by inhibiting infiltration and promoting runoff generation. Recent developments aim to restore these natural flows by designing infrastructure that reduces the load on the drainage system. The main idea is that water use and drainage, as well as their impact on the environment are considered holistically (Butler et al., 2018). This section aims to give an overview of the state of the art of these developments. The overview was obtained from the aforementioned book. There are different terminologies that describe this type of systems, such as Low Impact Development (LID) in North America, and Sustainable Urban Drainage Systems (SuDS) in Europe. China refers to 'sponge cities' as a new urban construction model to reinforce ecological and urban infrastructure. These terms all belong to the umbrella term is green-blue infrastructure. A few noteworthy recent developments are addressed below.

Inlet controls

Inlet controls aim to control the amount of stormwater that enters the drainage system. This can be established in different ways, for instance by harvesting the rainwater from household roofs. Rainwater harvesting requires a system to collect and store rainfall runoff, for instance by means of rain barrels. Another example are green roofs, which enable rainfall to slowly infiltrate into the underlying soil. Green roofs are able to retain a certain amount of water in the substrate, where water is stored and slowly drained away. The main benefit of these systems is that the runoff peak is reduced. An example of a green roof is shown on the right in Figure 3.3. Another example of an inlet control are so-called blue roofs, which are flat roofs that are able to exploit their storage potential by temporarily retaining rainwater. Temporary storage can also be found in paved areas on the surface, such as car parking lots and playgrounds.

Infiltration enhancement

Infiltration capacity can be enhanced in multiple ways, falling under the broad categories of *grey* and *green* solutions. These systems have the function to store stormwater, and to promote infiltration into the soil. Grey infiltration enhancement can be established using infiltration trenches and pervious pavement. Pervious pavement can be used in dense urban areas but only with light traffic, whereas infiltration trenches cannot handle any traffic and therefore take up more space. An example of an infiltration trench is shown in the middle in Figure 3.3. Green infiltration enhancement includes the use of bioretention systems and vegetative swales, shown on the right in Figure 3.3. Besides decreasing the runoff peak, another major benefit of infiltration-enhancing LIDs is that they help to reduce the detrimental effects that drainage systems have on natural waterways and groundwater. This is done by means of removal of nutrient, pathogens and metals from runoff as close to its source as possible (Davis et al., 2006; Guillette, 2016).

LIDs in Hanoi

In Hanoi, several studies with regard to the functionality and feasibility of LIDs have been conducted.

Figure 3.3: Examples of LIDs. Left: green roof, placed on top of the TU Delft University Library. Center: infiltration trench, right: vegetative swale. Source: Gambaro et al., 2012

Dank et al. studied the effect of green roofs on peak runoff and found that green roofs can reduce the peak flow by up to 50% and increase total delay time up to 30 minutes (Cuong et al., 2017). These are promising results and might have a large impact on urban hydrology, if implemented in the future. A cost assessment was made by H. Dang et al., 2016 to assess the feasibility of green roofs in terms of costs. The researchers concluded that green roofs might be remunerative for local inhabitants, if they are willing to maintain the vegetation.

3.3. Urban drainage modelling

This section gives a general introduction to the elements of urban drainage models. The role of uncertainty in these models is explained in subsection 3.3.1, and the underlying equations are addressed in subsection 3.3.2. Software packages that offer urban drainage models are addressed in subsection 3.3.3, and and subsection 3.3.4 discusses modelling studies that have been done in Hanoi.

The purpose of flow models in urban drainage systems engineering is to represent a drainage system such that its responses can be studied. Flow models can be used to predict the functioning of a drainage system under different weather conditions, its response to changes in the urban environment, or they can be used to design new systems. The drainage system itself is represented by links (pipes), nodes (manholes), and an outlet (combined sewer overflow (CSO)). Main types of input include rainfall, infiltration, and wastewater flow, and the desired outputs are flow rate and water depths within the system and at the outlets. Some modelling studies aim to model the overland flow with a 2D model and connect it with the 1D underground drainage model. Overflow is better modelled by 2D models, whereas 1D models provide a good approximation of flow in pipes (Leandro et al., 2009). For large storm events that induce floods, it is also common to only model the overland flow in 2D and neglect the drainage system. This is useful when rainfall is so severe that the drainage system can be neglected.

3.3.1. Uncertainty

An important aspect of models in general is that they are a *representation* of reality, and by making assumptions they simplify processes. No model captures every raindrop or every plant. These simplifications introduce uncertainty to models, and it is very important to understand these uncertainties in order to adequately interpret modelling results. It is naive to assume that models exactly predict the behaviour of systems, therefore results should be recommended as indicative (Butler et al., 2018). This holds for all types of models, and urban drainage models are not an exclusion. Uncertainty in urban drainage modelling can arise from a multitude of sources. Some processes are inherently random, such as the natural variability of soil characteristics and rainfall. Observational errors arise when field data is collected with e.g. uncalibrated measuring equipment or because of human errors. Other processes or properties are simply unknown, and cannot be approximated with certainty. The outcomes of model calculations are therefore always surrounded by uncertainty. In other words, it is insurmountable to encounter uncertainties in every step of modelling.

There are different types of models that each deal differently with uncertainty. In deterministic models, every model run with the same input parameters results in the same model output. These models do not account for randomness. It is, however, possible to explore uncertainties with deterministic models. Sensitivity analyses can be performed by running numerous simulations, each with different input parameters. The input parameters are manually changed, usually across a pre-specified range. By comparing the model output of each run, the extent to which input parameters affect the output is evaluated (“Deterministic Sensitivity Analysis”, 2016)

Besides deterministic models, there are stochastic models that add noise to the input parameters. The main starting point is to treat data and model parameters as random variables, and represent their uncertainty using probability distributions. Model runs are done by sampling from these distributions and adding noise, which results in output parameters that also take the form of probability distributions. A popular example of such a technique is known as Monte Carlo (MC) (Devroye, 1986; Knighton et al., 2014). This type of stochastic modelling is computationally intensive; typical MC methods require 1,000 to 10,000 runs (Heijungs, 2020). Another popular method known as First Order Reliability method (FORM) takes a semi-probabilistic approach and is therefore much faster technique than MC. Although FORM is considered less reliable than MC, it is useful for an estimate of the output uncertainty. Both Monte Carlo as well as FORM are commonly used methods in probabilistic modelling.

3.3.2. Underlying equations

The representation of unsteady flow is an important part of drainage models, because no reliable predictions of water depth can be made if steady flow is presumed. Many urban drainage models assume that urban flooding occurs as shallow overland flow, such that uniform distribution of the velocity along the vertical axis may be assumed. This results in shallow water equations, also known as the St. Venant equations, which are derived from depth-integrating the Navier-Stokes equations. The St. Venant equations are characterised by Equations 3.4 and 3.5 (see for the derivation Chow, 1959).

Continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{3.4}$$

Conservation of Momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial Q^2/A}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{3.5}$$

Where:

x = distance along the conduit [m]
t = time step [s]
A = cross sectional area [m^2]
Q = flow rate [m^3/s]
H = hydraulic head of water at node [m]
S_f = friction slope [m/m]
h_L = local energy loss per unit length of conduit [m/m]
g = acceleration of gravity [m/s^2]

Solving the St. Venant equations, especially for high-resolution 2D models, requires a high computational power. There are different methods of simplification, that each neglect specific terms in Equation 3.5. These methods include steady flow routing, the kinematic wave approximation, the diffusive wave approximation, and the dynamic wave approximation. The following definitions were derived from Butler et al. Steady flow actually assumes no routing, and uses the normal flow equation to relate flow rate to flow area/depth. This oversimplification is only appropriate for preliminary analysis. The kinematic wave approximation assumes that bed slopes equal the slope of the water surface. This approximation therefore does not support reverse pipe flow, and thus does not apply to looped networks. The diffusive wave approximation ignores inertial and advective terms, which is the second term in Equation 3.5. Dynamic wave routing solves the complete one-dimensional St. Venant-equations and yields the most theoretically accurate results. Figure 3.4 below represents the approximations schematically.

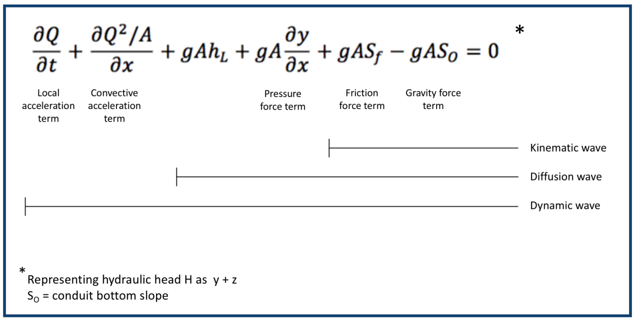


Figure 3.4: Schematic representation of kinematic wave, diffusion wave, and dynamic wave approximations. Image adapted from the article 'Flow Routing', PCSWMM documentation, www.support.chiwater.com

3.3.3. Software packages

There are many software packages available that offer the requirements and processes described above, of which the most well-known is the Storm Water Management Model (SWMM). This model was first developed in the early 1970s and is still developing. Many software packages run on the SWMM engine, including PCSWMM, EPA-SWMM, and Mike Urban (Rossman, n.d.). Other popular software packages that do not run on SWMM are HEC-RAS and HydroCAD. A comprehensive overview of all available software packages including practical applications can be found on in the Minnesota Stormwater Manual (Manual, 2022). When selecting an appropriate stormwater model, it is important to be clear about the requirements of the model and the differences between the available models. Each model or software package has its own assets and liabilities, which determines what practical application is best suitable. A guide to choose which stormwater model suits requirements the best is also included in the Minnesota Stormwater Manual.

3.3.4. Modelling studies in Hanoi

The few modelling studies that have been conducted in Hanoi are all either 1D or 2D and all deterministic. This subsection gives a brief introduction of these modelling studies. The flood hazard of 2008 was modelled by Dang & Hieu, showing that most of Hanoi's flat areas were submersed by 0-4 meters of inundation (K. B. Dang & Hieu, 2013). The researchers did not take the drainage system into account, but only modelled the 2D overland flow using geographic information systems (GIS) and geomorphological features. Omitting the drainage system altogether can be appropriate in severe flood situations, where the contribution of the drainage system is negligible compared to the total amount of stormwater. In the 2008-event, the rainfall was so 563.3mm in 3 days; the drainage system could not compete with this. A similar inundation assessment was done by Luo et al., with the addition of three theoretical precipitation events (Luo et al., 2018). They also omitted the drainage system and used Flo-2D to make a model of the overland flow. The projected inundation after the 2008-event from Luo et al. was also shown in Figure 1.1 in the Introduction. The Flo-2D model was also used to study potential flood damage under the effects of climate change (Kefi et al., 2018). Kefi et al. combined the modelling study with a survey aiming to understand how the inundation problems in Hanoi are perceived by residents. The researchers concluded that residents could benefit from an early warning system to attenuate flood risk.

The similarity between the three modelling studies performed by Dang & Hieu, Luo et al., and Kefi et al., is that their models have the whole city of Hanoi as a study area. Consequently, the resolution of the results is quite low: Luo et al. used grid cells of 30×30 meters. Only slope and surface roughness are considered, and buildings that inhibit flow are not incorporated in the model. Besides, they only consider 2D overland flow and omit the underground drainage system. These results give useful but rough estimates of the flood extent in certain areas, but it is not possible to draw conclusions at the drainage system level. To study drainage system failure, a smaller model at pipeline and street level is required.

Two modelling studies of the drainage system in Hanoi have been conducted on a smaller scale. First, Huan et al. investigated flood mitigation measures by modelling the drainage system in Hanoi's rural area My Dinh (Huan et al., 2016). The model results showed that the mitigation strategies proposed by Huan et al. could reduce peak flows up to 19.4$. In Hanoi's urban area, Chau et al. conducted a modelling study of the drainage system in the Cau Giay district (Chau et al., 2019). Their main finding was that the system needs to be renovated, i.e. the conduit diameters need to be enlarged. The study from Chau et al. comes close to the aim of this thesis. Namely, Cau Giay district is similar to Thanh Xuan in terms of population density and inundation frequency, and Chau et al. simulated the drainage system under different weather conditions. However, in order to understand what mitigation measures are effective, a thorough analysis of the functioning and failure of the drainage system itself is required. This involves quantifying the uncertainties involved and determining the risks associated with the drainage system. In the next section, Probabilistic risk assessment is introduced, which constitutes a useful tool in quantifying the relevant uncertainties and risks.

3.4. Principles of probabilistic risk assessment

The contents of this section are mainly based on two publications. The first is Cur 190 'Kansen in de Civiele Techniek' (Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997). This document is referred to as "Cur 190". This publication describes the principles of probabilistic design in civil engineering in general. The second publication is 'Fundamentals of Flood Protection' by Kok et al. (or: Grondslagen voor hoogwaterbescherming) (Jongejan et al., 2021). These two publications are frequently used for probabilistic design in The Netherlands. The probabilistic analysis and modelling methods presented in Fundamentals of Flood Protection are mainly focused on coastal and fluvial flooding. The present study aims to investigate whether the theory extends to other fields. One essential thing that these two publications have in common, is that they make use of fault tree analysis (FTA). This is a form of probabilistic risk management that considers different types of failure separately. The method of fault tree analysis dates back to 1960 and is often attributed to H. A. Watson. It was first developed to assess the safety of launching a missile, and quickly attained worldwide interest (Ericson, 1999). Nowadays, FTA is applied in many civil engineering practices such as coastal and riverine levee assessment. FTA is a useful tool for authorities, engineers and decision makers because it provides insight in the relative contribution of failure mechanisms.

The standard methodology of probabilistic risk assessment as presented in Cur 190 and Fundamentals of Flood Protection is schematically represented by the flowchart shown in Figure 3.5. The following subsections describe each step.

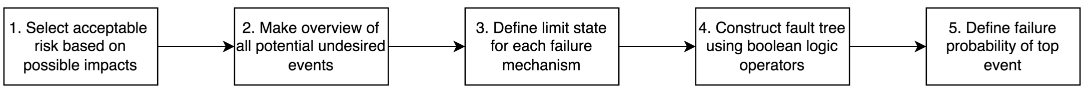


Figure 3.5: Flowchart of standard PRA methodology

3.4.1. Acceptable risk

The first step in fault tree analysis in to select a risk that is acceptable. From there on, design standards and criteria can be developed. Using these criteria, it is then assessed whether or not the structure obeys to the acceptable risk. The selection of an acceptable risk depends heavily on the impact that failure potentially has. Namely, risk is in this thesis defined as the impact of flooding $\times$ the probability that it will occur. There are different kinds of impacts to consider, such as the amount of lives that are in danger and potential monetary damage (expressed in €). In monetary terms, the impact of failure in a structure that protects a e.g. a nuclear power plaint is much higher than when a structure fails that protects an agricultural area. In such a case, the acceptable risk of the first structure is much lower than of the second structure.

The impact of failure of an urban drainage system is in general less severe than failure of coastal or fluvial levees. Therefore, the acceptable risks used for urban drainage systems are much lower than for coastal or fluvial levees. Typical acceptable risks associated with urban drainage systems are below ten years (Butler et al., 2018), while for coastal levees this value can be well above once every thousand years (Jongejan et al., 2021). Determining the acceptable risk is usually a subjective judgement made by weighing different interests. These interests include the livability of the potentially affected area, and economic interests. Economic interests include the costs of construction and maintenance on the one hand, and the costs of potential damage on the other hand.

Acceptable risk in Vietnam

In the Vietnamese design norms for urban drainage, different types of land use are discerned, and ranges of acceptable risks are assigned to them (Ministry of Construction, 2008). The acceptable risks are shown in Table 3.1. The document does not further elaborate on the definition of the different urban area types, but the ranges give an indication of the frequency with which urban flooding in Vietnamese cities is considered acceptable. Industrial park type I refers to industry with ”normal” technology, type II refers to industry with ”production units having special requirements”; these definitions are cited from the design principles. Furthermore the document mentions that urban areas that are situated in a mountainous region require an acceptable risk of 10-20 years.

The values and land use types described in the Vietnamese design norms are fairly vague, but what can be taken from this is that acceptable risks for urban areas in Vietnam range around once every 1-10 years.

Table 3.1: Acceptable risks defined in the Vietnamese design norms for different land use types. The land use types are not further specified in document. (copied from Ministry of Construction, 2008)

Land use type	Acceptable risk
Big city, type I	5-10
Urban area, type II, III	2-5
Other urban areas	1-2
Industrial park with normal technology	5-10
Industrial park with production units with special requirements	10-20

3.4.2. Failure mechanisms

The next step is to make an extensive overview of all potential failure mechanisms events and the consequences thereof. According to the Cur 190, more accidents are caused by not recognising mechanisms than through an incorrect analysis of a known mechanism. In other words, it is important that this step is carried out thoroughly.

3.4.3. Limit states

Once the acceptable risk and all potential failure mechanisms are known, the third step is to define the limit states (Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997; Jongejan et al., 2021). Recall from Section 3.1 that limit states are the states in which no failure occurs just yet. Limit states can be defined for single structures such as pipelines, but also for entire drainage systems. In levee assessment, two types of limit states are distinguished:

1. Serviceability limit state (SLS). This limit is reached when major deformation or damage occurs, which necessitates measures. It does not immediately lead to flooding. For example, when a drainage pipe is clogged with solids buildup, but it is still capable of discharging sufficient amounts of water. The function of the construction might be compromised, but that does not cause the probability of flooding/failure to exceed the required level.

2. Ultimate limit state (ULS): When this state is reached, the construction is permanently unable to function. This happens for instance when subsidence occurs and underground pipelines are deformed, such that they cannot discharge water anymore (Bakker Vrijling, 1980).

A simple reliability or limit state function for component i is defined by Equation 3.6.

$$Z_i = R_i - S_i \tag{3.6}$$

In which R_i is the resistance of structure i, and S_i is the stress applied to structure i. Z_i is the limit state function for structure i. If $Z_i < 0$, then failure of the structure occurs. Both R and S are functions that comprise a number of uncertain variables (Bakker & Vrijling, 1980; Jongejan et al., 2021; Mai Van et al., 2007).

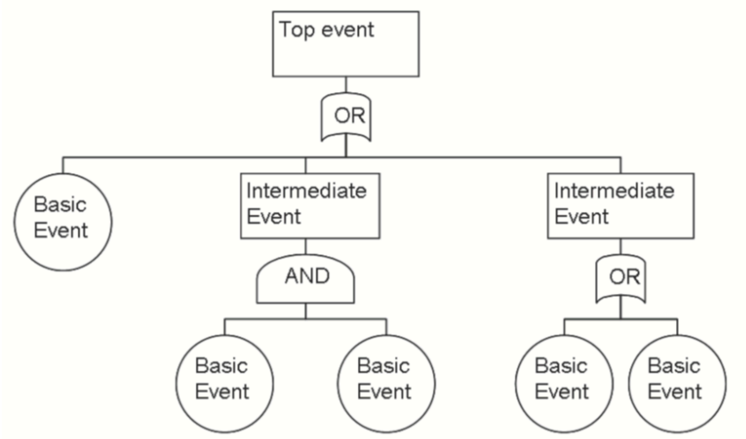


Figure 3.6: Elements of a fault tree model. Source: Ten Veldhuis, 2010

3.4.4. Fault trees

The next step is to construct a fault tree, of which an example is shown in Figure 3.6. As the figure shows, a fault tree consists of different basic events and a top event, and are connected to each other by so-called AND and OR gates. The top event refers to the main problem that is studied, and the basic events form the most detailed level of a fault tree: the failure mechanisms. The AND and OR gates are used to designate how basic events relate to each other and the top event (Ten Veldhuis, 2010). To illustrate, if two basic events are connected by an OR gate, flooding occurs if at least one of the basic events occurs. Similarly, if two basic events are connected by an AND gate, flooding only occurs if both basic events occur.

3.4.5. Failure probability

The last step of fault tree analysis is to determine the failure probability of each basic event and, consequently, of the top event. This can be approached quantitatively as well as qualitatively. Quantitative approaches include solving the limit state function (Equation 3.6) for each system component. This involves an understanding of the loads on the structure as well as its resistance. Detailed elaborations are available for failure mechanisms in the field of e.g. levee assessments and structural engineering (Chen & Lui, 2005; Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997; Jongejan et al., 2021). However, in urban drainage engineering PRA is not as developed and these are not available. The state of the art of PRA in urban drainage engineering is addressed in the following Section 3.5. Another method to determine the failure probability quantitatively of events is by creating a database of failure events, and associating them with the causes for each failure. Examples that have been investigated in the field of urban drainage are newspaper articles, data from emergency call centres, fire brigade action records. A high level of detail is required for these sources to be reliable for a quantitative analysis.

An example of a qualitative approach is to use expert judgement to define the failure probability of basic and top events. Experts that work with the construction on a daily basis are likely to know its flaws and functioning, and remember the problems that caused failure. Experts may be consulted through interviews or by means of surveys.

3.5. PRA of urban drainage: state of the art

Although most modelling studies on urban drainage systems take a deterministic approach (Butler et al., 2018), there are also studies that take a probabilistic approach. The literature described in this section each considered one or more failure mechanisms of urban drainage systems and each research assessed the risk of these mechanisms in a different way. Table 3.2 presents a few of these failure mechanisms.

Gouri and Srinivas (2015) performed a reliability assessment in the city of Bangalore, India, where they considered three different failure modes, included in Table 3.2. To this end, they considered three parameters to be random variables: roughness coefficient, slope and conduit dimensions. The researchers took the semi-probabilistic approach of FORM in combination with SWMM to estimate the reliability of the three failure mechanisms. Lee and Kim (2019) developed a method to calculate the reliability of the drainage system through three factors: nodes, damage, and flood volume. The researchers took the city of Jeongup, Korea, as a case study. The reliability indexes for the three factors nodes, damage, and flood volume are 0.4584, 0.9750, and 0.7726, respectively. They used SWMM to determine the total flood volume as a function of rainfall input with a 100-year return period. It was considered that a node has failed whenever flood occurs, regardless of the flood volume. This resulted in a low reliability index for the nodes but high for the flood volume, because many flooded to a small extent. Flood damage was estimated from the loss off property, which is a function of inundation depth and damage functions that depend on three types land use. The reliability was considered high because only empty sub-areas in the urban study area were the only regions vulnerable to flooding.

A third relevant work is the doctoral thesis 'Quantitative risk analysis of urban flooding in lowland areas' by Ten Veldhuis (2015). Similar to this thesis, Ten Veldhuis conducts a probabilistic risk assessment (PRA) of the Dutch cities of Haarlem and Breda, where much smaller inundation events occur. However the research is fundamental and gives a detailed description of how the probability of seven different failure mechanisms was estimated, which makes it useful for this study. Three out of seven relate to urban drainage systems, which are listed in Table 3.2. Ten Veldhuis used call data in order to assess the frequency of occurrence of each mechanism., which was obtained via call centres and it involved claims and complaints of local flooding. This type of data is textual and must be analysed manually in order to transform it into numerical values.

It stands out that the set of studied failure mechanisms is different for each research. This shows that, in different case studies, different failure mechanisms are considered relevant. Some failure mechanisms only occur in e.g. steep catchments, or in catchment with outdated pipelines. Hence, the set of relevant failure mechanisms is characteristic for each case study, and to assess the risk of Hanoi's drainage system they need to be known first. What is missing is a fundamental approach on how all failure mechanisms of a system are found. Additionally, the literature described in this section relied on specific data types, such as system dimensions and parameters (Gouri and Srinivas), damage functions (Lee and Kim), and call data from call centres (Ten Veldhuis). Call data is not available in Hanoi, because inundation is ubiquitous and people generally do not notify authorities, nor is this data type stored. This research is aimed at probabilistic risk assessment of urban drainage systems under limited data availability.

3.6. Research gap

The main research gap that was identified is that there are many uncertainties when it comes to urban drainage, and that there are little methodologies suitable to cope with this uncertainty. Studies that address uncertainties in urban drainage are often site-specific and only consider one or a few failure mechanisms. In other words, these studies are not transferable to other study areas such as Hanoi. In particular, FTA is a promising probabilistic risk assessment tool which is scarcely applied to urban drainage. These claims are further justified in the following paragraphs.

Urban drainage systems are scarcely modelled probabilistically
Previous PRA's that have been performed on urban drainage systems require large amounts of data. These data are not always available or reliable, which introduces various types of uncertainty in the research. For instance, Ten Veldhuis (2010) used call data to assess the drainage system's reliability. This type of data is not available in areas such as Hanoi, where inundation may occur multiple times per week and not every inundation event is properly reported. Conventional urban drainage models are often deterministic and hence do not effectively account of randomness of underlying processes or uncertainties in general. Urban drainage systems ought to be modelled probabilistically if one wants to capture the effects of the uncertainty.

Previous research is not transferable

Table 3.2: Failure mechanisms of urban drainage systems that have been studied in previous research

Failure mechanism	Description	Article
Runoff exceeding discharge capacity	Water from the drainage system flows onto the surface due to local system overload or downstream component failure	Gouri and Srinivas, 2015; Lee and Kim, 2019; Ten Veldhuis, 2010
Flow velocity too high	The maximum velocity is set to control erosion of the pipelines When it is exceeded occurs, the pipelines start to erode.	Gouri and Srinivas, 2015
Flow velocity too low	The minimum velocity is set to control deposition of the dry weather flow. When deposition of solids occurs, the discharge capacity of the conduit lowers.	Gouri and Srinivas, 2015
Inflow route interruption	Rainwater that falls on an urban surface cannot flow away to a drainage facility and as a result forms pools on the surface	Ten Veldhuis, 2010
Depression filling	Rainwater that has fallen at an upstream location flows over the surface to a downstream location where it cannot enter a drainage facility but remains on the surface.	Ten Veldhuis, 2010
Gully pot blockage	Internal blockage that complicates the flow of water through it	Rietveld et al., 2020

The literature discussed in Section 3.5 always focused on one or a few failure mechanisms, and there is little overlap between the failure mechanisms considered by these studies. This can be seen in the summary of these studies, presented in Table 3.2. The lack of overlap is due to the fact that there is no standard methodology to perform probabilistic risk assessment on urban drainage systems. However, if one wants to apply PRA to Hanoi's urban drainage system, a complete overview of all potential failure mechanisms is required. Hence, there is a need for a unifying framework obtain a full overview of potential failure mechanisms.

FTA is scarcely applied to urban drainage

The only research that could be found that applied FTA to urban drainage systems was performed by Ten Veldhuis (2010). This claim was verified by examining the related articles and the articles that cited Ten Veldhuis on Google Scholar. Google Scholar mentioned 94 related articles, of which three performed FTA as well. Additionally, Google Scholar mentioned 53 articles that cited Ten Veldhuis, of which 5 articles involved FTA. However, none of these articles applied it to urban drainage. It could be concluded from this that FTA is widely used throughout various fields of research, but not in urban drainage. FTA investigates the effects and likelihood of different failure mechanisms and thus a model is required that is capable of capturing these different scenarios. PCSWMM has been used in the past to perform probabilistic risk assessment, but not to apply FTA in particular. That is why this research also functions to examine whether PCSWMM is a useful tool for fault tree analysis and scenario modelling.

Based on the research gap defined in this section, the research questions presented in the introductions were set up. The methodology that was performed to answer these questions is described in the next chapter.

4

Methodology

This chapter describes the methodology used to address the first three research questions stated in the introduction. A general overview of the workflow including these questions is presented in a flowchart, shown in Figure 4.1. As can be seen in this figure, the questions are accompanied by two or more research activities in the middle column. Each research activity has a corresponding output shown in the right column, and are numbered for future reference. Interviews with the drainage company SADCO played an important role in reaching each of the three questions, therefore the approach is presented separately in Section 4.1. The fourth objective was to understand to what extent FTA and PCSWMM are useful tools to carry out PRA of urban drainage systems. This research question is not shown in Figure 4.1, but addressed in the discussion in Chapter 6.

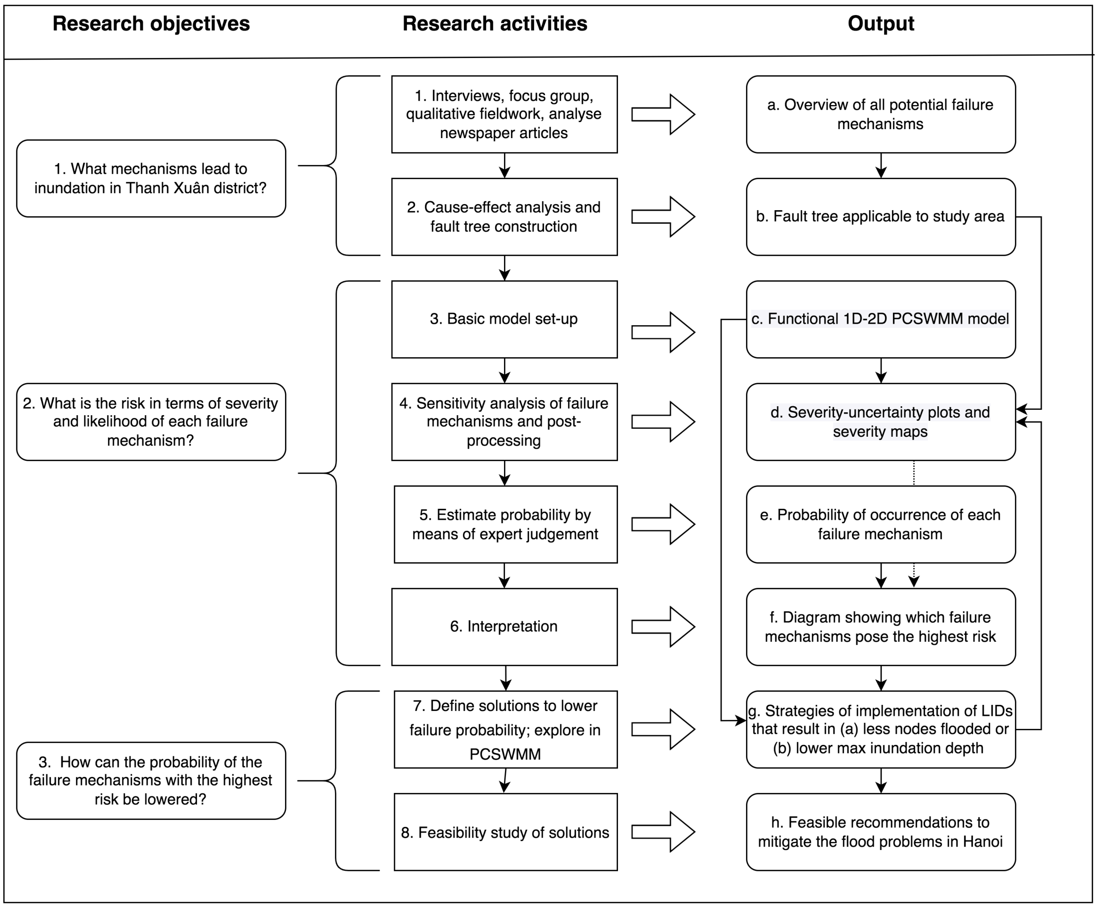


Figure 4.1: Workflow of the methodology to reach the first three research questions. Eight different research activities were carried out, resulting in eight different outputs. The arrows in the right column indicate how the research outputs relate to each other.

4.1. Interviews

The results of the interviews were useful for each of the three research questions depicted in Figure 4.1, so the methodology of the interviews is addressed separately here.

In regard of the first research question, the interviewees were asked to reflect upon the overview of failure mechanisms that was obtained, and asked if there were failure mechanisms missing from the overview. In regard of the second research question, the contribution of each failure mechanism to the total failure probability was discussed. The interviewees were asked to estimate the frequency with which each failure mechanism occurs in a year. In regard of the third research question, recent developments were discussed and the interviewees were asked about what they deem to be realistic and effective measures. To steer the interviews in the right direction and ensure useful results, an interview guide was set up, which is presented in Appendix A.2. This guide includes questions regarding failure mechanisms and solutions, but also other topics such as consequences of inundation, maintenance routines, the role of inhabitants. These topics were included because they could be relevant in formulating effective solutions.

Two interviews with employees from drainage company SADCO were conducted. The first interviewee was senior employee Nguyen Huu Trong, who has more than 10 years experience with Hanoi's drainage system. This interview has been referred to before in Section 2.4.1. The second interviewee was Vu Hoa Linh, engineer at Factory No. 2, who is responsible for the functioning of the drainage system in Nam Từ Liêm district. It has been attempted to interview more employees, but this was not possible due to the language barrier. A translator for extra interviews could not be found in time. The employees of SADCO are assumed to have direct knowledge of the drainage system of Thanh Xuân and its inundation problems: as soon as inundation occurs, SADCO's employees rush to the location of inundation to make a quick assessment of the problem and they try to resolve it on the site. More specifically, they know from experience when and which failure mechanism occurs.

4.2. Causes of inundation

Research question 1: What mechanisms lead to inundation in Thanh Xuân district and how do they relate to each other?

The standard methodology of probabilistic risk assessment, described in the Cur 190 and in Fundamentals of Flood Protection, does not prescribe a method to obtain an overview of failure mechanisms, or to construct fault trees Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997; Jongejan et al., 2021. Therefore, descriptions in this section are derived from the disciplines of levee assessment, and the usefulness in urban drainage is evaluated in Chapter 6 (Discussion). An overview of all potential failure mechanisms was made in collaboration with local experts during a focus group, by means of qualitative fieldwork, and by analysing newspaper articles. This is represented as research activity 1 in Figure 4.1. Research activity 2 corresponds to a cause-effect analysis that enabled to make the mutual relationships clear between the failure mechanisms, such that fault tree could be constructed.

4.2.1. Overview of all mechanisms

Focus group
The (thus far largely undocumented) knowledge regarding dominant failure mechanisms in Thanh Xuân district is mainly posessed by inhabitants and experts. This realisation formed the starting point in forming a focus group.The benefit of having a focus group in addition to separate interviews is that in a focus group, knowledge is exchanged through discussion. The focus group discussion was held on January 13th 2022 online through the platform Zoom. The session was recorded and afterwards transcribed to disclose the arguments that were referred to. An invitation was sent to Hanoi University of Natural Resources and Environment (HUNRE), a university where Vietnamese water resources including urban and rural flooding is researched. In this invitation, the participants were asked to prepare by writing down their experiences and potential causes of failure. During the focus group, these preparations were written down on 'sticky notes' on a digital blackboard, using the visual cooperation platform Miro ("Miro", 2022). The precise course of the focus group is included in Appendix A.

Nine participants with different backgrounds responded and attended the focus group; a full list of the participants and their background and experience is shown in Table 4.1. The different backgrounds facilitate in having a fruitful discussion. All participants either lived in Hanoi at the time of focus group, or had lived there in the past. Hence, every participant had site-specific knowledge and was familiar with Hanoi's inundation problems. One interested researcher from HUNRE was not able to attend and was therefore interviewed individually, as indicated in Table 4.1

Qualitative fieldwork
In April and May of 2022, qualitative fieldwork was carried out in Thanh Xuân district, which involved multiple research activities described in this section. First, site visits served to map flow routes in the study area by localising ditches and drains, and evaluating their dimensions and condition. This was partly done to confirm the assumptions that were made for setting up the drainage model, which is further described in Section 4.3. Another motivation for this was to detect possible failure mechanisms or problems in the form of obstructions or blockages. One of the site visits was undertaken together with an urban drainage master student from the Thủy lợi university.

Table 4.1: Focus group participants including their background and experience at the time of the focus group

Name	Background/experience
Hoang Tung Dao (co-moderator)	PhD in Coastal Engineering at Delft University of Technology (TU Delft) and Lecturer at HUNRE
T. Thu Thuy Nguyen	Water Resources Engineering; Project assistant at RoyalHaskoningDHV
Van Tinh Tran	Water Resources Engineering; Lecturer at HUNRE
Ngoc Huan Tran	PhD in Flooding management in the countryside of Hanoi in Germany; Lecturer at HUNRE
Hong Son Truong	PhD in Coastal Engineering at TU Delft; Lecturer at Thủy lợi Univeristy Hanoi
Van Lan Vu	Lecturer at HUNRE in water resources engineering
Thuy Chi Tran	PhD candidate in China, researching Urban flooding in Central Vietnam; Lecturer at HUNRE
Juliette Eulderink	Project manager at TU Delft. Project: Climate Proof Vietnam collaboration with Thủy lợi Univeristy and HUNRE

Interviewed individually:

Thi Van Le Khoa	PhD candidate water resources engineering at Wageningen University and Research (WUR) and lecturer at HUNRE

An excursion to Nam Từ Liêm district (Hanoi) was undertaken with students and a lecturer researching Hanoi's drainage system, which was led by SADCO's employee Vu Hoa Linh, who was mentioned before in Section 4.1. The excursion involved a brief presentation of recent developments on the drainage system in Nam Từ Liêm district held by Vu Hoa Linh, and a demonstration of the functioning of pumping stations during storm conditions. Furthermore, another purpose of the site visits was to identify potential locations for mitigation measures. This was done by designating areas that were relatively unoccupied, such that LIDs could potentially be constructed. This is further addressed in Section 4.4.1.

Newspaper articles
Whenever a big inundation event takes place, there are many online (Vietnamese) newspapers that report them. Among others, these include VNexpress, Vietnam and Hanoi Times. These articles include pictures of affected sites, and sometimes SADCO or another affliated institute is interviewed. Moreover, some articles report on likely causes of the inundation, citing their interviewees. For this research, these newspaper articles were studied and every cause they addressed was stored, resulting in a long list of mechanisms. Articles were considered relevant if they addressed Hanoi's inundation problems in general, or a specific inundation event, and if they addressed potential causes. To confirm that the articles were reliable, only articles were considered that report events that are also referred to by other newspapers.

The search for articles was conducted from November 2021 to August 2022, and the results were limited to articles published in the last 5 years, so starting from 2017. This was done because Hanoi is quickly changing and the causes addressed in older articles might not be relevant anymore. The search terms were entered into Google Search rather than on the news websites themselves, because of the language barrier. It was only possible to search on e.g. VNexpress.net in Vietnamese, and not in English. The search terms that were used are shown in Figure 4.2.

4.2.2. Fault tree construction

Cause-effect analysis
After transcription, the focus group discussion and the newspaper articles resulted in a long and unordered list of potential causes that relate to inundation in different ways. In order to move from this unordered list to a structured fault tree, a cause-effect analysis was done. In this cause-effect analysis, the ultimate causes of inundation are determined, which resemble the failure mechanisms. The

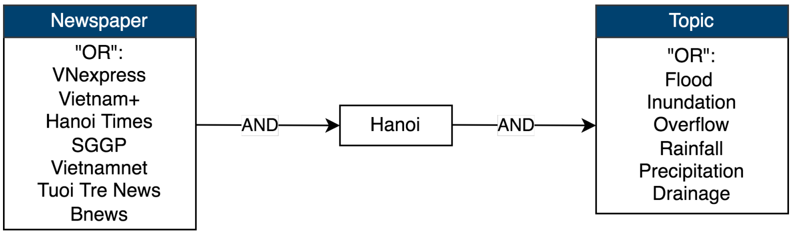


Figure 4.2: Search terms used for collecting newspaper articles on the causes of Hanoi's inundation problems. The newspaper articles in the left column are conjoined by an ”OR” statement, as well as the topics in the right column.

Ishikawa method was used to do this, as it is an efficient method that categorises failure mechanisms (Ishikawa, 1976; Lewis, 2020). This type of diagram is often used as a visualisation tool because it combines the practice of brainstorming with a type of mind map template. The method results in an Ishikawa or fishbone diagram, an example can be seen in Figure 4.3. In this example, the causes were classified into six categories. To determine where the items from the unordered list should be placed in the diagram, the 5W1H method was used (Lynch, 2022). This method requires to ask 6 different questions, which are shown in Table 4.2. For demonstration, the method is applied to one example that that was addressed during the focus group: ’the drainage system is outdated’. The 5W1H method aids in placing every item in the right place in the fishbone diagram. In the example depicted below, the ’why-question’ leads to the realisation that the system is labelled outdated, because of the underlying cause the city has expanded. In other words, the underlying cause of the outdated system is that the city has expanded.

Table 4.2: Demonstration of the 5W1H method with application on the topic ’Hanoi's drainage system is outdated’

What	What components are outdated? What does ’outdated’ mean?
Where	Where are the outdated components located?
When	When does this cause problems? Or: since when is this a problem?
Who	Who is responsible for keeping the system up to date?
How	How did the system become outdated?
Why	Why is the system outdated?

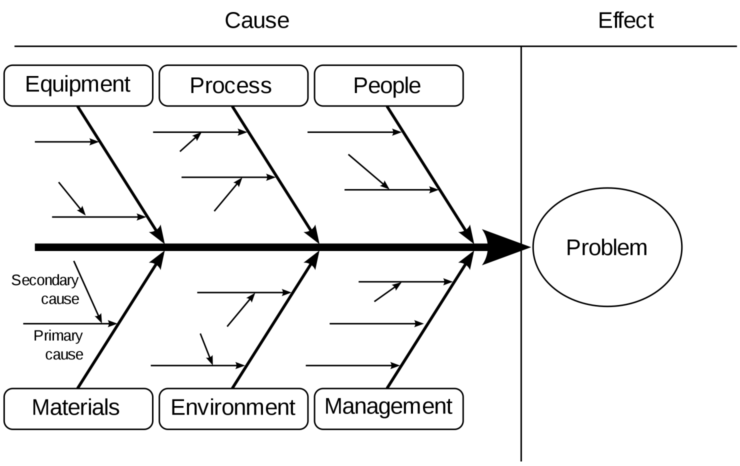


Figure 4.3: Example of an Ishakawa or fishbone diagram

Fault tree construction
The output of the cause-effect analysis is used to construct the fault tree. There are many different types of causes included in the fishbone diagram, and not all of them are failure mechanisms for the drainage system. Only the causes that *directly* lead to inundation are considered failure mechanisms. The resulting fault tree was reviewed and confirmed by supervisor Dr. C. Mai Van, senior lecturer hydraulic engineering and who has extensive experience with fault trees. The fault tree has been verified by the interviewees and SADCO's experts Mr Trong and Mr. Linh. This was done by confirming whether the mechanisms included in the fault tree all occur in Thanh Xuân, and by asking whether they were still missing failure mechanisms in the overview.

4.3. Risk assessment

Research question 2: What is the risk in terms of severity and likelihood of each failure mechanism?

The second part of the research was focused on assessing the risk of each failure mechanism. As stated before, risk is defined by the severity times probability that an event occurs. The severity of inundation induced by failure mechanisms is quantified by means of a modelling study conducted with PCSWMM software. Modelling was done because it gives insight in hypothetical situations, such as rare failure mechanisms or extreme rainfall. The probability of failure mechanisms was estimated with the help of expert judgement. The methodology described in this section follows the structure of the workflow presented in Figure 4.1, and involves research activities 3 to 7.

4.3.1. PCSWMM model

The PCSWMM modelling software was selected for this study, primarily because of two reasons. First, PCSWMM does not require a high degree of modelling experience, as it runs on the SWMM engine, which is very well documented and easy to learn and use. PCSWMM has it's own comprehensive documentation and tutorials, which can be found on www.support.chiwater.com (last consulted Sep 14, 2022). PCSWMM is developed by Computational Hydraulics International (CHI), and obtained by means of an educational grant. The second reason is that PCSWMM offers useful tools including sensitivity analysis and integrated 1D-2D modelling. Sensitivity analysis is useful to determine how input uncertainty relates to output uncertainty, which is in line with the objective of this research to explore uncertainties in urban drainage. Integrated 1D-2D modelling is required to obtain understanding of the inundation events, because extensive overland flow is assumed. This is because typical inundation depths after a heavy rainstorm are up to 500 mm. This could be concluded from newspaper articles and interviews with local drainage authorities (An, 2021; Khanh, 2021; The Smart Local, 2021; VNexpress, n.d.). Additionally, the inundation assessment by Luo et al. showed that the inundation depths after the extreme precipitation event of 2008 were around 0.5-1 metres (Luo et al., 2018). This is much higher than the rainfall that precedes the inundation, which means that runoff is likely to come from the drainage system as well as overland flow.

An overview of the model lay-out is shown in Figure 4.4. The figure shows the conduits, nodes, outfall and system boundary. The system drains towards the outfall OF1, which is located at the To Lich river. As stated before, the model set-up is described in detail in Appendix D. The area that the model covers is approximately 10% of the size of Thanh Xuân district. Initially, a larger model of the whole district was set up, but it was learned that the underlying hydraulic equations are not scalable. A high-resolution model of the entire district would lead to computation times of $\pm$ 30 minutes per run, which is not feasible for sensitivity analysis. The implications of this are discussed in subsection 6.1.2 of the Discussion (Chapter 6).

Modelling with limited data
The main challenge of setting up a model of the study area was data scarcity, and the assumptions that needed to be made regarding model parameters. Data regarding the subcatchment characteristics, system dimensions, and also flood records were not available, and it was outside the scope of this

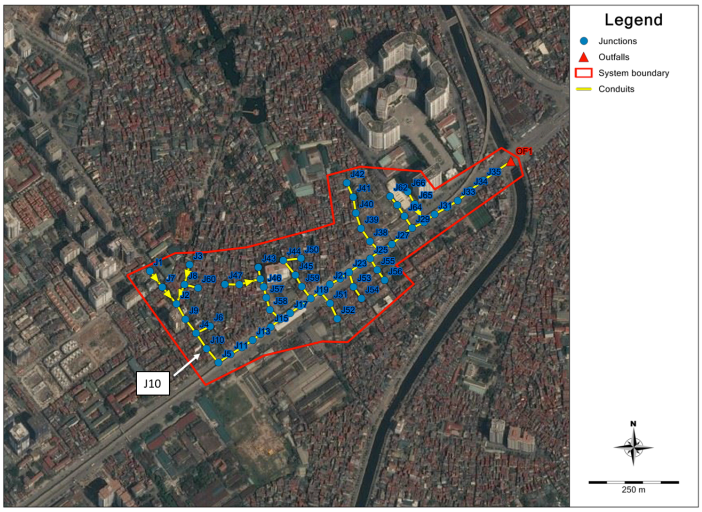
3 

Figure 4.4: Overview of the PCSWMM model layout. Node J10 is indicated; this node floods first in each simulation.

research to collect field measurements. It was attempted to obtain data through SADCO, but this type of data is not publicly available and the language barrier complicates contact as well. Therefore, assumptions were made and a sensitivity analysis was done to investigate the impact of these assumptions. Fourteen parameters were selected to represent the failure mechanisms (further explained in Section 4.3.2), and sixteen more parameters needed to be assumed. These parameters are listed and briefly described in Table 4.3, including their assumed values. For parameters one to eleven, PCSWMM assumed an initial value. Initial assumptions for the remaining five parameters needed to be estimated or otherwise defined. This was done as follows. The subcatchment slope was derived from the DEM and is thus different for each subcatchment. Common seepage or exfiltration rates vary widely between 0.01 for loamy clay, 0.4 for clay, and 10 mm/hour for sand (Alemaw et al., 2016). An initial value of 0.1 mm/hour was assumed, because the dominant soil types of Hanoi are clay and loamy clay clay (Speth, 2020). For the scale factor, it was assumed that the wastewater was mainly produced during 10 hours of the day, so 24/10 = 2.4. The dry weather flow (DWF) was obtained by assuming an average water use per capita of 81 L/day (Ngoc Bao et al., 2013), and by multiplying that with a population of 30,000. As the study area size is roughly 10% of Thanh Xuân, the population of the study area was taken to be 10% of Thanh Xuân's population. This comes down to 0.027 m^3/s.

Assumptions regarding the value of the parameters shown in Table 4.3 introduce an uncertainty in the model. The effects of these assumptions on the model output were quantified, before further model runs were performed. It is important to know the consequences of assumptions, because it gives an indication of the applicability of the model. If the uncertainty in the assumptions affect the model output to a large extent, more research is required with respect to these assumptions. The effects were quantified by means of a sensitivity analysis, such that the system's response to different values for the parameters could be studied. For this analysis, the Sensitivity Based Radio tuning Calibration (SRTC) tool was used, and a precipitation event with a return period of three years was applied. This was done such that inundation would occur, and the sensitivity to the parameters becomes visible. A precipitation event with a return period of two years would not lead to inundation. The parameter uncertainty was set to 100%, to explore a wide range of parameter values. The results were visualised using sensitivity gradients for the node where the largest amount of flooding [m^3/s] occurred, which was node J10. Sensitivity gradients are graphs that show for each parameter the relation between the parameter uncertainty and the maximum flooding [m^3/s] through node J10. The sensitivity gradients are included in the model setup in Appendix D.

The results of this sensitivity analysis showed that the model is especially sensitive to the DWF, which means that it is important that the DWF is as accurate as possible. For this reason, a closer look was

Table 4.3: Sixteen PCSWMM parameters of which the effect of the assumed value on the model output has been investigated.

	Parameter name	Unit	Description	Assumed value
1	Surcharge Depth	m	Depth in excess of maximum depth before flooding occurs	30
2	Dstore Imperv	mm	Depression storage of the impervious area	2
3	Dstore Perv	mm	Depression storage of the pervious area	4
4	Zero Imperv	%	Percent of impervious area with no depression storage	25
5	Percent Routed	%	Percent of runoff routed between sub-areas	100
6	Max. Infil. Rate	mm/hr	Maximum rate on the Horton infiltration curve	3
7	Min. Infil. Rate	mm/hr	Minimum rate on the Horton infiltration curve	0.5
8	Decay Constant	1/hr	Decay constant for the Horton infiltration curve	4
9	Conductivity	mm/hr	Soil saturated hydraulic conductivity	0.5
10	Initial Deficit	-	Initial moisture deficit for soil (fraction)	0.25
11	Suction Head	mm	Soil capillary suction head	3.5
12	Subcatchment slope	-	Ground slope of subcatchment	-
13	Seepage rate	mm/hr	Rate of seepage loss into surrounding soil	0.4
14	Scale factor	-	Scale factor of direct inflow to account for peak water use	2.4
15	Baseline DWF	m^3/s	Baseline value of direct inflow	0.027
16	Ponded Area	m^2	Area of the ponded water when flooded	Area/4

taken to define the DWF for each catchment using characteristic values and a peak flow pattern. Subsection D.1.6 in Appendix D is devoted to the DWF, explaining how it was estimated as accurately as possible. The model showed minimal sensitivity to the other assumed parameters, which can be seen in the results in the next chapter.

System layout and dimensions

Besides the parameters mentioned above, there was no data available regarding the current system layout and dimensions. Reasonable assumptions needed to be made with regard to the conduit and node locations, conduit lengths, directions, slope, and pipeline diameters. The conduit and node locations were chosen in such a way that a conduit is present under every street and every alley. These assumptions were based on the observations that drains were present in every alleyway. Nodes were placed on every corner, at every conjunction of more than two pipelines, and every 30-40 metres. The directions of the conduits were set to be from node J1 to OF1, because the water drains towards the To Lich river at the east side of the study area (see Figure 4.4. The locations and directions of the system elements can be seen in Figure 4.4. Furthermore, the slope of the conduits was set at 0.3% (3 metre per km conduit). This value is adapted from the Vietnamese design norms (Ministry of Construction, 2008, See Table 13 in paragraph 4.7.2). Finally, the pipeline diameters were set using the 'pipe sizing' tool built in PCSWMM. This tool relies on the maximum computed flow through each pipeline after a simulation. The pipeline diameters were considered realistic if they were below 2 metres. According to SADCO's employee Vu Hoa Linh, this is the maximum size for pipeline diameters in Hanoi's city centre[1].

4.3.2. Simulating failure mechanisms

Once the basic model is set up and running, the failure mechanisms were simulated one by one. This was done by selecting parameters that represent the specific failure mechanisms, and setting up experimental value ranges for each parameter. In this way, it was determined under which circumstances flooding would occur and to what extent inundation takes place. The parameters that represent each failure mechanism and their experimental ranges were found by consulting two different types of docu-

[1]This was stated in a personal interview.

	Failure mechanism	Parameter	Initial value	Experimental range
A1 + A2	Elevation mismatch	Junction invert elevation [m]	Variable	-50%-50%
		Conduit inlet offset [m]	0	0.0 – 2.0
		Conduit outlet offset [m]	0	0.0 – 2.0
B	Pipeline blockage	Conduit diameter [m]	Variable	30% - 100%
		Conduit roughness [$m^{1/3}/s$]	0.014	0.01-0.03
C1	Increased imperviousness	Imperviousness [%]	85%	60% - 100%
		Manning's N imperviousness [$s/m^{1/3}$]	0.015	0.01 – 0.02
		Manning's N perviousness [$s/m^{1/3}$]	0.1	0.05 – 0.3
C2	Catchment size increases	Catchment size [m^2]	Variable	1x - 2x
		Catchment width [m]	Variable	1x – 2x
D	Drains are not accessible	Orifice discharge coefficient	0.85	0 - 1
E	Downstream water levels too high	Water level [m]	3	3 – 8.8

Table 4.4: Selected parameters for each failure mechanism and corresponding experimental ranges

ments: Vietnamese design norms and the CHI documentation. The Vietnamese design norms contain tables and guidelines with characteristic values for a variety of parameters. The CHI documentation contains a detailed overview of all parameters, including characteristic uncertainty ranges for each parameter ("Categories of uncertain data", n.d.). For the uncertainty ranges, CHI refers to *Rules for Responsible Modeling* by William James (James, 2005). The selected parameters and their assigned ranges are presented in Table 4.4. Justifications for these parameters and ranges, and notes on how the failure mechanisms were precisely implemented in the model are given in Appendix C.

Once the selected parameters were assigned experimental value ranges, model runs were performed for each parameter value. A choice must be made regarding the amount of model runs for each parameter, to keep the computation time reasonable. Each model run takes approximately 3 minutes and there are 11 uncertain parameters. 9 samples out of each value range were taken, including the initial preset value. In this way, non-linear behaviour of the system response was captured and computation time stays reasonably low (i.e. less than one night). SRTC assumes a uniform distribution for each value range, which entails that the distance between samples is always the same. For example, the range for imperviousness is 60-100%, which means that samples are taken every $\frac{100-60}{9} = 4.44\%$.

Post-processing and visualisation
Given the number of uncertain parameters and the amount of model runs for each parameter value, the model output is very extensive. In total, there are thirty output parameters that can be found in the status report of each of the 99 model runs. Hence, a selection needed to be made on how to interpret and visualise this. Three indicators were chosen: maximum inundation depth [m], maximum flow velocity [m/s], and total flood volume [m^3]. The maximum inundation depth and total flood volume were selected because they designate the magnitude of the event. The total flood volume was visualised together with the inundation depth by plotting it against the parameter uncertainty [%]. These plots are referred to as severity-uncertainty plots. Using these plots, it was possible to find out what the relationship is between the inundation depth and the total flood volume. The maximum inundation depth and maximum flow velocity indicate the danger level of an inundation event, and are used to create severity maps (Kreibich et al., 2009). For each of the six failure mechanisms, two severity maps were created, and for each of the twelve uncertain parameters, a severity-uncertainty plot was created.

Severity-uncertainty plots
The severity-uncertainty plots were created using the SRTC-tool. After each model run, two model output parameters were stored: maximum inundation depth [m] and total flood volume [m^3]. As node J10 has the lowest surface elevation, this node was always the first one to flood. The maximum inundation depth is thus always equal to the inundation depth of node J10. The total flood volume is the sum of the the flood volume of each node. These values are plotted against the parameter value of each parameter, creating 12 different plots. These plots give insight in the influence of the input uncertainty on the output uncertainty.

Severity maps
2D severity maps were created to designate which areas are vulnerable to inundation. For each failure mechanism, two severity maps were created. One that shows the computed maximum inundation depth for each cell, and one that links the inundation depth to the flow velocity in each cell. The first one indicates where inundation occurs and to what extent, and the second one indicates in which cells *dangerous* flooding occurs. Danger is namely not only determined by inundation depth, but also by flow velocity. In order to create the severity maps, PCSWMM requires Standard Query Language (SQL) statements that define the distinct risk levels. These statements signify the thresholds for inundation depth and flow velocity. However, as there is no standard methodology to define these thresholds, a practical approach was chosen. This avoids unnecessary complex mathematical formulations and it is easily interpreted by stakeholders such as SADCO, the people's committees, and residents. The method used to define the thresholds for maximum inundation depth was suggested by Krøgli et al. (2018). It makes use of the height of four different rainboots to classify the maximum inundation depth, see Figure 4.5. The specific heights were determined by Li et al. (2020), and are shown below.

Risk level	**Level 0: Green**	**Level 1: Yellow**	**Level 2: Orange**	**Level 3: Red**
Max. inundation depth [m]	< 0.15	0.15-0.23	0.23-0.43	>0.43

The second type of severity map that was created was by considering the maximum flow velocity [m/s] in each cell. Critical flow velocities were linked to the computed inundation depths using U.S. guidelines for hazard classification (Trieste, 1988). In these guidelines, several graphs are presented that relate flow velocity and inundation depth to danger levels for buildings, vehicles, adults and children. The latter is chosen to use, because children are the most vulnerable and these graphs are the most conservative with regard to danger. Besides, the depth-velocity-danger relationships for children are timeless and transferable to other areas because the vulnerability of children is the same everywhere. This is not the case for the relationships for vehicles and buildings, as these are different throughout the world, and the danger relationships may change over time. The graph for children is shown in Figure 4.6a.

The PCSWMM tool that was used to create severity maps has limited logical operators, which entails that the curves shown in Figure 4.6a could not be followed precisely. The logical operators include ’=’, =<>=, ’>’, ’<’, ’≤’, and ’≥’, and only allow for statements that cover rectangular-shaped areas. In order to follow the curves closely, rectangles with widths of 0.1 m/s were drawn, as shown in the lower image in Figure 4.6b. These areas were translated to SQL statements, which were used as input for PCSWMM's tool ’create severity maps’. The SQL statements can be found in Figure D.8 in Appendix D.

4.3.3. Probability of occurrence
Expert judgement was considered the most reliable method to estimate the probability of occurrence of each failure mechanism. A survey was drawn up to allow as many employees from SADCO to estimate the failure probability of each mechanism. It was attempted to reach employees such as engineers, planners and maintenance workers, but due to challenging communication through a language barrier, the survey did not successfully reach SADCO. The survey has been added to Appendix A, so that it could be used in the future.

Expert judgement was acquired during the two interviews with SADCO, where the interviewees were asked to estimate the frequency with which each failure mechanism has occurred in Thanh Xuân in

Figure 4.5: Practical representation of flood risk levels, symbolised by rubber boots (Krøgli et al., 2018)

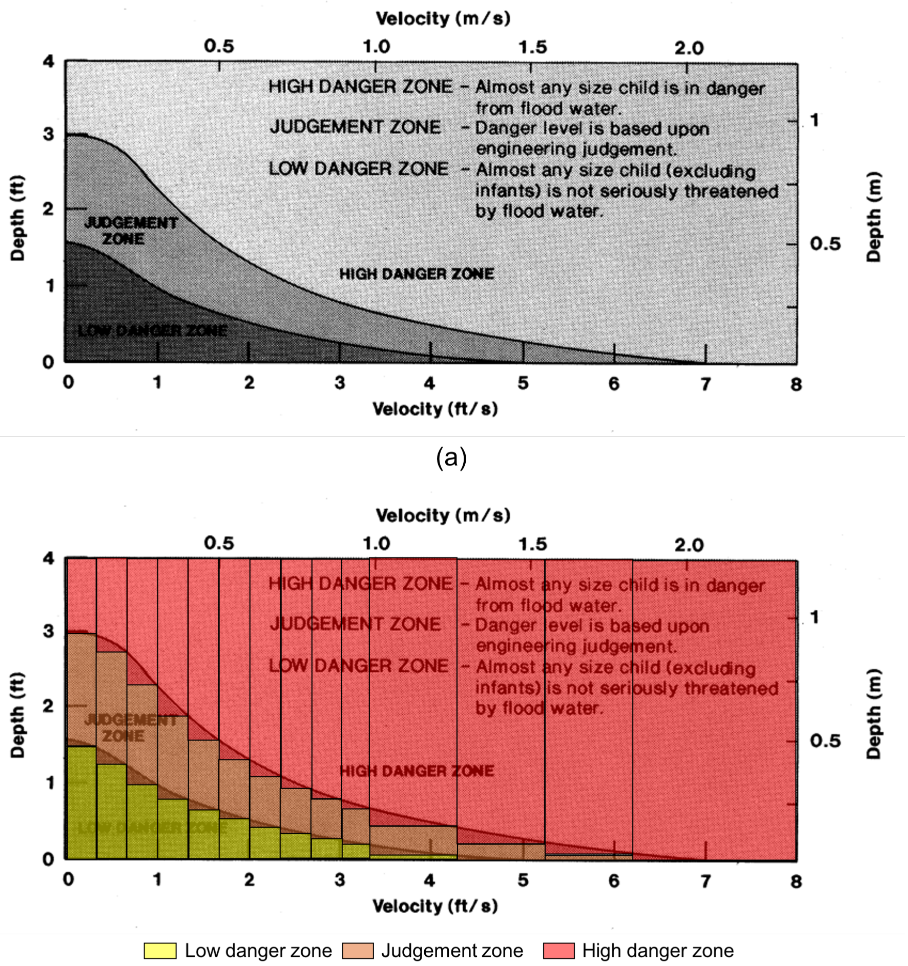


Figure 4.6: Relationship between danger, inundation depth, and flow velocity according to U.S. guidelines for hazard classification (Trieste, 1988) (b): PCSWMM severity map representation.

the last five years. This value was translated to probability: if a failure mechanism occurred 3 times in 5 years, this means that the probability that it occurs in a year is $\frac{3}{5} \times 100\% = 60\%$. Note that the theoretical probability of such an event actually depends on the probability distribution assigned to the event. This number is a rough estimate. For a detailed analysis of probability theory, see e.g. Chapter 2 of Cur 190 (Civieltechnisch Centrum Uitvoering Research en Regelgeving, 1997).

It was attempted to obtain flood records of the inundation events in the study area, ideally including causes of failure. In virtue of this, real-time inundation was tracked over the monsoon period of 2022 using the application HSDC maps, which has been referred to before in Section 2.4.1. However, the information stored in this application is limited to total precipitation [mm] of 42 rain gauges, and inundation depth [m] at 31 locations in Hanoi. The application does not provide further information, such as the cause of the failure. A few other sources were appealed to, trying to obtain relevant data. It was attempted to obtain flood records via contacts via HUNRE and Thủy lợi university, but this did not succeed. SADCO was also asked directly to share these documents, but they are not publicly available. The only documents that could be obtained via Thủy lợi and SADCO referred to precipitation records that report on the annual average, and records of the water level of the Red River. Both documents were not directly useful, therefore expert judgement was considered the most reliable data source.

4.3.4. Interpretation

Urban flooding in Hanoi is ubiquitous, and it is not feasible to consider every occurrence of inundation as failure that requires a solution. This thesis aims to recommend the most effective solutions to tackle the failure mechanisms that are both likely to occur and induce severe inundation as well. Therefore, failure mechanisms are not only considered if they have an insufficient failure probability, but also if they are considered 'severe'. Severity of an event is difficult to define, because it is subjective and also depends on damage, and damage assessment is outside the scope of this research. It was therefore decided to only consider failure mechanisms that lead to inundation events that are large enough to inundate a small alley and induce damage. This holds for total flood volumes of 100 m^3 or more.

The accepted probability was assumed to be once every two years. This value is based on two sources. First, the Vietnamese design norms indicate a range of once every 1-10 years for the acceptable risk (see also Table 3.1). Second, Prof. Dr. Vu Trong Hong stated that the discharge capacity of the drainage system is 100mm in two hours (An, 2021). According to the IDF curves derived by Nguyen et al. (2009), this has a return period of 1.85 years. This indicates that the system was originally designed to fail every 1.85 years (A. T. Nguyen, 2009). Hence, failure is not acceptable if it occurs more frequent than $\frac{1}{1.85} = 0.54$ times per year, and thus the total sum of probabilities of each failure mechanism is <54%. In order to realise this, the aim is to reduce the probability of occurrence of every failure mechanism to a maximum of 10%. As stated before, theoretical probability theory prescribes a more complex approach to these calculations. However, it was outside the scope of this research to determine these exact numbers completely. Additionally, since there are no flood records available, little is known about the frequency of inundation, let alone the probability distributions of these events. Therefore, this research works with rules of thumb and provides recommendations for further research.

The last step is to plot the probability of occurrence and the total flood volume against each other to clarify the risk of each failure mechanism. A high risk indicates that mitigation measures are required, and a low risk indicates that the failure mechanism is not a priority.

Table 4.5: LID implementation strategies that were tested in the PCSWMM model

Strategy	LID type	Amount per subcatchment
A1	Green roof	50
A2	Blue roof	50
A3	Infiltration trench	50
A4	Rain barrel	100
A5	Rain barrel	10

4.4. Solutions

Research question 3: How can the probability of failure mechanisms with an unacceptably high risk be lowered?

This part of the research proposes solutions to lower the failure probability of the failure mechanisms with an unacceptably high risk. Depending on the type of failure mechanism, there are different types of solutions to be recommended, which can be roughly divided in two categories. The first category has a focus on the existing drainage system and will be referred to as *grey* solutions. Such solutions include more frequent cleaning and maintenance, enlarging pipelines, and replacing other system components. The second category has a focus on reducing the runoff peak by implementing green-blue infrastructures or LIDs, as addressed in subsection 3.2.3. This category is referred to as *green* solutions. The PCSWMM model was used to test the effectiveness of the second type.

4.4.1. Modelling LIDs

Eight types of LIDs are included in the PCSWMM software, of which four include the soil layer and rely on percolation into the ground soil. Since the dominant soil type is clay, high percolation rates are not realistic in Hanoi and therefore these LIDs were not considered for this research question (Speth, 2020). The remaining four LID types were implemented in the model and two outputs were generated. First, the potential storage of each LID type was investigated by running 4 simulations per LID type and storing the output parameter 'Final storage'. Next, the implementation strategies shown in Table 4.5 were added to the model one by one to test their influence on the total flood volume induced by the failure mechanisms. The model output with and without LID's was compared and the potential to reduce the total flood volume [m^3] is used as an indicator of the effectiveness of the LID. The following assumptions were made. The surface area of blue and green roofs is assumed to be 25 m^2, and the storage potential respectively 300mm and 100mm. The potential storage of rain barrels is 1000 mm, and they are connected to a surface area of 10 m^2. Infiltration trenches hav a storage depth of 300 mm and a surface area of 15 m^2. These values are estimates based on guidelines that are set up by Jeffers et al., 2022.

4.4.2. Feasibility study

It was outside the scope of this study to perform tests with the LIDs in the field and to make a cost assessment, but two research activities were performed to test the feasibility of the proposed solutions. The results of the feasibility study were taken into account in formulating solutions for each failure mechanism.

The first research activity was a site visit to designate areas that could possibly offer space for LIDs. This was done because most LIDs take up space, which is scarce in the densely populated Thanh Xuân district. Spatial restrictions are likely to be the limiting factor when implementing LIDs. The second activity is that the proposed solutions were submitted to two different experts to find out to what extent they are in line with the works of SADCO, and to discuss the role of local inhabitants. The first expert was SADCO's senior employee Nguyen Huu Trong, who has been referred to before. Mr. Trong indicated that local residents can play an important role, but due to the language barrier, this could not be elaborated further. Therefore, a second expert was interviewed, who was Le Quanh Binh, director of ECUE consultancy and coordinator of the Livable Hanoi committee. Mr. Binh is committed to engage local citizens to create a resilient and liveable city. He was interviewed to get an image of the extent to which residents are familiar with the inundation problems and their potential role in it. This is useful to estimate whether residents are willing to maintain LIDs such as green roofs and rain barrels, and to discuss certain handles that are useful for devising an implementation strategy, such as educational programs.

5 Results

This chapter presents the results that were obtained in this study. Similar to the methodology, this chapter follows the workflow shown in Figure 4.1. Whereas Chapter 4 explained eight different research activities, this chapter presents the eight resulting research outputs. It is divided into three main sections, which correspond to the first three research questions. The fourth research question is addressed in the discussion.

5.1. Causes of inundation

Research question 1: What mechanisms lead to inundation in Thanh Xuân district and how do they relate to each other?

5.1.1. Collecting all potential failure mechanisms

The focus group discussion and the analysis of newspaper articles both resulted in a long list of processes and mechanisms relating to failure of the urban drainage system. They are shown in Tables B.1 and B.1 in Appendix B, respectively. Below some notes are given regarding these results, and the findings from the site visit are described.

Thirty remarks relating to Hanoi's drainage system were written down during the focus group on the digital blackboard by the participants. Some refer to processes or mechanisms that directly affect flooding, such as 'too much pavement', and some are more casual comments such as 'too many skyscrapers'. Many notes showed overlapping content and were grouped together. The notes that referred to processes and mechanisms that induce flooding are included in the list in Table B.1.

The search for newspaper articles resulted in a lot of articles (>200) discussing potential causes of the inundation problems. Not all newspapers reported on the inundation problems equally frequent or useful. VNExpress published a lot of articles that involve interviews with experts, whereas Hanoi Times barely reported on inundation events. An overview of ten of the most relevant articles is given in Appendix B. The overview includes the precise search terms, titles of the articles, and the causes that are discussed. Other findings from the articles were also denoted, for example about the mitigating solutions that have been constructed or planned. Some articles also reported on SADCO's activities during precipitation and inundation events. The causes and other findings are excerpts from the articles. The remaining articles that were found showed overlapping content with the ones presented here. The overlap of articles from 2016 and 2022 suggests that the causes from 2016 have not yet been solved.

The site visit turned out to be a useful addition to the focus group and the newspapers, because observations were made that were not apparent from these sources. Figure 5.1 shows three examples of these observations. The left picture shows a mat that was placed on a drain, preventing runoff from entering the system. Through personal communication with local inhabitants, it turned out that these

Figure 5.1: Observations from the site visit. Left: inhabitants placed a mat on a drain. Middle: stolen lid, leaving an entrance for large objects. Right: blocked drain due to lack of maintenance

were deliberately placed by local residents to reduce the odour coming from the sewer. The amount of drains that were blocked in this way varied throughout Thanh Xuân district. In some streets roughly 50% of the drains were blocked in this way. The middle picture shows the entrance of the drainage system where the metal lid that covers the system was stolen. This clears the way for large objects to enter the drainage system by accident, which block the flow during rainfall conditions. At the same time, large objects might be placed in the drains to prevent accidents while also blocking the flow. The right picture shows a drain that was completely blocked by debris, possibly due to overdue of maintenance. These are three examples of failure that were observed during the site visit.

5.1.2. Cause-effect analysis and fault tree

The list that resulted from the focus group, fieldwork and newspaper articles was used as input for the cause-effect analysis. The completed Ishikawa cause-effect diagram is shown in Appendix B. Many mechanisms could be traced back to one underlying cause, namely that the drainage system is outdated due of urbanisation. This was extensively discussed in the focus group and mentioned in most newspaper articles. The outdated drainage system gives rise to a multitude of failure mechanisms, such as a deficient discharge capacity at different locations in the drainage system and prolapsed pipelines due to subsidence. Another indirect way in which urbanisation affects the drainage system, is that the increase of population density means an increase in waste, both in the form of dry weather flow (DWF) and waste in the form of rubbish on the streets. An increase in either types of waste means an increase in required maintenance and cleaning frequency. If the maintenance and cleaning schedules do not keep up with the pace of urbanisation, the condition of the drainage system deteriorates.

The mechanisms from the Ishikawa diagram that directly induce flooding were eventually selected to be modelled. As described in the methodology, the final overview of failure mechanism has been confirmed by SADCO's experts Mr Trong and Mr. Linh. The fault tree is shown in Figure 5.2. The failure mechanisms are shown in the rectangle boxes on the bottom of the figure and are numbered A1 to E. They are all connected by an OR-gate, meaning that drainage system failure occurs if at least one of the failure mechanisms occurs. Three other OR-gates are placed. One connects 'rainfall exceeds threshold' with 'drainage system failure', because inundation of the streets happens when one of these two occurs. Furthermore, a mismatch of system components is brought about by failure mechanism A1 or A2. Last, 'insufficient discharge capacity' can result from mechanisms C1 or C2, hence they are connected by an OR-gate as well. Table 5.1 indicates which sources addressed each failure mechanism. A brief description of each failure mechanism is given in Table 5.2 and a more detailed one is presented in Appendix C. This appendix also includes how the mechanisms were simulated.

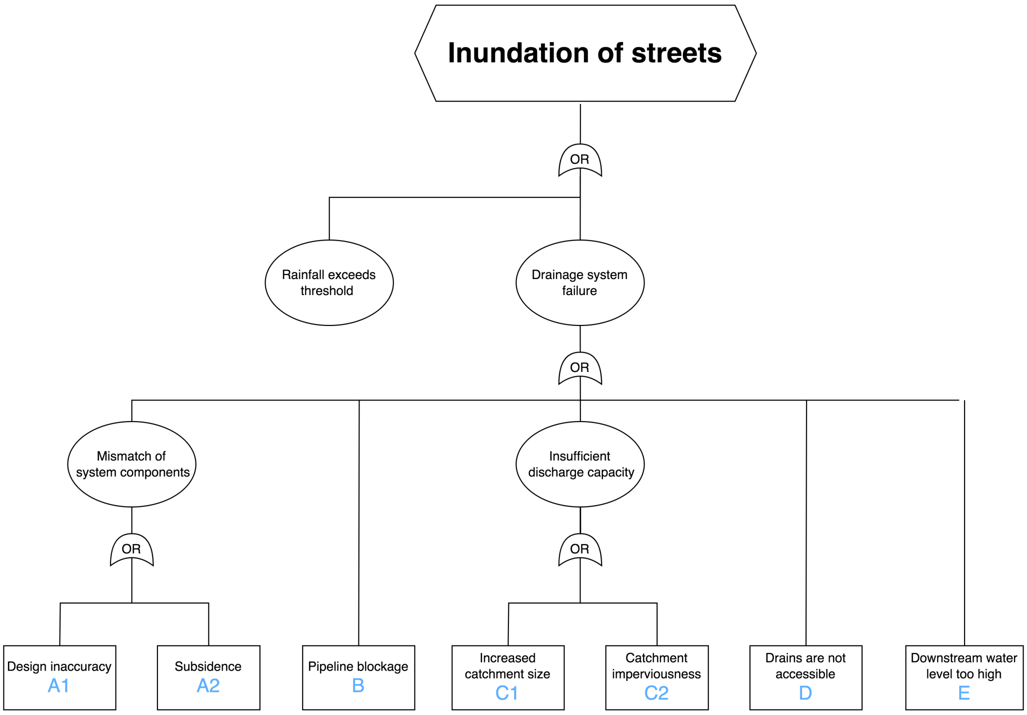


Figure 5.2: Fault tree for Thanh Xuân district, Hanoi. The failure mechanisms are numbered A1 to E for future reference

Table 5.1: Overview of the failure mechanisms and the sources that referred to each of them

		Newspaper articles	Site visit	Focus group	Interviews
A1	Design inaccuracies			x	x
A2	Subsidence	x			
B	Pipeline blockage	x	x		x
C1	Increased catchment size	x		x	
C2	Increased imperviousness	x		x	x
D	Inaccessible drains		x		x
E	Downstream water levels too high			x	

Table 5.2: Brief description of the seven failure mechanisms

	Failure mechanism	Description
A1	Design inaccuracy	This failure occurs when new system components are built and do not properly connect to the existing system because there is no design standard used. The resulting elevation mismatch causes sudden drops and rises in the system, and insufficient slopes of conduits.
A2	Subsidence	Disruptions in elevation due to e.g. construction works and groundwater extraction. Subsidence causes similar problems as failure mechanism A1.
B	Pipeline blockage	It can occur due to the accumulation of solids in wastewater, or because large objects enter the drainage system via drains.
C1	Increased imperviousness	Strongly associated with urbanisation. The main drainage system was initially designed for a certain catchment, and that area has increased since then.
C2	Increased catchment size	As green areas make room for paved areas such as streets and buildings, the infiltration capacity reduces and more rainfall ends up as runoff. The main difference with C1 is that the catchment size does not necessarily increase
D	Inaccessible drains	The access to drains is often deliberately blocked by local residents to block the foul stench from the sewer.
E	Downstream water levels too high	This failure mechanism entails that drainage through the system outlet is complicated, because the water level of the downstream surface water is too high. The failure can be caused by insufficient further downstream.

5.2. Risk assessment

Research question 2: What is the risk in terms of severity and likelihood of each failure mechanism?

The preliminary modelling results are presented in Section 5.2.1, and the results of the sensitivity analysis are shown in Section 5.2.2. The estimated probability of occurrence of each failure mechanism is presented in Section 5.2.3. Finally, the severity maps that resulted from post-processing the modelling results and the interpretation are given in Section 5.2.4. The interpretation involves the answer to the second research question and a selection of failure mechanisms that have an unacceptably high risk and require a mitigation strategy.

5.2.1. Preliminary modellings results

Preliminary modelling results are shown here to demonstrate the functioning of the model under wet weather conditions. That is, without the application of failure mechanisms. The model was calibrated such that its discharge capacity is 100 mm in 2 hours. This aspect is demonstrated in Figure 5.3, which shows profiles of the model with two different precipitation events. One event with a total rainfall of 95mm in 2 hours, and one with 105 mm in 2 hours. It can be seen in the figure that with 95 mm precipitation, the system is fully surcharged. with 105 mm of precipitation, the hydraulic grade line (HGL) exceeds the surface elevation at node J10, causing water to leave the system and inundate the street.

5.2.2. Sensitivity analysis

The results of the sensitivity analysis are presented in this section, which includes the severity-uncertainty plots, inundation maps and 2 types of severity maps. An interpretation of these results is given in subsection 5.2.4.

Only six out of fourteen input parameters affected the model output parameters to a noticeable extent. The six resulting severity-uncertainty plots are shown in Figure 5.4, and the remaining eight plots for the parameters that showed little or no response are included in Appendix E. As described in the methodology, the severity-uncertainty plots were used to find the conditions to create one inundation map and two severity maps for each failure mechanism. The first severity map only takes inundation depth into account, the second one also takes flow velocity into account. The inundation maps are presented in Figure 5.5, the severity maps for depth in Figure 5.6 and the severity maps for depth and flow velocity are shown in Figure 5.7.

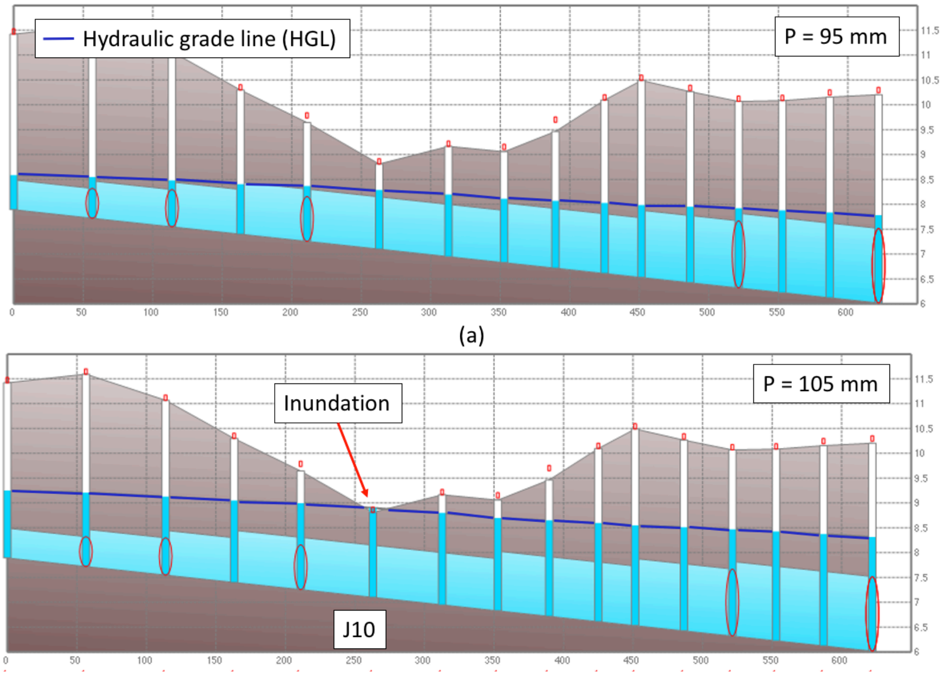


Figure 5.3: Profiles of the main drainage pipe at the peak flow during a 2-hour rainfall event with a rainfall intensity just below the design discharge (upper), and just above the design discharge (lower). In the lower image, the hydraulic gradient line (HGL) rises above ground level at node J10.

5.2.3. Probability of occurrence

The estimated probability of occurrence of each failure mechanism is given in Table 5.3 below. The estimates were given by Mr. Nguyen Huu Trong. It is important to note that the estimates in this table were given by only one interviewee from SADCO. Although Mr. Trong is experienced with the system and its failure, it is just one person. Despite efforts to reach more experts, the results could not be verified by confirming with others.

Table 5.3: Estimated probability of occurrence of each failure mechanism, per year.

	Failure mechanism	Probability of occurrence
A1	Design inaccuracy	30%
A2	Subsidence	5%
B	Pipeline blockage	100%
C1	Increased catchment size	100%
C2	Increased imperviousness	5%
D	Inaccessible drains	50%
E	Downstream water levels too high	5%

5.2.4. Interpretation

This subsection interprets the modelling results and probability of occurrence per mechanism by addressing each failure mechanism separately. Subsequently, the severity in terms of total flood volume [m^3] is plotted against the probability of occurrence [%] for each mechanism, to give a clear image of the risk of each mechanism.

A1 and A2: Design inaccuracies and subsidence

Failure mechanisms A1 and A2 were considered together, because the selected model parameters and experimental ranges were equal for both mechanisms. The model output was not affected by the inlet and outlet offsets of the conduits. The likely reason for this is that PCSWMM requires either conduit

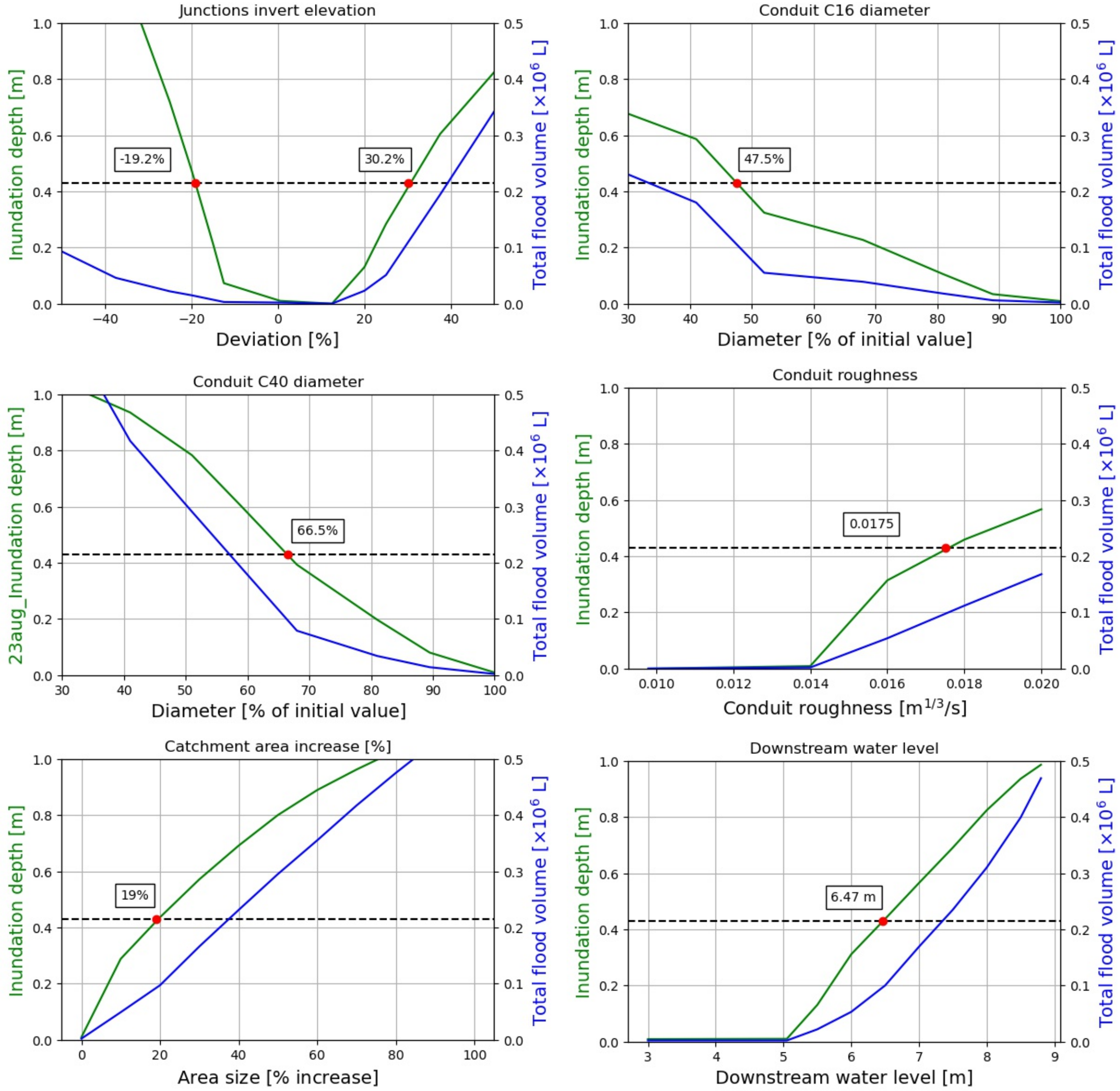


Figure 5.4: Severity-uncertainty plots indicating the relation between parameter value and output parameters max. inundation depth [m] and total flood volume [m^3]

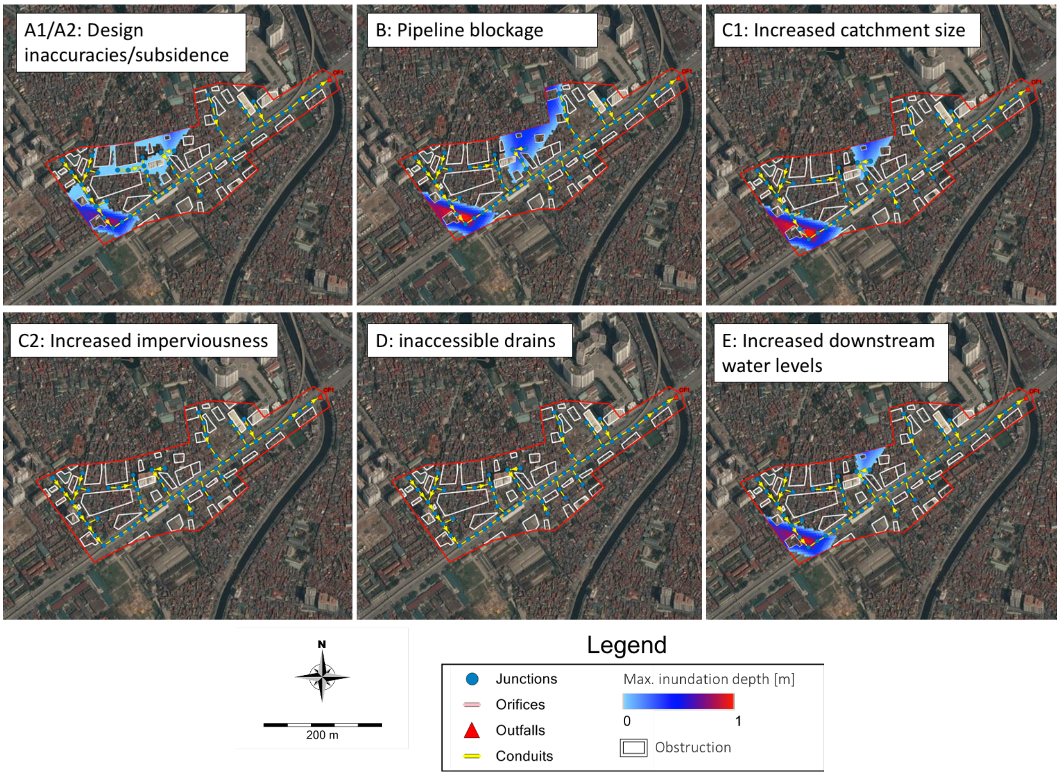


Figure 5.5: Inundation maps for each of the six failure mechanisms

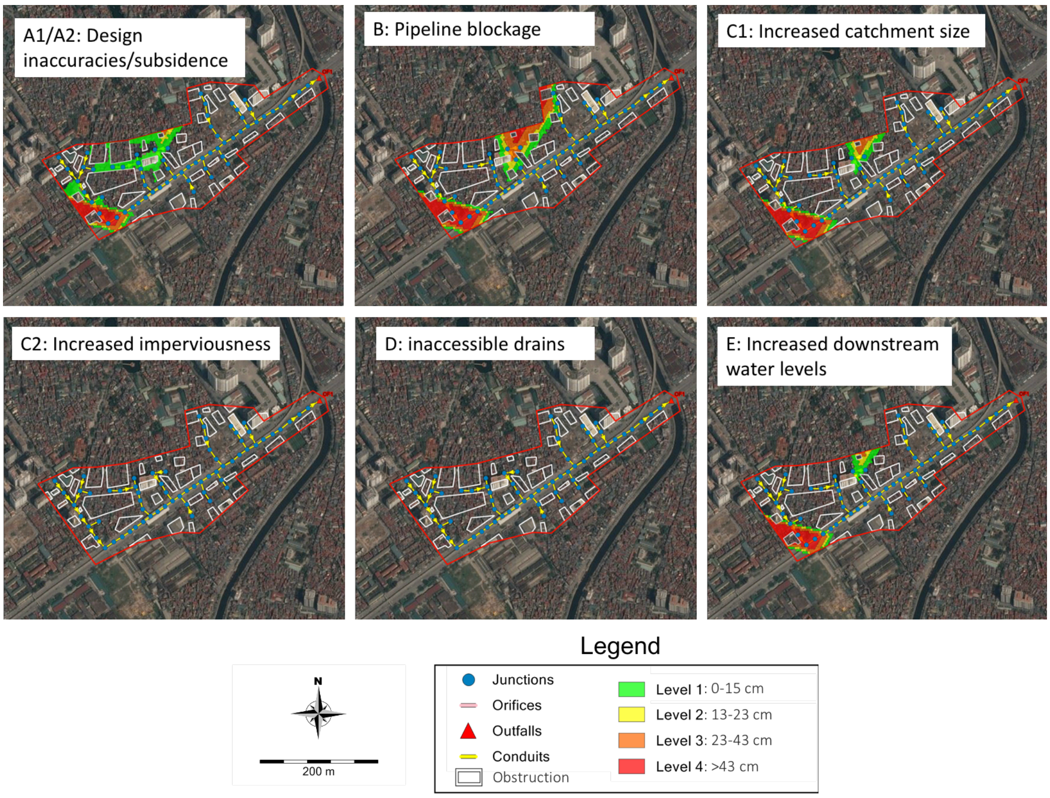


Figure 5.6: Severity maps indicating the severity of the maximum inundation depth [cm]

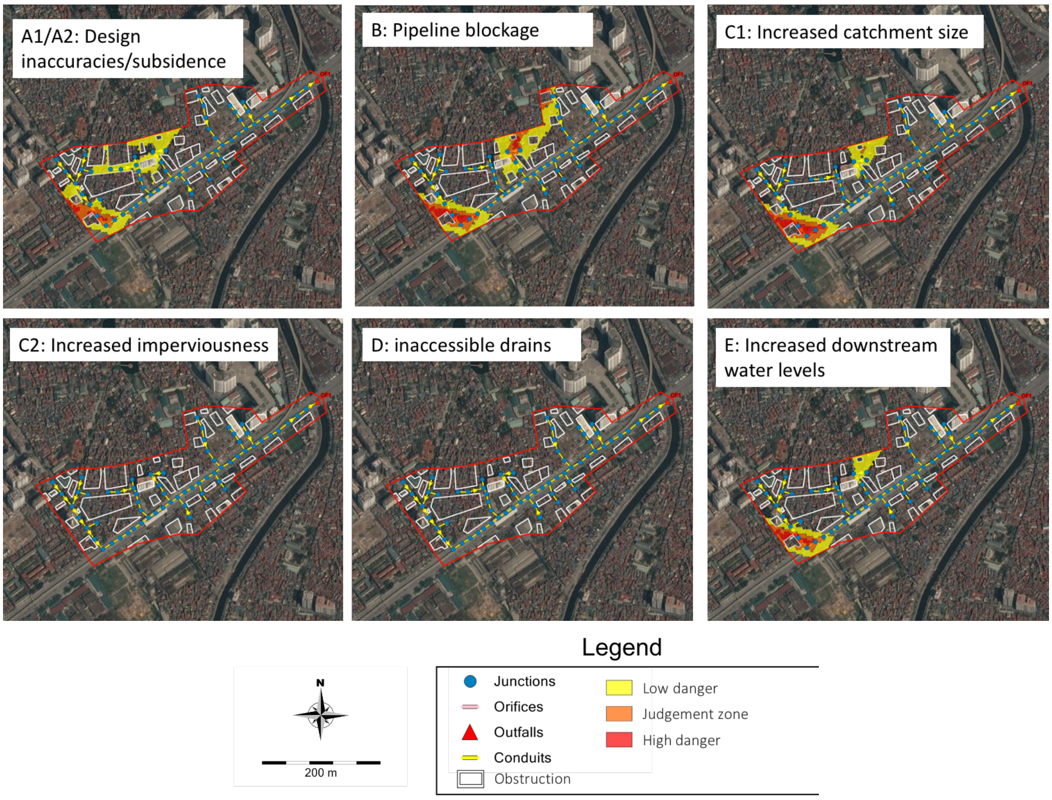


Figure 5.7: Severity maps indicating the danger level using maximum inundation depth [m] and maximum flow velocity [m/s]

offsets, or junction invert elevations; not both. In this case, the junction invert elevation is crucial as it is the reference point of all other elevations in the system. Hence, uncertainty of the junctions invert elevation affected the inundation extent a lot. This holds for both a decrease as well as an increase of the junction invert elevation. However, although a lower junction invert elevation causes high inundation depths, the total flood volume increases especially with a higher invert elevation. This indicates the a lower elevation is likely to cause local inundation (less total flood volume), whereas a higher elevation causes inundation problems spread over a larger area.

Regarding the probability of occurrence of design inaccuracies, the interviewee from SADCO admitted that many decisions regarding design and maintenance are made based on experience of the company. When new system components such as new conduits are designed, there is no certain calculation method to be followed. This entails that design inaccuracies occur very frequent and were assigned a probability of 30%. Subsidence was assigned a probability of 5%.

B: Pipeline blockage

Based on the modelling results, pipeline blockage can cause high inundation depths, total flood volumes and flow velocities, although it depends on where the blockage occurs. From the four locations where pipeline blockage was modelled, the results showed that upstream locations have little effect on inundation. A 33.5% decrease of the diameter of conduit C40 and a 52.5% decrease of C16 result in inundation depths that exceed the threshold of 0.43 metres. This failure mechanism was also simulated by exploring the effects of the conduit roughness uncertainty. Based on the modelling results, a conduit roughness of 0.175 causes inundation depths up to the threshold of 0.43 metres. The severity of inundation caused by failure mechanism B depends a lot on the location of the blockage. The total flood volume is therefore represented as a range in Figure 5.8.

C1: Catchment size increases

Based on the severity-uncertainty plots, an area size increase of 19% would lead to a maximum inundation depth of 0.43m. The area width affects the model output minimally. This is most likely because the time between the rainfall peak and the maximum inundation is about 15 minutes, while the rainfall peak has a duration of 60 minutes. Increasing the width would only affect the model if the time of concentration would exceed the rainfall peak duration.

C2: Increased imperviousness
All three parameters that were used to simulate the increase in imperviousness affect the model output minimally. This is presumably due to two reasons. First, the % imperviousness was already very high to begin with (85%). An increase to 100% did not alter the composition of the study area enough to increase the probability of inundation. The second reason is, again, that the time of concentration is too little, or the duration of the rainfall peak too high. Namely, the other two parameters, Manning's roughness coefficients for impervious and pervious area, affect the time of concentration, of which the effects are not visible in the model output. Additionally, failure mechanism C2 was assigned a low probability of occurrence and can therefore be considered negligible.

D: Inaccessible drains
Failure mechanism D could not be simulated by the PCSWMM model, despite different efforts described in Appendix C. The total flood volume induced by failure mechanism D could thus not be modelled. However, the interviewees of SADCO have indicated that it is a major problem for the drainage of Hanoi. It should therefore not be omitted from the risk analysis. A rough estimation of the total flood volume is shown in Figure 5.8 by the dashed line.

E: Downstream water levels too high
Based on the severity-uncertainty plot, it can be seen that the maximum inundation depth depends linearly on the water level in the To Lich river. The severity threshold of 0.43 metre inundation depth is reached if the water levels exceed 6.47 metres. However, the failure mechanism has a low probability of occurrence and can be considered negligible.

Summary
To summarise, four out of seven failure mechanisms turned out to have an unacceptably high risk and require solutions that lower their failure probability. Figure 5.8 shows an overview of the results, where the severity is plotted against the probability of occurrence. Based on the probability of occurrence, three out of seven failure mechanisms can be considered negligible, and four mechanisms have a failure probability higher than 10%. Based on the severity maps, two out of these four potentially lead to inundation with dangerous inundation depths and flow velocities: pipeline blockage and increased catchment size.

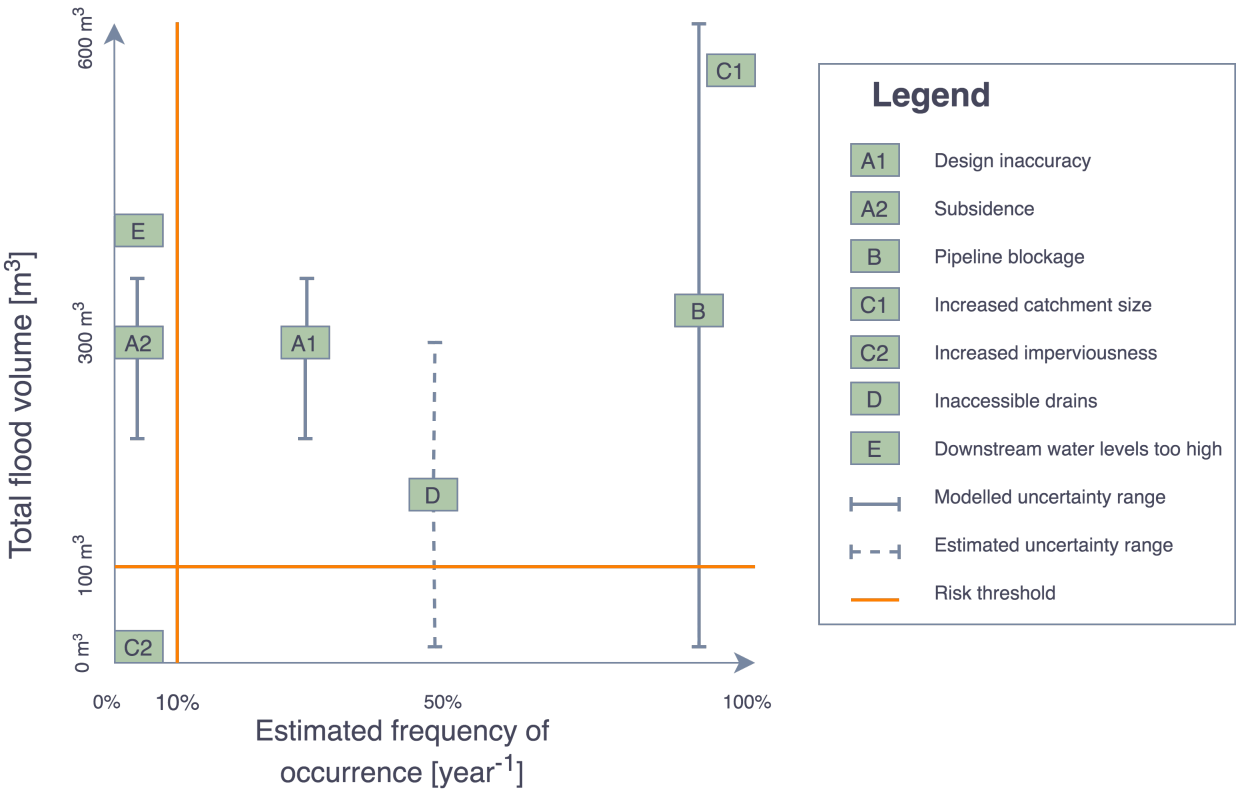


Figure 5.8: Severity of failure mechanism plotted against the probability of occurrence. The failure mechanisms above and right to the orange lines require mitigation strategies

5.3. Solutions

Research question 3: How can the probability of failure mechanisms with an unacceptably high risk be lowered?

This section presents solutions to reduce the failure probability of the four mechanisms with an unacceptably high risk. The modelling results are presented in subsection 5.3.1, solutions for each mechanism are suggested in subsection 5.3.2, and a discussion regarding their feasibility is given in subsection **??**. The solutions were developed based on two things: model runs where the total flood volume was reduced by implementing LIDs, and observations made during the qualitative fieldwork. The proposed solutions function as a recommendation for further research and need to be worked out further by means of obtaining field data on the effectiveness of peak reduction and a cost assessment.

5.3.1. Modelling results

The storage potential of four different LID types is plotted in the in Figure 5.9. All LID types show a linear relation, because their storage potential is higher than the total precipitation amount. In other words, the reservoirs were empty at the beginning of the simulation. Model simulations with and without LIDs implemented showed that the total flood volume was reduced for all failure mechanisms, because they reduce the runoff peak and total runoff. However, the use of LIDs are mainly recommended to mitigate the consequences of an increased catchment size. This mechanism induces failure by increasing the runoff peak, and the aim of LIDs is to reduce the runoff peak. For the other three failure mechanisms, other solutions are more effective. Figure 5.10 shows the effect of different LID implementation strategies on failure mechanism C1. It can be seen in the figure that strategy A2 reduces the total flood volume the most.

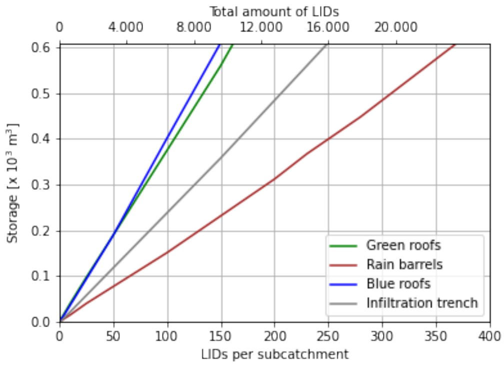


Figure 5.9: Potential storage of four types of LID. The upper x-axis indicates the amount LID's required for the entire model study area.

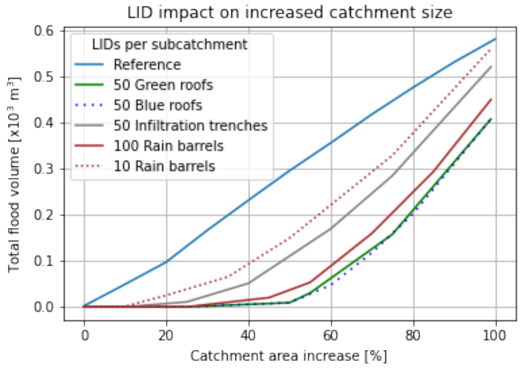


Figure 5.10: Effect of different LID implementation strategies on total flood volume generated by an increased catchment size.

5.3.2. Mitigating solutions

A1: Design inaccuracy

Inundation induced by design inaccuracies can only be structurally reduced by re-designing the erroneous system components. It is therefore recommended to develop design standards and maintain that they are used when new system components are designed. These standards must be in line with the current system that already exists and at the same time keep up with the rate of urbanisation. This can be established monitoring the current system in order to identify bottlenecks where design inaccuracies have taken place and re-designing needs to be done.

B: Pipeline blockage

The probability of pipeline blockage can be reduced by more effective maintenance and cleaning of the existing drainage system. During the interviews with SADCO, it was stated that the major system is annually cleaned around July. However, every year inundation events take place in May and June. This indicates that the annual cleaning is done too late and should be pushed forward, for example in April.

C1: Increased catchment size

To reduce the consequences of an increased catchment size, it is recommended to install LIDs, especially rain barrels and blue and green roofs. As can be seen in Figure 5.10, installing 100 rain barrels in each subcatchment will considerably reduce the amount of total flood volume. To decide what strategy yields the most desirable results, a cost assessment should be done to estimate the ratio between investment and damage averted. A good starting point are the calculations from the cost assessment of the feasibility of green roofs in Hanoi by Dang et al. (2016). Besides a cost assessment, the structural integrity of buildings needs to be assessed first before green or blue roofs can be installed. In the densely populated study area, there is very little space for LID types such as infiltration trenches. Besides, debris that comes with flood waters easily clogs infiltration trenches, making them futile. For new urbanising areas, it is strongly recommended to incorporate more green areas in the city plan. Additionally, new urban areas should drain directly towards other surface waters such as the river Nhuệ, and not towards other urban areas.

D: Inaccessible drains

The short term solutions is to clear the way for stormwater whenever heavy precipitation is expected. This means that the weather forecast must be closely monitored, and SADCO has to go out to clear the drains from blockages as soon as a heavy shower is expected, e.g. >50mm. Local residents can help with this, but they need a motivation to do so. This can be established by informing them about the problems caused by the blockages. Developing such an informational program requires time and is a long term solution. Another long term solution is to tackle the problem at the root, which is the bad odour that comes from the sewer. An investigation is needed on what exactly causes the stench and what can be done to neutralise it.

6 Discussion

This chapter evaluates the applicability of the developed methodology by addressing the main limitations and their practical implications (Section 6.1). Subsequently, in Section 6.2, the research is placed into context by reviewing the contribution of the findings to the field. This was done by recalling the research gap that was identified in Chapter 3.

6.1. Effectiveness of the methodology

6.1.1. Subjectivity

An important limitation of the methodology is that it is reliant on expert judgement, which is subjective. Since this research used the input from only two experts for assessing the probability of occurrence, it is likely that the results are skewed to the experience of the interviewees. This might be problematic, because from experience, people could emphasise certain failures and overlook others. This could have been prevented by interviewing more experts from the responsible authorities (i.e. SADCO and Thanh Xuân's people's committee), such that the answers from interviews can be compared. Confirmation among the different answers would then contribute to the confidence of the outcome. However, this would require more personal communication with local experts, which was hindered by the ever present language barrier. For future research that relies on expert judgement, it is therefore recommended to ensure to have a reliable translator that helps with the interviews. Alternatively, subjectivity could be averted altogether by taking a more formal, numerical numerical approach to probabilities. This would, however, require comprehensive documentation of inundation incidents, which were not available for the case study area of Thanh Xuân or Hanoi.

Besides the subjectivity of expert judgement, there is also subjectivity involved in setting an acceptable risk and judging whether or not failure mechanisms have an unacceptably high risk. As mentioned in the methodology of interpretation in subsection 4.3.4, the distinction was set at a failure probability of 10%. In fact, the acceptable failure probability is a function of the acceptable risk and it is ultimately up to the drainage company and the people's committees to define this risk.

6.1.2. Model accuracy

There are a few limitations to the PCSWMM model, of which the most important one is the uncertainty of the drainage system layout. Understanding these limitations helps in knowing when and how to apply the type of model to other case study areas.

Data scarcity

The model was not calibrated with field data, which entails a reduced reliability of the modelling results. Hence, the outcomes of this study do not function as absolute numbers and values, but as indications for the sensitivity of a typical catchment in Hanoi. The recommended solutions will in any case have a favourable effect on the runoff peak. However, it is recommended to first have a good idea of the failure mechanisms and associated failure probabilities by calibrating the model for the specific area.

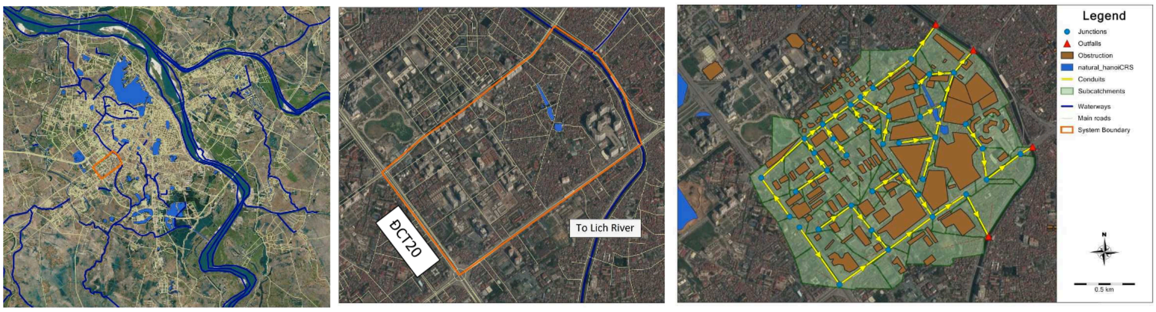


Figure 6.1: Study area (left) with the initial modelled area (middle) and initial model (right)

An important example of field data that could not be acquired, was elevation data. PCSWMM derives the slope of the model from the DEM, which was artificially created in QGIS for the purpose of this study, as described in subsection D.3 of the model setup. An implication of the elevation and slope uncertainty is thus that the computed flooded locations might differ from the actual locations. It is important to keep in mind that, as stated before, the study area is mostly flat; there are no real hills or mountains present. This means that the assumed slope could not vary much from the real slope. However, if the model would be applied to an urban area with more variability in regard of the elevation, it is recommended to combine using elevation data with a site visit to verify its accuracy.

Scalability

In principle the PCSWMM could be scaled up such that it represents the whole city, but this would take an excessive amount of time to set up and compute. Computation times for integrated 1D-2D models in combination with a sensitivity analysis would easily exceed months. If a model for the whole city is desired, it is recommended to perform the sensitivity analysis on a smaller and representative catchment, similar to Thanh Xuân for example. Once the sensitivity analysis is performed, the 1D-2D model could be expanded to the whole city. This is an option when, for example, large investments are involved and the functionality a newly proposed design needs to be checked. However, the model does not function properly if it is scaled up and the dimensions are not conserved. This is because the hydraulic equations that are underlying the PCSWMM engine are not linear, meaning that the behaviour of the model is dissimilar at different scales. This was tested as initially, a much larger area the whole area between the To Lich river and ĐCT20 was modelled (see Figure 6.1. The dimensions were also enlarged in this model. Because of this, some failure mechanisms such as pipeline blockage could not be properly simulated. In other words, the most relevant output is found if the model is set up at the same scale as the real drainage system.

Modelling inaccessible drains

The failure mechanism of inaccessible drains could not be simulated by the PCSWMM model. Despite multiple efforts (see Appendix C), the model did not respond as expected i.e. result in inundation. The hypothesis is that PCSWMM only recognises water that exits the drainage system through a flooded node as flood water. This means that runoff that cannot enter the drainage system at all is not recognised as flood water. PCSWMM stores this water as runoff with a longer time of concentration. This is a limitation of the modelling software, and the implication is that the inundation extent caused by this failure is very uncertain.

Design storm

The methodology described in the Vietnamese design norms to calculate design storms is not very detailed, and there are multiple assumptions that need to be made that affect the modelling results (subsection 4 of Ministry of Construction, 2008). For example, it prescribes to use IDF curves, but it does not specify which IDF curves. For this research, the equations developed by Nguyen (2009) were used because it was the only publication that provided the developed equations. The other publications only presented IDF curves for return periods of 2, 5, and 10 years and did not publish show the underlying equations (e.g. N. T. V. Hong & Nguyen, 2020; Mishra et al., 2015; T. A. Nguyen et al., 2008). There is a possibility that the actual precipitation extremes in the study area might be different than

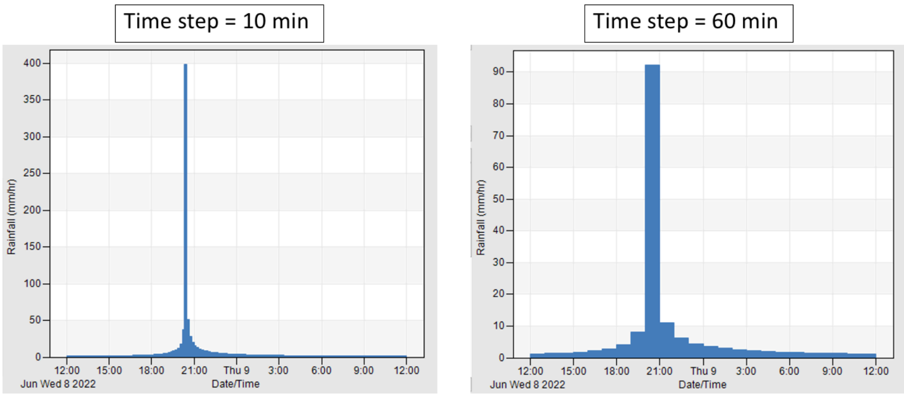


Figure 6.2: Two design storms with equal IDF constants, but different time steps. The y-axis shows the height of the peak, which differs a lot for the two different time steps.

prescribed by Nguyen (2009). The implications for the reliability of the model are very limited because the discharge capacity of the model was defined on the basis of the design storm. The dimensions of the conduits were calibrated using the IDF curves from Nguyen (2009) and Manning's equation; the methodology is described in subsection D.1.4 of Appendix D. Hence, if the IDF curves would not be accurate, the conduit dimensions are equally off.

An important feature of design storms that influences the modelled runoff is the selected time step of the hyetograph. This time step determines the precipitation peak: a smaller time step results in a higher peak, and vice versa. This can be clearly seen from Figure 6.2, where two storms are shown with equal IDF constants, but different time steps. In this study, a fixed time step of 60 minutes was chosen, which is the same as has been used in previous research (Luo et al., 2018). This time step was chosen such that the length matches the time step of the rain gauges. Data with a higher resolution is not publicly available. Since the chosen time step is relatively large, it is possible that the actual precipitation peak is higher than the modelled one. Additionally, a time step of 60 minutes was chosen because it resulted in realistic conduit dimensions, i.e. below two meters (Ministry of Construction, 2008). It was tested to use the 'pipe sizing' tool in combination with a hyetograph time step of five minutes. This lead to conduit dimensions up to 4 meters, which exceeds realistic values according to the Vietnamese design norms.

6.2. Addressing the research gap

The research gap defined earlier was threefold:

(a) Urban drainage systems are scarcely modelled probabilistically;

(b) Previous research is not transferable;

(c) FTA is scarcely applied to urban drainage.

The findings of this research with regard to each of these three topics are addressed separately.

6.2.1. Probabilistic modelling of urban drainage systems

The present research contributes to the field of probabilistic modelling of urban drainage systems by considering a wide variety of failure mechanisms and studying their influence on inundation risk. Urban drainage models are often of deterministic nature, this also includes previously conducted research in Hanoi (Chau et al., 2019; Huan et al., 2016; Luo et al., 2018). For instance, Chau et al. (2019) modelled the 1D underground drainage network of the Cầu Giấy district in Hanoi. As indicators they used flooding duration and max. water depth, the latter was also used in this study. Using a hydrodynamic model, two situations were simulated: one with the current pipeline dimensions, and one where the diameters of the main drainage route were increased. Another deterministic model of Hanoi's inundation problems was created by Luo et al. (2018). In their research, only elevation and not the underground drainage network was considered for a large study area ($\pm$ 100 km^2). However, as the discussion of their article mentions, their model output has numerous uncertainties that arise from the model structure, the lack of drainage system modelling and reliable data input. According to Luo et al., an important area of further study is to explore and resolve these uncertainties. The present study has (partly) accomplished this. By exploring the role of uncertainty, the effects of fourteen uncertain parameters were visualised which manifested vulnerabilities of the drainage system.

Probabilistic models of urban drainage systems have been developed in the past decades, albeit to a lesser extent than deterministic models and not for the case study of Hanoi. The main difference between previous models of Hanoi and the one described in this research is that this research did not assume set parameter values, but used experimental ranges. In this way, a large number of deterministic model realisations was created, which enabled to conduct a sensitivity analysis and create the severity-uncertainty plots shown in Section 5.2.2. These plots display what parameter values are critical and lead to inundation, and thus indicate under what circumstances inundation would occur. This would not have been possible with models that are strictly deterministic. The probabilistic drainage models that have been developed in the past are able to identify critical parameter values, yet are limited to only a few parameters (Gouri & Srinivas, 2015; Lee & Kim, 2019; Thorndahl & Willems, 2008). This research, however, aimed to identify as many failure mechanisms and uncertain parameters as possible to reduce the probability of failure being overlooked. The use of the SRTC-tool enabled to do this, because SRTC requires relatively little computational time compared to alternative approaches such as first order reliability (FORM) and Monte Carlo (MC). These probabilistic methods were addressed in Section 3.5. The main benefit of FORM and MC is that they are able to perform multivariate calculations, i.e. simultaneously investigate model sensitivity with respect to multiple parameters. This could be relevant because in the real drainage system, multiple failure mechanisms occur at the same time and they might affect each other. For instance, a blocked drain could cause overland flow towards an area where the discharge capacity is too little for the extra amount of runoff. FORM and MC are able to quantify these interdependencies. However, for the purpose of this study, it was too time consuming to perform FORM or MC calculations. As each run takes about 3 minutes, a Monte Carlo analysis with 10,000 runs would take almost 21 days.

The high computational cost is mainly due to the fact that the model developed in this study combines the subsurface pipeline network (1D model) and the overland flow (2D model). The main benefit of this integrated 1D-2D approach is that it provides insight in what happens after a node floods. This insight is useful, because it differs per situation what happens to flood waters as soon as it leaves the drainage system. It could lead to inundation depths of more than a meter, or cause dangerous flow velocities. This behaviour cannot be captured in a 1D model as these models are able to compute when and where the system is overloaded, but not what happens to the excess water once a node starts to flood. Integrated 1D-2D modelling using PCSWMM was also done by Mohd Sidek et al. (2021), but their main focus was on rivers and fluvial flooding, and not urban drainage. This is useful to consider if rivers are likely to overflow their banks. However, as could be concluded from the interviews, high water levels of the To Lich are not a common problem. Hence, the methodology of Mohd Sidek et al., could not directly be applied to the research problem of this study, but should be taken into account when modelling an area where rivers tend to overflow their banks.

To summarise, the model developed in this study combines a probabilistic approach, many experimental parameters, and a 1D-2D representation of the study area. To limit the computation time, only a small area in Thanh Xuân district was considered, and SRTC rather than FORM or MC was used. For expensive large-scale projects, it is advised to perform extensive FORM or MC calculations, because the simplified SRTC might overlook certain patterns. Therefore, the reliability analysis performed by Gouri and Srinivas, 2015 provides useful insights that should be used in combination with the results of this study. This can be done by adopting their algorithm to calculate the reliability index by FORM for each conduit in the PCSWMM model.

6.2.2. Transferability

The obtained fault tree can be used as a guideline in similar study areas, i.e. other flood-prone cities that suffer from high-intensity rainfall. Such cities include Ho Chi Minh City, Vinh City and Da Nang in Vietnam, but also Bangkok, Beijing or Manilla. These cities have in common that they have millions of inhabitants, they are still rapidly growing, and they have heavy rainfall during the monsoon season. As a result, each of these cities suffer annually from urban flooding and water nuisance. Previous research on failure of urban drainage systems focus on case studies that are not necessarily transferable to other study areas. For instance, the fault tree analysis performed by Ten Veldhuis (2010) focused on failure that occurs in the Netherlands. The inundation problems in The Netherlands, with relative small cities (<1 million inhabitants) and no monsoon season, are of different nature. This means that the FTA performed by Ten Veldhuis is not applicable to study areas such as Hanoi. Besides, not all study areas have the same type or amount of data available. For instance, Ten Veldhuis used call data to extract the causes of failure from. This type of data is not available for an area such as Hanoi, because inundation is ubiquitous, and therefore few calls to the emergency rooms are made whenever inundation occurs.

Since this study aimed to define a new standard methodology for probabilistic risk assessment of urban drainage systems in South East Asia, a wide applicability of the fault tree was desired. To this end, a methodology was developed that started from scratch, i.e. by assuming that there is no overview of failure mechanisms and the first step is to gather as many failure mechanisms as possible. After all, as stated in the CUR 190, failing to recognise *all* mechanisms is the main cause of accidents in structures. Obtaining this overview was done by a combination of methodologies that included confirmation with local experts. The method described in Section 4.2 is easily transferred to other study areas. However, it is important to keep in mind that some failure mechanisms will be more dominant in certain areas but could be of minimal impact in other areas. That is why it is always advised to consult local experts to confirm the applicability of the fault tree.

6.2.3. Effectiveness of FTA

The main benefit of using FTA is that a fault tree clearly and instantly communicates potential sources of failure and it highlights relevant problems, which makes it easy to use for Hanoi's drainage company and urban planners. This is important, because these people are responsible for development, maintenance and monitoring of the drainage system. It does not require complex mathematical skills or knowledge of the underlying model to understand the outcome of this study. Besides, it is useful to distinguish between failure mechanisms instead of flood-prone areas or system segments. Namely, if a certain area is prone to inundation, it could be that the true problem is elsewhere in the system. by looking at the failure modes rather than the failing areas, patterns are more likely to be recognised which makes it is easier to develop mitigating strategies. Examples of such patterns are the problems caused by urbanisation and the deterioration of the drainage system in general, causing an increased load on a system with insufficient capacity. The process of urbanisation was unravelled and represented by failure mechanism C1: increased catchment area. Looking at the drainage system from this different angle allows the drainage company and urban planners to look more systematically at the inundation problems. FTA allows to quickly zoom in and out and identify key problems.

Based on the results from this study, it can be concluded that FTA is a useful methodology for probabilistic risk assessment of urban drainage systems, but it needs to be worked out. In the disciplines where it is frequently used, methodologies to perform FTA are worked out in detail. This includes the use of conventional fault trees, mathematical definitions of limit states, and modelling techniques to simulate failure mechanisms. Since these conventions are not yet available for the field of urban drainage, the present research aimed to develop a new methodology to do so. To assess whether the it should be adopted as a new standard methodology, it needs to be compared to alternative methods. Alternatives to FTA include failure mode and effects analysis (FMEA) and event tree analysis (ETA). These types of probabilistic risk assessment are frequently applied in aerospace engineering, and are often used in combination with FTA (E.-S. Hong et al., 2009; Snee & Rodebaugh, 2008). Furthermore, the effectiveness of FTA on urban drainage system needs to be tested by considering more case study areas.

PCSWMM proved to be useful for an integrated 1D-2D model of the study area Thanh Xuân, and useful in simulating six out of seven failure mechanisms. The seventh failure mechanism that could not be modelled effectively was ’inaccessible drains’; potential explanations for this were addressed in Section 5.2.2. The effects of this failure mechanism could potentially be modelled by only considering the 2D overland flow, similar to what Luo et al. (2018) have done for the whole city of Hanoi.

7

Conclusion and recommendations

This study aimed to answer four research question, targeted at a societal problem and a scientific problem. The societal problem is that many Southeast Asian cities including Hanoi suffer frequent inundation problems and that the underlying causes are unknown. Thanh Xuân district in the city centre of Hanoi was taken to be the case study area because this area is representative of Hanoi's average built environment and it struggles with flooding multiple times per year. The scientific problem is that there is no standard methodology to apply probabilistic risk assessment on urban drainage systems. Three research questions were formulated to solve the societal problem: (1) what mechanisms lead to inundation in Thanh Xuân district, (2) what is the risk of each in terms of severity and probability, and (3) how can the failure probability of the drainage system be reduced? To solve the scientific problem, one research objective was formulated: to assess to what extent fault tree analysis (FTA) in combination with the modelling software PCSWMM can be applied in a probabilistic risk assessment framework for urban drainage systems. The conclusions are structured according to these four objectives.

7.1. Causes of failure

A broad range of data sources was consulted in order to obtain a representative overview of failure mechanisms as complete as possible. These sources included a focus group with experts from different background relating to water resources and (urban) flooding in Vietnamese cities, interviews with employees from the local drainage authority, and newspaper articles that reported on inundation events. A cause-effect analysis was performed on the results that yielded a comprehensive and clear fault tree that is ready to use for Hanoi's urban planners. The fault tree that was developed in this study is characteristic Thanh Xuân district, but can be used as a guiding example for similar study areas. It is recommended to consult local experts and other local sources to verify its applicability.

Seven failure mechanisms that lead to inundation Thanh Xuân's streets were identified. These include design inaccuracies (e.g. system components that do not properly connect), subsidence, pipeline blockage, increased imperviousness, increased catchment size due to urbanisation, downstream water levels that are too high for discharging, and inaccessible drains. The latter is caused by inhabitants that deliberately block drains to stop the stench coming from the sewer. The use of mixed data sources proved to be useful as there was a considerable amount of diversity in the results, ensuring a comprehensive analysis. Failure mechanisms that were only found in one of the data sources were considered less relevant, and mechanisms that were suggested in the newspaper articles as well as the focus group were considered more serious. This overlap confirms and emphasises the contribution of certain failure mechanisms. The interviews with the drainage company were considered decisive as the employees know the system's functioning and failure by heart.

7.2. Risk

To determine the risk of each failure mechanism, the concept of risk was divided into two parts: severity and probability of occurrence. The severity was assessed with a probabilistic model built with the urban drainage modelling software PCSWMM. A sensitivity analysis was carried out using the Sensitivity-based Radio Tuning Calibration (SRTC)-tool. Twelve uncertain parameters were selected to simulate the failure mechanisms, and were assigned experimental value ranges. Each run within these ranges that resulted in inundation was stored to demarcate under which circumstances each failure mechanism starts to cause flooding. This resulted in severity-uncertainty plots that indicate the inundation extent as a function of each parameter value. These graphs were used as input to create 2D severity maps for each failure mechanism that indicate different levels of flooding. A distinction between three different levels of danger was made, such that the consequences are put in perspective. The total flood volume [m^3] was used as an indicator

The results of the probabilistic risk assessment are summarised in Figure 7.1 The probability of occurrence was estimated based on expert judgement from employees of Hanoi's drainage authority. The failure mechanisms designated as occurring annually are design inaccuracies, pipeline blockage, increased catchment size and inaccessible drains. The severity maps showed that from these four mechanisms, the most severe inundation problems arise from a catchment size increase. Doubling of the catchment area could potentially lead to maximum inundation depths of 1.14 meters, based on the modelling results. The second most severe inundation is caused by a narrowed or blocked pipeline, although it depends a lot where the blockage occurs. Narrowing the diameter of upstream pipelines to 30% has a negligible effect and does likely not induce inundation. For downstream pipelines, the same narrowing could lead to maximum inundation depths of 1.04 meters. Based on the modelling results, design inaccuracies cause severe but local flooding. An elevation mismatch of +2 meters might cause inundation depths up to 1.685, but the total flood volume induced by the failure mechanism is half of the volume induced by the other two mechanisms. The failure mechanism of inaccessible drains could not be simulated in the PCSWMM model, but based on a site visit it was estimated that the access to 0-50% of the drains in the study area are blocked. The modelling results did not show inundation caused by the failure mechanism of increased imperviousness. The modelling results indicated that too high downstream water levels could cause severe inundation, yet the probability of occurrence of this failure mechanism is negligible.

The main limitation of the modelling study was the limited amount of available data such as up-to-date flood records and extensive precipitation data. Without this data, calibration and validation was not possible and the outcome of the PCSWMM model remains indicative. The results do, however, show the relative severity of each failure mechanism. This is relevant to compare the impact of each failure mechanism and to distinguish the mechanisms that lead to severe inundation. Yet, for a more accurate representation of the actual inundation problems, flood records are required to calibrate the model.

To summarise, the probabilistic risk assessment led to the conclusion that four failure mechanisms had an unacceptable high risk. These mechanisms are design inaccuracies, pipeline blockage, increased catchment size, and inaccessible drains. Each of these three failure mechanisms require solutions to lower their probability of occurrence.

7.3. Lowering the failure probability

For the four aforementioned failure mechanisms, solutions were proposed to reduce their probability of occurrence. To prevent design inaccuracies in the future, it is recommended to develop and maintain design standards that keep up with the pace of urbanisation. The Vietnamese design norms laid down in the document TCVN 7957-2008 are mostly indefinite and outdated, and need to be updated and it must be enforced that they are actually used. The failure probability of pipeline blockage is lowered by adopting a more effective maintenance schedule. It was found that all major pipelines are annually cleaned around July. However, large inundation events that took place in May in 2021 and 2022 indicate that the rainy season has already started by the time the annual clean up takes place. It is therefore advised to reconsider the vulnerable period and adjust the maintenance schedule likewise. In regard of the inaccessible drains, the short-term solution is to monitor weather forecasts closely, and go out to remove the blockages just before heavy rainfall. The long-term solutions is to start at the source of the issue i.e. the sewer itself. By improving the water treatment facilities, inhabitants lose the incentive to block drains and the impact of the failure mechanism will disappear.

For the failure mechanism of increased catchment sizes, the implementation of low impact develop-

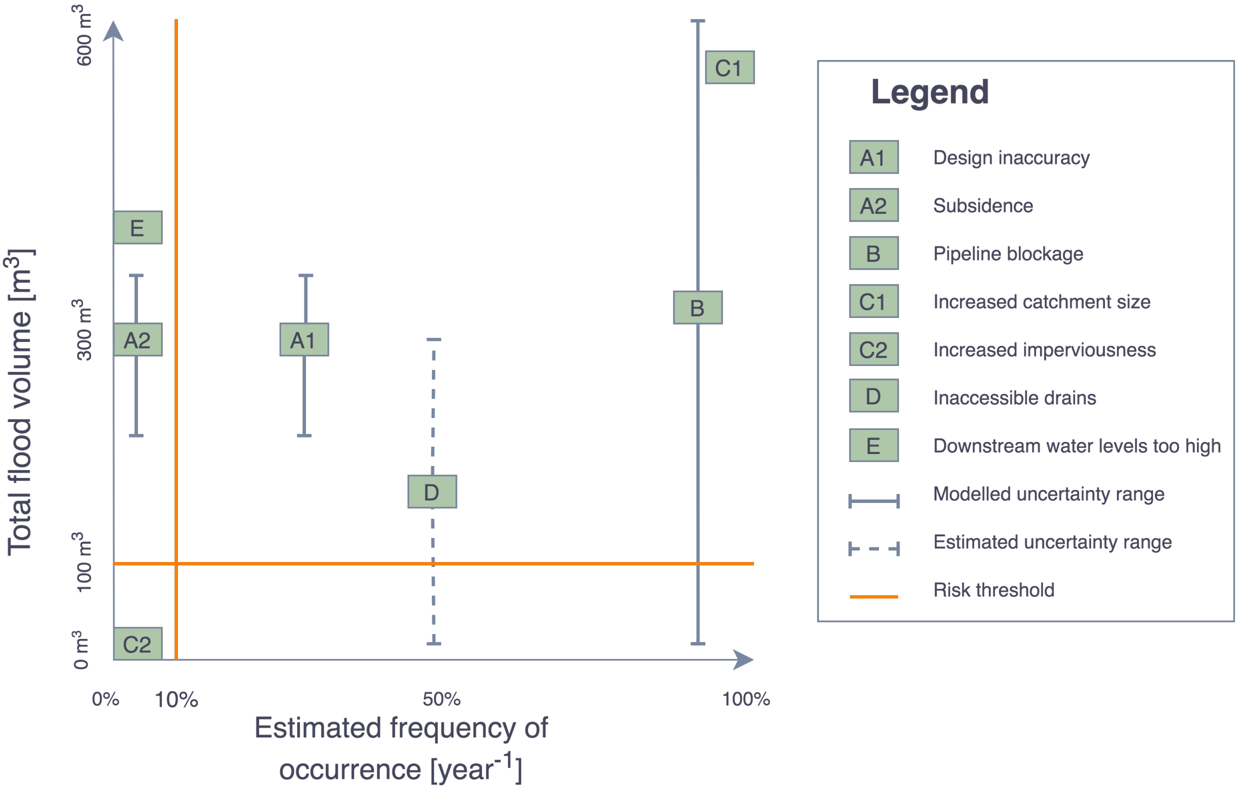


Figure 7.1: Summary of the results from the probabilistic risk assessment. The failure mechanisms in the upper right corner pose the most serious risk.

ment (LID) is the most effective. Due to spatial limitations in Thanh Xuân district and potential clogging of infiltration facilities, the most effective LID types are green roofs, blue roofs and rain barrels. Five implementation strategies were tested in the model and the results showed that with a catchment size increase of 50%, the total flood volume could be reduced by 90-95%, compared to a situation without LIDs. This could be established through installing 50 green or blue roofs or 100 rain barrels per subcatchment, i.e. respectively 3200 and 6400 in total.

This reduces the load on the drainage system significantly, and it is therefore recommended to install rain barrels at every household and to encourage residents to plant green roofs and gardens on their roofs. The main challenge of this is that residents are not willing or do not have the financial means to cooperate. This is assisted by raising awareness of the impact of Hanoi's urbanisation on the inundation problems and giving subsidies. Blue and green roofs showed equal storage potential, but differ in terms of maintenance and it is unclear weather older buildings in the residential area have the structural integrity to carry the amount of stormwater collected by blue and green roofs.

7.4. Applicability of FTA and PCSWMM

Besides the case study-related findings, the key take away from this study is that it provides a methodology to perform a probabilistic risk assessment of urban drainage systems using a combination of FTA and PCSWMM. The conventional method of FTA was adopted from the field of primary flood defence risk assessment to test whether it is useful to apply in urban drainage. This proved to be successful because it resulted in a comprehensive fault tree that instantly and clearly communicates all sources of failure and highlights relevant problems, and is ready to use for Hanoi's drainage company and urban planners. However, the conventional methodology was not entirely applicable to the field of urban drainage because of two reasons, and to innovations were made. First, there was no standard format for a fault tree for urban drainage systems. As every urban drainage system is different, different failure mechanisms are dominant in each city. That is why a choice was made to opt for mixed methodologies to obtain a fault tree which is as complete as possible. This was previously not included in conventional FTA, because standard fault tree formats exist. The second innovation that was added to the conventional method of FTA is that the definition of failure was more nuanced. Namely, this study did not only explore under which circumstances failure would occur, but especially *to what extent* failure i.e. water on the streets occurs. This extent was assessed in terms of maximum inundation depth [m], total flow volume [m^3], and maximum flow velocity [m/s]. These indicators were used to assess whether flooding occurred, and to distinguish between dangerous and non-dangerous flooding. Therefore, this study added a new step to the conventional method that reflects this nuance. Namely, to determine the severity in terms of inundation extent of each failure mechanism.

Regarding the use of PCSWMM for FTA analysis, the software proved to be able to successfully simulate six out of seven failure mechanisms. The failure mechanism 'inaccessibility of drains' could not be simulated, such that only a qualitative assessment based on expert judgement was made for this failure mechanism. To simulate all other failure mechanisms, it is recommendable to use PCSWMM. Especially the created severity maps give a clear view of the areas that are prone to flooding under different circumstances, and can be used for communication ends. However, many assumptions were made in this study regarding the model setup which affect the accuracy of the modelling results. To make better quantitative judgements, reliable input data such as system dimensions and flood records to calibrate are required.

7.5. Recommendations

Based on the conclusions drawn from this research, two kinds of recommendations can be formulated. First, recommendations to improve Hanoi's drainage system, such that the flood risk can be lowered. These recommendations are intended for Hanoi's drainage authorities, which are Hanoi Sewerage and Drainage Company (SADCO) and the people's committees. These recommendations address the societal problem. Second, recommendations for further research are formulated. These recommendations address the scientific problem.

7.5.1. Reducing Hanoi's flood risk

The recommendations intended for SADCO and the people's committee are targeted at improving the current drainage system, avoiding similar problems in the future, and at engaging local inhabitants.

The main recommendation for Thanh Xuân district specifically is to focus on the failure mechanisms design inaccuracies, pipeline blockage, inaccessible drains, and increased catchment size. Recommendations to lower the failure probability of each mechanism are given in Section 7.3. For other areas in Hanoi's city centre, it is recommended to distinguish between the failure mechanisms that were identified in this research and to make use of the constructed fault tree. Although the fault tree is specifically constructed for Thanh Xuân, it can be used as a guideline for other areas in Hanoi. Currently, there are many uncertainties with regard to the condition and failure of the drainage system, and for future studies on Hanoi's drainage system, it is strongly recommended to gather and store flood records, including accountable failure mechanisms. This documenting is useful in estimating the failure probability of each failure mechanism. The application HSDC maps developed by SADCO is a useful starting point, and it is recommended to include functions that store inundation data as well as rainfall intensities.

As Hanoi's urban area is expected to extend further in the future, it is recommended reserve more space for natural drainage facilities such as LID's. Green and blue infrastructure such as parks and ponds are multifunctional in the sense that they reduce the runoff peak, promote wastewater treatment, and serve as recreational area for residents. In the coming decades, Hanoi should move towards a greener future in which urbanisation goes hand in hand with a development of green-blue infrastructure. Before LIDs are designed and installed, it is recommended to make a cost assessment to decide to what extent it is desirable to reduce flood risk against a certain cost.

The recommendation to engage local inhabitants is especially directed towards the people's committee of Hanoi. It is recommended to raise awareness among local inhabitants regarding urban flows, to make them aware of their (potential) role in the inundation issues. During this research, it was noted that local inhabitants play a role in the functioning and failing of the drainage systems, and their behaviour will not change unless people gain more insight into the consequences of their actions. Besides, raising awareness increases the willingness of residents to maintain green infrastructure such as rain barrels and green roofs. Raising awareness could be done in cooperation with organisations such as ECUE or Keep Hanoi Clean. These organisations have experience in motivating Hanoi's residents to be more committed to their environment. Besides, they have experience with the design of public spaces that serve functions desirable for the residents.

7.5.2. Recommendations for further research

First and foremost, it is recommended to explore other methods of applying probabilistic risk assessment on urban drainage systems. This study aimed to develop a new method of doing this by using FTA and PCSWMM, but there are alternatives to both of them. By using an alternative method (e.g. event tree analysis) and an alternative modelling software (e.g. MIKE), and comparing the results to this study, a standard methodology for probabilistic risk assessment of urban drainage systems can be developed.

Further research is recommended to improve the validity of the PCSWMM model by collecting inundation data (depth and velocity) and calibrating the model. A database of flood occurrence and corresponding precipitation values can be made using HSDC maps. The validity of the model can be further improved by determining damage functions relating to the economic value of the urban area. This study focused on inundation extent, but it did not consider the potential damage done.

The scope of this study was limited to water quantity, although water quality is an important component in inundation issues as well. It is recommended to study the mechanisms that lead to deteriorated water quality because surface water pollution is a major problem in Hanoi. The methodology developed in this study can be adopted; PCSWMM allows for water quality modelling, and a fault tree specifically designed for water quality needs to be constructed. A probabilistic risk assessment of LIDs is also an interesting topic for future research, such that their potential for both flood reduction as well as water quality enhancement can be investigated.

One of the findings in this research is that local inhabitants play an important role in the functioning of the drainage system. Engaging local inhabitants for example in the form of citizen science is a promising opportunity for the future. Further research is needed to assess how to motivate inhabitants and how to make their contributions useful. In interesting starting point is the application Anecdata.org. This app operates in Hanoi and allows users to record and notify authorities when they observe problems relating to the city's infrastructure.

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A

Interviews and focus group

This appendix provides additional material that was used to conduct the interviews and focus group. In section A.3, the survey is included that was intended to distribute among employees of SADCO, but failed to reach them. The survey has overlapping content with the interview guide. Translation was done by Hoang Tung Dao, lecturer from HUNRE university.

A.1. Focus group schedule

1. Moderators introduce themselves
2. Participants are asked to introduce themselves and explain their background and how they relate to the topic
3. Brief presentation of the topic, explaining the purpose of the session
4. Using the interactive platform MIRO, participants indicate where and when failure is likely to occur based on their experience
5. Discussion of the results. Questions that were asked include:
    - How frequent does this cause inundation?
    - What is the underlying cause of this failure, if there is any?
    - Where and when does this type of failure occur?
    - Could this problem be solved? If yes, how?
    - What land use changes have taken place in the past decade?
6. Participants vote for the failure mechanisms that are the most likely to occur in Thanh Xuân
7. Closing. Thanking participants and explain how their contribution will be used

A.2. Interview guide

General

1. When was the drainage system designed?
2. What design method was used? (e.g. in terms of design storm, allowed frequency of flooding)
3. How often does flooding occur in the study area?
4. How is inundation usually solved?
5. If a lot of precipitation is expected, what do you do to prepare?

Maintenance

6. Does monitoring of the system's functioning take place?
7. How are all the different parts of the system maintained?
8. How often and when does maintenance take place?

Causes

9. Are there any causes you miss in the current overview?
10. What changes in the last +- 20 years have affected the urban drainage system in Thanh Xuân?
11. During a site visit, it was noted that many drains are blocked by mats. Why is this and are they removed during precipitation events?

Consequences

12. What are the most important consequences of flooding?

Severity

13. What failure mechanisms cause the worst inundation problems (in terms of inundation depth)?

Likelihood

14. What failure mechanisms occur the most often? And what mechanisms second and third most often?
15. For each failure mechanism, please indicate how frequent it occurs.

Mitigation

16. Does the area have stormwater storage facilities?
17. What mitigation measures have been realised in the past 5 years?
18. What would you suggest/advise as an effective flood mitigation measure?

Engaging local citizens

19. Do local citizens play a role in functioning of the drainage system?
20. How could local inhabitants contribute to increase the functioning of the drainage system?

A.3. Survey

1. What is your background in the field of urban drainage systems? // Chuyên môn của bạn trong lĩnh vực thoát nước đô thị?
2. How frequent does inundation occur in this area, approximately? // Mức độ thường xuyên xảy ra ngập lụt trong khu vực này?
   (a) Once every 5 years // 5 năm một lần
   (b) Once every 1-2 years // 1-2 năm một lần
   (c) 3-10 times per year // 3-10 lần mỗi năm
   (d) > 10 times per year // > 10 lần mỗi năm
   (e) I do not know // Tôi không biết
3. To what extent in terms of depth does inundation occur at least once a year? // Khi ngập lụt xảy ra một lần trong năm, độ sâu nước ngập là bao nhiêu?
   (a) A few puddles on the street // Một số vũng nước trên đường phố
   (b) As high as the sidewalk // Ngập đến vỉa hè
   (c) Knee-high // Ngập đến đầu gối của bạn
   (d) Waist-high // Ngập đến thắt lưng của bạn
   (e) Above waist-high // Ngập sâu hơn thắt lưng của bạ
   (f) I do not know // Tôi không biết
4. To what extent in terms of duration does inundation occur at least once a year? // Khi ngập lụt xảy ra một lần trong năm, khoảng thời gian kéo dài của ngập lụt là bao nhiêu?
   (a) 0-60 min // phút
   (b) 30-60 min // phút
   (c) 1-3 hours // giờ
   (d) 3 -12 hours // giờ
   (e) > 12 hours // giờ
   (f) I do not know // Tôi không biết
5. What was the extent of the most extreme case in the past 10 years in terms of depth? // Trong 10 năm qua, nước ngập trong trường hợp khắc nghiệt/lớn nhất là bao nhiêu?
   (a) A few puddles on the street // Một số vũng nước trên đường phố
   (b) As high as the sidewalk // Ngập đến vỉa hè
   (c) Knee-high // Ngập đến đầu gối của bạn
   (d) Waist-high // Ngập đến thắt lưng của bạn
   (e) Above waist-high // Ngập sâu hơn thắt lưng của bạn
   (f) I do not know // Tôi không biết
6. What was the extent of the most extreme case in the past 10 years in terms of duration? // Trong 10 năm qua, thời gian ngập trong trường hợp khắc nghiệt/lớn nhất là bao nhiêu?
   (a) 1-3 hours // giờ
   (b) 3 -12 hours // giờ
   (c) 12-24 hours // giờ
   (d) 24-48 hours // giờ
   (e) > 2 days // > 2 ngày
   (f) I do not know // Tôi không biết

7. In which month do inundation events mostly take place? // Ngập lụt xảy ra nhiều nhất vào tháng nào?
    (a) May // Tháng Năm
    (b) June // Tháng Sáu
    (c) July // Tháng Bảy
    (d) August // Tháng Tám
    (e) September // Tháng Chín
    (f) October // Tháng Mười
    (g) I do not know // Tôi không biết
8. Please indicate the severity on a scale of 1 to 5 of each consequence listed below. // Bây giờ, chúng ta hãy nói đến mức độ ảnh hưởng từ ngập lụt. Vui lòng cho biết mức độ nghiêm trọng của từng hậu quả được liệt kê dưới đây.
    (a) Damage to vehicles// Thiệt hại cho phương tiện
    (b) Public health // Sức khỏe con người
    (c) Environmental pollution // Ô nhiễm môi trường
    (d) Structural damage to buildings // Thiệt hại cho các nhà cửa và toà nhà
9. Is there any consequence you want to add in the previous question? // Có hệ quả nào mà bạn muốn thêm trong câu hỏi trước không?
10. There are several causes that might lead to inundation. Please indicate their relative contribution. // Bây giờ, chúng ta hãy nói đến nguyên nhân gây ra ngập lụt. Có một số nguyên nhân có thể gây ra lũ lụt. Vui lòng cho biết đóng góp tương đối của họ.
    (a) Inner pipeline blockage (due to solids accumulation) // Tắc (nghẽn) đường ống cống (do chất rắn tích tụ)
    (b) Subsidence of the ground // Lún mặt đất, mặt đường
    (c) Surface waters and green areas are replaced by buildings, concrete surface // Nước mặt và các khu vực cây xanh được chuyển đổi thành các toà nhà hoặc mặt bê tông/đá
    (d) New drainage system design does not connect well to old system components // Thiết kế hệ thống thoát nước mới không phù hợp với hệ thống cũ
    (e) Expansion of urban area, causing farmland to turn into urban area // Mở rộng và chuyển đổi đất nông nghiệp thành vùng đô thị
    (f) Rubbish blocks access to drains // Rác thải chặn lối vào cống
11. Are there any causes you want to add in the previous question? // Có nguyên nhân nào mà bạn muốn thêm vào trong câu hỏi trước không?
12. What would you suggest/advise as an effective flood mitigation measure? // Bạn sẽ đề xuất hoặc tư vấn biện pháp nào để giảm thiểu ngập lụt một cách hiệu quả?
13. Do you agree with the following statement? Local inhabitants play an important role in increasing the efficiency of the urban drainage system. // Bạn có đồng ý với nhận định sau đây không? Người dân địa phương đóng vai trò quan trọng trong việc tăng cường hiệu quả quá trình vận hành hệ thống thoát nước đô thị
    (a) Strongly agree // Hoàn toàn đồng ý
    (b) Agree // Đồng ý
    (c) Neutral // Đồng ý và không đồng ý
    (d) Disagree // Không đồng ý
    (e) Strongly Disagree // Hoàn toàn không đồng ý
14. How could local inhabitants contribute to increase the efficiency of the drainage of stormwater in the study area? // Người dân địa phương có thể đóng góp như thế nào để nâng cao khả năng thoát nước mưa trong khu vực?

B

Additional results 1

In this appendix, additional results from research question 1 are presented. The results from the focus group, site visit, and the analysis of newspaper were not included in the main report, because they were merely used as input for the cause-effect analysis.

B.1. Results focus group and newspapers

Table B.1: Overview of all mechanisms and processes relating to failure mentioned during the focus group

• Wealth increases water use per capita • Decrease in available surface water • Improper waste management • Decrease of green area • Subsidence due to groundwater extraction • No water retention areas • Heavy rains (extreme variability) • Population is larger than predicted • A lot of impervious area • Outdated drainage system • Lack of observation/monitoring/forecasting • Dry weather flow affects probability of blockage • Drains have wrong elevations • There is no standard elevation • Elevations do not match at borders of neighbourhoods • Surface water level is too high • The drainage system remained the same, while the population doubled • No money for expensive projects • Domestic waste increased • Land use changes • People put their rubbish on the streets which blocks drains • Groundwater extraction leads to subsidence • Elevation of surface is not considered in design phase • Households do not use private groundwater pumps anymore • Increase of drinking water demand • Drinking water companies use groundwater too • New neighborhoods are built upstream of old neighborhoods

B.2. Newspaper articles

Search term	Title of article	Date	Causes	Other relevant findings
VNExpress + Hanoi + Flood	Why flooding returns to haunt Hanoi after heavy downpours	May 27, 2016	• The system is unable to cope with the city's development. • The drainage system consists of small pipes with limited capacity that can get blocked easily by sediment buildup. • Surface waters disappeared • The concrete embankment at To Lich River has reduced its drainage capacity. • The west of Hanoi used to be agricultural land, but it has been paved • The rainfall intensity exceeded the capacity of the city's drainage system.	
VNExpress + Hanoi + Flood	Commuters struggle as downpour floods Hanoi streets	July 25, 2019	• Trash blocks access to drains	
Vietnamnet + Hanoi + drainage	Hanoi fails to complete city drainage project	29/05/2016	• Incomplete connections between drainage systems in old living quarters and new ones.	• Vietnamnet mainly reported on the costs of recent construction works on the drainage system, and the fact that it is not finalised years after the deadline has passed. The instruction works are mainly delayed because sites are not properly prepared.
Vietnamnet + Hanoi + drainage	Huge money spent on drainage system, but Hanoi still floods	10/06/2016	• Poor urban planning • Lakes, ponds and rivers have been filled up to make room for houses: 70 out of 112 ponds and lakes in the inner city have been filled up in 2011-2016.	
Bnews + Hanoi + Inundation	Hanoi: The rainwater flooded Thang Long Boulevard basically drained out	April 17, 2021	• Low elevation of the road surface compared to the surrounding area • water drainage depends entirely on nature [gravity]	
	Hanoi explains about heavy rain causing flooding	May 12, 2021	• The design capacity was exceeded by an average intensity of 100 mm, continuously for 1 hour	• During rainfall event, SADCO mobilized human resources and machinery to carry out planned measures such as collecting garbage at the sluice gates and clearing the flow
VNExpress + Hanoi + Flood	Long-drawn urban planning issues blamed for Hanoi flooding	May 31, 2022	• Insufficient drainage capacity • Poor urban planning; overlap in planning by various agencies. Homes and other urban structures are built without consideration for water drainage systems that are needed • Disappearing lakes: 7 lakes in the downtown area have completely disappeared while only seven new ones were created. The total water surface area reduced as a result from 2,100 ha before 2010 to just 1,165 ha in 2015. • Increased imperviousness	• The drainage system can drain 310 mm of rain in two days • Nhue river has a modest drainage capacity, lacks reservoirs and its key pumps have not yet reached their full capacity. • Solution: enlarge lakes, ponds and grass fields • Solution: building underground reservoirs
SGGP + Hanoi + Inundation	Major cities should strictly observe planning to eliminate urban flooding	June 03, 2022	• Asynchronous planning without a clear long-term vision. • Infrastructure building projects and sewers are not constructed in harmony with one another. • Projects block the drainage of previously built structures • Subsidence: the surface ground is lower than storm drains to To Lich River,	
VNExpress + Hanoi + Flood	Downpours turn life upside down in Hanoi	July 5, 2022	• Ongoing construction projects affect drainage	• Larger vehicles cause waves that knock other people off their vehicles
Vietnamnet + Hanoi + drainage	Hanoi streets turn into rivers in rainy season, anti-flooding work stalls	July 13, 2022	No causes mentioned	• The drainage system was built in the first years of the 20th century, designed for about 500,000 people. • Drainage capacity is 50 mm in two hours. In the conditions of 50-100 mm in two hours, the city has 18 flooded areas.

Figure B.1: Overview of most relevant newspaper articles, the causes that they discuss and other relevant findings

B.3. Pictures from site visit

Figure B.2: Examples of drainage system components that are stolen. The drainage company places objects in the gap to prevent accidents. These objects block practically block flow through the pipeline. Source: Hanoi's drainage company, pictures taken by Nguyen Trong Nam

Figure B.3: Drains with stolen lids before and after repair work. Source: Hanoi's drainage company, pictures taken by Nguyen Trong Nam

Figure B.4: Blocked drains due to a lack of maintenance

Figure B.5: Drains that are covered by mats or rubbish

B.4. Cause-effect analysis

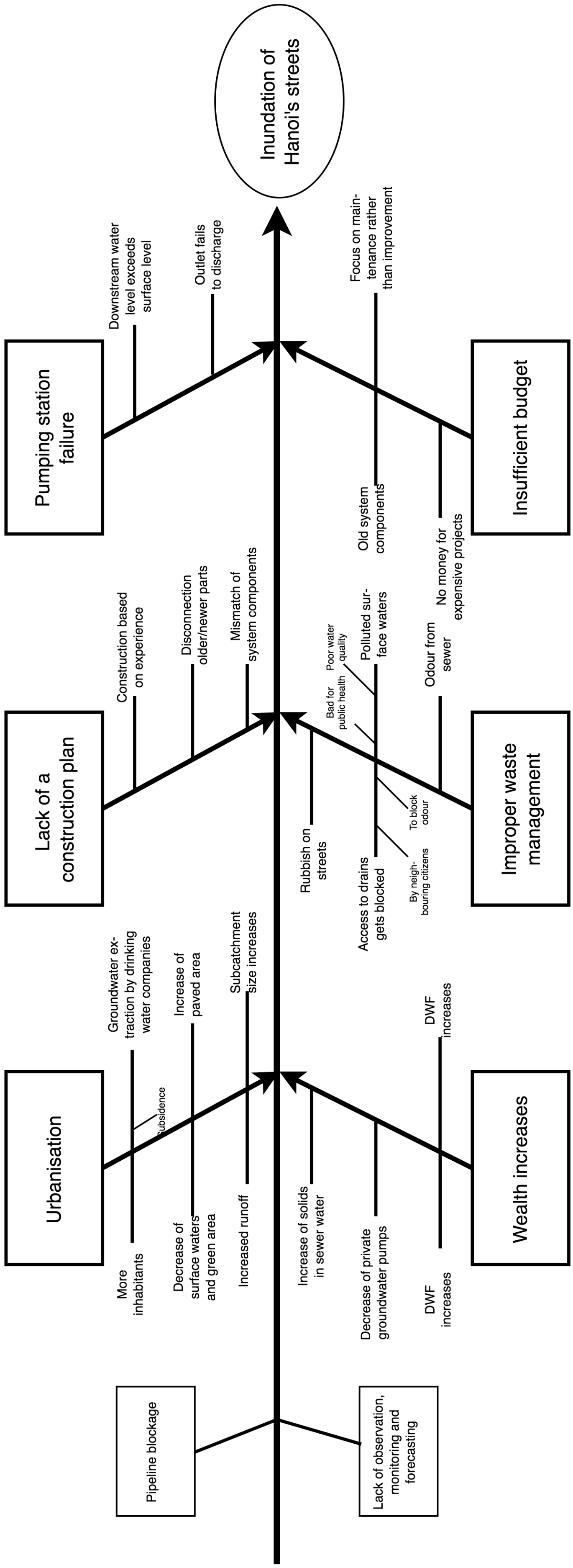


Figure B.6: Ishikawa diagram of the cause-effect analysis

C
Failure mechanisms

In this Appendix, each failure mechanism is described separately, and the methodology of simulating them in the PCSWMM model is presented.

A1: Design inaccuracy

Design inaccuracies were extensively discussed during the focus group, and newspaper articles reported on it as well (see for example Van, 2022). According to T. Thu Thuy Nguyen (participant of the focus group), this type of failure occurs when new system components are built and connected to older ones. It is often the case that elevation of the components do not match one another, resulting in a sudden rise or drop in the system. The main reason why this occurs is that there is no standard methodology for designing new system components. Design of new system components is merely based on experience of the company. The failure mechanism is simulated using three uncertain parameters, each relating to the elevation of different system components. The first parameter is the junction invert elevation [m] for the junctions at locations where more than two branches come together. These locations were chosen, because this is where new system components can be coupled to older ones. They were assigned an uncertainty range of 2 meters. The second and third parameters are the conduit inlet and outlet offset [m]. These parameters define the vertical distance at the end of each conduit to each junction, and thus represents a mismatch of elevation, see Figure C.1 for an illustration. The experimental ranges of these two parameters are set to [-2, 2] meters as well.

A2: Subsidence

Subsidence occurs as a consequence of mainly two things. First, Hanoi's increasing population has an increasing demand for drinking water, which is derived from groundwater extraction. Research on Hanoi's long-term ground subsidence and groundwater depletion has shown that many areas in

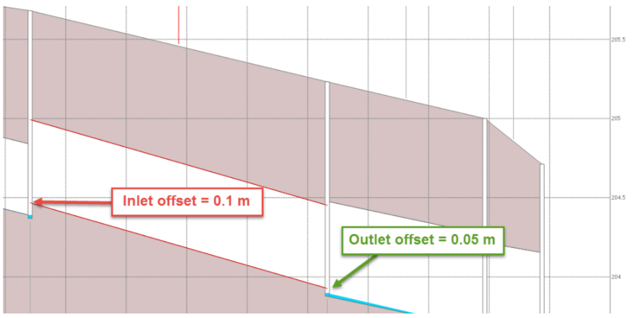


Figure C.1: Illustration of two parameters: the conduit inlet offset (red) and outlet offset (green)

Figure C.2: 4 Conduits that were selected for simulating failure mechanism B: pipeline blockage.

central Hanoi have subsided between 30 and 90 centimetres (M. Nguyen et al., 2022; Thu & Fredlund, 2000). The second cause for subsidence is that large constructions that are newly built pose pressure on the soil, making it more compact. This failure mechanism is simulated in the same way as failure mechanism A1.

B: Pipeline blockage

Pipeline blockage occurs due to multiple causes. Large objects might enter the drainage system via drains that have their lids stolen. This was observed from one of the site visits, see the middle picture in Figure 5.1 and other examples in subsection B.3 in Appendix B. It may also occur due to the accumulation of solids coming from households wastewater, narrowing the passage. This might especially happen at the end of the dry season, when there are longer periods without stormwater to flush the system. This failure mechanism is simulated by two parameters: the Manning's roughness coefficient for the conduits [$m^{1/3}$/s] and the diameter of pipelines [m] at four different locations were was narrowed. These four locations are depicted in Figure C.2 for the locations. The experimental range of the diameter is such, that the discharge through the pipeline has a range of 10% to 100%. Hence, the range of the diameter is 31.6% ($3.16 = \sqrt{10}$) to 100% of it.The experimental range of the Manning's roughness is set to 0.010 to 0.024. These values are based on Table 8 of the Vietnamese design principles, and the *Gravity Sanitary Sewer Design and Construction* from ASCE (Bizier, 2007; Ministry of Construction, 2008). The latter is also referred to in the CHI documentation.

C1: Increased catchment size

The growth of Hanoi's urban area is associated with an increase of the catchment, and thus an increased amount of stormwater to be collected by the drainage system. The failure mechanism was simulated by varying the catchment area and catchment width. The catchment width refers to the time of concentration: the larger the width, the longer it takes for runoff to reach the drainage system. For the width, an uncertainty range of 50-100% was applied, as suggested in the CHI documentation (page 'Subcatchment uncertainty', consulted last Sep 20, 2022).

C2: Increased imperviousness

The increase in imperviousness that is associated with urbanisation reduces the infiltration capacity and increases the generated runoff. During the site visit, it could be observed that virtually the whole study area is paved. Three parameters were selected to simulate this failure mechanism. The imperviousness [%] represents the percentage of the catchment that is paved. The physical boundary of the imperviousness is 100%, and the lower boundary is chosen to be 60%, such that there a large experimental range. The second and third parameters are the Manning's roughness coefficients [$m^{1/3}$/s] of the impervious and pervious areas. These parameters are selected to study effects of the land use changes. The range for the impervious area is 0.01-0.03, and the range for the pervious area is 0.05-0.3. These values are suggested as characteristic values in the CHI documentation, (page

'Subcatchment uncertainty', consulted last Sep 20, 2022).

D: Inaccessible drains

During the site visit, it was observed that the access to a large amount of drains was blocked by mats or rubbish, see for example the pictures depicted in subsection B.3 of Appendix B. These are likely to be deliberately placed by inhabitants to block the odour from the sewer. The amount of drains that were blocked in this was counted on May 9, 2022 and varied between 0% and 50%. During that time, heavy rainfall and flood incidences could be expected based on events in the previous years, which indicates that they are not removed during the rainy season.

A multitude of methodologies to simulate this failure mechanism have been executed, but none of them resulted in the expected output. This type of failure occurs at the boundary between the 2D overland flow and the 1D drainage system. PCSWMM uses orifices to represent the link between 1D and 2D. Therefore, an initial experimental range of [0, 1] was assigned to the orifice discharge coefficient. As can be seen in the orifice equation (C.1), a discharge coefficient of 0 means that there is no flow and the orifice is fully blocked. A coefficient of 1 means that there is no obstruction. The initial value of 2D orifices in PCSWMM is 0.85. The hypothesis was that, by lowering the discharge capacity, less runoff would enter the drainage system. However, the model did not respond to alterations of the discharge coefficient, nor did it to the other parameters of the orifices.

$$Q = CA\sqrt{2gh} \tag{C.1}$$

A second method was to remove some of the orifices, such that runoff should travel to the next drain. PCSWMM registered a total flood volume of only 0.003 m^3. By removing the orifices, the runoff is not able to enter the drainage system at all, which is not recognised by PCSWMM as inundation, but as runoff. The third method was to use flap gates on all orifice, which are structures that prevent backflow: water is able to leave the system, but not able to enter (depending on the direction of the flap gate). This mimics the observation of mats that were placed over the drains. The model did also not respond to the flap gates: the total flood volume remained the same, with and without the flap gates.

E: Downstream water levels too high

High water levels in the To Lich river complicate discharge from the system outlet. This can happen when the Yen So pumping station further downstream experiences failure and cannot pump the water out of the To Lich into the Red River. The failure mechanism was simulated by varying the downstream water level of both the 1D as well as the 2D boundary outfalls. The range that was assigned to this parameter is [3, 8.8]. The lower boundary corresponds to the elevation of the outlet, and the upper boundary corresponds to the lowest elevation of the subcatchment. If the downstream water level exceeds this value, the routing error becomes too large (>5%) (James, 2005).

D

Model set-up

The setup of the PCSWMM model is described in this appendix, and it is written as a step-by-step guide such that it can be easily reproduced. The model consists of 2 main components: a 1D representation of the underground drainage system (Section D.1), which was coupled to a 2D mesh that represents the overland flow (Section D.2). The 2D mesh was shaped using a digital elevation map (DEM), which was artificially created using QGIS as described in Section D.3. Section D.4 shows the SQL statements that were used to create the severity maps. The PCSWMM model was built using the coordinate reference system *Hanoi 1972 + 6-degree Gauss-Kruger zone 18*.

D.1. 1D drainage system

D.1.1. System boundaries

First, the system boundaries were defined as shown by the red line in Figure D.1. For accurate modelling results, the conduit dimensions should resemble realistic values i.e. in the range of 0.2m to 2m (Ministry of Construction, 2008). This entails that, if the entire Thanh Xuân district is to be represented, a detailed model should be built requiring large computation times (about an hour per run). This large of a computation time is not desirable, and a smaller area of $\pm$ 50 hectares within the district was defined. This area was defined by using the watershed delineation tool, which delineates watersheds based on an input DEM. For this tool, PCSWMM makes use of the D8 method, meaning that the flow direction in each cell is determined by considering the difference in elevation with the 8 adjacent cells. The resulting flow is in the direction of the steepest slope (PCSWMM support: Watershed Delineation, n.d.). The boundaries of the watersheds are defined by the cells that have no inflow from other cells. Hence, it could be assumed that the inflow and outflow along the system boundary are net zero. Notes on the input DEM are given in Section D.3.

The final system boundary was adjusted such, that the To Lich River was included on the east side as a system outfall, and the main drainage canal is situated under the Nguyễn Trãi street, which is depicted on the cover page of this report. Vũ Trọng Phụng street was included on the west because this street is known to be one of the flooding hotspots (SADCO, n.d.).

D.1.2. System layout

The model layout was drawn by placing 66 conduits, 66 junctions and 1 outfall within the system boundary. Conduits were placed under each road, and junctions were placed on each corner and at every 50 meters. See Figure D.1 for an overview. Google Streetview was consulted to check whether drains, represented as junctions, are present in small alleyways. One outfall was placed at the To Lich river. Shapefiles of the roads and alleyways were obtained via `www.mapcruzin.com` and can be seen in Figure D.4a. (Meuser, n.d.).

The next step was to define 66 subcatchments, i.e. the areas of land from which all runoff flows to each junction. The subcatchments were defined using the `watershed delineation` tool and selecting the 66 junctions as the 'delineation points layer'. The resulting subcatchments were only used for the model setup and not for the model runs. 2D models do not require subcatchments as input, as

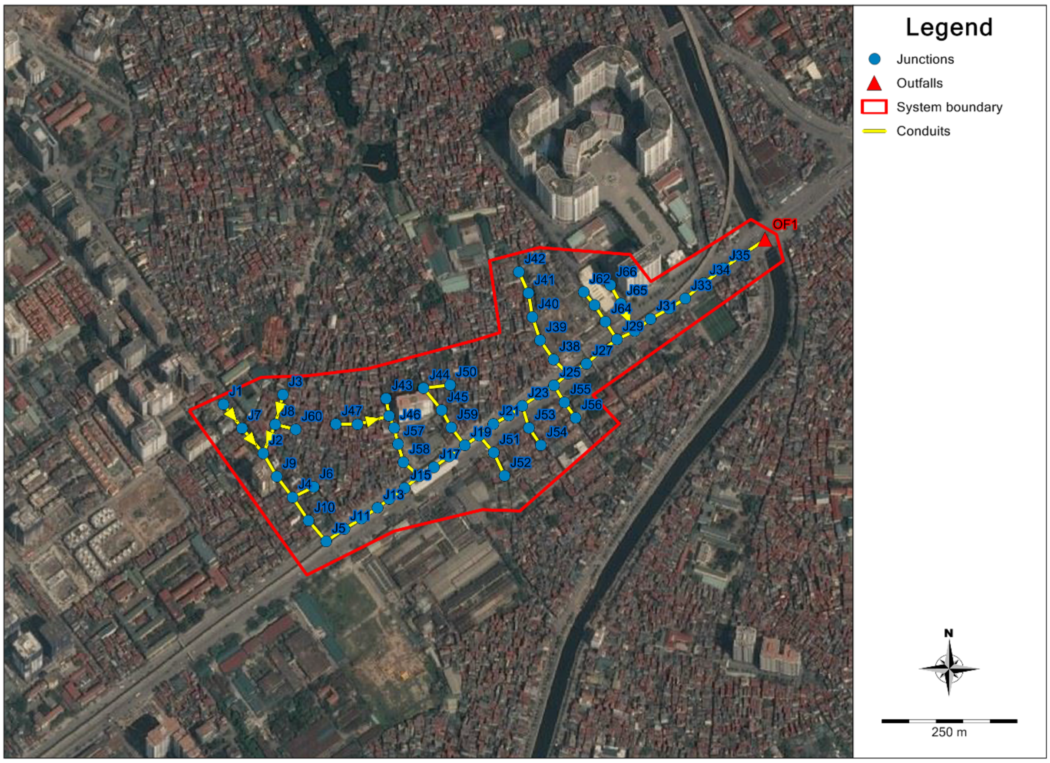


Figure D.1: Layout of the PCSWMM model, located in Thanh Xuân district. The junction's labels are shown in blue they subdivide the entire model area into mesh cells and compute the flow through each cell, making subcatchments obsolete.

D.1.3. Area characteristics

To capture the area characteristics as closely as possible, assumptions were made regarding the following parameters and processes:

- Infiltration model;
- Flow paths;
- Surface area roughness;
- Depression storage on the surface.

These parameters and processes are addressed separately below.

Infiltration model

Infiltration into the unsaturated soil zone can be represented by different models, depending on the rainfall intensity and degree of complexity (CHI documentation, page 'infiltration', last consulted Sep 10, 2022). The Horton model was selected with minimum and maximum infiltration rates of 0.5 and 3 mm/hour, respectively, and a decay coefficient of 4. The effects of these assumptions were tested by means of sensitivity analysis as described in Section D.1.5. The infiltration model is expected to affect the model output minimally, because infiltration in general is expected to be very little compared to the rainfall intensity. Besides, most area is paved and the main soil type is clay, allowing little infiltration (Speth, 2020). Hence, most precipitation water ends up as runoff, rather than infiltrating into the soil.

Flow paths

Flow paths refer to the path that stormwater travels between falling on the surface and reaching the drain. The length of the flow path determines the time of concentration i.e. the time between the precipitation peak and the discharge peak in the drainage system. The time of concentration is represented by the so-called 'width' [m] of the subcatchment, as calculated according to Equation D.1.

$$W = \frac{A}{L} \tag{D.1}$$

Where:
W = Width [m]
A = Subcatchment area [m^2]
L = Flow path length for the subcatchment [m]

It was assumed that flow routing occurred over all streets, alleyways, and open surfaces (so it could not run through buildings). The road maps from `www.mapcruzin.com` were used to draw flow paths; every road or open surface was drawn as a potential flow path. The drawn flow paths as well as the road map are shown in Figure D.4c. The drawn flow paths were used as input for the `set flow length/width` tool, which calculates the width of each subcatchment.

Surface area roughness

The manning coefficients for surface roughness were set based on table 8 in the Vietnamese design principles (Ministry of Construction, 2008, p. 11). This was done for two different surface types: aggregated road surface (n = 0.145 $m^{1/3}$/s) and roofs (n = 0.24 $m^{1/3}$/s).

Depression storage

The depression storage is the ability of a type of area to retain water on its surface. The values for depression storage on impervious surface and pervious storage were assumed to be 2 and 4 mm, respectively. The effects of these values were tested with a sensitivity analysis using, of which the results are shown in Figure D.2). The depression storage of impervious area affected the model minimally, and the pervious area imperceptibly little.

D.1.4. System characteristics

Pipeline diameters were estimated using the `pipe sizing` tool and the subcatchments as input. This tool iteratively solves the Manning's equation that expresses the relationship between peak flow rate Q [m^3/s], Manning's roughness coefficient n [$m^{1/3}/s$], minimal cross-sectional area A [m^2], hydraulic radius R [m], and slope S [-] in all conduits:

$$Q = \frac{1}{n} A R^{2/3} \sqrt{S} \tag{D.2}$$

To compute the peak flow, a design storm of 100mm in 2 hours was used. This value was suggested by Prof. Dr. Vu Trong Hong, former Deputy Minister of Agriculture and Rural Development, former President of Vietnam Irrigation Association, in a public interview (An, 2021). According to this interview, Hanoi's threshold for flooding is 100mm in 2 hours. Therefore, the diameters were defined such that their maximum discharge equals a precipitation event of 100mm in 2 hours. Furthermore, according to the Vietnamese design principles, conduit diameters range between 0.4m and 4m (§4.5.1, Table 10 Ministry of Construction, 2008).

The slope and elevation of the conduits in the model were based on the Vietnamese design principles. According to the principles, the slope of each conduit should be set to 0.3%. The junction invert elevations followed accordingly (see paragraph 4.7.2, Table 13 in the Ministry of Construction, 2008). The implication of using the Vietnamese design principles as a guideline for the model set-up is that the model will probably be different from the actual drainage system. This is partly because the system has deprecated over the years, but also because new system components are not always built according to the standards (Nguyen Huu Trong, 2022; Vu Hoa Linh, 2022).

D.1.5. Testing assumptions

The effects of seventeen parameters have been investigated by means of a sensitivity analysis using the SRTC tool. This resulted in seventeen sensitivity gradients, which are depicted in Figure D.2. The gradients show the projected change in flooding [m^3/s] at node J10 as a function of parameter uncertainty [%]. It can be seen in the figure that the value of the baseline DWF affects flooding in node J10 the most as it has the steepest gradient. The upper image includes all seventeen gradients, and for the lower image the DWF baseline was omitted such that the remaining sixteen gradients become better visible. The fact that the DWF affects the model output to a considerable extent entails that it is important to use reliable values for it. Namely, if values are used that are far from the actual DWF, the model output will be less accurate. For this reason, a closer look was taken at the DWF, see the next subsection.

Besides the DWF baseline, the uncertainty of all other parameters affect the model minimally. This can be concluded from Figure D.2 as the slopes of all gradients are small. Some parameters have show no effect at al, such as the suction head. The minimum impact of these parameters on this model output does, however, not entail that they are irrelevant in PCSWMM modelling. PCSWMM can also be used for other purposes, such as water quality analysis and for studying groundwater flows. Many of the assumed parameters relate to these topics, and are useful for these purposes. For this study, where inundation extent in terms of flood quantity is modelled, these parameters are not relevant.

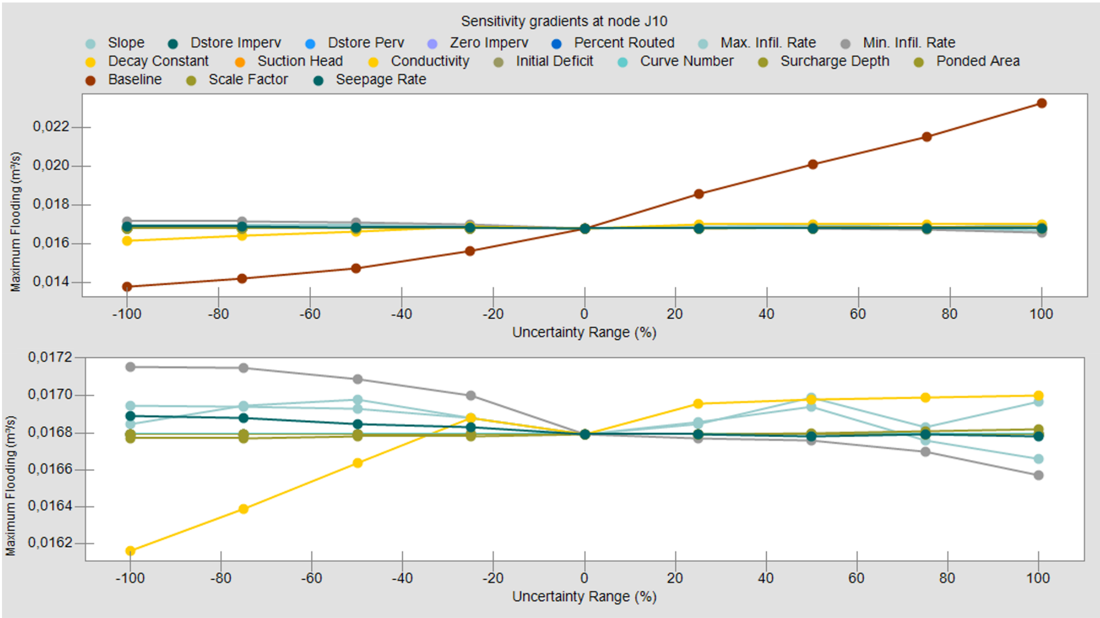


Figure D.2: Sensitivity gradients at node J10 for seventeen parameters. The y-axis depicts the flooding at the node for each specific parameter value, the x-axis depicts the uncertainty [%].

D.1.6. Dry weather flow (DWF)

The sensitivity analysis showed that the DWF affects the model output to a considerable extent. It was therefore important that representative estimates of the DWF were used, such that the modelling results were accurate as possible. A publication from 2013 by Bao et al. was consulted to obtain estimates for Thanh Xuân district (Ngoc Bao et al., 2013). Using DWF Equation D.3, the DWF was estimated for each subcatchment. The DWF equation was obtained from Butler & Davies (2000).

$$DWF = PG + E + I \tag{D.3}$$

In which

DWF = dry weather flow [m^3/s]
P = population
G = average per capita domestic water consumption [m^4/s]
E = average industrial effluent [m^3/s]
I = infiltration [m^3/s]

The population in each subcatchment was determined by multiplying the total population of the study area (30,000) by the fraction of the subcatchment size. For example, a subcatchment that is 5% of the total area size is assumed to have 30,000 × 0.05 = 1500 inhabitants. Hanoi's average water usage per capita per day is less than 81.3 L/capita/day (Ngoc Bao et al., 2013). Bao et al. also reported that household water use accounts for about 70% of the total water consumption Hanoi. Hence, to account for the average industrial effluent, the water use per capita is multiplied by $\frac{10}{7}$. Last, Butler & Davies suggest that the conventional approach is to specify infiltration as a fraction of 10% of the DWF. To summarise, the DWF for each subcatchment was defined as follows:

$$DWF = 81.3 * 1.1 * \frac{10}{7} * \frac{\text{subcatchment area}}{\text{total area}}$$

The DWF of each subcatchment was then determined by summarising the DWF of all upstream subcatchments.

D.1.7. Design storm

The final step in setting up the 1D drainage model was constructing a design storm and a hyetograph. The IDF curves from Nguyen (2009), described in Section 3.2.1, were used to compute the design storm. To determine an appropriate return period, two interviews with experts were consulted. One with Prof. Dr. Vu Trong Hong who is the former Deputy Minister of Agriculture and Rural Development, former Chairman of the Vietnam Irrigation Association, and has a lot of experience with Hanoi's drainage system. This interview was conducted by Thanh An for Emagazine. The other interview was the personal interview with Nguyen Huu Trong, which has been referred to before. Prof. Dr. Vu Trong Hong stated that the capacity of the drainage system is 50-100mm precipitation in 2 hours (An, 2021). However, Nguyen Huu Trong stated that the this threshold was already reached if 50mm precipitation falls within 30 minutes (Nguyen Huu Trong, 2022). These values are quite divergent, which could be explained by the fact that the capacity of the drainage system varies strongly for different parts of the city. That is why the IDF curves developed by Nguyen were consulted as a third source (A. T. Nguyen, 2009). Using Equations 3.1a and 3.1b, it could be estimated that 100mm/2 hours has a return period of 1.85 years, and 50mm in 30 minutes has a return period of 0.9 years (see Figure D.3). To be conservative, a design storm with a return period of 1.85 years was used. The return period was used to construct the hyetograph shown in Figure **??**.

The Chicago method (or alternating block method) was used to compute the hyetograph, which is applicable in urban areas and a straightforward method to compute hyetographs (Keifer & Chu, 1957). Besides, the Chicago method makes use of the IDF curves that were already established for Hanoi. A precipitation event of 24 hours was created with a time interval of 1 hour. The Chicago distribution is defined by Equations D.4a and D.4b (Corrugated Steel Pipe Institute, 1996).

$$i_b = \frac{a\left[(1-b)\frac{t_b}{r} + c\right]}{\left(\frac{t_b}{r} + c\right)^{1+b}} \tag{D.4a}$$

$$i_a = \frac{a\left[(1-b)\frac{t_a}{1-r} + c\right]}{\left(\frac{t_b}{1-r} + c\right)^{1+b}} \tag{D.4b}$$

Where:

i_b and i_a	=	average rainfall intensity before (b) and after (a) the peak[mm/hr]
t_a and t_b	=	time before (b) and after (a) the peak [min or hrs]
a, b, c	=	IDF constants dependent on storm recurrence interval and time units
r	=	Relative value indicating the starting time of the peak

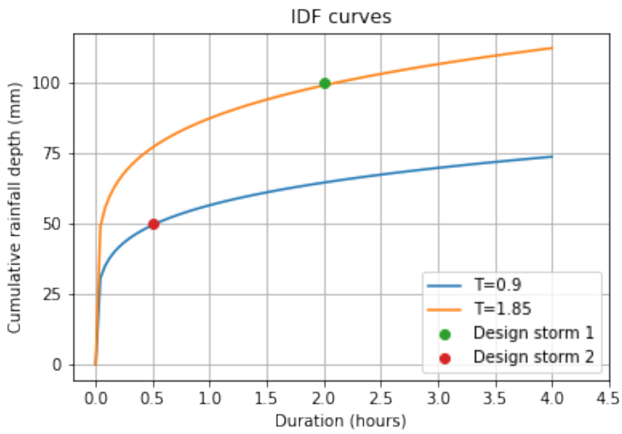
For r, a value of $r = 0.35$ was used as this lies within the typical range of 0.3 to 0.5. The abc time units are set to minutes, as this is advised for wetter areas and calibrated values of a higher than 100 (Keifer & Chu, 1957). The resulting hyetograph is shown in the left picture in Figure D.3 in Chapter 4. For the integrated 1D-2D model runs, only the 3-hour peak was modelled, represented by the red area in Figure **??**. This was done to lower the computation time by a factor of 8 (24/3 = 8).

D.2. 2D overland flow model

As described before, the 1D drainage model was coupled to a 2D overland model. This section describes how the 2D model was defined, and how the two models were coupled.

D.2.1. Creating 2D layers

The first step is to enable 2D modelling in PCSWMM's backstage menu, and to create the desired 2D layers. The layers used in this study were the DEM, Obstruction, Centerline, Bounding, and a 2D Nodes layer. Maps showing these different layers are shown in Figure D.4b. The DEM layer is addressed in Section D.3.



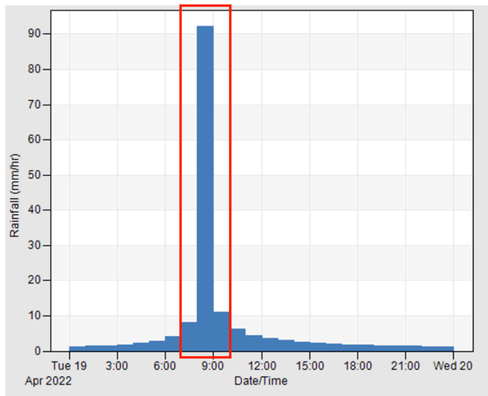


Figure D.3: Left: Design storm 1 described by Prof. Dr. Vu Trong Hong and design storm 2 described by Nguyen Huu Trong. The return periods of the events are 1.85 and 0.9 years, respectively. Right: Hyetograph used for model simulations. For the integrated 1D-2D model simulations, only the red area was taken into account to reduce computation time.

The *obstruction layer* defines impervious obstructions that influence the flow direction, such as buildings or walls. An obstruction shapefile from www.mapcruzin.com was used for this purpose, but this shapefile only included larger buildings. The contours of dense residential areas were added manually using Bing Satellite imagery that is included in PCSWMM. The *centerline layer* was represented by a shapefile of Vietnam's waterways including the To Lich river. The shapefile was obtained from www.mapcruzin.com and can be seen in Figure D.4a. The system boundary was drawn in the *boundary layer*, following the contour lines of the watershed delineation as explained in Section D.1. Using this boundary layer and the obstruction map, an adaptive grid of 2D points was generated with a resolution of 10 meters using the obstruction map. An adaptive grid has a higher resolution around edges of obstructions, around corners, and at locations with a relatively steep slope. The distance tolerance was set at 15 meters, and the elevation tolerance was set to 0.05 meter. The adaptive grid has a lower resolutions at relatively flat areas that are free of obstructions, reducing computation times to a significant extent. The final layer, the *2D nodes layer*, defines the approximate locations of the 2D cells in the 2D network. It is used to create the 2D mesh and is automatically generated using the Generate Points tool in combination with the bounding layer, obstruction layer, and the DEM.

D.2.2. Boundary conditions

Once all desired 2D layers were created, the boundary conditions were defined. As described in Section D.1, it was assumed that there is no inflow or outflow along the system boundary. However, at the East side, the model is adjacent to the To Lich river. This was represented by adding seven boundary outfalls that were connected to the 2D mesh: one outfall for each time the 2D mesh intersects the waterway. For each outfall, normal flow is assumed, meaning that the slope of the water surface and channel bottom is the same and the water depth remains constant. For later experiments with the failure mechanisms, this boundary condition was altered. This is further explained in Appendix C. A close up of the boundary outfalls is shown in Figure D.4d.

D.2.3. 1D-2D Connection

The 1D model of the drainage system and the 2D model of the surface were connected to each other using 66 orifices. To each 1D junction, the closest 2D junction was coupled with a bottom orifice with set parameters. This was done using the `Connect 1D to 2D` tool.

An illustration of the functioning model is shown in Figure D.5. The flow through conduits C8, C22, and C43 is shown in the graph on the right to illustrate the cumulative flow through the system. On top of the graph, the hyetograph is shown with a peak showing from 20:00 to 21:00.

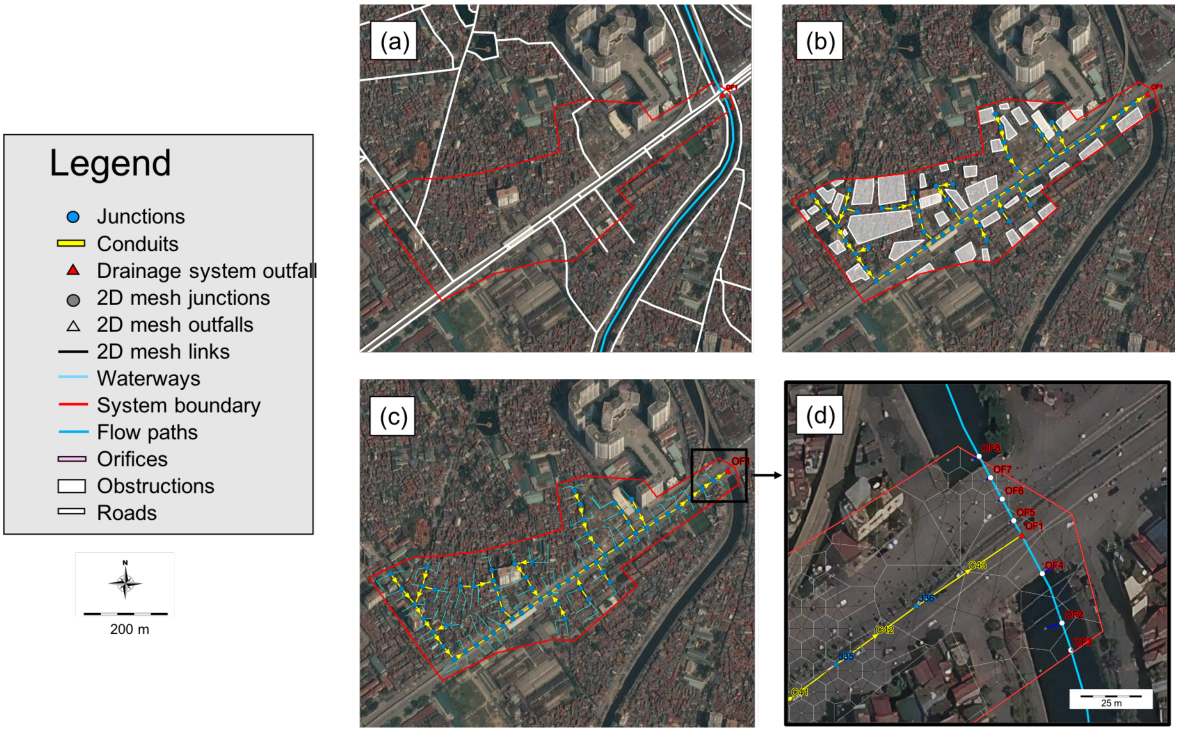


Figure D.4: Illustration of different 1D and 2D layers: (a) roads and waterways, (b) obstructions, (c) flow paths, and (d) a close up showing the 2D mesh including 2D outfalls along the waterway.

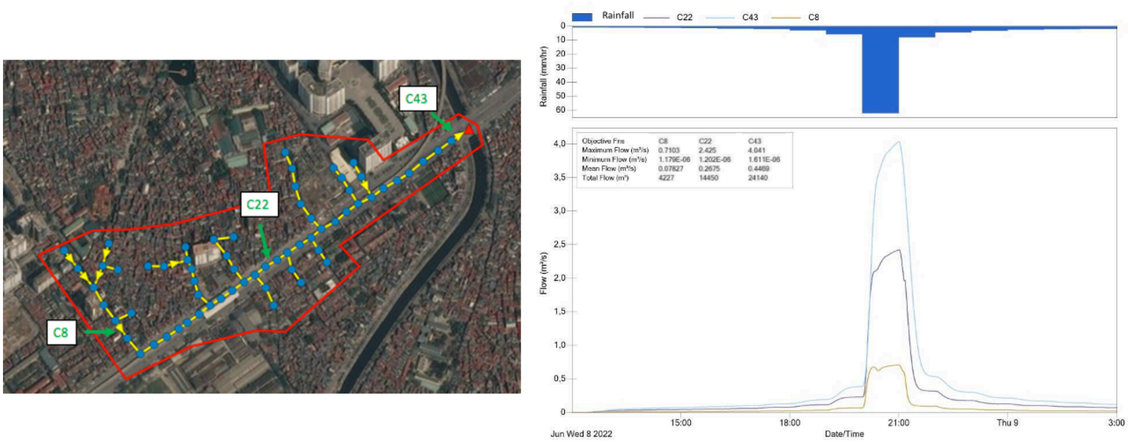


Figure D.5: Flow through three conduits during a 24-hour event with a return period of 1 year at different locations of the system: C8, C22, and C43. At the top of the figure, the rainfall depth is shown.

D.3. Digital elevation model

This section explains a little more about the elevation data or DEM that has been used in this study. Sections D.1 and D.2 already referred to this DEM, as it was used as the surface elevation for the model setup. This section starts with reviewing the elevation datasets that have been tested and explaining why these datasets were not sufficient (Section D.3.1). Because all of the reviewed datasets were not sufficient, an artificial DEM was generated using QGIS. The methodology of this is described in Section D.3.2.

D.3.1. Tested datasets

Three different publicly available datasets were obtained and tested, each showing very different values for the elevation of the study area. The first one is the SRTM 1 Arc-Second Global dataset from U.S. Geological Survey (USGS) (USGS, n.d.). This dataset has a resolution of 30×30m. The second dataset is the ASF DAAC L1.1_PALSAR dataset from 2010, with a resolution of 12.5×12.5m. There were various reasons why the datasets were not realiable, of which five are enlisted below.

1. Based on site visits, it could be seen that the area was mostly flat. There could be small height differences, but the elevation range could not be more than 5-6 meters. The USGS dataset showed an elevation range of [-4, 21] metes and Alos Palsar a range of [5, 17]. This deviation from the expected range is potentially due to the fact that it concerns an urban area, and satellites are not able to discern between ground level and high-rise buildings. Additionally, a lot of construction is taking place in Thanh Xuân district, such that the elevation is expected to be variable. The DEMs even showed negative values, which are potentially due to the digging and laying of foundations prior to construction. During model simulations, these pits kept inundating, making accurate simulations nearly impossible.
2. The resolution of both datasets is too low for a dense urban environment such as Hanoi. Reference points such as streets and the To Lich river have a width of ± 10-20 meters, and can only be captured with resolutions higher than this. The implication of the low resolution are deviating ranges as explained under 1.
3. The To Lich river on the East side was used as a reference point, as the elevation along the river should be approximately equal. However, the To Lich river could not be distinguished at all, while larger rivers such as the Red River in the East of Hanoi, however, could be distinguished clearly. This indicates that the datasets are reliable on larger scales, but not on a scale of one by one kilometre.
4. There were hardly any similarities between the datasets.
5. Previous research shows elevation maps that show much smaller ranges (Hung et al., 2007; Luo et al., 2018). This includes a publication from Go Yonezawa from 2009, in which a DEM was generated for the whole city of Hanoi (Yonezawa, 2009). This publication shows elevation ranges of only a few meters. The DEM maps created by Yonezawa were requested, but unfortunately not received.

Because of the five reasons stated above, a third type of elevation data was used, which was NASA's Shuttle Radar Topography Mission (SRTM), extracted from Google Earth. The resolution of this dataset is ±16m, and a quick inquiry in Google Earth shows that tall buildings are not considered in the elevation (Sharma, 2010). This was done by extracting a large amount of data points (± 10,000 points) and using QGIS for inverse distance weighthing (IDW) interpolation. This resulted in a DEM with values ranging from 10 to 17 meters, which is a much more realistic range. This methodology was described by El-Ashmawy (El-Ashmawy, 2016). Still, the DEM created with Google Earth did not look as expected, as it contained a lot of pits and hills. Additionally, the To Lich could still not be recognised. Besides, it was strongly concluded that the accuracy of elevation data extracted from Google Earth is tested by comparing it with reference data before using it (El-Ashmawy, 2016). Acquiring reference data in the field would help to calibrate the elevation map, but it is very labour-intensive and outside the scope of this research. It was therefore decided to opt for generating an artifical DEM manually using QGIS, as described in the next section.

D.3.2. Creating an artificial DEM

The artificial elevation model was created in QGIS in generating random samples and interpolation. It is important to ensure that the coordinate reference system is equal to the one that will be used in PC-SWMM. The CRS used was *Hanoi 1972 + 6-degree Gauss-Kruger zone 18*. Two assumptions were made to have as reference points. First, the elevation range is 8-14 meters. Second, there are no abrupt pits and elevation, only gentle gradients. This can be realised by using sample points based on nearest neighbour point information.

The DEM was created in four steps, the results of each step are shown in Figure D.6. The first step was to create a random raster layer using a binomial distribution. Poisson and uniform distributions were also created to compare, but the binomial distribution showed the most realistic results. This resulted in a raster with random values between 0 and 1. Next, the Raster Calculator was used to rescale the random values to the desired range i.e. 8-14. Equation D.5 was set up for this purpose.

$$\texttt{new\_value} = \frac{\texttt{new\_min + (old\_vec - old\_min)}}{\texttt{(old\_max - old\_min) * (new\_max - new\_min)}} \qquad \text{(D.5)}$$

In which:

`new_value` = new value
`old_value` = old value
`old_max` = old maximum bound, depends on input raster
`old_min` = old minimum bound, depends on input raster
`new_max` = new maximum bound (14)
`new_min` = new minimum bound (8)

The third step was to create a points layer with random points. Some experiments were done with ranging the numbers of points between 5 and 200. It was concluded that a relatively low number of points (20) results in the smallest and most realistic slopes. The points layer was used to take samples from the raster layer, resulting in a points layer with values ranging between 8 and 14. The points layer could then be used as input for interpolation, which was the fourth and last step. Two types of interpolation were tested: inverse distance weighting (IDW) and triangular interpolation network (TIN). With IDW interpolation, sample points are weighted during interpolation so that the influence of one point relative to another decreases with distance from the unknown point of interest. With TIN interpolation, a triangular network is formed based on the point samples, creating small ridges that look similar to an elevation map. Both types of interpolation are included in Figure D.6, and this study continued with using the TIN-interpolated variant. An image showing the final elevation map loaded in PCSWMM is shown in Figure D.7.

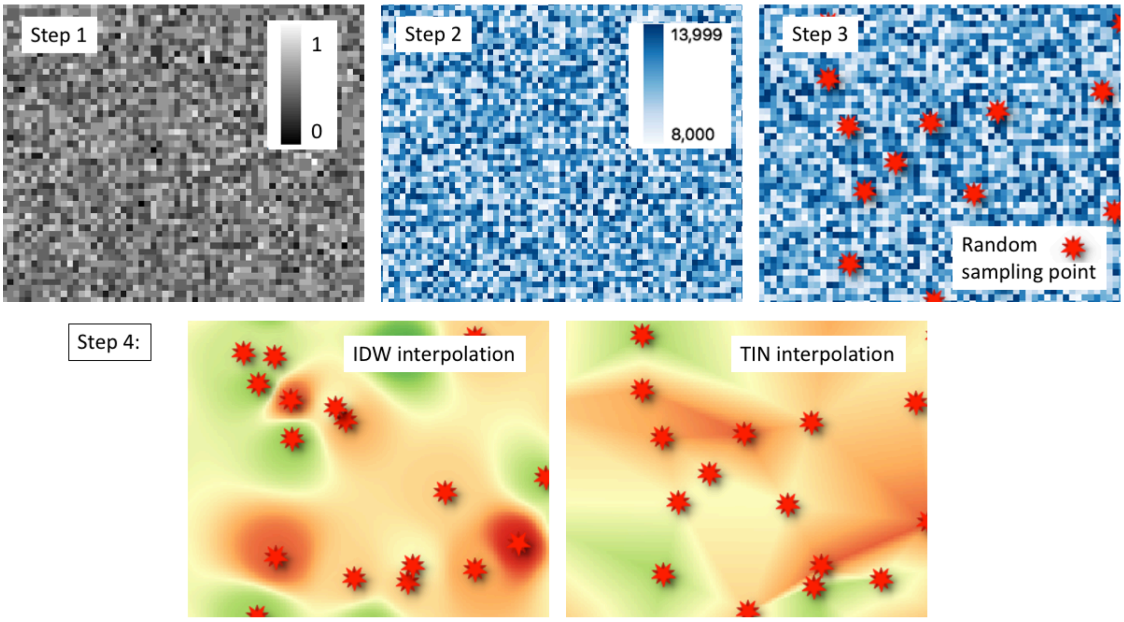


Figure D.6: Interim results of the DEM-creation process. Two types of interpolation were tested in Step 4, both results are shown and only the TIN-interpolated variant was used in this study.

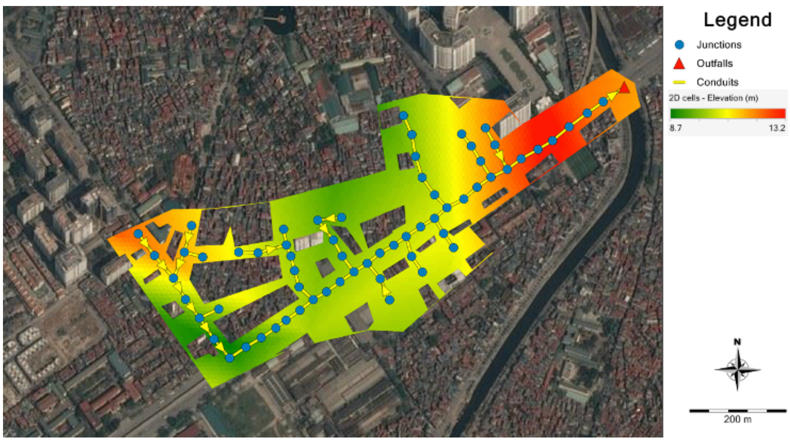


Figure D.7: Elevation of the model. DEM artificially generated in QGIS using TIN interpolation

D.4. Standard Query Language (SQL) statements

The methodology of post-processing the PCSWMM results and setting up the severity maps is described in subsection 4.3.2 in the methodology chapter. As described there, SQL were used to define the severity maps. The SQL statements for severity map 1, which only depends on the maximum inundation depth, are presented in Table D.1. The SQL statements to create the second severity maps, which are based on the maximum inundation depth as wel as the maximum flow velocity [m/s] were very comprehensive and are summarised in Figure D.8.

Table D.1: SQL statements used to create severity maps type 1

Risk level	**SQL statement**
Level 0	MaxDepth > 0 AND MaxDepth < 0.15
Level 1	MaxDepth >= 0.15 AND MaxDepth < 0.23
Level 2	MaxDepth >= 0.23 AND MaxDepth < 0.43
Level 3	MaxDepth >= 0.43

Low danger zone

```
    MaxDepth > 0 AND(
   (MaxDepth < 0.48  AND MaxVelocity < 0.1)
OR (MaxDepth < 0.40  AND MaxVelocity < 0.2)
OR (MaxDepth < 0.33  AND MaxVelocity < 0.3)
                  [...] )
```

Judgement zone

```
   (MaxDepth    < 0.9  AND MaxDepth    ≥ 0.48 AND
    MaxVelocity < 0.1)
OR (MaxDepth    < 0.85 AND MaxDepth    ≥ 0.40 AND
    MaxVelocity ≥ 0.1  AND MaxVelocity < 0.2)
OR (MaxDepth    < 0.7  AND MaxDepth    ≥ 0.3  AND
    MaxVelocity ≥ 0.2  AND MaxVelocity < 0.3)

                  [...]
```

High danger zone

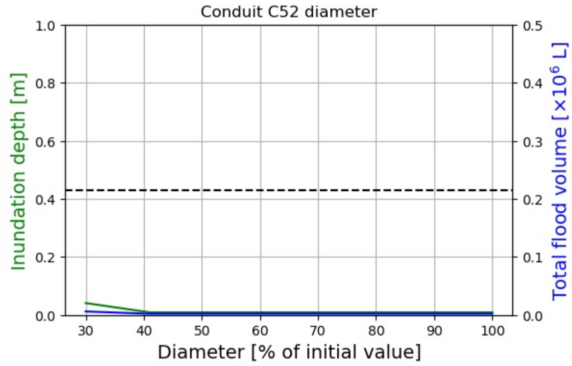
```
    MaxDepth ≥ 0.9
OR (MaxDepth ≥ 0.85  AND MaxVelocity > 0.1)
OR (MaxDepth ≥ 0.7  AND MaxVelocity > 0.2)
                  [...]
```

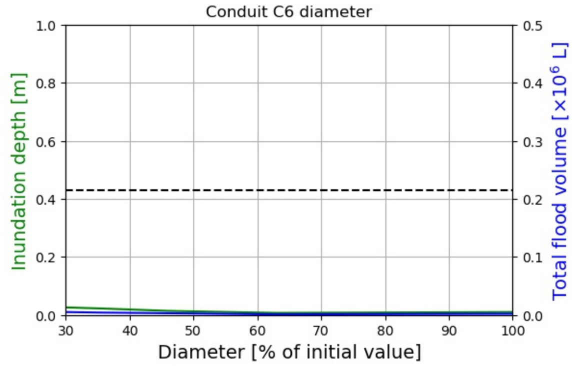
Figure D.8: SQL statements used to designate three different risk zones. The code was used as input for the severity maps in PCSWMM.

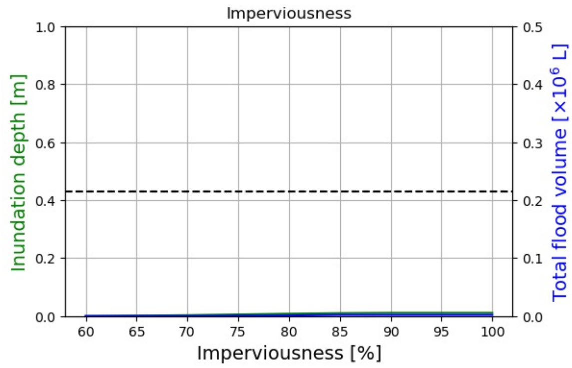
E

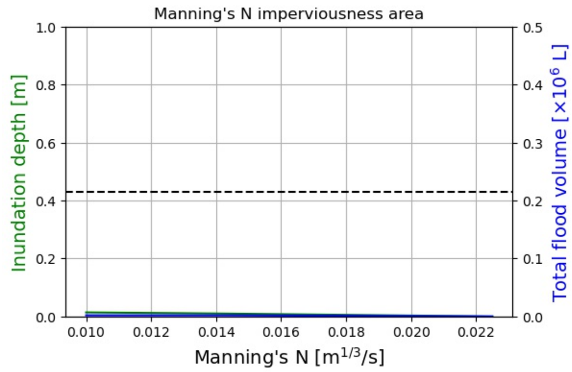
Severity-uncertainty plots

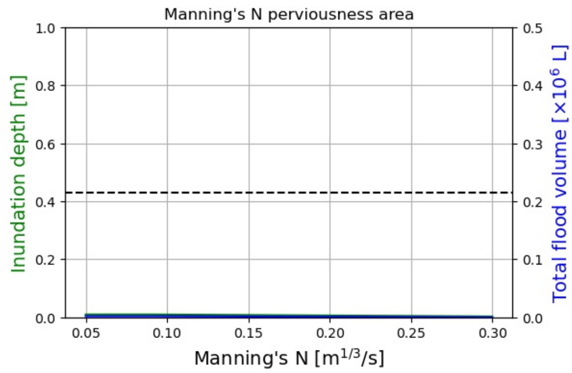
E.1. Severity-uncertainty plots

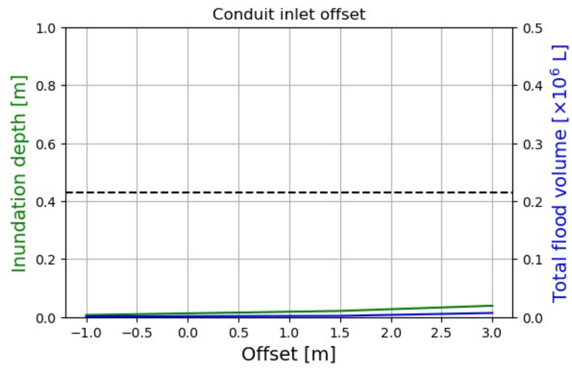












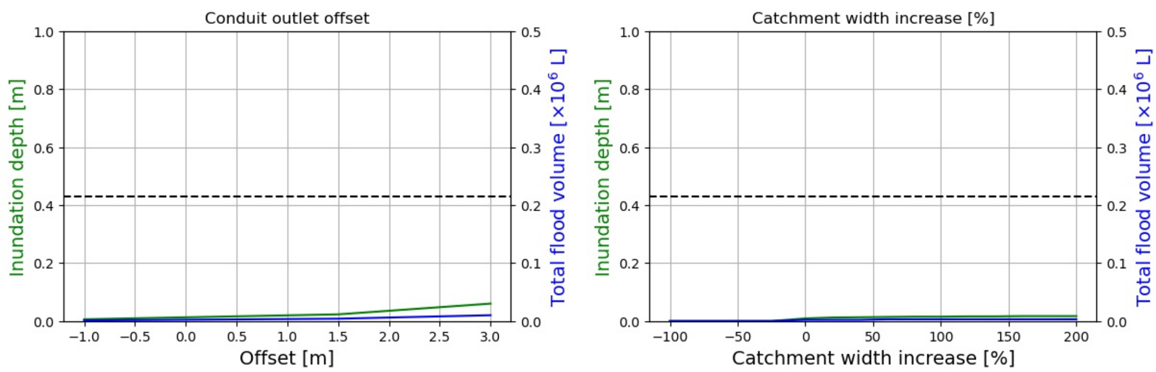


Figure E.1: Severity-uncertainty plots for the experimental parameters that had little to no effect on the model output.