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Building Resilience:

Analyzing Beira's Drainage Network and Flood Management

The impact of failure mechanisms on flooding in informal settlements

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The impact of failure mechanisms on flooding in informal settlements

by

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Picture on cover: by author.

Preface

This is the final report of the thesis that I have been working on for the past nine months, which marks the end of student time. During these six years, the freedom to do stuff that was not directly related to my studies - organise activities, build an artwork, do a world record attempt, obtain my teachers degree and collaborate in a research in Costa Rica - made me to the person that I am today. Obtaining my Master's degree would therefore never have been possible without all the people that were together with me during these experiences.

While some students only get one office during their thesis, I had the privilege to choose between four. Firstly, the Netherlands Red Cross have opened their organisation for me and gave me an insight in the humanitarian world. Michel's enthusiasm about Mozambique immediately intrigued me during our first call and he has guided me in every step since then. I also want to thank everyone else from the Water Advisory and Innovation Unit, as well as everyone else from International Aid and 510 for their interest in my research. Coming to the office in The Hague was always a true pleasure because of you.

My second office was at the faculty of Civil Engineering and Geosciences, where my other two supervisors work. Erik has helped me from the beginning and I am grateful that his door was always open, even for the smallest doubts that I had. Jeroen was always critical, but never left me out of a meeting without mentioning how interesting he found the research. In the faculty, working in the Afstudeerhok and together with all the people from the other Master's tracks all over the faculty gave me great support throughout the whole process.

Thirdly, working in Mozambique would never have been the same without the collaboration with Associação FACE. They immediately saw me as one of their own colleagues and learned me the first words in Portuguese. In the evenings and weekends, the many expats and locals that I met gave me a warm welcome to the Mozambican culture, encouraging me to return to Beira again. I would like to say 'muito obrigado' to all of them!

My last office was the most important one: that office could be everywhere; in the train, on the couch or in a bar. Discussing (and sometimes complaining) about my research with all my parents, grandparents, brother and other friends and family was a welcome relief from the thesis process. They made me enjoy the time and encouraged me to follow the passion for the humanitarian work.

Ending with a final appreciation for the financial contributors of my trip to Mozambique, being the Lamminga Fund, FAST | Delft University Fund and TU Delft Global Initiative. The trip would not have been possible without their support.

Enjoy reading my thesis!

Job Knoop
Delft, November 2023

List of Abbreviations

AIAS	Administração de Infraestruturas de Abastecimento de Água e Saneamento	20
AMOR	Associação Mocambicana de Reciclagem	32
CMB	Conselho Municipal da Beira	67
CAM	Consorzio Associazioni con il Mozambico	33
CRS	Coordinate Reference System	99
DEM	Digital Elevation Model	18
FACE	Associação FACE	20
INGD	Instituto Nacional de Gestão e Redução do Risco de Desastres	20
INAM	Instituto Nacional de Meteorologia	18
LiDAR	LIght Detection And Ranging of Laser Imaging Detection And Ranging	18
MZN	Mozambican metical	45
NGO	Non-Governmental Organisation	7
NDBI	Normalized Difference Built-up Index	35
NDWI	Normalized Difference Water Index	35
NLRC	The Netherlands Red Cross	20
ppm	parts per million	44
RGR	Relative Growth Rate	9
RVO	Rijksdienst voor Ondernemend Nederland	20
SASB	Serviços Autónomos de Saneamento da Beira	20
TN	Total Nutrient	10
TP	Total Phosphorus	10
VNG International	Vereniging voor Nederlandse Gemeenten International	20

Contents

Abstract

This research analyses and evaluates the performance of the drainage system in Beira, Mozambique. It considers its formation, maintenance, failure modes and connections, to recommend improvements on its performance. The research identifies six primary failure modes - vegetation overgrowth, human interference, waste accumulation, sedimentation, underdimensioned structures and 'other' - highlighting the disparities between technical design and real-world complexities. The study quantifies the presence of these failure modes by direct observations and transect walks, and uses hydraulic modeling software, D-FLOW FM 1D2D, to simulate their impact on inundation depths.

The results show that widespread flooding can be found even without failure modes. Additionally, it prioritises the risks of vegetation and human interference. Therefore, it recommends an increase of hydraulic capacity of a part of the system, proactive vegetation management, water level control, and community engagement in system management. It also underscores the importance of early land demarcation in urban planning, the implementation of flexible yet delineated canals, and the involvement of communities in flood adaptation.

1

Introduction

1.1. Problem Statement

Beira is a rapidly expanding city in Mozambique and holds nearly 600,000 inhabitants (Instituto Nacional de Estatística, 2017). Mozambique, being one of the world's lowest-income countries, has a significant portion of its population living below the international poverty line (World Bank, n.d.). This economic strain has given rise to numerous informal neighborhoods where housing and sanitation is poor.

The city contends with intense precipitation events and cyclones. The rainy season, typically occurring from December to March or April, brings substantial rainfall. Notably, cyclones result in frequent pluvial and coastal flooding events. The most severe one, Idai in 2019, caused extensive damage and exposed vulnerabilities in the city's infrastructure, many of which have remained unrepaired even years later.

To manage these precipitation events, the city has a formal drainage system designed to handle flooding. The drainage network has one outfall and can be divided into two main branches: Phase 1 and Phase 2, each presenting unique characteristics and challenges. The Phase 1 section of the network is characterized by lined canals made from concrete and a large retention basin, constructed in 2018. The Phase 2 segment consists of unlined canals dating back to the colonial era, for which rehabilitation plans are currently being developed.

Besides these formal drainage networks, the informal settlements hold a large network of informal drains constructed by communities themselves. The drains are typically unstructured and not incorpo-

Figure 1.1: A flooded neighborhood in Munhava, Beira (picture by author)

rated in drainage modelling as 'big, high-tech engineering companies are not capable of working on such small-scale issues' (van Hemmen, 2022). Consequently, there is a lack of information regarding the impact these canals have on flood management.

Despite the presence of this extensive drainage network, the city has to deal with frequent floodings. Some inhabitants of the informal neighbourhoods report having floodings during eight months per year, with water levels ranging from ankle to waist height. According to the damage-depth curve for urban Mozambican houses, damages reach approximately 10% at water depths of 10 centimeters (Huizinga et al., 2017), which is assumed to be an acceptable yearly damage. These floodings disrupt daily life and lead to frequent outbreaks of cholera and malaria.

It is currently unknown what the main drivers are for these floodings. From background interviews, it was found that besides a lack of capacity, the most prevalent failure modes are human interference, sedimentation, underdimensioned structures, vegetation, waste, and other. Both parts of the network show different failure modes, but the frequency and extent of these failures and their impact on flooding are currently unknown.

1.2. Research Objectives

1.2.1. Main Objective

Against the light of this problem, this research aims to analyse and evaluate the performance of the drainage system in Beira, Mozambique, taking into consideration its formation, maintenance, failure modes and connections, to recommend improvements. To fulfill this objective, three research questions and multiple sub-objectives are formulated and listed below:

1. What does the drainage system in Beira look like and how was it formed?
   (a) To explain how the tertiary drainage canals are formed and maintained in similar regions, in order to gain better insight in the formation of the drainage system in Beira.
   (b) To describe the general climatic and geological context of the study area.
   (c) To describe the stakeholders active in the field of water drainage in the study area.
   (d) To explain what the main failure modes in the drainage system are, like vegetation, human interference, waste accumulation, sedimentation, and underdimensioned structures.
   (e) To describe the layout and formation of the primary and secondary drainage canals.
   (f) To explain the formation of the primary and secondary drainage canals.
   (g) To describe the state of the connections between the primary, secondary, and tertiary canals.
   (h) To describe the state of the primary and secondary canals.
   (i) To describe the water quality in the study area.
2. What is the performance of the drainage system in Beira?
   (a) To predict inundation depths in the as-designed state of the drainage system.
   (b) To predict inundation depths increases caused by the explained failure modes in the drainage system.
   (c) To evaluate the most impactful failure modes in the drainage system.
   (d) To evaluate the effectiveness of the stakeholders active in the study area.
3. What are possible improvements to the drainage system in Beira?
   (a) To advise on measures that can be taken to improve the performance of the drainage system.
   (b) To advise on what should be considered while designing a drainage system with similar properties.

1.3. Report Outline

This report consists of the following chapters: in Chapter 2, a theoretical framework is given for the research and in Chapter 3 the context of the study area is elaborated. Research question 1 is answered in these chapters. In Chapter 4, the research methods are defined and the results of this will presented in Chapter 5 to answer research question 2. In Chapter 6, the results will be discussed after which conclusions will be drawn from the results and the discussion in Chapter 7. Recommendations are given in Chapter 8 to answer research question 3.

An overview of the outline of the report and the used methodologies is presented in Table 1.1.

Research Question	Related section	Method used
1 a	2.1	Literature study
1 b	3.1, 3.2, 3.3	Literature study
1 c	3.5, 4.2, 5.2	Literature study, interviews
1 d	2.2	Literature study
1 e	3.4, 4.1.3	Literature study, technical measurements
1 f	3.4	Literature study
1 g	4.1.1, 5.1.1	Direct observations
1 h	4.1.2, 5.1.2	Transect walks
1 i	4.1.5, 5.1.3	Sample testing
2 a	4.1.4, 5.1.2	Hydraulic modeling
2 b	4.1.4, 5.1.2	Hydraulic modeling
2 c	5.1.2, 5.2	Interviews, literature study
2 d	4.2, 5.2	Interviews
3 a	8	
3 b	8	

Table 1.1: Results of the assessment of the connections, structures and inlets

2

Literature Study

The literature review offers insights from comparable regions regarding the forming and structure of tertiary drainage canals in unplanned urban settlements. Moreover, it examines failure modes in drainage canals exhibiting similar characteristics.

In literature and during expert conversations, primary, secondary, and tertiary canals are often discussed, yet determining their specific order can be challenging due to the absence of a clear definition. This research uses the following classifications: primary canals serve as drainage systems for multiple neighborhoods; secondary canals are primarily responsible for drainage within a single neighborhood or a specific neighborhood section, and tertiary canals are formed to address drainage needs at a smaller scale, typically serving a single street or household.

An important contextual condition in the Sub-Saharan African region is that infrastructure is commonly affected by the build-neglect-rebuild cycle. This pattern worsens due to the lack of emphasis on maintenance, a challenge rooted in organizational and institutional issues. Consequently, assets deteriorate rapidly, requiring faster reconstruction compared to when regular maintenance practices were in place. Therefore, maintenance is a crucial area of focus for the drainage network (Facility, 2013).

2.1. Forming and structure of tertiary drainage canals in informal settlements

Tertiary drainage canals in unplanned urban settlements are generally defined by a strong heterogeneity and do not necessarily form a network (Reed, 2013) (Jiusto and Kenney, 2016). Both open or closed canals are found and the surface of the canals can differ from region to region. Topographical differences of the area influence the layout and properties of the canals. Additionally, social differences can create vastly different flooding outcomes in drainage networks with similar physical properties (Mulligan et al., 2016). To understand these drainage systems, it is therefore required to appreciate their heterogeneity (Jiusto and Kenney, 2016)

In general, there is very little information available on storm water management in the Global South (Parkinson and Mark, 2005). Even if there is literature available, it is rather superficial and does not supply in-depth information on canal performance in different situations.

2.1.1. General remarks on informal settlements

The development of informal settlements follows similar patterns in all regions, with more external stakeholder involvement as development progresses. Starting with no intervention at all, the upgrading of the informal settlement progresses through disaster intervention, ad-hoc upgrading, systemic upgrading, and ends with replacement of the whole system to meet standard practices (Jiusto and Kenney, 2016). As drainage networks are essential infrastructural assets, one can expect that a similar pattern applies to these networks.

Figure 2.1: Bridge made from local materials in Chota, Beira (picture by author)

Flooding perceptions in informal settlements diverge from those in Western regions. Flood management is generally lower prioritized compared to other critical issues like access to health services and employment; floodings are seen as an inevitable consequence of living at that location. Another difference is that drainage solutions primarily target sewage and the reduction of flooded days, rather than focusing on flood height (Parkinson et al., 2007).

2.1.2. Formation, layout and materials used

Formation of informal drainage canals occurs in an ad-hoc manner. The materials used depend on the available resources at each location and the inhabitants' resources. Design decisions are rarely based on engineering factors; rather, they are typically rooted in practical considerations (Figure 2.1). Examples exist of pipe dimensions being increased to reduce the likelihood of blockages, rather than being determined by required dimensions (Norman and Chenoweth, 2009). Given that available materials are generally similar within the same neighborhood, instances of material homogeneity can be observed (Mulligan et al., 2016).

During the formation of these canals, other design considerations are made than generally expected, like the choice between open and closed drains. Generally, open drains experience a higher influx of solid waste but are more straightforward to clean and operate compared to closed drains. Moreover, residents in areas with open drains are more susceptible to fecal contamination from these drains (Parkinson et al., 2007). While the evaluation of these alternatives is important, the choice between an open and closed drain can be made in an ad-hoc manner. In Lahore, for instance, inhabitants covered open drains to increase available housing space and reduce solid waste inflow (Parkinson et al., 2007).

The scale of constructed measures is typically small. A settlement in Kibera, Kenya, as described by (Mulligan et al., 2016), outlines flood impact reduction measures categorized by size. Many flood protection measures are undertaken at a small (household) scale, with fewer executed on larger scales. Measures such as building waterproofing, raising floor levels (like in Figure 2.2), elevating internal assets, floor drainage, local flood walls, rainwater harvesting, and drainage widening were commonly implemented. However, measures beyond the community level are infrequently encountered. Similar findings were identified in Cape Town, South Africa (Jiusto and Kenney, 2016).

Some critical infrastructural assets can define the structure and lay-out of an informal canal system. Jiusto and Kenney, 2016 describes three different global paths to managing storm water:

- Barriers to stop water flowing in unwanted locations, like houses or pathways, are common. Whatever materials available are used, like metal, cloth, tyres or vegetation. Mixed media barriers,

Figure 2.2: Raised doorstep as a flood mitigation measure on a household scale in Manga, Beira (picture by author)

where different materials are combined, are widespread throughout informal settlements (Button et al., 2010).

- Diversions to shunt water from one place to another are also quite common. Generally, small ditches are dug to dump greywater and sometimes sewage on the street. Some of these canals are also demarcated, using concrete or masonry to maintain the location of the canal.
- Soakways to infiltrate water are generally not constructed for stormwater - although urban rice fields have a role in infiltration - but pit latrines for black water are common in these areas. A major difficulty in the implementation of these solutions is that the pressure for land is often intense and soakways can be seen as bare land available for new housing (Jiusto and Kenney, 2016).

In summary, these factors collectively contribute to the lack of structural clarity in tertiary drainage canals, making the mapping of such canals a challenging task. Furthermore, the geometry of these canals undergoes continuous alterations during both dry periods and flood events. Given that these canals can be as narrow as 10 cm, the use of high-resolution remote sensing data becomes necessary, which is not always available. Consequently, mapping efforts typically require a social analysis in addition to the physical analysis.

2.1.3. Social differences

Given the highly organic and ad-hoc nature of tertiary drainage canal formation, social differences have a significant influence on the formation of the canals. While drainage systems generally show heterogeneity, residents of informal settlements tend to replicate what they observe in their neighbors (Mulligan et al., 2016), causing homogeneity in neighbourhoods.

Challenges related to implementation of solutions are generally also related to social factors. Mguni et al., 2015 describes a hydro-social contract - a combination of values, implicit agreements, historical context, ecologies, geographies and socio-political dynamics - which directly impacts governmental structures. In the case of Dar es Salaam, this problematic hydro-social contract originates from its colonial heritage, giving rise to fragmented and overlapping governing bodies that complicate solution implementation.

In the absence of a strong governing body capable of managing affairs, local initiatives play a pivotal role in forming small drainage canals (Parkinson et al., 2007). Non-Governmental Organisation (NGO)'s and community-based organisations play an important role in the hydro-social contract and exert substantial influence on the creation of tertiary drainage canals.

Another example of a system that is influenced by social differences can be found in La Paz, Bolivia. Because the city has a similar, weak institutional structure, a decentralised drainage system was implemented. Residents were responsible for the construction of a tertiary sewer system and secondary and primary sewers were supplied by the government (Ashipala and Armitage, 2011). Although technically successful, this solution failed to consider the hydro-social contract that normally dictates free plumbing access for residents. Consequently, a considerable portion of the population remains disconnected from the formal drainage network (Ashipala and Armitage, 2011).

Concluding, the success of small-scale drainage solutions is dependent of the capabilities of local communities. Jiusto and Kenney, 2016 distinguishes cooperative and non-cooperative "hot spots," each having different collaboration perspectives. Cooperative hot spot residents emphasize communal efforts, compliance, and mutual assistance, while non-cooperative counterparts have an individualistic stance. Given that solutions for one resident can negatively impact others, drainage canals in informal settlements can be a subject causing emotions and frustrations (Button et al., 2010).

2.1.4. Water quality in drainage canals

Water quality in drainage canals in informal settlements is generally extremely poor. Poor water quality in drainage canals can have a significant impact on public health, increasing the risks of waterborne diseases such as cholera, diarrhea, dysentery, hepatitis A, typhoid, and polio (WHO, 2022). The F diagram, a tool used to understand the fecal-oral transmission routes of waterborne diseases, highlights how contaminated water in these canals can serve as a transmitter for various pathogens (Wagner and Lanoix, 1959). As presented in Figure 2.3, contaminated water can infect other hosts if used to wash food or via direct consumption of this water. Secondly, contaminated water can mobilise during floodings, directly infecting new hosts and contaminating crops. Lastly, hands of people and flies can spread diseases directly or via consumed food.

The F diagram shows that proper sanitation can stop contamination via water, flies and fields/floodings, although it is usually lacking in informal settlements. Toilet units often discharge into the regular drainage canals. Additionally, pit latrines overflow during floods, causing widespread cholera outbreaks. Jiusto and Kenney, 2016 describes that in Cape Town, local inhabitants claim that the pit latrines are self-cleansing because after each flooding, the excreta are washed away. Ninety-three percent of experts in water sanitation recognize that fecal contamination caused by these pit latrines is or could be a significant problem in dense urban areas (Norman and Chenoweth, 2009).

An important consideration for improving the water quality of the canals is to reduce the influx of feaces in the canals (Parkinson et al., 2007). One solution would be to separate black water from grey water using pour-flush latrines; black water can then infiltrate a leach pit while the grey water enters the drainage system. Another solution would be to construct a separate sewer system with distinct canals for rainwater and drainage, as well as separate canals for domestic wastewater. However, an issue is that this solution requires a large initial investment and it is likely that users unintentionally convert the

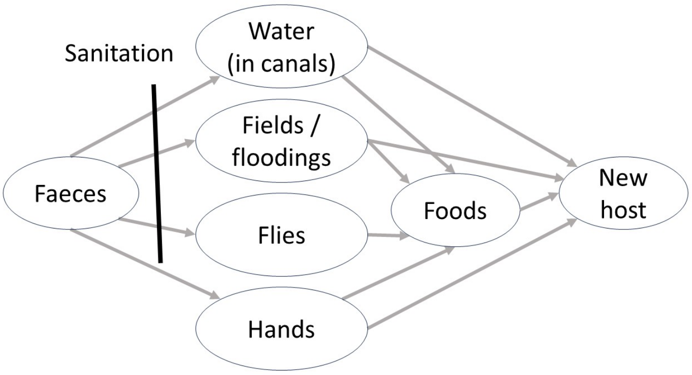


Figure 2.3: The F diagram (after Wagner and Lanoix, 1959)

separate sewer system into a combined sewer by constructing illicit connections after sewer blockages (Parkinson et al., 2007).

Summarizing this section, tertiary drainage canals in informal settlements are largely unstructured and do not follow a clear pattern. Social factors play an important role in the formation and maintenance of these canals. As the structure is unclear and sanitation is generally weak, the water quality in these canals is poor.

2.2. Failure modes in drainage canals

Knowing what the structure and formation of tertiary drainage canals looks like, this section zooms out and considers canals from all three orders - primary, secondary and tertiary. It discusses the primary failure modes relevant to drainage networks with similar properties. In consultation with local experts, the following failure modes were determined:

- **Vegetation** such as *Phragmites australis* (common reed) or *Pontederia crassipes* (water hyacinth), obstructing the water flow.
- **Human interference**, which are changes made by users ranging from small sand barriers to large mixed media barriers.
- **Waste accumulation**, caused by waste ending in canals and structures.
- **Sediment** accumulating in structures and canal stretches, decreasing available flow area.
- **Underdimensioned structures** are bottleneck structures such as underdimensioned culverts under bridges.
- **Other** failure modes could be possible, like collapsing of canal side walls and unequal subsidence of the concrete canals.

2.2.1. Riparian vegetation

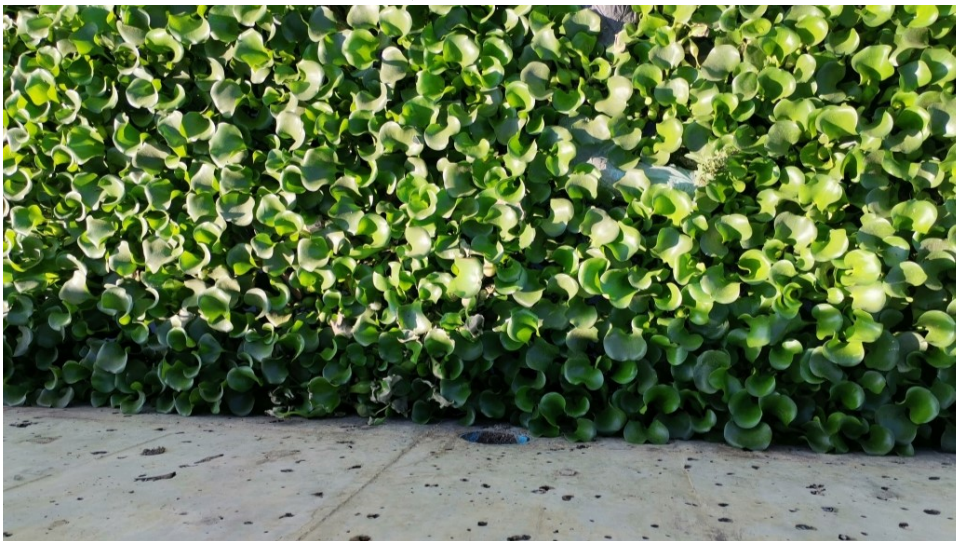
Vegetation in canals can have impact on the performance of drainage canals. Vegetation directly obstructs water flow and can lead to severe flooding in neighboring areas during heavy rainfall events (Dersseh et al., 2019). Furthermore, it is known to diminish a waterway's effectiveness in draining water by increasing sedimentation (Puigdefábregas, 2005). Two vegetation types are common in drainage canals. The first one, *Phragmites australis*, is generally found on the sides and in shallow parts of drainage canals. In still-standing canal waters, *Pontederia crassipes* is commonly found.

Commonly known as common reed or caniço in Portuguese, *Phragmites australis* (Figure 2.4a) is a perennial grass that is found in wetlands and other aquatic habitats around the world. It is known for its high Relative Growth Rate (RGR) - a measure for the growth of vegetation. The RGR of *Phragmites australis* is influenced by a variety of factors, including salinity, availability of nutrients and water depths (Cronk and Fennessy, 2016).

Studies have shown that *Phragmites australis* has the highest RGR at low salinities (0-5‰), with growth rates slowing down as salinity levels increase. At 22.5‰ salinity, RGR is close to zero, indicating that the plant is unable to grow in such saline conditions. Furthermore, increasing salinity levels also affect the mortality of leaves on the plant. At salinity levels of 22.5‰, all leaves for juvenile plants have died, and for rhizome-grown plants, full leaf mortality occurs at 35‰ salinity (Lissner and Schierup, 1997).

A study on *Phragmites australis* in the Huanghe River Delta, China, found that plant coverage peaked at water depths equal to the ground level. Plant coverage decreased if water levels were lower or higher than ground level, with an absence of the plant at water levels lower than -0.5 meters and higher than 0.5 meters. Additionally, the study found that plant height was lowest when the groundwater level was deep. As water depth increased, plant height increased as well, reaching its peak when the water depth was equal to the ground level. Beyond this point, plant height decreased again until the water depth reached 0.5 meters (Cui et al., 2010).

(a) *Phragmites australis* in Chota, Beira (picture by author)



(b) *Pontederia crassipes* in a drainage canal in Munhava, Beira. Note that there is no flowering, as the picture was taken in June (picture by author)

Figure 2.4: Riparian vegetation in canals

The plant is able to absorb nutrients based on the surrounding phosphorus and nutrient levels. Zhao et al., 2013 reports that the plant tissue is well capable of absorbing larger amounts of Total Nutrient (TN) and Total Phosphorus (TP) as the TN and TP of the surrounding water increases, making the plant capable of decreasing the TN and TP concentrations of the surrounding waters. For the growth of *Phragmites australis*, a TN:TP ratio lower than 14 indicates an TN limitation and a TN:TP higher than 16 indicates a TP limitation (Koerselman and Meuleman, 1996).

Phragmites australis also affects other properties of the water in the drainage canals through a combination of physical, chemical, and biological processes, including filtration, adsorption, and biodegradation. *Phragmites australis* can have a high removal efficiency for pathogens, including fecal coliforms (Odinga et al., 2019).

Pontederia crassipes, commonly known as water hyacinth and depicted in Figure 2.4b, is a perennial aquatic plant recognized for its rapid growth and ability to form dense mats on the water's surface. In Europe, the plant is an invasive species, disrupting natural water ecosystems and causing various ecological issues (Datta et al., 2021). The proliferation of extensive mats of this plant presents a substantial threat to drainage canals and waterways worldwide due to its aggressive growth and its capacity to create dense mats on the water's surface on a large range of depths (Dersseh et al., 2019). The floating carpets of lush green foliage obstruct sunlight from reaching the water underneath (Huang et al., 2007). Although the plant can usually be identified by its purple flowers, flowers are typically less frequently found between June and October compared to other months of the year in the southern hemisphere (Carranco, n.d.).

Pontederia crassipes thrives best in temperatures ranging from 25 to 30 degrees Celsius, with growth stalling at temperatures exceeding 40 degrees Celsius and falling below 10 degrees Celsius (Gaikwad and Gavande, 2017).

2.2.2. Human interference

(a) A concrete bridge in a canal in Munhava-Matope, Beira (picture by author)

(b) An illegal house constructed in a vegetation-overgrown canal in Chota, Beira (picture by author)

Figure 2.5: Human interference in canals

In this research, human interference is defined as the unauthorized construction of properties inside or in close proximity to the canals without the approval of a governing body. Construction within or around a canal has negative effects for several reasons: firstly, it directly reduces drainage capacity as it decreases the available flow area. Secondly, it occupies space next to the canal, complicating maintenance and future expansion of the canal. Thirdly, it can decrease flow velocities in the canals, leading to stagnant areas, increasing the risk of sedimentation.

Even canals that are precisely designed remain susceptible to dynamic changes, often occurring within a short span of a few years. In Dhaka City, numerous existing canals have fallen victim to human interference, with households erecting structures on stilts within the canal boundaries (Ishtiaque et al., 2014). Such encroachments have significantly reduced the hydraulic efficiency of the canals and lead to the creation of stagnant water ponds that cause mosquito proliferation. The challenge of controlling these encroachments is exacerbated by the limited capacity of governmental bodies to manage the drainage network and intervene, generally worsened by corruption.

Human interference is typically observed in the form of complete houses constructed within the canals (Figure 2.5b), as well as bridges over the canals constructed using tires, concrete, or sand (Figure 2.5a). In informal settlements, it is generally difficult to displace, let alone prosecute individuals who have built illegally in the drainage canals due to the lack of alternative construction locations and the absence of a proper cadastral information system. Numerous examples exist of governments being unable to identify those responsible for illegal construction (Adigun, 2023).

2.2.3. Blockage caused by waste

Drainage canals are, next to their water drainage capacity, also an important means to transport solid waste. In the absence of an appropriate trash collection system, trash is thrown on sidewalks, from where it is flushed into the drainage system (Jiusto and Kenney, 2016) or in rivers (Mulligan et al., 2016). In many developing countries, the challenge arises from the limited self-cleansing capacity of the drains. Excessive solids accumulation, prolonged dry periods, and flat gradients prevent the effective flushing of the drainage system by rainwater during precipitation events, leading to persistent solid waste issues. (Parkinson et al., 2007).

Figure 2.6: Waste accumulating at a bar screen in Beira (picture by author)

The influx of solid waste into canals can be mitigated through various methods. As a substantial portion of solid waste is conveyed by water during precipitation events (Jiusto and Kenney, 2016), covering open drains can reduce the inflow of solid waste, simultaneously increasing available land space. Trash can also be trapped by bar screens and sediment traps (Figure 2.6)(Parkinson et al., 2007) or by illegal housing built on stilts within the canals, as observed in Dhaka City, Bangladesh (Ishtiaque et al., 2014). A crucial requirement is the subsequent collection of trash from these traps. To achieve this, experiments have been conducted with community-based trash collection systems where participants receive compensation for each bag of waste they submit (Jiusto and Kenney, 2016), or through the efforts of youth groups (Mulligan et al., 2016). These experiments were not always successful because proper handling of the collected waste was lacking. In conclusion, effective waste management requires a plan that includes not only collection but also proper storage and processing of waste streams.

Quantifying the input of waste is difficult as the sources are highly variate. In the canals, the residual waste is generally transported under the water surface. This makes it difficult to assess the size of the waste stream as it is not always visible on the surface level. Alternatively, waste can be quantified at locations with low flow velocities, as waste accumulates in these areas (Salles et al., 2012).

2.2.4. Sediments

Sediment accumulation within canal systems can significantly impact the efficiency of the system as settling sediment particles reduce the cross-sectional flow area over time. Sediments accumulate in locations with low flow velocities, like puddles and connections (Figure 2.7, constraining the volume of water that can pass the canal. Furthermore, sediment deposition can alter the canal's shape and cross-sectional profile, exacerbating hydraulic inefficiencies, particularly in low-lying areas.

Figure 2.7: Accumulation of sediments in Palmeiras, Beira (picture by author)

Mitigation of sediment accumulation is a widely employed approach in reservoir management. According to Annandale et al., 2016, four distinct categories can be identified: sediment inflow reduction, sediment rerouting, sediment adaptation, and sediment removal. Techniques aimed at reducing sediment inflow typically affect large upstream regions and erosion-reducing practices, such as afforestation and canal stabilization. Rerouting sediments is not applicable to drainage systems. Adaptive strategies involve implementing measures to enhance the system's capacity to handle higher sediment loads. Lastly, sediment removal is a reactive strategy that can be implemented. It can be achieved mechanically, through methods like dredging or excavating the canal's bottom to eliminate sediment, or using hydraulic scour. In this latter technique, flow velocities exceeding the scour velocities of the sediment bed cause erosion in the canal, leading to sediment removal (Annandale et al., 2016).

2.2.5. Underdimensioned structures

Various underdimensioned structures can be identified that can impact the functionality and effectiveness of a drainage system. Firstly, improper slopes within drainage canals can lead to inadequate water velocities, hindering proper drainage. Insufficient water flow can result in sedimentation, further exacerbating the drainage problem.

Figure 2.8: Bridge in the drainage system in Chota, Beira (picture by author)

Secondly, structures and connections within the drainage system, such as the one depicted in Figure 2.8, can induce backwater flows upstream of these structures. This risk is heightened if the available flow area of the structure is small. The effects of such underdimensioning can be observed over significant distances upstream from the affected structures (Charbeneau and Holley, 2001).

Thirdly, a critical design concern arises when the inlet to the drainage system is situated at a higher elevation than the land it is intended to drain. This blocks water flow and may hinder effective drainage in certain areas. Additionally, water might be diverted into another inlet, potentially overflowing it if its capacity cannot accommodate a larger flow.

Lastly, a lack of retention capability poses a significant challenge in tide-driven drainage systems. Tide-driven drainage systems can only drain during the so-called tide window, which is the period when the sea level is lower than the water level in the canal. To manage water outside of the tide window, retention becomes essential. These may involve the use of retention basins or incorporating retention within the drainage canals themselves. Proper retention is critical for storing water until low tides allow for drainage. Ensuring that the storage capacity within the system is at least equivalent to the cumulative precipitation occurring outside of the tide window is essential to prevent overflows. This concern becomes particularly pertinent as global sea levels rise, resulting in a reduction of the tide window (Waddington et al., 2022).

2.2.6. Other failure modes

Other failure modes that can occur in a drainage system are, but not limited to:

- **Collapse of side canal walls:** The collapse of side walls represents a failure mode capable of altering the course of a drainage canal and leading to an influx of sediments into the system. This type of failure can occur in both lined and unlined canals. In unlined canals, sliding of outer slopes, shearing and erosion of the outer slope are failure modes that can be found in dikes. In unlined canals, failure modes such as sliding of outer slopes, shearing, and erosion of the outer slope are observed in dikes (Technical Advisory Committee on Water Defences, 1998) as well as in canals. Lined canals can experience failure due to sliding, eccentric forces, structural breakage (depicted in Figure 2.9a), and bearing (Shamsabadi et al., 2017).
- **Erosion:** Erosion is generally caused by large precipitation events, resulting in high water velocities and mobilisation of soils. This erosion can change the course and dimensions of canals or cause damage to structures in the canals (Figure 2.9b).

(a) A broken side wall in Munhava, Beira (picture by author)

(b) Erosion of a canal side wall, causing the collapse of a house next to a bridge in Manga, Beira (picture by author)

Figure 2.9: Pictures related to other failures

3

Study Area

This chapter presents a contextual analysis pertinent to the research. It begins by offering an overview of the socio-economic, climatic and geological context in Beira. Subsequently, it provides an understanding of the existing formal drainage system within the city. Finally, it mentions the key stakeholders which are actively engaged in the field of urban drainage.

3.1. Context

Mozambique is country located in the southeast of Africa (Figure 3.1). It is one of the lowest-income countries of the world; the GDP per capita is the 9th lowest in the world (World Bank, n.d.). From the population of Mozambique, 64.6% lives below the international poverty line of $2.15 per day (World Bank, 2023). The country has a long colonial history, starting in the late 15th as a colony of Portugal. It became a major supplier of enslaved Africans and natural resources like gold, ivory and minerals. The People's Republic of Mozambique as we know it know has been founded on June 25, 1975 (Newitt, 2017). After the culmination of the proclamation of independence, the country has suffered from human rights issues, mainly in the war-stricken province Cabo Delgado in the north (Human Rights Watch, 2022).

Figure 3.1: Location of Beira in Sofala, Mozambique and the African continent

Beira is a city situated in the central region of Mozambique, specifically in the Sofala district along the coast. According to a population count conducted in 2017, the city was home to nearly 600,000 residents (Instituto Nacional de Estatística, 2017). Projections suggest that the city will experience growth in the upcoming years, aligned with the general population increase in Mozambique and global urbanization trends (AIAS et al., 2022). Notably, a significant influx of new residents is observed: in 2017, approximately 30% of Beira's population were individuals who were not born in the city but had chosen to relocate there at some point in their lives (Instituto Nacional de Estatística, 2017). To accomodate these new residents, the Masterplan Beira 2035 (Deltares et al., 2013) outlines strategies for managing and accommodating this projected population expansion up to the year 2035.

3.2. Weather and climate

Analyzing historical precipitation data collected between 2000 and 2020 from the INAM weather station in proximity to Beira International Airport (Instituto Nacional de Meterologia, 2022), a distinct pattern of rainy and dry seasons becomes evident. The rainy season prevails from December through March or April, whereas the period from May to November is predominantly dry. This seasonal pattern is presented in Figure 3.2.

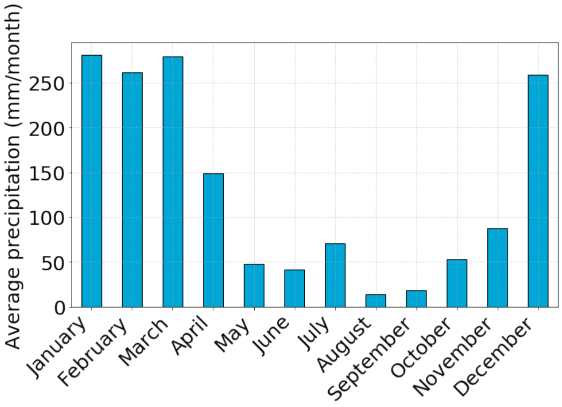


Figure 3.2: Average monthly precipitation at Instituto Nacional de Meteorologia (INAM) weather station, Beira airport

During the rainy season, rain events of more than 100 mm/day are not exceptional. Figure 3.3 shows how many times the daily precipitation has exceeded a certain value between the years 2000 and 2020. It shows that there were more than 20 days with more than 125 mm/day in these 20 years. The largest rain event in this timeframe was recorded on January 22th, 2019, when 288.5 mm of rain fell during cyclone Desmond.

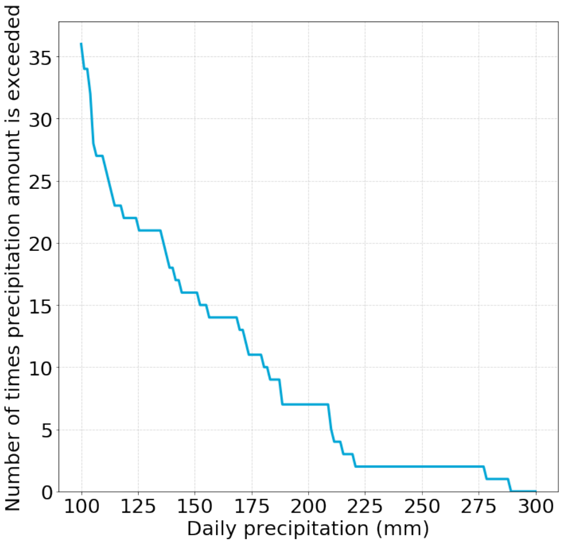


Figure 3.3: Large precipitation events at INAM weather station, Beira airport. The y-axis shows the frequency of precipitation events between the years 2000 and 2020

This climatic context causes frequent natural disasters; pluvial flooding events are frequent. Furthermore, as the coastal protection in the city is weak, a number of coastal flooding events have occurred in the last five years.

Both of these flooding mechanisms occurred at the same time during cyclone Idai, in 2019. Ninety percent of the city was estimated to be damaged, with roofs blown off, floodings and cholera outbreaks (IFRC, n.d.-b) (Unicef, n.d.). Even four years later, much of the infrastructure and housing that was destroyed during Idai has not been repaired.

3.3. Geological context

Beira is predominantly situated at a low elevation, with substantial areas not surpassing an altitude of 5 meters above sea level. Figure 3.4 shows the Digital Elevation Model (DEM) that was retrieved during a LIght Detection And Ranging of Laser Imaging Detection And Ranging (LiDAR) mission conducted in 2014. The city's topography can be likened to that of a 'bathtub,' wherein the coastal area is surrounded with dunes that enclose and retain water within the lower-lying sections of the urban landscape. The natural drainage channels that are present direct the water flow towards outfalls located in the southern, eastern, and western parts of the city.

Findings from a soil study conducted within the city (Batista et al., 2017) reveal the presence of fluvial terraces in the lowest-lying eastern region, characterized by deposits of sandstone, siltstone, and claystone. Moving towards the western part of the city, there exist deposits composed of a combination of fluvial terraces as well as the Areias do Dondo formation, with the latter containing sandstone and siltstone. The northern section shows remnants of the Areias do Dondo formation, fluvial terraces, and the Mazamba formation. This Mazamba formation is comprised of conglomerate, sandstone, as well as deposits of silt and clay.

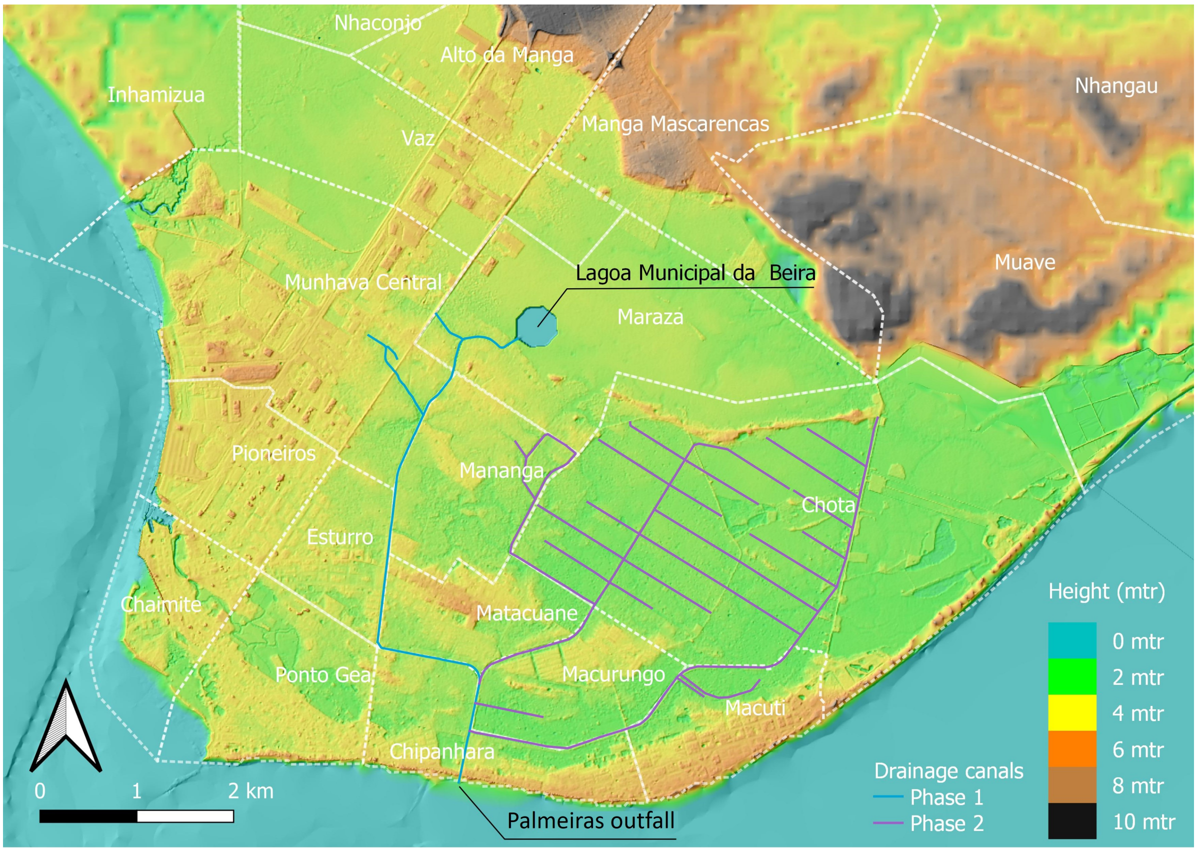


Figure 3.4: The neighbourhoods in Beira, the drainage network and the elevations of the city

3.4. Formal drainage system in Beira

3.4.1. Overview of the drainage system

The drainage system's characteristics exhibit variation throughout the city. The entire network which is in the study area of this research ultimately discharges at an outfall refered to as Palmeiras, positioned at the boundary between the Chipanhara and Ponto Gea neighborhoods. Upstream of this outfall, two distinct branches of the drainage system emerge, each with unique attributes. Specifically, the drainage network on the western side underwent rehabilitation during a project which is referred to as the Phase 1 Project, while the rehabilitation of the eastern side is scheduled for a project called the Phase 2 Project. Figure 3.4 shows an illustrative overview of the whole drainage network, its key components and the neighbourhoods that are present in the city.

3.4.2. Phase 1

The western segment of the drainage system drains the areas of Ponto Gea, Esturro, Pionieros, Munhava Central, as well as portions of Mananga and Mataguane neighborhoods. This region is characterized by its low-lying and flat terrain, situated at altitudes ranging from 2 to 4 meters above sea level. It features many sinks in which water comes to a standstill. To drain these locations, concrete canals were constructed in 2018. This decision was taken by the inadequacy of the existing drainage system to sufficiently safeguard Beira from flood risks (AIAS, 2014) (TPF, 2013). The canals within this drainage segment are comprised of concrete side walls and a sand bottom. The width of these canals varies, measuring between five meters for the secondary canals to thirty meters at the primary canal close to the outfall.

The ten meter wide primary canal starts in Lagoa Municipal da Beira, which is a 400 meter wide octagonal artificial lake in the north of the area (Figure 3.4). This lake is a retention basin for the whole Phase 1 part of the network. From the retention basin, there is a primary canal of 6 to 10 meters wide and 6 kilometers long towards the Palmeiras outfall. There are two secondary canals which split off from this primary canal. These are also made from concrete; the southern canal is 1 km long and the northern canal is around 300 meters long. Both canals end close to the industrial area in the western part of the city.

An evaluation of the revitalized section of the canal system is carried out in response to the rainfall brought by cyclone Eloise (AIAS and Consultec, 2021). While a hydraulic model was not executed for the system's analysis, recommendations were derived from practical insights into its functioning. The study pinpoints particular areas requiring intervention, with a specific emphasis on enhancing the capacities of certain stretches of the primary canal. Additionally, it gives operational guidance, including suggestions such as upgrading the memory capacity of the computer at the Palmeiras control station and implementing initiatives aimed at capacity building.

3.4.3. Phase 2

The eastern drainage system drains Chipanhara, Macurungo, Chota, Maraza and parts of Mananga and Mataguane. It the most low-lying part of the city. The neighbourhood offers space for many urban farmers who grow rice and other vegetables in their gardens. The primary and secondary canals in this section originate from the colonial times and were constructed in the 1960's for the rice fields that were present in this region. The canals follow structured paths in a clearly distinguishable pattern.

While the drainage canals in the Phase 1 part of the network have undergone recent rehabilitation, those in the Phase 2 part have remained unattended. Currently, the majority of canals in this region have cross-sections in a nearly trapezoidal shape and have an unlined bed. Initiatives for revitalizing this segment of the system were initiated in 2021 under the umbrella of the Phase 2 Project (TPF, 2023).

3.5. Stakeholders

Several local and foreign stakeholders are active in Beira. Administração de Infraestruturas de Abastecimento de Água e Saneamento (AIAS) is the national governmental body that is responsible for the construction and maintenance of the drainage network. Daily operations are in the hands of Serviços Autónomos de Saneamento da Beira (SASB), which is the autonomous sanitation service of the city. A number of actors from the Dutch water sector (Vereniging voor Nederlandse Gemeenten International (VNG International), Rijksdienst voor Ondernemend Nederland (RVO) and Blue Deal) are currently working on the strengthening of SASB and the municipality of Beira. Additionally, international players like Deltares and CDR International are collaborating with AIAS to develop masterplans and large-scale rehabilitation plans such as the Phase 2 project.

Associação FACE (FACE), a Mozambican NGO, works together with the The Netherlands Red Cross (NLRC) to offer help in tertiary drainage canals and the development of governments and communities. The national government institute Instituto Nacional de Gestão e Redução do Risco de Desastres (INGD) is responsible for overseeing early warning and early action systems directly after disasters like floods, which is executed by the risk committtees. Furthermore, The World Bank provides funding for particular projects. Lastly, the inhabitants of Beira are an important stakeholder group represented by local politics.

The indicative Power Interest Grid in Figure 3.5, established during this research using background interviews, provides an indication of the power and interest of the most important stakeholders. On the y-axis, stakeholders are ranked according to their level of influence, ranging from low power (limited impact) to high power (significant control). The x-axis represents their level of concern, from low interest (minimal engagement) to high interest (deeply invested). Appendix B provides more information about all stakeholders.

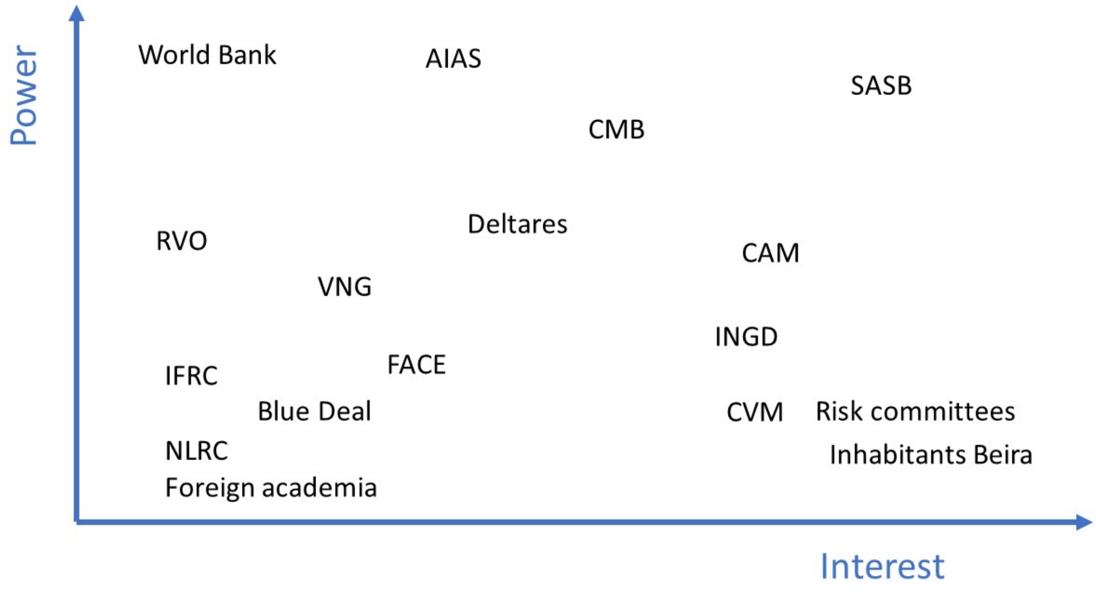


Figure 3.5: Power Interest Grid of the stakeholders in the drainage system of Beira. Made during this research using background interviews

4

Methodology

This chapter outlines the research methodology and is divided into two sections. The first section covers quantitative analysis methodologies; it includes direct observations of connections, structures, and inlets in the network (Section 4.1.1), transect walks along the canal stretches (Section 4.1.2), and technical measurements (Section 4.1.3). These data are used to in the D-FLOW FM 1D2D hydraulic model, which is used to simulate inundation depths (Section 4.1.4).

The second section focuses on the qualitative analysis methods (Section 4.2), which include key informant interviews (Section 4.2.1) and interviews with local inhabitants (Section 4.2.2). An overview of the research process is illustrated in Figure 4.1.

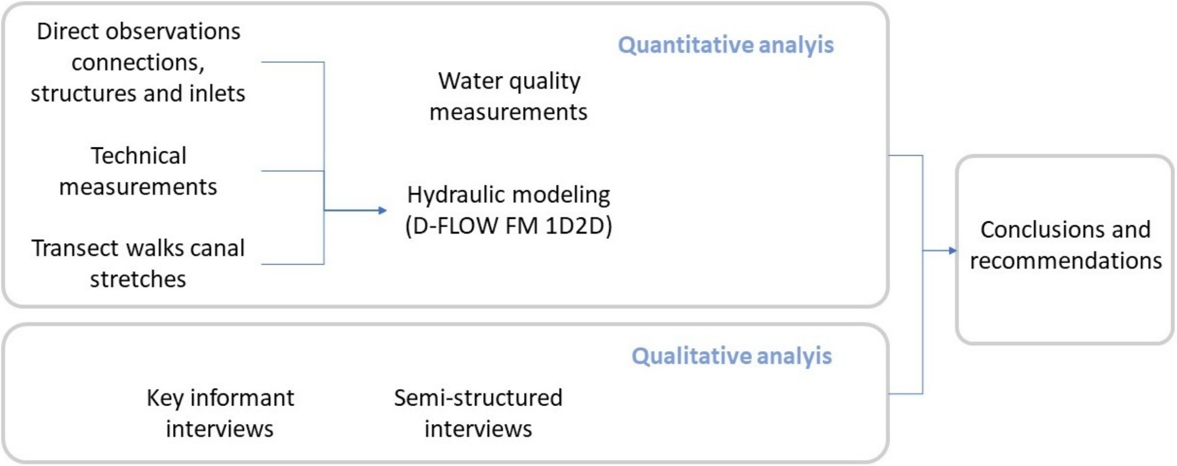


Figure 4.1: Overview of the methodology

4.1. Quantitative analysis

During the quantitative analysis, direct observations, transect walks, technical measurements, hydraulic modeling, and water quality analysis are performed. These are used to quantify the impact of the failure modes present in the system.

4.1.1. Direct observations of connections, structures and inlets

Direct observations are performed during the visit in Mozambique in order to assess the state of the connections, structures and inlets in the research area. During walks along the canals, pictures are made of every connection, structure and inlet, which are used to categorize the state of the connecting element. These points are stored in a table with the following attributes: ID number, connection type, canal type, failure type, failure percentage, comments, geographical location, data storage location and date of visit. Appendix G gives a further elaboration on these attributes.

Ten types of connections are used to categorize the connecting elements. These types are differentiated based on the presence of waste traps, the ability to collect sediments and the expected resistance against failure modes. The ten types are the following:

- **Open Pipe** Open pipes are pipes that directly connect two canals with each other. The length or width of the pipe is not relevant. There is no designed obstruction in the pipe.
- **Bar Screen Pipe** The bar screen pipe is similar to the open pipe, but holds a bar screen that traps solid waste.
- **Open** The open connection does not have an upper boundary and is therefore not restrained in vertical sense. Typically, open connections are ditches or open drains that connect without a connecting structure.
- **Gullypot** The gully potis an inlet structure which is typically located on the side of the street. It consists of a water collection box of approximately 50x50 cm. It is closed off by a lid with rectangular holes which filters large solid waste. A pipe approximately 10 centimeters above the bottom allows water to flow out of the gullypot, so that sediments are collected on the bottom of the box.
- **Gully pot, no lid** The gully pot without a lid is similar to a gully pot but does not have a lid.
- **Closed Pit Inlet** The closed pit inlet consists of a box of approximately 1x1 mtr which collects water through a hole in the side of the pit. It is closed off with a concrete lid which has small holes for inspection. The water exits the pit through a pipe approximately 3 cm above the bottom of the pit.
- **Open Pit Inlet** The open pit inlet is similar to a closed pit inlet but does not have a lid.
- **Control Station** There are five control stations in the system that can be completely opened or closed using gate doors. Some control stations have a bar screen to collect solid waste. Each control station typically has 4 or 5 doors. One of these control stations is the Palmeiras outfall.
- **Sewer Inlet** The sewer inlet is the connection of a part of the underground sewer network to a canal.
- **Other** Other connection types.

A further elaboration, including pictures of the types of connections, structures and inlets, is presented in Appendix A.

Processing data

The datapoints of the connections, structures and inlets are processed in a Python-based data analysis. The analysis comprehends three processing steps to determine what failure modes are most commonly found in the dataset.

To begin, if a connection can be associated with more than one failure mode, it is divided accordingly. The analysis assumes that all failure modes within a specific connection contribute equally to its failure. Therefore, connections with multiple failure modes are separated into distinct connections, each representing a single failure mode.

The *weight* column in the dataset is calculated based on the fraction of different failure types present at a specific connection. For instance, if a connection exhibits two failure types, two separate rows are created in the dataset, each with a weight of 0.5, indicating equal contribution from each failure type.

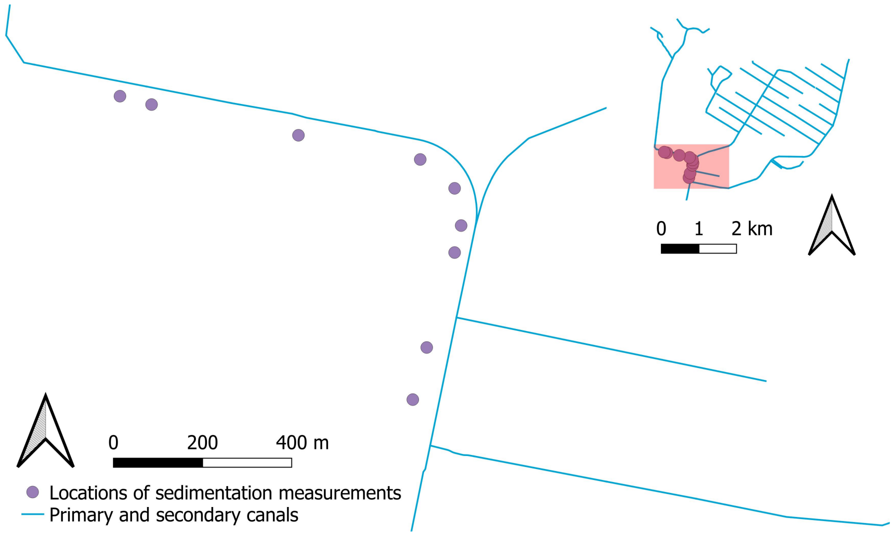
A column *severity_weight* is added to the dataset, which is equal to the product of the failure percentage and the weight column. This includes the relative importance of the failure mode into the analysis. It is calculated by multiplying the *failure percentage* column with the *weight* column.

4.1.2. Transect walk of the canal stretches

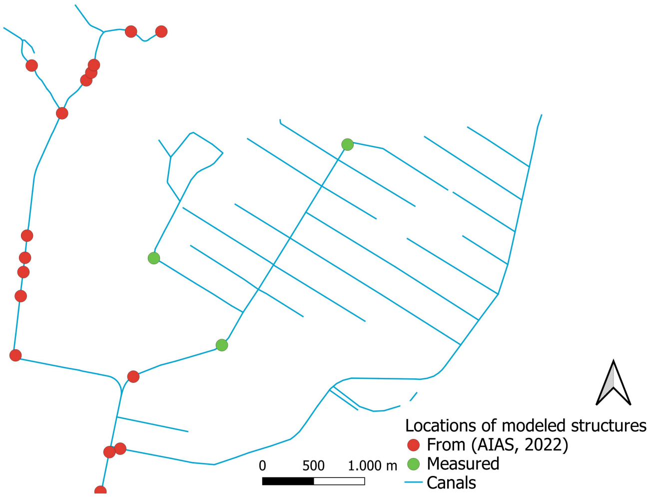
For the canal stretches, a similar approach is applied as for the connections, structures and inlets. The locations of the canals are identified using satellite imagery and visited for categorization. The following parameters are noted: ID, whether the canal is lined or unlined, order of the canal, whether the canal has been visited, failure type, failure percentage, comments, data storage location, date of visit and length of the canal. Further elaboration on these parameters is provided in Appendix G.

The analysis of the canals is also similar to the analysis of the connections, structures and inlets; there is one minor difference required to include the length of the canals. After determining the *weight* column in a similar manner as for the connections, this column is multiplied with the length of the canals. The *severity_weight* column is calculated in the same way as for the connections: by multiplying the *weight* column with the *failure mode* column.

4.1.3. Technical measurements



(a) Locations of sedimentation measurements



(b) Locations of modeled structures

Figure 4.2: Locations of technical measurements

Technical measurements are utilized to quantify sedimentation within the system and the dimensions of specific structures. Sedimentation is quantified by measuring the depth of the sediment bed relative to the top of the canal's side wall. This measurement is then compared with the design specifications (AIAS, 2014) to assess the level of sedimentation. It is important to note that only rectangular canals are subjected to sediment bed measurements due to practical constraints, as measuring the sediment bed of trapezoidal canals proved to be impractical.

Next to sedimentation, dimensions of certain structures within the system are measured. The locations of the structures which are measured are illustrated in Figure 4.2.

4.1.4. Hydraulic modelling

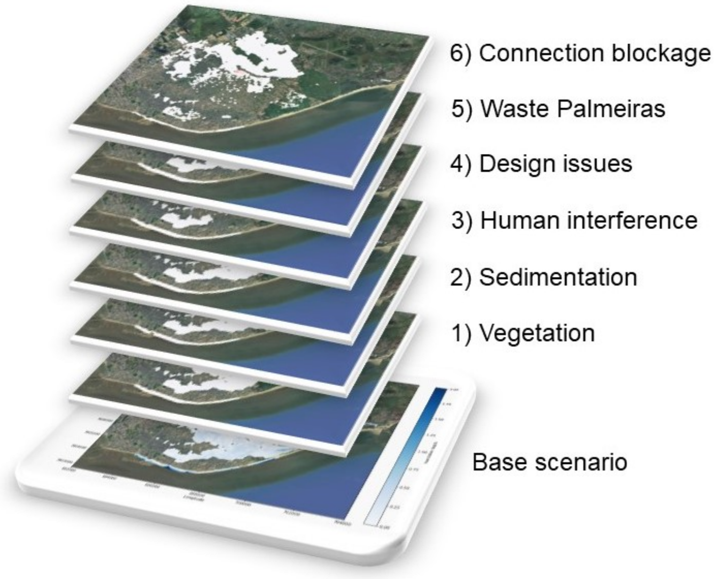


Figure 4.3: Overview of modeled scenarios and the base scenario

The direct observations of connections, structures, and inlets, along with technical measurements and transect walks along canal stretches, are integrated into a hydraulic model. Initially, a base scenario with no failure modes is created and serves as the starting point. This base scenario is then compared with six other failure scenarios. An overview of the scenarios is presented in Figure 4.3.

Principles behind D-FLOW FM 1D2D
D-FLOW FM 1D2D is a hydraulic modelling software developed by Deltares. The model consists of a rainfall-runoff, 1D and 2D model. The rainfall-runoff model converts evaporation and rainfall to lateral inputs into the 1D model. In the 1D model, water heights and velocities in the defined canals are calculated. If the water height exceeds the maximum height in the canals, inundation is calculated in the 2D model.

The model is chosen because it is able to simulate flood risk in 2D and can calculate inundation depths at all locations in the study area. It is therefore suitable to assess the impact of a certain failure mode on flood risk. Furthermore, the model is used for the design of the new Second Phase system and geographical locations and dimensions of the primary and secondary canals are already available.

Geographical inputs of the model
An exported overview of the links, nodes, laterals, cross-sections, structures and catchments in the model is presented in Figure 4.4. The 2D model - which is presented in the Figure 3.4 in the previous chapter - uses the DEM from the 2013 LiDAR survey.

The dimensions of the canals within Phase 1 of the project are determined using the detailed design that was made prior to construction (AIAS, 2014). Discrepancies between these dimensions and those utilized by Deltares, TPF, and CDR International during the rehabilitation project's design phase in Phase 2 area (AIAS et al., 2022) are identified and rectified. The bed roughnesses are modeled using the Manning coefficient, determined by TPF in the design of the First Phase Project (AIAS, 2014).

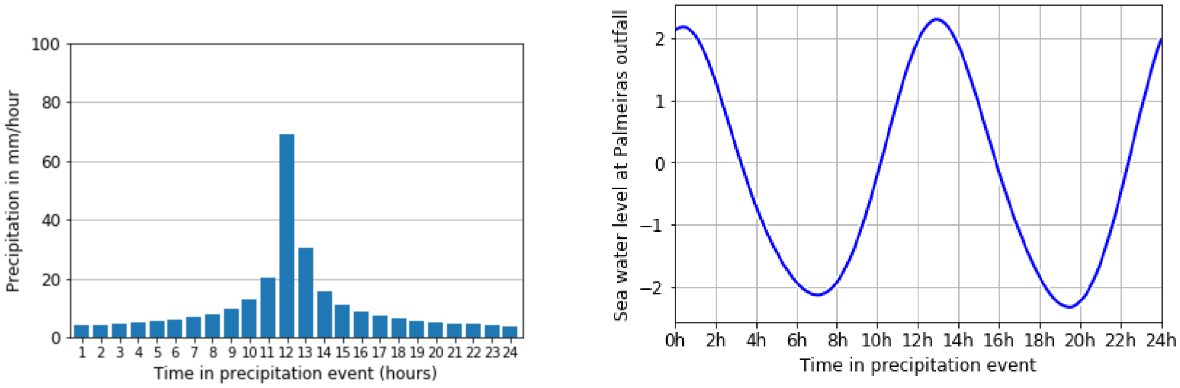
Based on prior research, the physical locations and dimensions of all canals are established. The geographical positions of the canals in the Phase 1 part of the network are acquired through the DEM

Figure 4.4: Overview of the D-FLOW FM 1D2D model (after AIAS et al., 2022)

of the 2013 LiDAR mapping with a resolution of 2x2 meters. Furthermore, a total of 12 cross-sections from the unlined canals are extracted from this mapping and employed as inputs for the model.

Other inputs for the model

The model has a number of boundary conditions, adapted from AIAS et al., 2022. Firstly, an initial water depth in the canals is assumed with the use of a restart file. This is equal to the 1-in-2-year rainfall event in the canals and in the river basin. Also, the sea level is defined as an astronomical sea water level boundary condition at the location of the Palmeiras outfall; these water depths are describes in Figure 4.5b.



(a) Precipitation event with a return time of ten years, used in model

(b) Sea levels of the boundary condition at the Palmeiras outfall

Figure 4.5: Other inputs for the D-FLOW model

Precipitation events with return periods of 1, 2, 5, 10, 20, 25, 50 and 100 years and a duration of 24 hours are used to model the system. The time series of the precipitation event which is mostly used, with a return period of ten years, is presented in Figure 4.5a. The model uses a timeframe of 24 hours, with intervals of 20 minutes.

Calibration of the model has been done based on the inundations depths determined by AIAS and Consultec, 2021, which uses the precipitation event during cyclone Eloise. Although the model showed similar inundations as observed, there are some mistakes in canal dimensions in this version of the model. Furthermore, it is uncertain which failure modes are present in the canals at the time of the calibration measurements.

Overview of modeled scenarios

The following scenarios are modeled:

- **Base scenario** simulates floodings in the state of the system without any failure modes and is similar to what is described by AIAS et al., 2022.

1. **Impact of vegetation and waste in canals** includes the waste and vegetation which is observed in the canals. It is executed by increasing the bed resistance by changing the Manning's coefficients of the canals which are affected by vegetation. To indicate what the effects of vegetation could be, a scenario with maximum increase of Manning coefficients caused by vegetation is also executed.
2. **Impact of sedimentation in canals** includes the sedimentation that is observed in the canals. It is executed by changing the hydraulic surface area of the canals which are affected by sedimentation.
3. **Impact of human interference in canals** includes the human interference that is observed in the canals. It is executed by changing the hydraulic surface area of the canals which are affected by human interference.
4. **Impact of underdimensioned structures in canals** analyses the impact of the bridge that is found in the primary canal in Chota. The bridge has a flow surface area which is expected to be smaller than required.
5. **Impact of waste in the Palmeiras outfall** describes the scenario in which waste is accumulated in the outfall at Palmeiras. Although this is a virtual scenario that is not observed during the visit to Beira, many stakeholders and a report from FACE, 2023b state that there is waste accumulation at this location. It is executed by reducing the flow width of the orifice in Palmeiras.
6. **Impact of blockage of the connections** gives an analysis of the hypothetical blockage of certain dead-end canals with lateral inflows, which are used to simulate blockage connection. These findings are later extrapolated in a qualitative sense for the whole study area.

The outputs of these scenarios are maps with the inundation depths during the design rain event. Furthermore, all scenarios are compared to the clean situation by calculating the difference between the scenario and the clean situation.

Scenario 1: Impact of vegetation and waste in canals

The modeling of vegetation and waste within the canals involves altering the Manning coefficient. In D-FLOW FM 1D2D, it is possible to adjust the Manning coefficient on a per-canal basis. Arcement and Schneider, 1989 offers a formula to calculate the impact of waste and vegetation on the Manning coefficient, as presented in Formula 4.1.4.

$$n = (n_{basevalue} + n_{surface} + n_{shape} + n_{obstructions} + n_{vegetation})m \tag{4.1}$$

The sum of the base value ($n_{basevalue}$), a correction factor for the effect of surface irregularities ($n_{surface}$) and the correction factor for the variations in shape (n_{shape}) is equal to the Manning coefficient of the canal in the base scenario. The factor for obstruction ($n_{obstructions}$) is mainly dependent of waste and provided in Table 4.1; similarly, the factor for vegetation ($n_{vegetation}$) is provided in Table 4.2. It is assumed that the m parameter, a correction factor for meandering of the canal, is always 1.0 as the canals are relatively straight.

Table 4.1: Correction of Manning's coefficient for waste ($n_{obstructions}$) in canals (average values from Arcement and Schneider, 1989).

Observed waste percentage	Amount of waste	$n_{obstructions}$
10%	Minor	0.010
11-50%	Appreciable	0.025
51-100%	Severe	0.045

Table 4.2: Correction of Manning's coefficient for vegetation ($n_{vegetation}$) in canals (average values from Arcement and Schneider, 1989)

Observed vegetation percentage	Amount of vegetation	$n_{vegetation}$
10-25%	Small	0.006
50%	Medium	0.018
75%	Large	0.038
90-100%	Very large	0.075

Scenario 2: Impact of sedimentation in primary canal

Sediment accumulation is modeled in the primary canal since the designed dimensions of this canal are known from the design and it is impossible to measure dimensions of the unlined canals. To quantify sedimentation, bed heights are measured on the sides of the canals and the depths in the center are estimated. To model this, the cross-sections of the affected canals (Figure 4.1.4) are altered based on the technical measurements which are performed. An overview of the old and new cross-sections per canal provided in Appendix E.

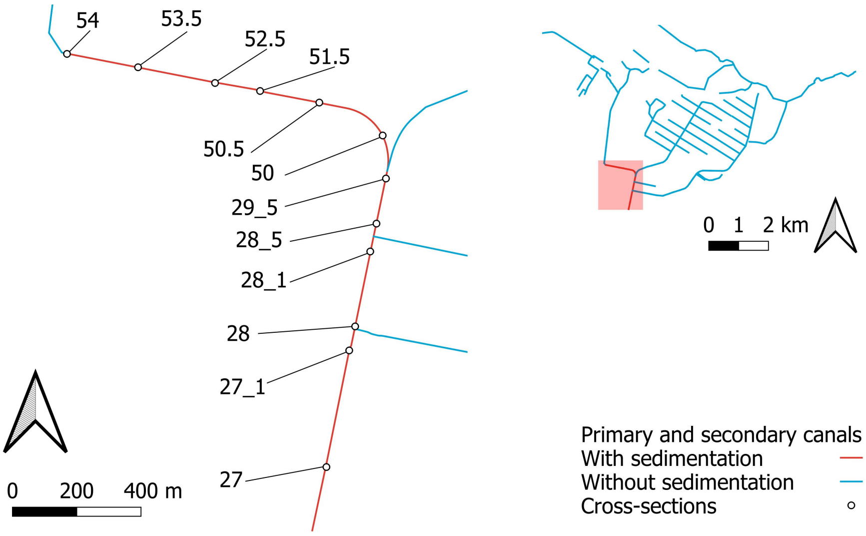


Figure 4.6: Canals which are affected by sedimentation

Scenario 3: Impact of human interference in canals

Human interference is modelled similarly as sedimentation, by changing the cross-sections of the canals. The new cross-sections are determined by visual estimations. The locations of the canals which are affected by human interference are determined during the transect walks. Figure 4.7 presents the locations of the canals which are affected by human interference. Appendix E presents the cross-sections of the initial situation versus the situation with human interference.

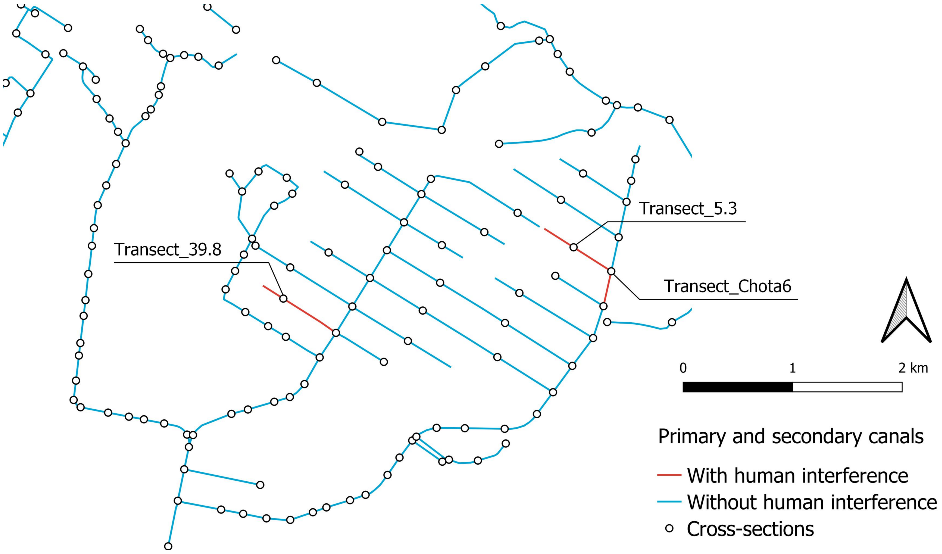
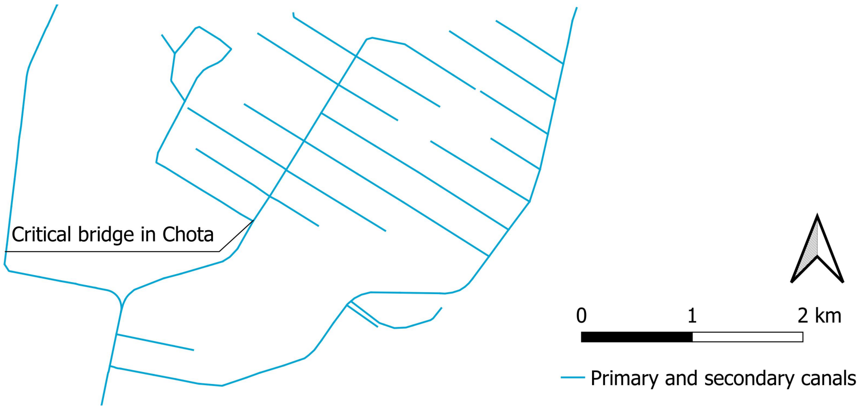


Figure 4.7: Canals which are affected by human interference

Scenario 4: Impact of underdimensioned constructions in canals



(a) Location of critical bridge

(b) Critical bridge in Chota (picture by author)

Figure 4.8: Critical bridge in Chota

The impact of underdimensioned constructions is focused on one critical bridge in the system; this bridge, located in Chota (Figure 4.8a), has a small available flow surface area. It consists of three circular culverts next to each other. Technical measurements in the field showed that the outer two culverts have a diameter of 1.5 meter and the central culvert has a diameter of 1.4 meter; the total flow surface area is therefore 5.1 m².

Hydraulic modelling in D-FLOW FM 1D2D does not allow three culverts next to each other in the same canal. The three different culverts are therefore simplified into one larger culvert. The width of this culvert at a certain height is equal to the sum of the widths of the three culverts. Figure 4.9 presents the dimensions of the culverts which are measured and the dimensions of the culvert which is applied in the model.

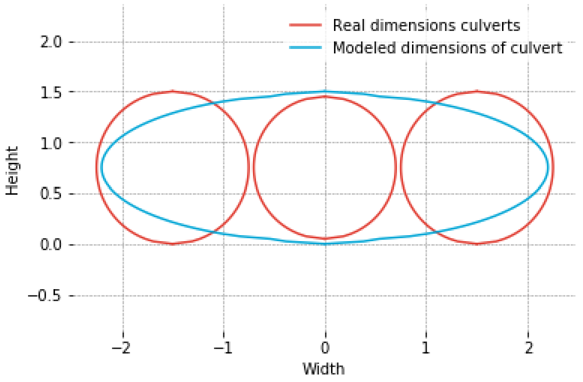


Figure 4.9: Size of the culvert, representing the underdimensioned bridge

Scenario 5: Impact of waste in the Palmeiras outfall

To model waste in the Palmeiras outfall, the quantity of waste that would accumulate in this location is estimated. In a span of three weeks, FACE undertook a cleanup initiative at several locations, including the Palmeiras outfall, Control Station 2, and the control station at the Maraza basin (FACE, 2023b). Collected waste was quantified in the duration of his initiative. During the second week of March 2023, 24 m³ of waste was successfully cleared from the Palmeiras outfall. Over the subsequent two weeks, the corresponding figures are 73 m³ and 36 m³, resulting in an average weekly removal rate of 44 m³ from this site. Concurrently, within the same period, 24 m³ of waste was extracted during the second week at Control Station 2, while the control station at the Maraza basin saw a removal of 12 m³ during the final week.

It is rather difficult to convert these volumes to blocked surface area in the outfall structure. An assumption is made that the blocked surface area is equal to 20% of the total surface area. As the width of the orifice of the Palmeiras outfall is 17.5 meter in the design, it is assumed that accumulation of waste would decrease the orifice width with 3.5 meter to 14.0 meters.

Scenario 6: impact of blockage of connections

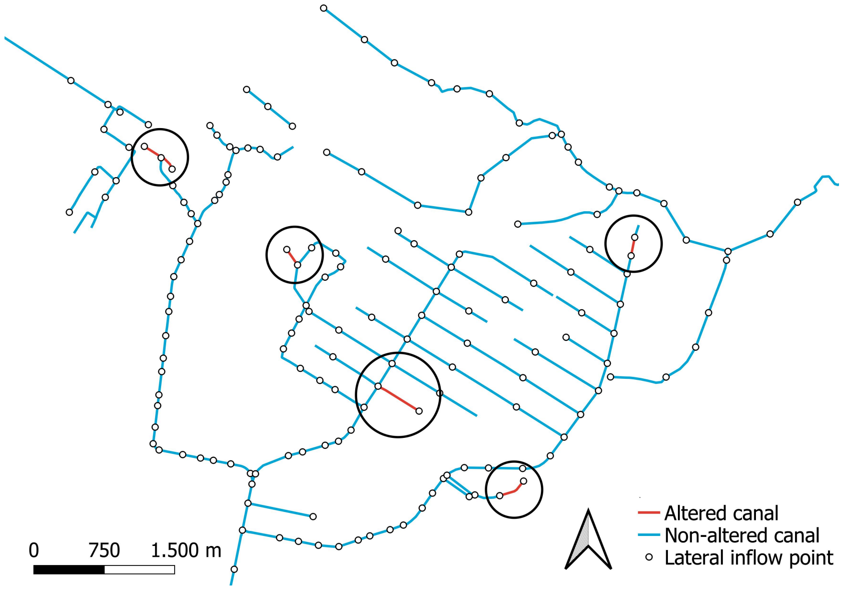


Figure 4.10: Canals with reduced sizes to investigate connection blockage

To model the impact of blockage of connections, an approach is chosen which gives an indication of the effects of a blockage of a connection. In order to do this, cross-sections in certain existing dead-end canals are reduced in size, to force overland flow out of these canals. The canals which are chosen to be altered are indicated in Figure 4.10. All altered canals are replaced with a canal with a width of 0.10 meter and a depth of 0.10 meter.

4.1.5. Water quality

Water quality measurements are done in multiple parts of the system in order to asses the impact of floodings. On several locations in the research area, measurements of total coliform are done in surface waters, ground waters and drinking water points from the water company FIPAG. Groundwater is measured in shallow, open groundwater wells. The locations are selected based on accessibility and variability of drainage canal type. The locations of the measurements are presented in Figure 4.11.

The presence of coliform in water samples is an indicator for potential existence of Escherichia coli. Commonly refered to as E. Coli, is a prevalent bacterium inhabiting the intestines of warm-blooded animals. It serves as an effective indicator of fecal contamination in water sources. Consequently, it indicates fecal matter and therefore waterborne pathogens that can pose significant health risks to humans. Coliform can be readily cultured and identified using standard laboratory techniques and handheld methods (Odinga et al., 2019).

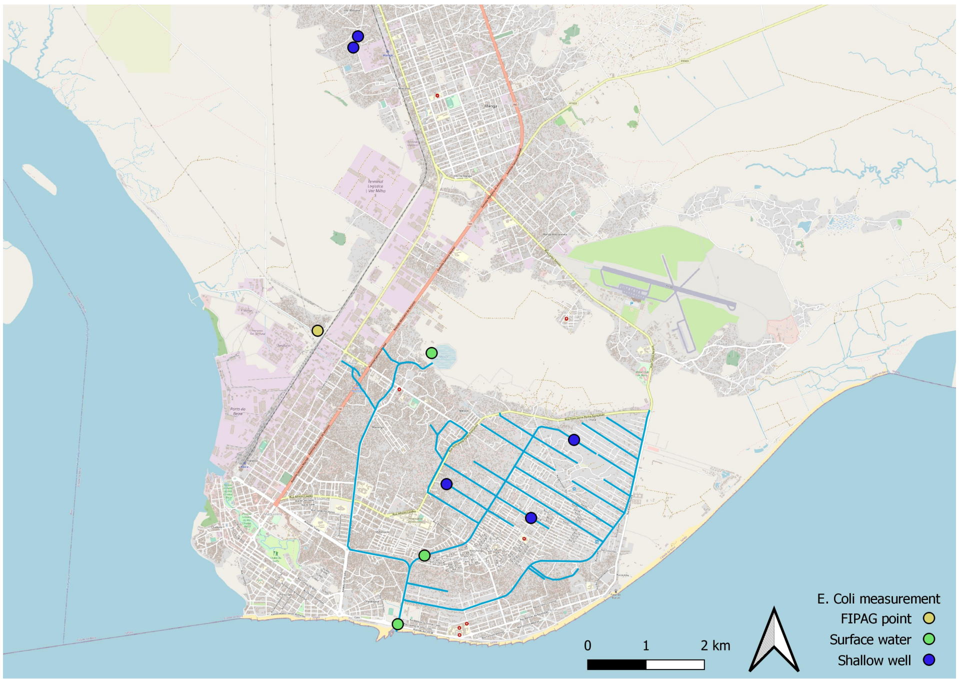


Figure 4.11: Locations of water quality measurements (background: OpenStreetMap contributors, 2017)

In this study, handheld screening test tubes are employed to determine the total coliform. These tubes indicate whether the sampled water contains more or less than 1 CFU/ml of total coliform, which is sufficient for this research's purposes. The test tubes are utilized following the instructions provided.

4.2. Qualitative analysis

4.2.1. Key informant interviews

A number of key informants are chosen from the stakeholders which are present in Beira, based on availability, interest and power of the organisations. In general, these interviews had the goal to obtain general information about the drainage network and the context of the city.

The unstructured interviews are conducted with representatives from various organizations, namely FACE, SASB, VNG International, NLRC, Blue Deal, Deltares, Associação Mocambicana de Reciclagem (AMOR) and Consorzio Associazioni con il Mozambico (CAM). All stakeholders are interviewed multiple times throughout the visit in Mozambique. The discussions revolved around the organizations' activities and objectives. In the case of SASB and FACE, the interviewees are questioned about their maintenance efforts and their perspectives on the primary challenges in drainage network maintenance. Additionally, the conversations with CDR International and Deltares delved into details about the upcoming Second Phase drainage project.

4.2.2. Local interviews

In addition to these interviews, five residents of illegal houses near or within a drainage canal are interviewed to assess the motivations to accommodate a house in such a location. The interviews are performed a semi-structured manner, according to the questions presented in Appendix C. The interviews are done in Portuguese but the appendix also provides the English translation. The interviewees are asked about their living conditions and reasons for residing there. The audio of the conversations is captured.

The interviewees are chosen based on the location of their houses; all of them resided in the area of interest, which is a canal in the Chota neighbourhood. As can be seen on satellite imagery, this canal is clearly narrowed by illegal construction. Additionally, the neighbourhood is low-lying and known to be prone to flooding. Figure 4.12 presents the location of the neighbourhood in which the interviews are conducted.

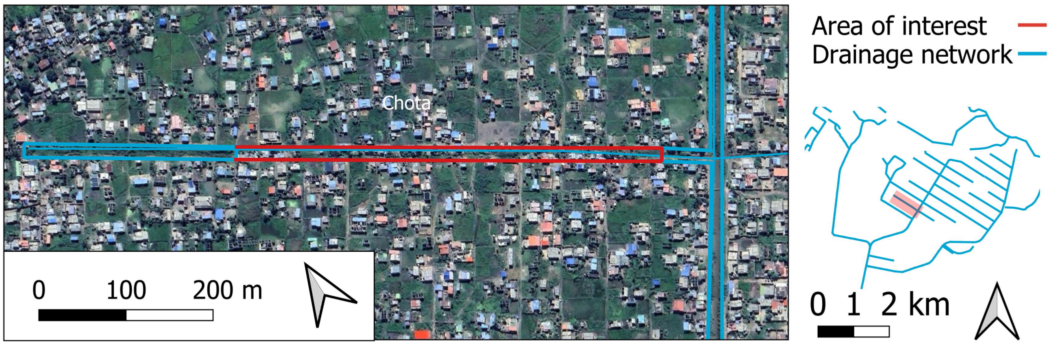


Figure 4.12: Area of interest and upstream area for interviews (background: Google, 2023). The exact locations of the interviews are known, but left out for privacy reasons.

5

Results

This section contains the results of the quantitative and qualitative analysis. Section 5.1.1 holds the current state of the connecting structures and canals. The results of the hydraulic modeling using D-FLOW FM 1D2D are presented in Section 5.1.2. Lastly, this chapter presents the results of the water quality measurements (Section 5.1.3) and the results of the interviews in the qualitative analysis (Section 5.2).

5.1. Quantitative analysis

All local measurements of the quantitative measurements were performed in the timespan of one month in June, 2023. This is the dry season in Beira and only two precipitation events were noted during this month.

5.1.1. State of the drainage network

This section describes the state of the drainage network. The analysis includes more than 33 kilometers of canal stretches and 257 connections, structures, and inlets. All data points, including geographical locations, failure percentage and fail type, are provided in Appendix G. These results were used as an input for the hydraulic modeling.

Although his section shows findings that are relevant for this research, more analysis has been done on this dataset. Appendix D presents a further analysis on the connections and canal stretches. For connections, this includes the distribution of failure percentages in connections and a comparison between the failure percentage and the canal order of the canals that it connects. Additionally, relations with remote sensing factors like Normalized Difference Built-up Index (NDBI) and Normalized Difference Water Index (NDWI) are investigated, but not found. Lastly, it shows the distribution of failure percentages in connections and how this relates to canal order and lined or unlined properties of the canals.

Connections, structures and inlets

Table 5.1: Results of the assessment of connections, structures and inlets after the first processing step

Failure mode	**Occurrence**	**Occurrence per 100 connections**	**Average Failure**
Clean	91	35.4	0%
Unknown	52	20.2	0%
Sediment	49	19.3	72%
Waste	33	13.1	41%
Vegetation	24	9.3	57%
Human Interference	5	1.9	70%
Other	2	0.7	22%

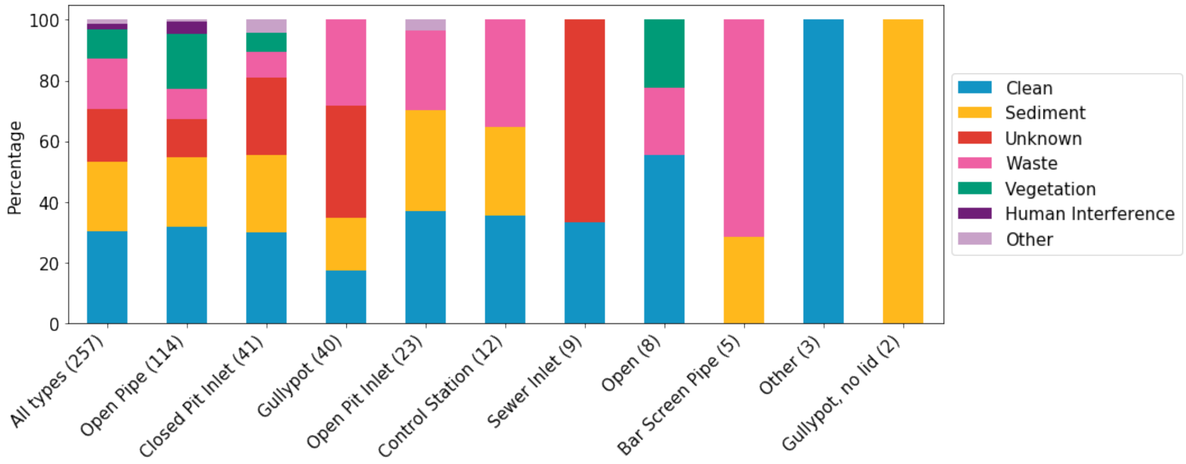


Figure 5.1: Failure per connection type

This section comprehends the results of the analysis of 257 connections, structures, and inlets. All data points are provided in Appendix G. From these datapoints, 38 points had two failure types and two connections had three failure types. As a result, a total of 299 elements were generated after the first processing step. Table 5.1 presents the occurrence of each failure mode, including points with more than one failure mode.

Firstly, failures per connection type are discussed. Figure 5.1 presents the results of the failure modes per connection type. This analysis shows that 30.4% of the connections were clean. Besides this, the main failure modes are sedimentation, waste and vegetation. Human interference and other failures are found less often. A fraction of the failure modes was unknown (17.4%); this mainly included closed pits and gully pots which were too dark to make an appropriate assessment of the failure.

Considering different connection types, the largest part of the dataset consists of open pipes, followed by closed pipe inlets and gully pots. The bar screen pipe should be highlighted; all five observed bar screen pipes contain waste to some extent as this is trapped in the bar screen. Furthermore, the fraction of waste is high in control stations and inlet points.

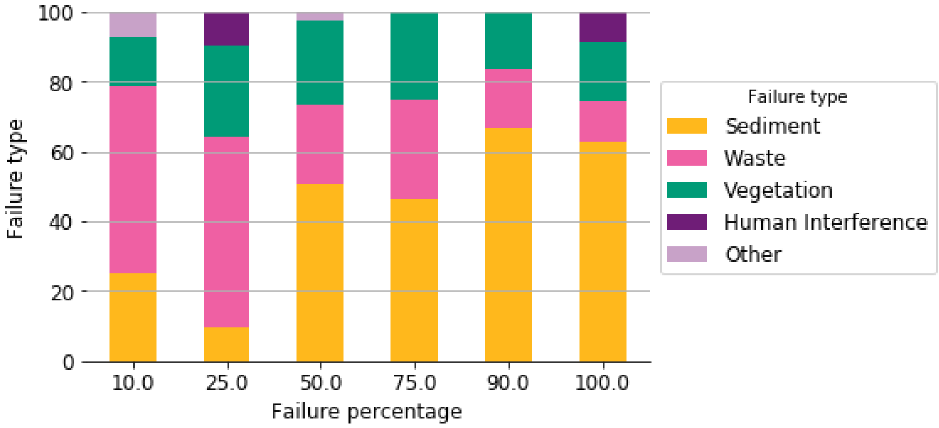


Figure 5.2: Failure Type versus degree of failure in connections

Figure 5.2 presents the relation between the failure percentage and the failure modes. It shows that as the degree of failure increases, the portion of sediment in the total failures increases as well. An opposite trend can be found for waste; waste accounts for around 50% of the small failures with a lost surface area of less than 25%. Vegetation can be found in small and large failures and is therein accountable for approximately 10% of the failures.

Canal stretches

In total, 89 separate canal stretches are identified with a total length of 25704 meter. From these canals, 16779 meter was unlined and 8925 was lined. 17 of these canals had two or more failure modes. The canals with multiple failure modes are split, assuming that each failure mode has an equal effect to the total failure. An overview of the occurrence, average failure and weighted occurrence is presented in Table 5.2.

Table 5.2: Results of the assessment of canals after the first processing step

Failure mode	**Occurrence** (in meters)	**Occurrence per kilometer** (in meters)	**Average Failure**
Vegetation	11991	466	43%
Clean	6611	257	0%
Sediment	3900	152	31%
Unknown	1664	65	0%
Human Interference	1129	44	78%
Waste	349	14	45%
Other	61	2	50%

The results from the stretches show that overall, failure is more commonly found in the canals as in the connections, inlets and structures; almost 75% of the canals have a failure to some degree. The failure mode that was observed the most was vegetation, followed by sedimentation. Smaller portions can be found for human interference and waste. 25.7% of the canals have no failure and for 6.5% of the canals, the failure type is unknown. The unknown canal is a primary canal that was identified using satellite data but was not visited during the visit.

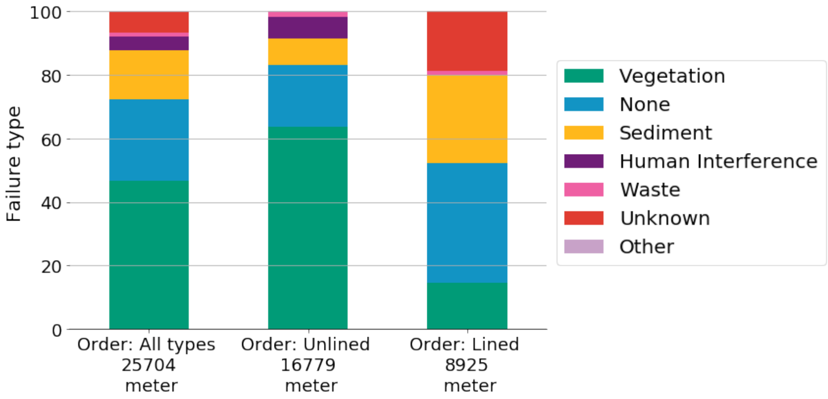


Figure 5.3: Failure modes in lined versus unlined canals

Figure 5.3 compares failure modes in lined and unlined canals. Lined canals more often have no failure mode, compared to unlined canals (38% versus 9%, respectively). In unlined canals, vegetation accounts for more failures (64%) than in lined canals (15%). Human interference is not found in lined canals whilst it accounts for 7% of the failures in unlined canals. As it was generally difficult to measure the degree of sedimentation in unlined canals, this fraction is higher in lined canals.

No registration is done on the vegetation type that was observed, but during the transect walks, it became evident that different vegetation types are found in unlined and lined canals. In lined canals, the predominant type was *Pontederia crassipes*, whilst *Phragmites australis* was mainly found in unlined canals.

Combining both failure type and degree of failure, an opposite trend for sedimentation was found compared with the connections; sedimentation was generally found in canals with smaller failures. This can be seen in Figure 5.4. Furthermore, human interference generally causes larger failures. Vegetation is widely found in the canals and there does not seem to be a trend in the occurrence of this failure mode.

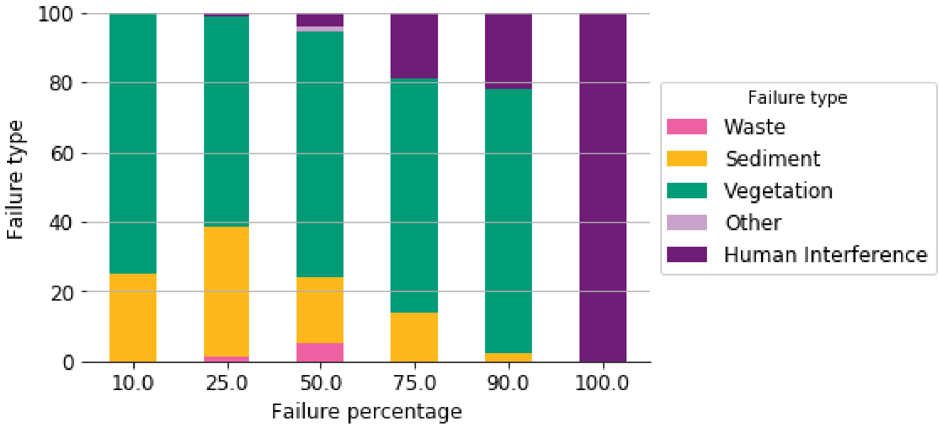


Figure 5.4: Failure Type versus degree of failure in canal stretches

5.1.2. Hydraulic modelling

The results from the state of the canals are used in the hydraulic modeling in D-FLOW FM 1D2D. This section holds the outcomes of this hydraulic modeling and points to some trends. It presents the results obtained from modeling in the base scenario, alongside the outcomes from the failure mode scenarios. Table 5.3 gives and overview about where which results are presented.

Table 5.3: Location of results for each failure mode

Scenario	**Observations used as input for the model** in appendix	**Most important results**	**Elaborate presentation floodmaps** in appendix
Base scenario		5.1.2	5.1.2.1
1: Impact of vegetation in canals	E	5.1.2.2	F.2
2: Impact of sedimentation in canals	E	5.1.2.3	F.3
3: Impact of human interference in canals	E	5.1.2.4	F.4, F.5 and F.6
4: Impact of underdimensioned structures in canals		5.1.2.5	F.7 and F.8
5: Impact of waste in the Palmeiras outfall		5.1.2.6	F.9
6: Impact of blockage of the connections		5.1.2.7	F.10

Inundation depths in base situation

The inundation depths in the clean scenario – without any failure modes – are depicted in Figure 5.5. This image shows the areas which flood for more than 10 centimeter under precipitation events with different return periods. Analysing this image, it becomes evident that the drainage network in the base scenario is incapable of preventing flooding for precipitation events occurring once per year in large parts of the study area.

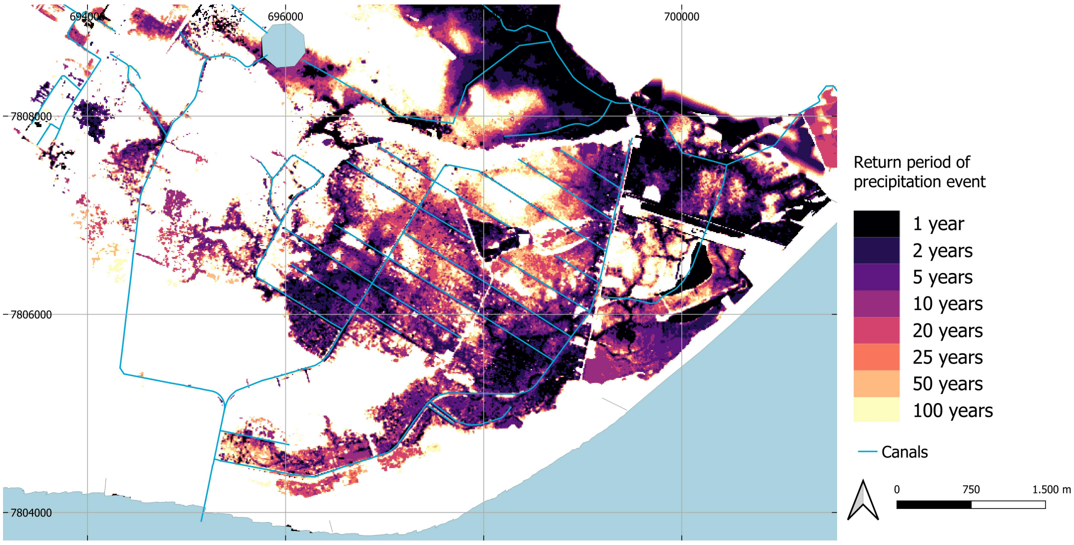


Figure 5.5: Flooding of more than 10 centimeters in base scenario under different return periods

Scenarios

The inundation depths for all scenarios are compared with the base scenario. Figure 5.7 shows the difference in inundation depth between the base scenario and the scenarios with failure modes, all under the precipitation event taking place once per 10 years. Figure 5.7 also presents the contour of the area in which the inundation is more than 10 centimeters under the precipitation event which takes place once per year.

Scenario 1: Impact of vegetation in canals

The difference in inundation depths caused by the observed vegetation is presented in Figure 5.7a. It shows that the increase in inundation between 2 and 5 centimeters and can be mainly found in the Chota neighbourhood. This is coherent with the fact that most of the canals affected with vegetation can be found in Chota.

Considering the fact 64% of the canals in the unlined section contain vegetation to some degree, the increase in inundations seems to limited. However, if all canals would have a severe blockage caused by vegetation, this shows a more concerning image. If this is modeled, the inundation increases with more than 20 centimeter and peaks of 50 centimeter. The map is presented in Figure 5.6.

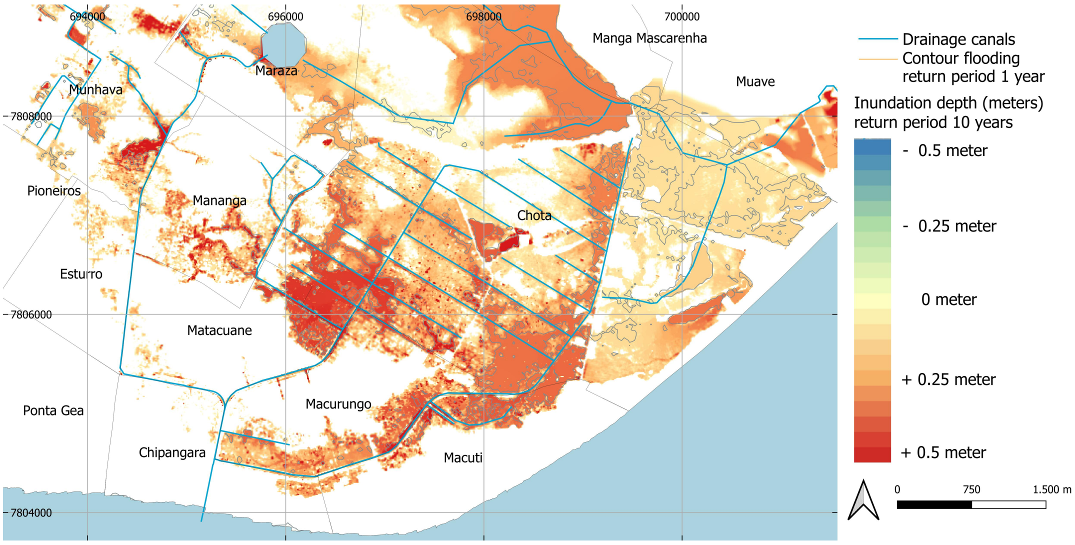


Figure 5.6: Inundation increases caused by overall severe vegetation at t = 24 hours. The scale of this map ranges from -0.5 to +0.5 meter and is therefore different from the other maps

Scenario 2: Impact of sedimentation in canals

The effects of sedimentation is mainly visible in the retention basin Lagoa Municipal da Beira in the north of the Phase 1 area. Increased inundation levels in this basin can be observed caused by the decrease of the retention capacity in the primary canal. After 12 hours, just following the peak of the precipitation event, it can be observed that this causes a sharp increase in inundation in a small part of the western region of the Phase 1 area, with inundation levels rising by up to 20 cm. The differences in inundation decrease after 24 hours, resulting in increases of approximately 1 cm in some regions, as shown in Figure 5.7b.

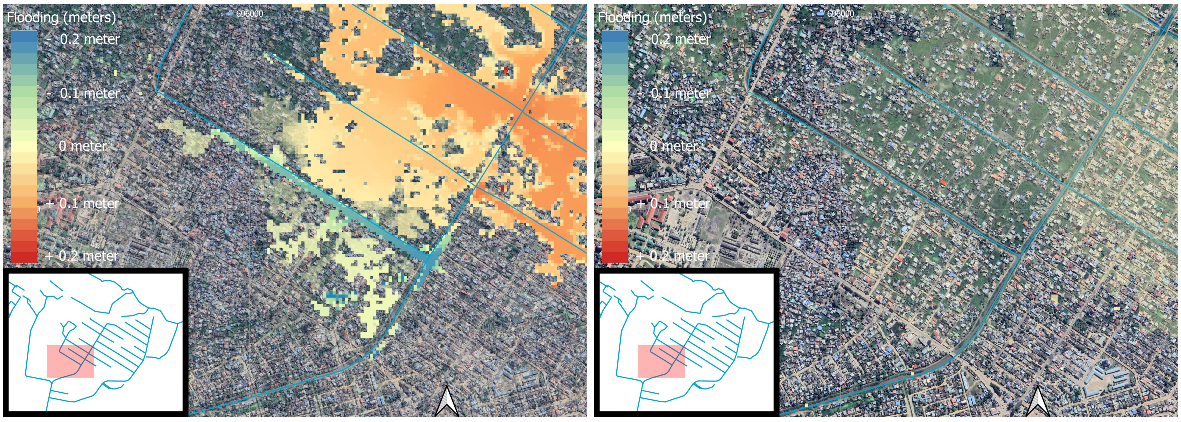
The effects of sedimentation on the inundation depths under a precipitation event with a return time of 1 year are not visible on the inundation maps; there is only some increase in water depth of the retention basin.

Scenario 3: Impact of human interference in canals

Figure 5.7c presents the results of the scenario with human interference. During the transect walks, it was observed that two canals were affected by human interference. After 24 hours, the inundation depth increase is around 0.5 cm around the southern canal and significantly more around the northern affected canal (35 centimeter).

In the southern canal, the areas surrounding the points of human interference experience increased inundation depths up until t = 11 hours. In this region, inundation depth increases of more than 10 cm are widespread and peaks of 30 cm can be found. However, beyond t = 11 hours, the difference between the modified scenario and the base scenario diminishes. In the northern canal, the difference in inundation depths between the base scenario and the scenario with human interference does not diminish after t = 11 hours but remains high.

Figure 5.8 compares the results of the inundation depth increases under the precipitation event happening once per year and once per ten years. It shows the inundation depth increase is stronger in under the precipitation event with a return period of one year (around 12 centimeter) versus the one with a return period of ten years (less than 2 centimeters). It therefore becomes evident that in this canal, human interference primarily impacts inundation depths for smaller precipitation events.



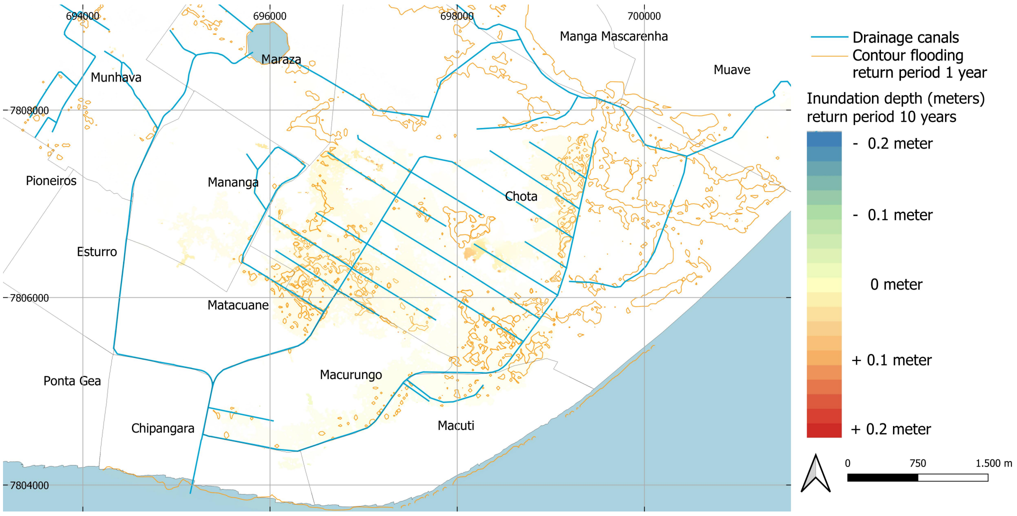
(a) Under precipitation event with a return period of 1 year

(b) Under precipitation event with a return period of 10 years

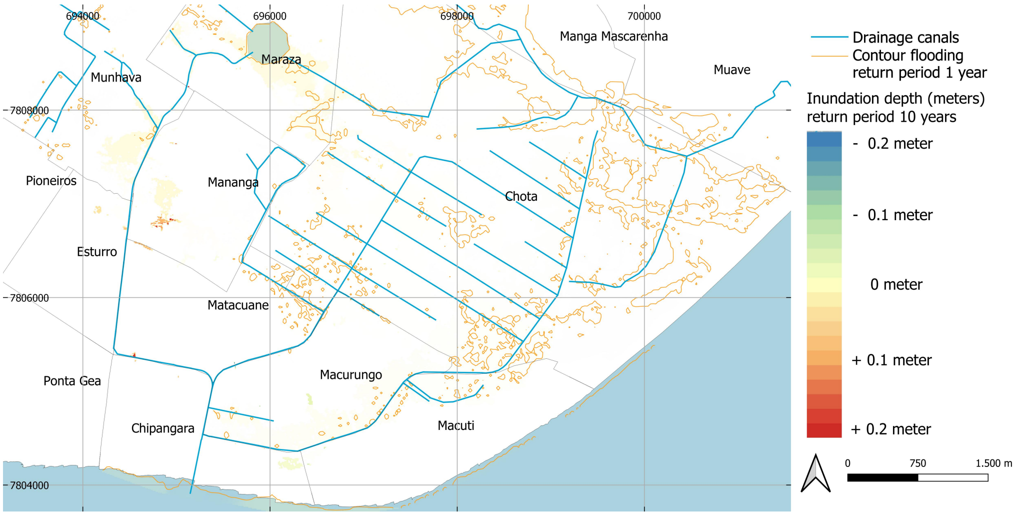
Figure 5.8: Inundation increases caused by human interference at t = 24 hours

Scenario 4: Impact of underdimensioned structures in canals

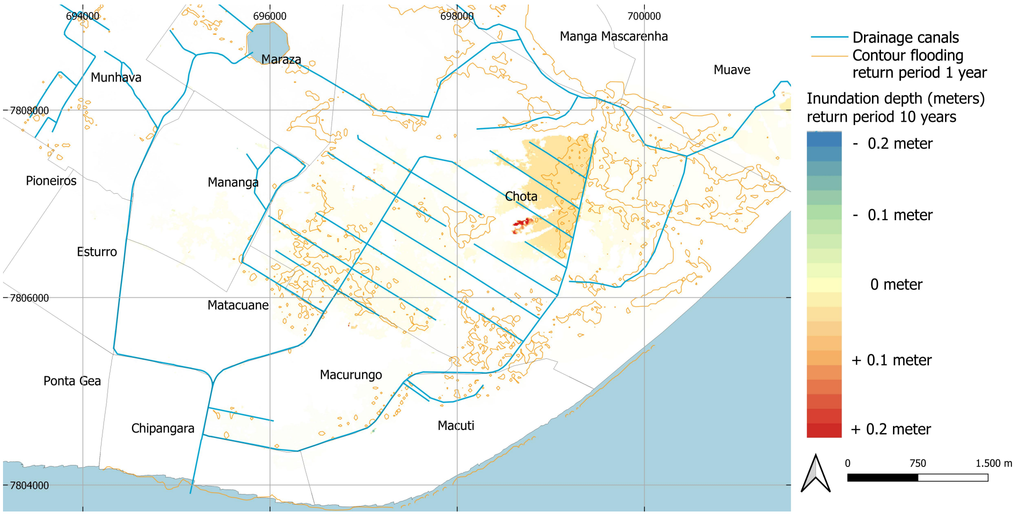
The impact of underdimensioned structures, which is modeled by including a bridge in Chota, mainly affects floodings in the end of the precipitation event. In the initial stage, inundation depth increases are mainly focused in the already existing canals. From 15 hours onwards, the increase in inundation extends to the entire upstream area of the bridge and peaks at a 2 cm increase over a large surface area after 24 hours. The bridge therefore seems to strongly affect the capacity to drain the flooded area



(a) Scenario 1: impact of vegetation in canals. Scale ranging from -0.2 to +0.2 meter

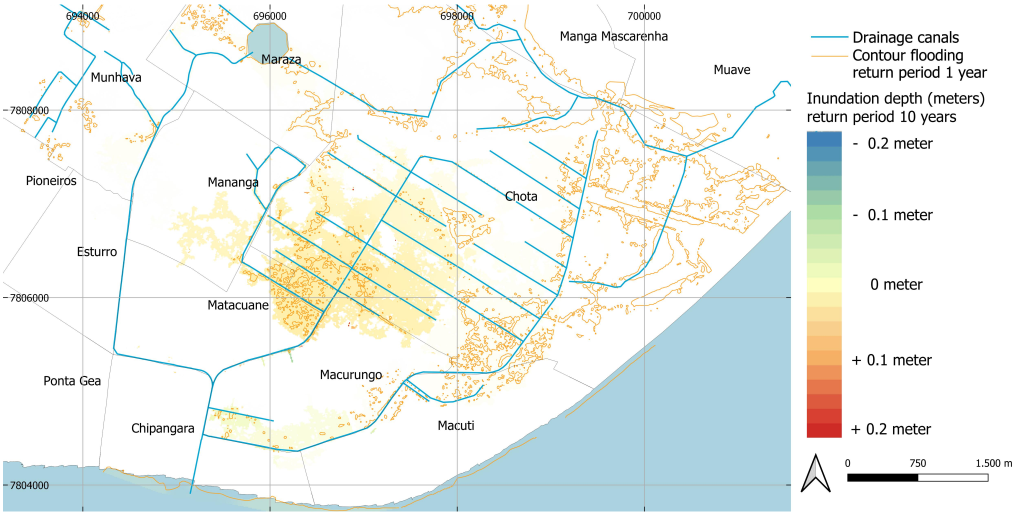


(b) Scenario 2: impact of sedimentation in canals. Scale ranging from -0.2 to +0.2 meter

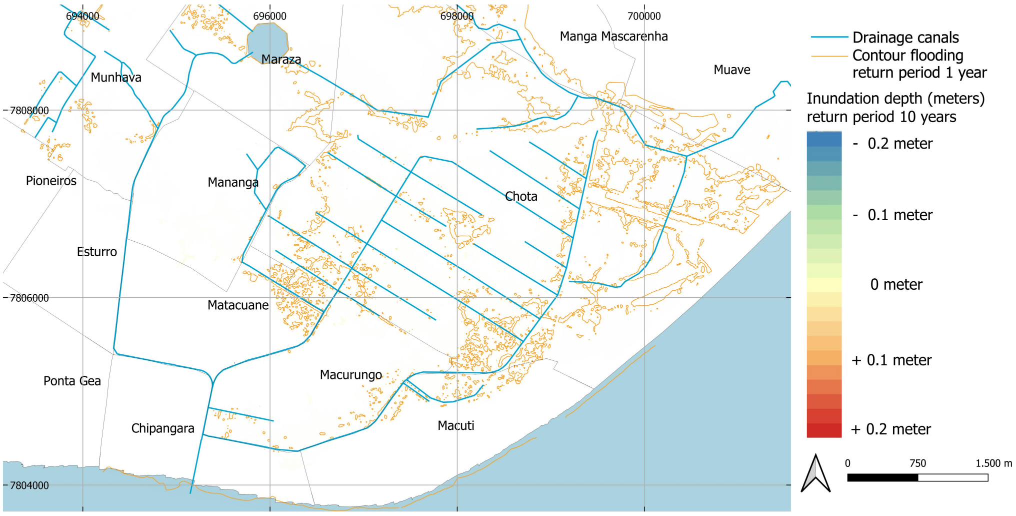


(c) Scenario 3: impact of human interference in canals. Scale ranging from -0.2 to +0.2 meter

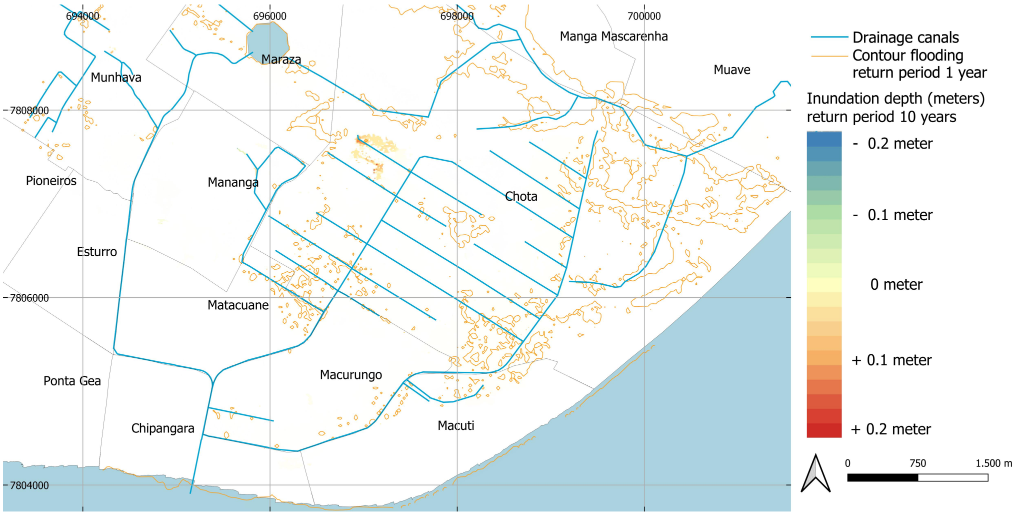
Figure 5.7: Inundation increases caused by failure modes at t = 24 hours



(d) Scenario 4: impact of underdimensioned structures in canals. Scale ranging from -0.2 to +0.2 meter



(e) Scenario 5: impact of waste in the Palmeiras outfall. Scale ranging from -0.2 to +0.2 meter



(f) Scenario 6: impact of blockage of the connections. Scale ranging from -0.2 to +0.2 meter

Figure 5.7: Inundation increases caused by failure modes at t = 24 hours

in a late stage of the precipitation event. Figure 5.7d presents the results on the scale of the whole city.

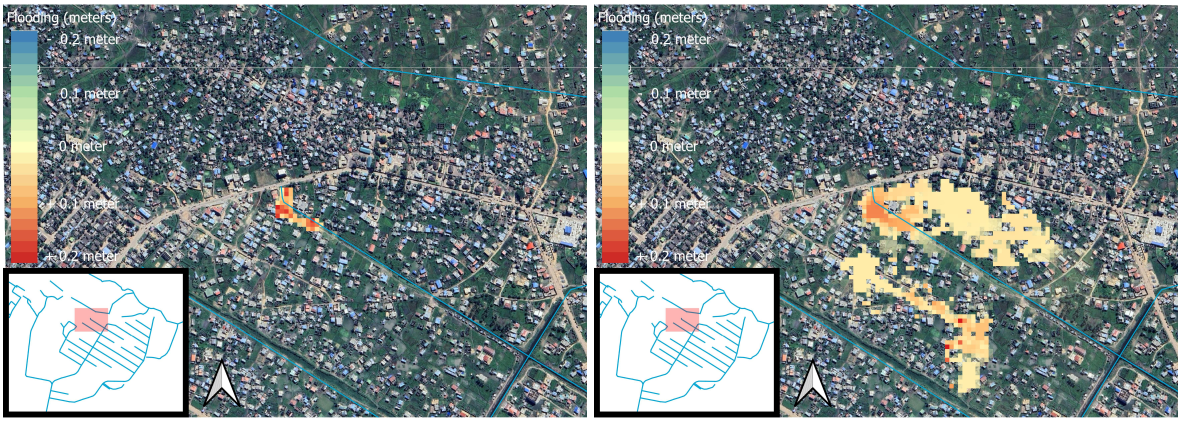
Under the precipitation event taking place once per year, the increase in inundation depths spans a smaller surface area, indicating that the bridge mainly affects inundation depths in large rain events.

Scenario 5: Impact of waste in the Palmeiras outfall

In the scenario where a part of the outfall in Palmeiras is obstructed, the model finds an initial increase in water depths during the flooding event. The water depth rises with a maximum of 2 cm in this situation on a relatively small area. There is hardly any difference in inundation depths between the base scenario and the scenario with this failure after t = 12 hours. Results are presented in Figure 5.7e.

Similar results are found for the precipitation event which takes place once per year; there are some differences in the initial phase of the precipitation event but these differences flatten out as the precipitation event progresses.

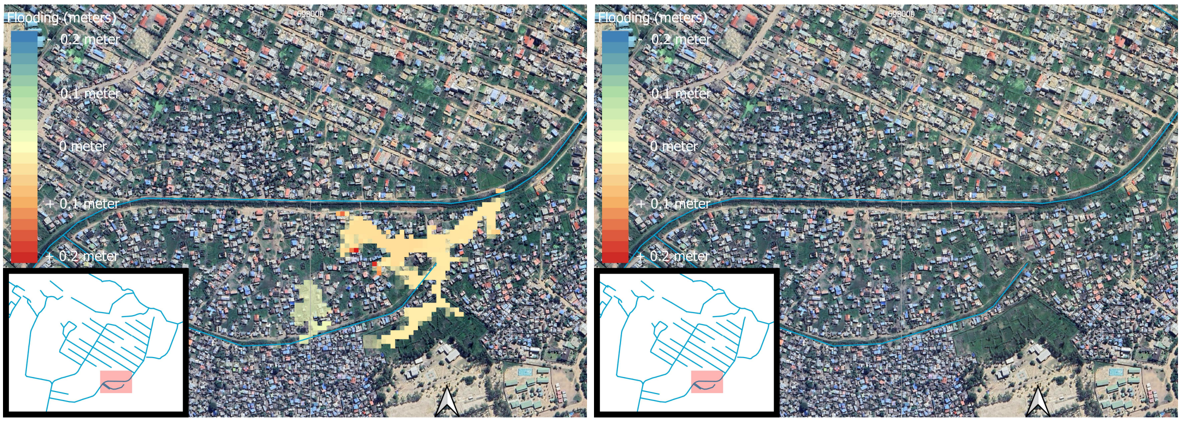
Scenario 6: Impact of blockage of the connections



(a) Time: 9 hours

(b) Time: 24 hours

Figure 5.9: Inundation increase caused by hypothetical blockage of the connections in the northeast of Chota



(a) Time: 9 hours

(b) Time: 24 hours

Figure 5.10: Inundation increase caused by hypothetical blockage of the connections in the Macuti neighbourhood

The scenario involving the blockage of connections focuses on certain dead-end canals, which are reduced in size in the model to simulate the obstruction of these canals. These canals show varying results depending on their location. In most cases, there is an increase in inundation levels just after the peak of the precipitation event (at t = 12 hours), followed by a reduction in differences. Results of the impact of the blockage of connections can be found in Figure 5.7f.

The impact of canal blockage varies across the system. In flood-prone areas, as shown in Figure 5.10, blockages affect inundation levels until 12 hours, after which overland flow becomes the predominant flow in both the base scenario and the scenario with blockages. In other regions where there is no overland flow in the base scenario, such as in Figure 5.9, the blockages cause a very localized increase in inundation depths, reaching up to 20 cm.

5.1.3. Water quality

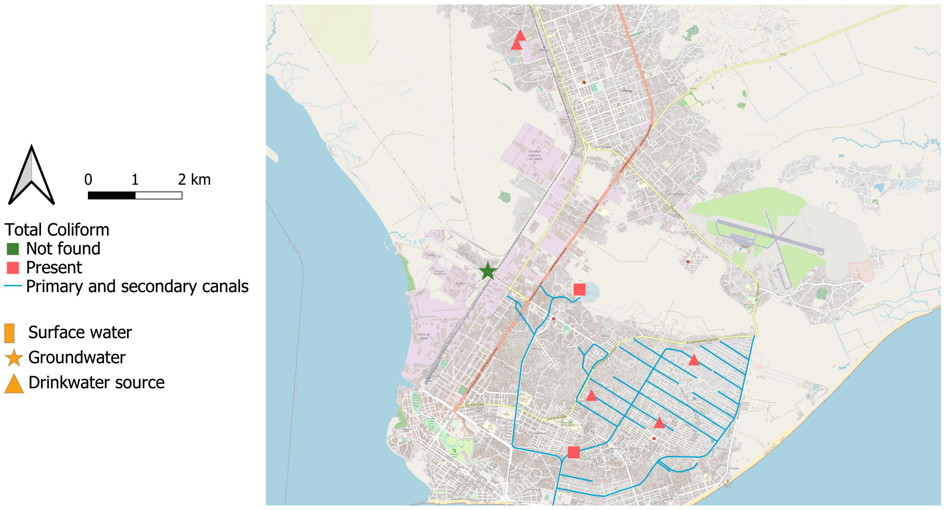


Figure 5.11: Results of the total coliform measurements

A total of 9 total coliform measurements were performed, of which 5 in shallow wells and 3 in primary canals. All total coliform measurements that were done in surface- or ground waters were contaminated with a CFU of more than 1 parts per million (ppm). One total coliform measurement of a drinkwater supply point was taken; this was the only measurement that showed a total coliform of less than 1 CFU. Results are presented in Figure 5.1.3.

5.2. Qualitative analysis

5.2.1. Key informant interviews

The key informant interviews gave an insight into the ease of mitigation of certain failure modes. Furthermore, the interviews provided some relevant background information.

SASB

A representative from SASB stated that they recognize the failure modes identified in the research and emphasize that human interference is a significant concern for them. The socio-economic situation of many city inhabitants complicates the process of relocating canal occupants. Since the occupants of these houses generally belong to the most disadvantaged segment of the community, they ”simply have nowhere else to go.” Consequently, when occupiers are compelled to move, they receive financial compensation. Furthermore, it was mentioned that relocating illegal inhabitants requires an official letter from the mayor of Beira, which is a time-consuming and highly challenging process. Nevertheless, relocation occurs ”very often, multiple times per week”.

Other representatives from SASB confirm the issue of uncontrolled property construction. One individual mentioned that in the Nghangua region, designated for urban development, no plots had been officially allocated for construction. However, a site visit revealed a substantial number of houses and preliminary fences already erected in the area. There are concerns that a similar situation might occur in regions designated for floodwater retention.

The removal of sediment, waste, and vegetation from canals is performed using two excavators: a large one and a smaller one used for shallower canals (Figure 5.12). Unfortunately, during the visit, the larger excavator was non-operational and unavailable. Additionally, vegetation is managed through tidal flushing of the canals during the dry season. This involves opening the sluice gates at Palmeiras during high tides to allow water inflow and increase water levels. Subsequently, during low tides, the sluice gates are reopened to flush the drainage network. This practice also enhances water quality.

Interviewees from SASB prefer maintenance of the canals with the excavators, as this is easier and regrowth times are shorter. However, costs are also higher: in August 2023, it was estimated that manual cleaning costs 42 Mozambican metical (MZN) per meter canal. Mainly fuel prices causes the costs of cleaning with excavators to be from 56 MZN/m (for a small excavator) up to 113 MZN/m for the large excavator.

Manual cleaning is performed by three teams, each consisting of ten individuals, recruited by FACE and supervised by SASB. Representatives from SASB and FACE mention that they are responsible for sediment, waste, and vegetation removal in connections. Additionally, they trim vegetation in some stretches of the canals. These teams are equipped with basic tools such as shovels and a small pump.

Figure 5.12: The only operational excavator from SASB (picture by author)

FACE

Representatives from FACE also recognise the failure modes identified in this research and emphasise the issue of waste in the canals. FACE regularly organises so-called ’cleanups’, in which they visit a certain neighbourhood, recruit a team of around 15 people and open the tertiary drains by removing waste. Contributors are given a lunch afterwards for their help in the cleanup. Simultaneously, employees from FACE visit houses in the neighbourhood to attend the inhabitants on increased flood risk caused by clogging of the canals.

One of these cleanup sites was visited during the visit in Beira (Figure 5.13). It became evident that there was significant enthusiasm for collaboration with these cleanups, as a discussion quickly arose about who would be permitted to participate. The cleanup lasted for two hours, during which the canals in a densely populated area of approximately 5 hectares were cleaned and cleared. Participants were equipped with gloves, boots and shovels, provided by FACE.

Although a lot of canal stretches were cleaned, it is noteworthy that certain sections of the canal, obstructed by human interference, remained untouched. These sections were considered ”too challenging to clean” and were consequently left blocked, obstructing the entire canal. Moreover, the canals were not excavated to connect with a secondary canal’s inlet, as this inlet was positioned higher than the ground level. Instead, water was let to flow towards a nearby swamp to evaporate. These cleanups are therefore effective for the removal of waste on locations which are easy to reach, but are less effective on locations with combined failure modes.

Figure 5.13: One of the cleanups organised by FACE (picture by author)

Other stakeholders

Other stakeholders that were interviewed also recognised the failure modes that are used in this research. A representative from a Dutch organisation stated that the three main failure modes were illegal construction and bridges, in this research clustered as human interference, waste and vegetation. Furthermore, CAM and AMOR recognise the importance of waste management in the performance of the canals.

Many stakeholders emphasised the need for simple and effective drainage infrastructure, that is not dependent of electricity. One of the interviewees mentioned that during storm Idai, the engines controlling the gates at the outfall of the system were broken. Luckily, the design of the gates allowed manual control over the gates, making opening during peak flow possible. The interviewee therefore advised against the use of pumps, as these depend on electricity, which is usually cut off during floodings.

Other stakeholders have also raised concerns about the city's deficient capacities, particularly the absence of a proper cadaster system. The lack of a comprehensive cadastral system has resulted in challenges for the government in terms of registering and relocating residents living in unauthorized constructions. Enhancing the cadaster system is regarded as a crucial measure to bolster local government enforcement capabilities, as it also presents an opportunity to generate revenue through property taxes. It is estimated that out of the 120,000 houses in the city, approximately 40,000 are eligible for property taxation. Currently, only 5,000 of them are currently subject to taxation.

One interviewee raised particular concern about the hardest-hit neighbourhoods. These challenges therefore require an integral approach for all the issues that are faced, including orphanhood, low educational attainment, high unemployment rates, teenage motherhood, indebtedness, and safety concerns. One interviewee suggested that addressing these neighborhoods' issues should involve a comprehensive approach that tackles all these problems simultaneously, rather than relying on multiple isolated programs that may overlap. Drawing inspiration from the Netherlands, the National Program for Livability and Safety (Volkshuisvesting en Ruimtelijke Ordening, 2022) employs such an integrated approach to coordinate interventions and align programs for more effective policy.

Budgetary reservations are required to replace the existing drainage structure at some point, or to do large maintenance. One interviewee stated that no reservations are currently done and that this will become an issue at some point.

5.2.2. Local interviews

In total, five interviews were conducted in and around the area of interest located in the southern part of Chota. This location comprehends a canal stretch with widespread illegal construction. Two interviews took place upstream of the area of interest, while the remaining three interviews were held within the area of interest, involving residents of houses located in canals.

All interviewees consistently reported experiencing frequent flooding incidents throughout the year, with water levels ranging from knee-height to waist-height. Typically, the water remains for a duration of 2 to 3 days. Many of the houses within the area of interest have been in existence for several years. Notably, one interviewee with a house in a drainage canal mentioned residing there since 2007. All interviewees asserted that they did not personally claimed the land within the canal; instead, it was pre-existing before they established residence in the area. However, it's worth considering that these responses may be influenced by a fear of potential consequences, as constructing in canals is illegal.

While inhabitants living upstream of the area of interest acknowledged that the construction might logically impact flooding, they could not verify this assertion since the houses have been in place for an long period. It is remarkable to observe the level of acceptance these canal-side houses have gained within the community. One interviewee even mentioned renting a house located in a canal, while another stated that the canal-side house was inherited.

5.3. Summary of the results

This section gives a summary of the discussed results. This list gives an overview of the most important findings from the quantitative and qualitative analysis.

- **Base Scenario**
  Quantitative: In the base scenario, flooding occurs frequently, leading to high inundation depths, especially in Phase 2 of the network.
  Qualitative: Current plans focus on rehabilitating Phase 2 to mitigate floodings.
- **Vegetation**
  Quantitative: Vegetation's impact is minimal but can be significant if not properly maintained. Is found widespread in the canals.
  Qualitative: Removal requires excavators or frequent maintenance to prevent adverse effects. SASB is experienced with water level control in the canals.
- **Human Interference**
  Quantitative: Local effects occur mainly under small precipitation events due to human interference.
  Qualitative: Resolution is challenging as it requires the rehabilitation of inhabitants. Makes future city development more difficult.
- **Waste**
  Quantitative: Waste causes blockages, leading to local effects during smaller precipitation events. Is found widespread in the connections.
  Qualitative: Removal demands few resources; international NGOs are addressing the issue.
- **Sediment**
  Quantitative: Sediment reduces retention capacity without a significant increase in inundation depths. Is found in both connections and canals.
  Qualitative: Difficult to remove due to limitations in available resources.
- **Underdimensioned structures**
  Quantitative: Inundation increases primarily at the end of precipitation events.
  Qualitative: Lack of communication between urban planning and SASB contributes to this issue.
- **Other**
  Quantitative: Rarely found; impact on flooding not quantified.
  Qualitative: Expected to increase over time; financial reserves needed, currently not accounted for.

6

Discussion

6.1. Limitations and uncertainties in D-FLOW FM 1D2D model

The D-FLOW FM 1D2D model suffers from several spatial and temporal limitations that impact results. Firstly, the model's level of detail falls short of the actual field data, especially concerning tertiary canals. Many tertiary canals were observed, which have not been included in the simulations. This limitation affects the modeling outcomes of the system's performance for small precipitation events, as evidenced by the scenario with blocked connections; large precipitation events remain unattended as overland flow is herein predominant. It is therefore likely that larger areas are flooded on the street level during small precipitation events than found in the results.

Beyond the spatial limitations, the research's observations and transect walk data only capture a snapshot of the drainage system during the dry season. It is important to note that the results may vary during the wet season, as some interviewees mentioned canal cleaning activities before the onset of the rains. Furthermore, the wet season typically witnesses significant mobilization of sediments and waste, resulting in an increase of the blockage of connections.

Another notable limitation lies in the uncertainty of rainfall predictions. Real rain events often deviate from the patterns described in this research due to inherent variations. Additionally, while the return periods are derived from precipitation measurements from the field, only 20 years of precipitation data is available, making predictions for precipitation events with return periods exceeding 20 years challenging.

The model's parameterization of Manning coefficients for vegetation and waste, though based on literature, lacks calibration against real-world data specific to the study area. While significant over- or underestimation of floodings is not expected, the absence of calibration reduces the accuracy and precision of the Manning parameterization, introducing a source of uncertainty into the model.

Lastly, the presence of adaptation strategies has not been included in the model. During the visit in Beira and an investigation performed by FACE (FACE, 2023a), it was found that many community-based adaptation measures are already taken, decreasing the real impact that inhabitants experience from these floodings.

6.2. Implications of future trends

In the employed model, the implications of global warming, such as heightened precipitation intensity and rising sea levels, have not been accounted for. AIAS et al., 2022 establishes certain assumptions to account for these effects. It assumes that precipitation will increase with 18% and sea levels will rise by 0.52 meter, resulting in a 1.8-fold increase in annual economic damages caused by floodings. Combining this with increased flooding impact caused by increased urbanisation and value increase of assets, the expected flood impact is expected to increase with a factor 6.1 in 2070.

It is reasonable to anticipate that specific failure modes will be more sensitive to precipitation increases than others. The results reveal that failure modes influencing tertiary and small secondary canals, such as connection blockages and human interference, generally contribute to more early-stage flooding and lesser inundation during the peak of a rainfall event. Conversely, large-scale failure modes predominantly affect inundation depths at the peak of the rainfall event.

Next to increased vulnerability to certain failure modes, these trends can also have an effect on the occurrence of certain failure modes. It is reasonable to anticipate that urbanisation patterns are accompanied by an increase in human interference due to increasing land stress. Moreover, it will increase waste production and therefore the risk of blockage by waste.

6.3. Covariance between failure modes

In the current modelling, it has been assumed that there is no covariance between different failure modes. In reality, this is likely present. One example is the relation between waste and vegetation; it can be assumed that waste gets stuck in vegetation and an increase in vegetation will therefore also increase the obstruction by of waste in the canals.

Additionally, human interference is a factor that is dependent of the other factors influencing the overall state of the canals. If other failure modes - mainly sedimentation, vegetation and waste - are present in the canal, legitimacy of the canals is decreased, making canals more vulnerable to human interference. If the state of a canal is good, human interference is less likely to occur.

6.4. Implications of socio-economic differences

The model used in this study does not account for socio-economic disparities. However, background interviews and the visit to Beira have indicated that these differences between neighborhoods are significant and play a crucial role in determining the resilience of communities in the face of flooding.

The vulnerability to specific failure modes is highly influenced by social factors. While not included in this research, the presence of waste in canals is likely correlated with the efficiency of waste disposal. In Beira, although waste collection used to be scarce, presence of waste collection bins is rapidly improving thanks to efforts of the municipality and certain NGOs. Likewise, communities with a stronger sense of communal cooperation are likely to be less susceptible to human interference. Additionally, during the visit in Beira, several examples were found where residents themselves cleared vegetation from the canals, thereby enhancing drainage. This illustrates that social interactions within the drainage system can have significant positive impacts on its overall condition.

Other ”less affluent” neighborhoods that are susceptible to flooding lack the resources to adapt to and mitigate the consequences of such events. Similarly, economically disadvantaged neighborhoods are often the hardest hit by flooding due to inadequate sanitation infrastructure, which increases the risk of waterborne diseases. An example, located just outside the study area in the northwest of Beira, is Munhava-Matope. According to one inhabitant, this neighborhood experiences flooding for approximately 7 months a year because of its deficient drainage network. This, combined with the absence of proper sanitation leading to widespread open defecation, increases vulnerability to waterborne diseases. Conversely, inhabitants with a stronger financial position are better equipped to deal with flooding. These individuals can afford adaptation measures such as raised platforms and boots to cross puddles.

6.5. Effects of tidal flushing

Tidal flushing of the drainage system is a common practice performed by SASB. During this process, seawater is introduced into the drainage network to dilute canal contamination and flush out waste. Additionally, this practice helps prevent vegetation growth and enhances canal legitimacy, guarding against human interference. If tidal flushing is conducted regularly, it can help reduce mosquito proliferation by preventing female mosquitoes from laying eggs.

However, there are also some drawbacks to consider. The influx of saltwater from the sea can significantly impact urban farmers that are commonly present in certain neighborhoods, such as Chota. The extent of salt presence in the city's water bodies and its influence on crop growth remain unknown, but salt levels are likely to rise with more frequent tidal flushing. This situation may necessitate cultivating crops that are more resistant to higher salt levels (De La Reguera et al., 2020).

6.6. Comparison to other regions

The quantification of the failure modes can be compared with findings from other regions. Jemberie et al., 2023 conducted a similar analysis of connections in Addis Ababa, Ethiopia. In the longitudinal drainage components, which constitute the most common component type in this research dataset, 52% were rated as 'good' or 'very good'. When focusing solely on components with failures, a comparable percentage of failures were attributed to waste (28.5% in Addis Ababa versus 29.5% in Beira). Additionally, the impact of sedimentation on the system in Addis Ababa was found to be lower (6.8% versus 43.5% in Beira).

6.7. Future research

While this research provides valuable insights into the impact of failure mechanisms on drainage network performance, it is evident that further investigation is necessary. Specifically, further research should delve into improving the model with a more detailed spatial scale, a broader temporal scale including other seasons and future weather trends, and in-field calibration. Additionally, possible extensions of the research include the potential of tidal flushing to mitigate failure modes, an impact analysis, potential adaptation- and early warning strategies, and assessing its applicability in other regions.

Firstly, a more detailed assessment of the performance of tertiary canals in the field is required to determine if the same failure mechanisms as mentioned above are applicable on this spatial scale and to assess their impact on inundation depths. This assessment would involve conducting transect walks at street level to quantify the failure modes in these canals and measuring cross-sections of the canals. Integrating these findings into the hydraulic model would enhance the understanding of failure effects within tertiary canals and micro-catchments, thereby improving the overall accuracy of the modeling.

Secondly, the conditions during the rainy season should be included in the modeling. This research has evaluated the condition of the drainage system in Beira during June, corresponding to the dry season. It is important to acknowledge that social and physical characteristics may lead to significant variations in the presence of certain failure modes in the drainage network. Therefore, it is advisable to conduct a similar assessment as has been done now, including transect walks and direct observations, during the rainy season.

Additionally, to ensure the continued relevance of this research in the future, it is imperative to incorporate anticipated trends. To begin, it is anticipated that human interference will increase alongside Beira's rapid urbanization and densification. This densification will, in turn, raise runoff factors and peak flows. Additionally, climate change is expected to increase the amount of intense precipitation events and raise sea levels. Incorporating these trends into the modeling process is likely to result in increased inundation depths within the city.

Thirdly, to improve the precision and accuracy of the D-FLOW FM 1D2D model, calibration with field measurements of inundation depths is required. A calibration has been done by AIAS and Consultec, 2021, but the failure modes were not included in this calibration; it is unsure which failure modes were present at the time of the calibration while this research has shown that these can have a large effect on the inundation depths. Calibration with failure modes should therefore be performed to validate the model.

Fourthly, the application of tidal flushing in the drainage network is a potential method to reduce vegetation growth, improve water quality, and eliminate sediment buildup. To evaluate the impact of tidal flushing on vegetation growth and water quality, combining tidal flushing events with water quality measurements and a vegetation growth assessment could be a next step. Additionally, investigating sediment removal is possible by sampling the sediment bed and measuring water velocities in the canals to determine if they exceed scour velocities.

Fifthly, to outweigh the costs and benefits of the failure mechanisms and the mitigation measures that are suggested, a flood impact assessment should be done. The Delft-FIAT model is a very suitable tool to do this; the model compares inundation depths with asset values and number of inhabitants to quantify the monetary value of the damages and the amount of people that are affected by the floodings. The outcomes of this model should be compared with the costs of maintenance strategies to outweigh these. Additionally, these impact models allow weighing between different adaptation strategies in certain neighborhoods, such as raising doorsteps or creating communal elevated platforms.

Sixthly, further investigation into the use and effectiveness of adaptation strategies is necessary. Strategies such as raised doorsteps, plateaus, retention areas in the form of rice fields, and early warning systems were commonly observed in communities. These measures can effectively mitigate the impact of flooding. However, more research is needed to determine the extent to which these strategies reduce the impact of floods.

Lastly, it is unsure whether the failure modes that are found in this research also apply to other regions. Although the variety between different informal settlements is usually large, this is not a field of extensive research. Applying the method of this research could therefore be considered to assess whether the same failure mechanisms hold and impacts of these failure mechanisms are similar. A study area of interest in Mozambique would be the city of Quelimane, situated in the north of Mozambique, as it is similarly low-lying as Beira.

7

Conclusion

The objective of this research is to analyse and evaluate the performance of the drainage system in the urban area of Beira, Mozambique. This is an urgent issue; flooding poses a significant threat to livelihoods and public health, as evidenced by the presence of coliform in all surface and groundwater samples, as well as the frequent damages to assets and frequent cholera outbreaks. This study has performed measurements in the drainage canals and hydraulic modeling using D-FLOW FM 1D2D under a scenario without failure and and six scenarios with failure mechanisms, being vegetation, human interference, waste accumulation, sedimentation, underdimensioned structures, and other factors. Significant inundation increases were found under the failure modes, underscoring the urgency to consider these while designing a drainage network.

The critical finding is that, under the base scenario, areas within the system experience annual flooding exceeding the acceptable threshold of 10 centimeters, with some parts reaching up to 35 centimeters. Frequent flooding is mainly observed the Phase 2 section of the drainage network, underscoring the need for rehabilitation in this area. Potential solutions include enhancing retention capacity or constructing an additional outlet; building pumping stations, however, is not a viable option. Urbanisation and climate trends like precipitation increases and sea level rise are expected to increase the damages caused by floodings with a factor of 6.1 in 2070.

The most critical factor contributing to failure in both lined and unlined canals is vegetation. Its widespread presence poses a significant threat to the drainage system. Although current hydraulic modeling indicates a relatively minor impact on system performance, an increase in vegetation has the potential to significantly increase inundation depths. The qualitative analysis highlights the vulnerable state of the drainage network, especially in unlined canals where a conducive growth medium is abundant and vegetation regrowth times can be as low as one month. Combining this with the fact that SASB faces resource constraints, maintaining the current state of the network is uncertain. To solve this, a comprehensive vegetation management plan is required, including solutions like complete removal using excavators, regular trimming, and ensuring a constant flow of non-stagnant water in the canals.

The hydraulic modeling indicates that human interference, resulting from unplanned construction within drainage canals, causes substantial inundation depth increases in the upstream area of the unplanned constructions. This can be up to 30 centimeters, mainly at the beginning of precipitation events when overland flow is not the dominant flow type. Furthermore, it can potentially prolong flood durations by blocking water flow through the canals. Interviews with key informants show that it is a challenging issue to address, as it requires rehabilitation and compensation for affected inhabitants. Combining this with the significant hydraulic impact makes human interference a major threat to the long-term performance of the drainage canals.

This research reveals that waste poses a relatively minor threat to the drainage system's performance. Waste, carried by water flow, is sparsely located in the canals but is more commonly found in connections, in similar fractions as in other regions. Modeling has showed that blockages in these connections primarily lead to localized flooding upstream of the connections during minor precipitation events. Additionally, the hydraulic modeling reveals that a 20% blockage of the outfall at the end of the system has negligible effects on the drainage system's overall performance. Furthermore, the site visit shows that removal demands minimal resources.

Sedimentation is primarily observed in connecting elements and the rectangular primary canals, with trapezoidal lined canals remaining unaffected due to higher water velocities during low discharges. While it directly reduces the retention capacity of the drainage network, modeling indicates that it does not lead to widespread increases in flooding. Interviews show that there is currently no established plan for sediment removal and monitoring, although methods like dredging and flushing can be feasible options.

Underdimensioned structures, as defined in this research, refer to bottleneck structures such as small culverts under bridges. These issues cause inundation increases in an large surface area, particularly in the later stages of precipitation events. Interviews show that there is limited knowledge and capacity in the organisation of SASB to avoid these issues and assess the hydraulic impact of these structures and even if so, it is uncertain whether there will be listened to.

Lastly, other failure modes, such as the collapse of side walls and intrusion of tree roots, are predominantly found in sections of older, lined drainage networks. The rehabilitated section of the drainage network is less susceptible to these issues as the system is relatively new. Nevertheless, as the system continues to age, substantial maintenance and replacement of sections will eventually become necessary. Unfortunately, at present, there are no financial reserves allocated to address this requirement.

During the qualitative analysis, many community-based adaptation measures were found. Mostly in the most flood-prone areas, raised doorsteps and elevated floors were widespread. These are expected to have some effects on the reduction of the impact of flooding; especially floodings with smaller return periods and lower inundation depths are easier to adapt to using small-scale adaptation measures.

8

Recommendations

Following from the conclusion that the hydraulic capacity is insufficient, the most important recommendation is that the hydraulic capacity of the drainage system should be increased to meet both current and future needs. It is assumable that the needs of the drainage network will increase in the future, as peak flow will advance due to climate changes and the increase of paved area coming along with the development of informal settlements.

Secondly, operation and maintenance of drainage infrastructure should be a focal point while designing. In an early stage, it is crucial to identify and reinforce an organisation capable of carrying responsibility for the system after its completion. Community-based organisations can play a role in these activities. Including these organisations in the design of the system can be an important step in avoiding the build-neglect-rebuild cycle.

Water quality measurements indicate extensive fecal contamination in both groundwater and surface waters, resulting from poor sanitation. Improving sanitation within the city should be a priority, as these contaminated waters become mobilized during flood events, contributing to the spread of diseases throughout flooded areas.

In the following sections, the recommendations per failure mode will be discussed.

8.1. Vegetation

To manage reed growth, this research recommends to completely excavate the entire plant, including roots. This method reduces regrowth times and increases the dimensional stability and formality of the canals, reducing sedimentation and human interference. If possible, the timing of vegetation management should be just before and during the rainy season, as this is the time during which the drainage system requires an optimal shape to process high amounts of water. Further research is necessary to determine the specific resources required, such as the number of excavators and employees. Additionally, the height of the canals should be monitored while excavating to maintain the same depth.

Drainage systems should be designed in a way that facilitates vegetation management. The presence of running water within the system plays a significant role in avoiding vegetation growth. Drainage network should be designed in a way that facilitates non-stagnant water with a water depth of more than 0.5 meter to be present. This reduces growth speeds of reeds, waterplants and mosquito proliferation. Additionally, space around canals should be reserved to perform maintenance.

Even though more vegetation was observed in unlined canals, advocating for the construction of lined canals solely to avoid vegetation growth goes too far. The presence of running water plays an important role. Additionally, other arguments like costs and environmental aspects would insist on choosing unlined canals over lined canals.

Shifting towards an approach where communities themselves serve as a pivot in the operation and management of water drainage networks can have a positive effect on the state of the drainage canals. Many examples were found where communities themselves remove vegetation in unlined canals. This should be embraced and promoted. Similarly, a system where inhabitants can report when the state of a drainage canal is weak, similar as for waste containers in Beira, could be a viable solution.

8.2. Human interference

To minimize the potential for human interference, constructed canals should be clearly demarcated. Uncertainty about the exact location of a drainage canal can make it more susceptible to human interference. Furthermore, these canals should allow for the addition of new subbranches along their sides and it should be easy to perform maintenance and minor repairs with minimal resources. Possible solutions may include the use of gabions, canals demarcated by poles or locally sourced materials. By clearly indicating the canal locations and necessary dimensions, the responsibility for canal maintenance can also be transferred to the communities.

During operation, illegal constructions should be promptly removed, as it becomes increasingly challenging to do so as time progresses. A priority for this should be the development of a cadastral system that registers the locations of all houses and canals, so that actions can be taken in the case of an illegal construction. Furthermore, canal legitimacy can be enhanced through regular maintenance and excavating the canals.

Besides issues after construction, these unauthorized constructions can also pose challenges during the construction of drainage networks. Once it becomes evident which areas will be utilized in a project, land space should be demarcated as soon as possible. Retention areas are particularly vulnerable for this issue as these require large areas. In Beira, this issue is already impacting current city development plans. Swift land demarcation is essential to prevent the displacement of residents.

Avoiding human interference can also be seen as an opportunity to create space for nature conservation, re-greening and eco-tourism. The Rio Chiveve park in Beira is an excellent example of a multi-purpose retention area where the existing natural drain is rehabilitated while giving space to urban green. It is currently a park with recreational facilities and a sports center.

8.3. Waste

Despite the limited effect of waste on canal performance, the efforts that are currently done on waste management should continue. It improves the overall cleanliness and controls vectors of diseases like mosquitoes and rats. A more comprehensive waste collection service, including access in the smaller streets of the informal neighborhoods, should be in place to process waste in the city.

On the scale of communities, the communities themselves can help in removing waste from smaller drainage canals and connections, as there is a lot of willingness to help and the required resources are little. During these cleanups, hygienic measures should be taken to minimize the transmission of waterborne diseases, including the use of protective clothing and thorough washing of the skin with soap. Besides efforts to remove waste from canals, the influx of waste can be reduced by managing single-use materials and promoting recycling.

During the design of drainage networks, simplification of connecting structures and blocking elements should be considered. This research found that waste, as well as sediments, tend to accumulate in these connecting elements, whereas they are less frequently found in the canal stretches. Reduction of the amount of blocking elements in the network therefore ensures that waste and sedimentation do not accumulate. Choosing trapezoidal over rectangular canals can also have a positive impact on reducing waste accumulation, as these canals maintain higher flow velocities during periods of lower discharge. At locations where essential connections must remain, a strategy should be formulated for the removal of waste and sediments.

8.4. Sedimentation

Similar to the issues regarding waste, reduction of the impact of sedimentation can be achieved in the design of the drainage network. The amount of connecting elements should be reduced, and trapezoidal canals should be preferred over rectangular canals, reducing places where sediments can accumulate. Additionally, common solutions for sedimentation which are applied in reservoir management, include dredging, flushing or management of upslope areas to reduce sediment inflow; these might be interesting viewpoints for the management of sedimentation.

8.5. Underdimensioned structures

Underdimensioned structures should be resolved by increasing knowledge within the sanitation service SASB and raising awareness on the impact of these structures on the performance of drainage canals. As the construction of large structures in canals are usually discussed with the municipality but not with SASB, communication lines between these two governmental institutions should improve to avoid underdimensioned structures in the canals.

In some cases, underdimensioned structures should be demolished and rebuilt. This research can not give an advice on the bridge that has been modeled as the costs of replacement are unknown, but assessments should be made to determine this for similar structures.

8.6. Other failures

For failures categorized as *Other*, it is advisable to set aside budgetary reserves, as these typically involve large repairs of defunct structures, canal sections and control stations. Through the increase of the system's lifespan, annual maintenance costs for this category are likely to increase, although there are currently no specific plans in place to address this. Since the initial costs for lined canals are significantly higher than those for unlined canals, additional budgetary reservations are necessary for these types of canals.

8.7. Residual risk

Even if there would be an improvement of the drainage network, a residual risk would still be present. This risk will only increase in future climate and urbanisation scenarios. An early warning and early action strategy should be in place in the case of a disaster. Therefore, the current efforts of the INGD should be continued and supported in order to prepare for disasters.

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A

Connection types

The types of connections, structures and inlets that are differentiated are presented in table A.1.

Open Pipe Open pipes are pipes that directly connect two canals with each other. The length or width of the pipe is not relevant. There is no designed obstruction in the pipe (picture by author).

Bar Screen Pipe The bar screen pipe is similar to the open pipe, but holds a bar screen that traps solid waste (picture by author).

Open The open connection does not have an upper boundary and is therefore not restrained in vertical sense. Typically, open connections are ditches or open drains that connect without a connecting structure (picture by author).

Gully pot The gully pot is an inlet structure which is typically located on the side of the street. It consists of a water collection box of approximately 50x50 cm. It is closed off by a lid with rectangular holes which filters large solid waste. A pipe approximately 10 centimeters above the bottom allows water to flow out of the gully pot, so that sediments are collected on the bottom of the box (picture by author).

Gully pot, no lid The gully pot without a lid is similar to a gully pot but does not have a lid (picture by author).

Closed Pit Inlet The closed pit inlet consists of a box of approximately 1x1 mtr which collects water through a hole in the side of the pit. It is closed off with a concrete lid which has small holes for inspection. The water exits the pit through a pipe approximately 3 cm above the bottom of the pit (picture by author).

Open Pit Inlet The open pit inlet is similar to a closed pit inlet but does not have a lid (picture by author).

Control Station There are five control stations in the system that can be completely opened or closed using gate doors. Some control stations have a bar screen to collect solid waste. Each control station typically has 4 or 5 doors. One of the control stations is the Palmeiras outlet (picture by author).

Sewer Inlet The sewer inlet is the connection of a part of the underground sewer network to a canal (picture by author).	
Other Other connection types.	

Table A.1: The different types of connections, structures and inlets

B

Stakeholders

This appendix holds the stakeholders that are active in the field of water drainage in Beira. These are presented in the PI grid in Figure 3.5. The stakeholders are sorted on alphabetic order.

AIAS

AIAS is the national organisation responsible for water and sanitation in Mozambique. The organisation is responsible for large-scale drainage projects, like the Phase 1 and Phase 2 projects. It headquarter is located in the capital of Mozambique, Maputo.

AMOR

The organisation AMOR has established a number of public waste collection points, so-called Eco-pontos where citizens can deposit their recyclable waste. AMOR has also introduced innovative waste separation techniques, such as composting and biodegradable waste disposal, to reduce the amount of waste sent to landfills (“Cleaning Day at Maquinino – Beira | AMOR”, n.d.).

Blue Deal

The Unie van Waterschappen (collaboration of Dutch water boards) has started the Blue Deal program in 2018. It has a local delegate in Beira collaborating with SASB. The Blue Deal program is led by Wetterskip Fryslan, the waterboard of the Dutch province Friesland. Currently, a pilot project on tertiary drainage canals in Beira is planned (Berghuis, 2022).

CAM

CAM is an Italian non-governmental consortium that works in Beira. It consists of the NGO’s APIBiMI, ACCRI, Midici Con L’Africa, A Scuola di Solidarieta and MLAL. They perform work in the field of solid waste management and flood mitigation. Their focus is on the informal part of the neighbourhood Macuti. (CAM, 2023).

Through the LimpaMos Moçambique and Rafforzamento Commune di Beira programmes, CAM has achieved strong relationships with the Università di Trento. The combination of both parties often work together and regularly publish scientific documents.

CMB

Conselho Municipal da Beira (CMB) is the municipality of Beira, responsible for the policies in the city. It is known for its marginal budget and deficits, as the city faces many challenges related to flooding, waste and infrastructure.

Deltares

Deltares (a Dutch knowledge institute) has been working together with Dutch and Mozambican actors to develop the Masterplan Beira 2035. In this report from 2014, infrastructural projects on roads and waterways are proposed. For urban drainage, the Masterplan proposes an expansion of the existing drainage system, a comprehensive stormwater management plan and emergency response plans. The Masterplan has resulted in the currently Phase 1 drainage network (Deltares et al., 2013).

After the Masterplan, Deltares has worked on other policy documents like GreenInfra 4 Beira (Letitre et al., 2015), which proposes a variety of nature-based solutions for the city, and a lagoon on the eastern side of the city. In general, Deltares continues to have an important impact on the infrastructural policymaking of the city.

Currently, Deltares is working on the feasibility study on the Phase 2 drainage network. In this, it works in a consortium with CDR International, TPF and Wissing for AIAS (AIAS et al., 2022).

FACE

FACE is a non-profit and non-governmental organisation in Beira which contributes to the implementation of programs and projects in the field of water, sanitation, solid waste management and environmental protection. It was founded in 2015 and supports other organisations in sustainable development (Associação FACE, n.d.).

One of the key initiatives undertaken by FACE is the regular cleaning campaigns of drainage canals in the community. By working closely with local residents and volunteers, the organisation is able to mobilise local communities for these campaigns. In addition to its community work, strong partnerships with international organizations such as NLRC have been established. Through these partnerships, FACE has been able to access valuable resources and expertise to support their programs and initiatives in Beira.

Foreign academia

A number of foreign academia, like Delft University of Technology and Wageningen University, have contributed to the development of knowledge on water drainage in Beira. Delft University of Technology and Wageningen University have done this in collaboration with the Netherlands Red Cross and Witteveen+Bos.

INGD

The INGD is an institute responsible for early warning and early action in response of a disaster (UN Spider, n.d.). The committee overlooks the risk committees present in Beira, which warn inhabitants in the case of an emergency.

Inhabitants of Beira

These are the people that live in Beira and are affected by floodings.

NLRC

The Red Cross/Red Crescent is a global volunteering organisation. Each country has its own local National Society, which has the mandate to operate in that country. The International Federation of Red Cross and Red Crescent Societies (IFRC) oversees all National Societies and provides assistance in emergency situations (IFRC, n.d.-a).

In addition to emergency aid, National Societies collaborate to enhance community resilience and promote localization efforts. The NLRC is actively engaged in the Beira region through the Living with Floods program, aimed at assisting flood-affected urban communities in building their capacity for flood risk awareness and climate adaptive water actions. Furthermore, it supports communities and local actors in developing their ability to prepare for and take anticipatory actions against flood risks. The NLRC collaborates closely with FACE and the local Red Cross Society in this program (NLRC, 2023).

Risk committees

The risk committees are an implementing partner of the INGD and support in case of emergencies. The committees are responsible for communication to inhabitants in the case of an evacuation.

RVO

The RVO is a funding partner of the NLRC, Blue Deal and VNG International. They support these partners in a financial way for their work in Beira.

SASB

SASB is the autonomous sanitation organisation of Beira. After its founding in 2002, its aim is to provide reliable and sustainable sanitation services to the city. It is responsible for the collection, treatment, and disposal of wastewater. The organisation is a part of CMB, the municipality of Beira.

One of the key challenges that SASB faces is the limited financial resources available to invest in new infrastructure and equipment. However, the organisation has been able to secure funding from international organizations such as the World Bank and the African Development Bank to support its operations and improve the sanitation system in Beira (World Bank, 2020).

VNG International

The VNG International is the international department of the association for Dutch municipalities. In Beira, it focuses on improving the cadastral data management in order to clarify land administration and to raise tax revenues. The organisation has a local delegate in Beira since 2017.

World Bank

The World Bank is a partner of AIAS and the municipality of Beira for the funding of projects that relate to water management. It gives loans to these parties for large rehabilitation project, like the Phase 1 and Phase 2 project.

C

Interviews

In this appendix, the interviews that were conducted during the field research are explained. The interviews were done with local inhabitants in Beira and involved the influence of blockage by human interference and the rain and flood impact assessment.

Initial information

Before each interview, the following information is shared with the interviewees:

- This is an investigation of Delft University of Technology on the failure modes in the drainage system in Beira. I will be investigating blockages in the canals due to various reasons, like vegetation, waste and use of the system by end users.
- No personal information will be shared, and the specific locations of blockages will be kept at the neighborhood scale, along with the type of affected canal.

In Portuguese:

- Esta é uma investigação da Universidade de Tecnologia de Delft sobre os modos de falha no sistema de drenagem na Beira. Irei investigar os bloqueios nos canais devido a várias razões, como vegetação, resíduos e utilização do sistema pelos utilizadores finais.
- Nenhuma informação pessoal será partilhada e as localizações específicas dos bloqueios serão mantidas à escala do bairro, juntamente com o tipo de canal afetado.

Questions

The following questions were asked in a semi-structured manner to the interviewees.

- How has the environment in your area changed in recent years?
- Have you noticed any changes in your lifestyle as a result of these environmental changes?
- Can you describe the construction you have made over the drainage canal near your property?
- What was the purpose behind this construction?
- How do you think this construction may affect the performance and functionality of the drainage canals?
- Have you experienced any problems, such as flooding or blockages, in the drainage canals since you made this construction?
- In your opinion, what are the potential risks and consequences associated with constructing over drainage canals?

- Did you seek any professional guidance or obtain permits before making these constructions?
  - If not, why did you choose not to do so?
  - If so, who did you obtain information from and what information did you obtain?
- Have you observed any changes in the water flow or drainage patterns since the construction was made? If yes, how would you describe these changes?
- Are there any measures or improvements you have considered implementing to mitigate the potential negative impacts of the construction on the drainage canals?
- In retrospect, do you think it was a good decision to make the construction over the drainage canals? If given the opportunity, would you have done anything differently?

In Portuguese:

- Como o ambiente na sua área mudou nos últimos anos?
- Você notou alguma mudança no seu estilo de vida como resultado dessas mudanças ambientais?
- Você pode descrever a construção que você fez sobre o canal de drenagem próximo à sua propriedade?
- Qual foi o propósito por trás dessa construção?
- Como você acha que essa construção pode afetar o desempenho e a funcionalidade dos canais de drenagem?
- Você enfrentou algum problema, como inundações ou obstruções, nos canais de drenagem desde que fez essa construção?
- Na sua opinião, quais são os riscos e consequências potenciais associados à construção sobre canais de drenagem?
- Você procurou alguma orientação profissional ou obteve permissões antes de fazer essas construções?
  - Se não, por que optou por não fazer?
  - Se sim, de quem você obteve informações e que informações foram essas?
- Você observou alguma mudança no fluxo de água ou nos padrões de drenagem desde que a construção foi feita? Se sim, como descreveria essas mudanças?
- Existem medidas ou melhorias que você considerou implementar para mitigar os possíveis impactos negativos da construção nos canais de drenagem?
- Olhando para trás, você acha que foi uma boa decisão fazer a construção sobre os canais de drenagem? Se tivesse a oportunidade, teria feito algo de forma diferente?

D

State of the system

Connections, structures and inlets

The results from the quantification of the failure modes in the connections, structures and inlets are presented in Appendix G. The occurrence of the failure types and the average failure percentage per failure type is presented in Table D.1.

Table D.1: Results of the assessment of connections, structures and inlets before the first processing step

Failure mode	Occurrence	Occurrence per 100 connections	Average Failure
Clean	91	354	0%
Unknown	52	202	0%
Sediment	33	128	78%
Sediment + Waste	24	93	68%
Vegetation	20	78	58%
Waste	19	74	23%
Human Interference	5	19	70%
Sediment + Vegetation	4	16	48%
Sediment + Waste + Vegetation	3	12	50%
Sediment + Waste + Other	2	8	50%
Vegetation + Waste	2	8	50%
Sediment + Other	2	8	10%

After splitting the datapoints that have more than one failure type, multiple assessments are performed. The results that are relevant for the research are presented in Section 5.1.1. Additionally, some assessments were done which were not directly relevant for the research; these are presented in this appendix.

The first part of the assessment comprehends the relations with the failure percentage. Firstly, it shows the overall distribution of the failure percentages (Figure D.1). Secondly, it displays the relation between the failure percentage and canals which are connected to the connection (Figure D.2).

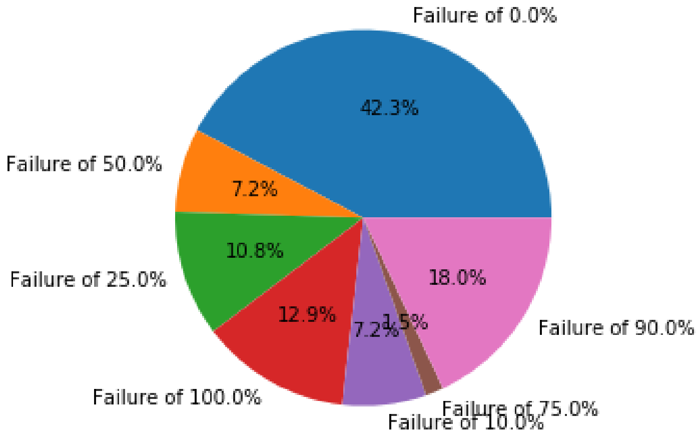


Figure D.1: Distribution of failure percentages in connections

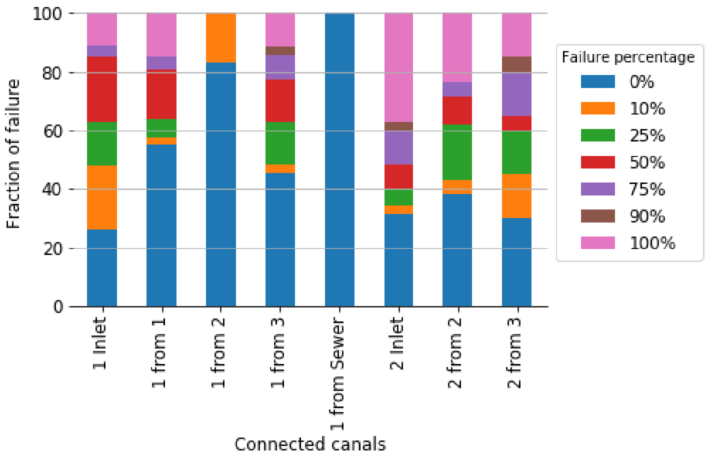


Figure D.2: Failure percentages versus connected canals in connections

Relation with remote sensing factors

An analysis has been performed where the failure modes are compared to remote sensing factors. The factors that were gathered are the NDBI and NDWI. The NDBI is a degree of build-up area dn the NDWI is a degree of the presence of water (Zheng et al., 2021). These are calculated using the Sentinel-2 dataset (Copernicus Sentinel data, 2023) and the following formulas, where the bands refer to specific bands in the Sentinel-2 dataset.

$$NDBI = \frac{Band8 - Band11}{Band8 + Band11} \tag{D.1}$$

$$NDWI = \frac{Band3 - Band8}{Band3 + Band8} \tag{D.2}$$

The NDWI and NDBI are sampled on the locations of the measurements of connections, structures and inlets. These are compared wit

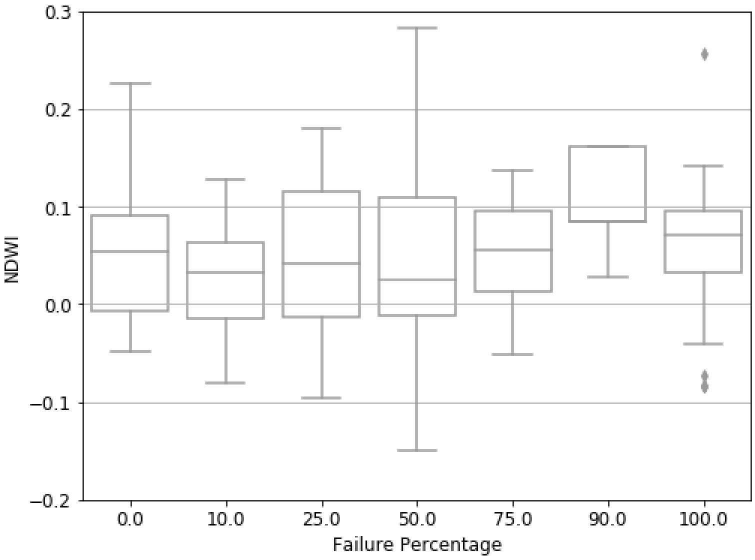


Figure D.3: Boxplot of the failure percentage versus the NDWI in connections

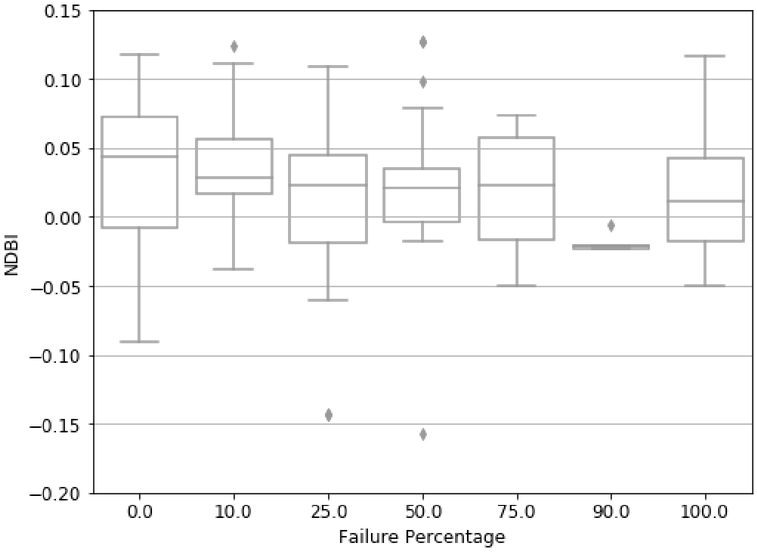


Figure D.4: Boxplot of the failure percentage versus the NDBI in connections

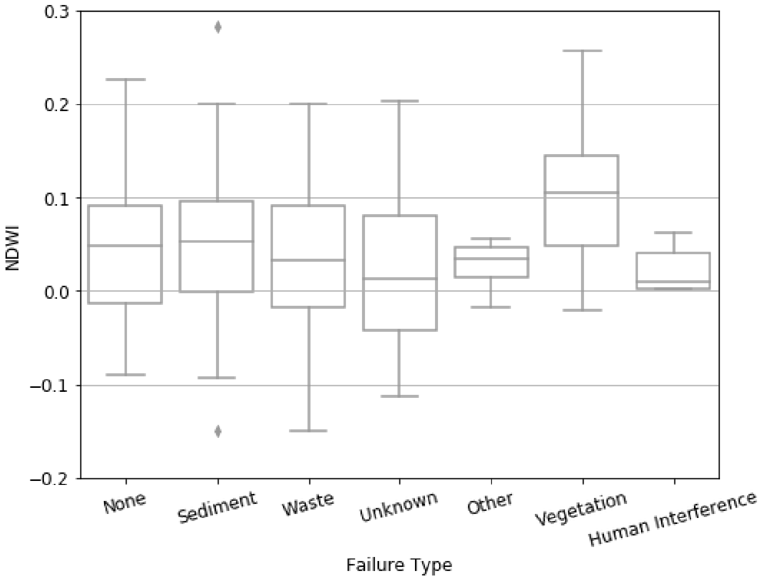


Figure D.5: Boxplot of the failure type versus the NDWI in connections

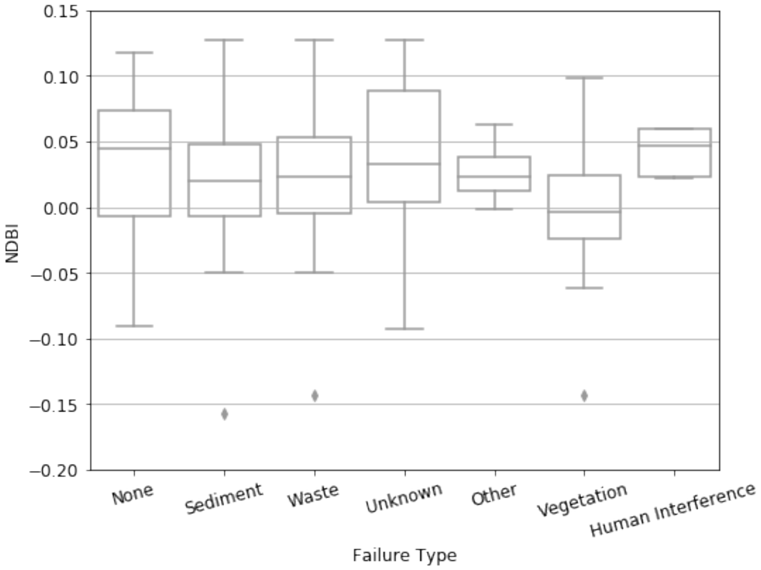


Figure D.6: Boxplot of the failure type versus the NDBI in connections

Canal stretches

Similarly, the results from the quantification of the failure modes in the canals are presented in Appendix G. The occurrence of the failure types and the average failure percentage per failure type is presented in Table D.2.

The same analysis are performed as for the connections, after splitting the datapoints. The results that are relevant for the research are presented in Section 5.1.1. The additional analysis are presented in this section.

The first part of the assessment comprehends the relations with the failure percentage. Firstly, it shows the overall distribution of the failure percentages (Figure D.7). Secondly, it displays the relation between the failure percentage and canal order (Figure D.8). Lastly, it represents the relatio between the failure percentage and the lined and unlined property of the canal (Figure D.9).

Table D.2: Results of the assessment of canal stretches before the first processing step

Failure mode	**Occurrence** (in meters)	**Occurrence per kilometer** (in meters)	**Average Failure**
Vegetation	10876	423	42%
None	6611	257	0%
Sediment	2624	102	21%
Unknown	1664	65	0%
Sediment + Vegetation	1583	62	48%
Sediment + Human Interference	770	30	55%
Human Interference	653	25	91%
Vegetation + Waste	302	12	37%
Sediment + Waste + Vegetation	243	9	50%
Vegetation + Human Interference	182	7	75%
Waste	98	4	50%
Other	61	2	50%
Sediment + Waste	37	1	50%

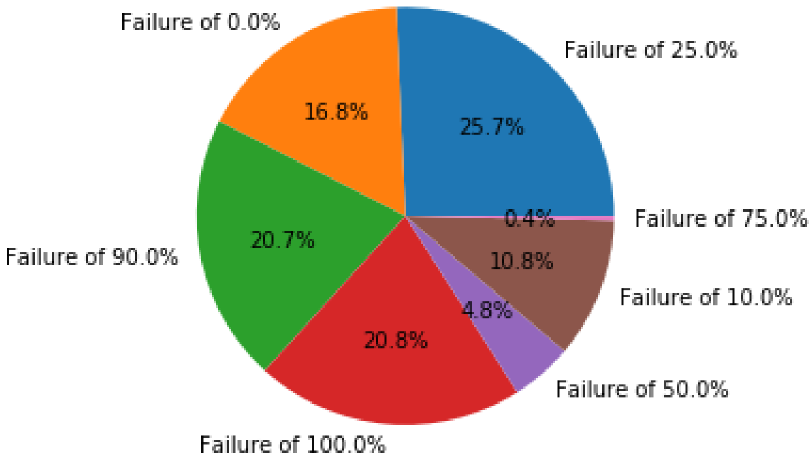


Figure D.7: Distribution of failure percentages in canals

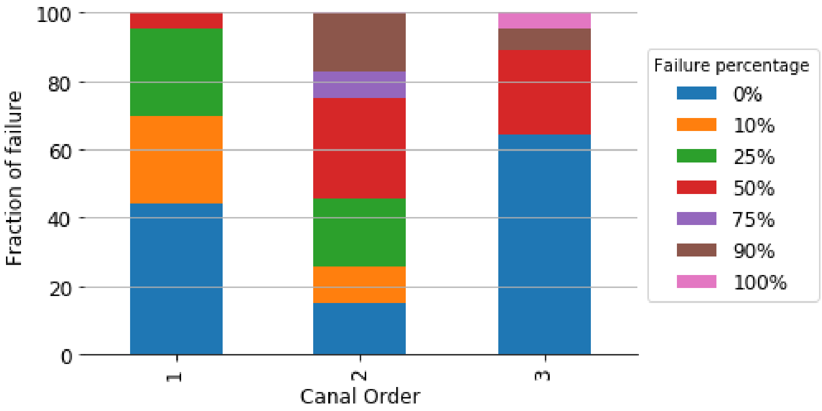


Figure D.8: Failure percentages versus canal order

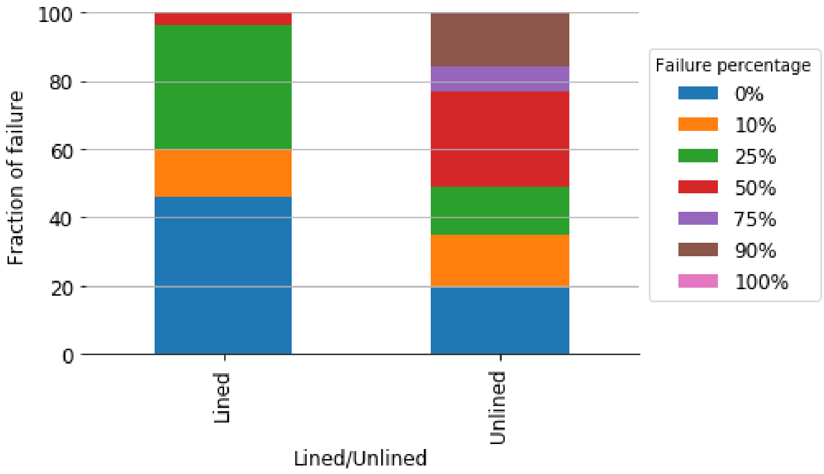


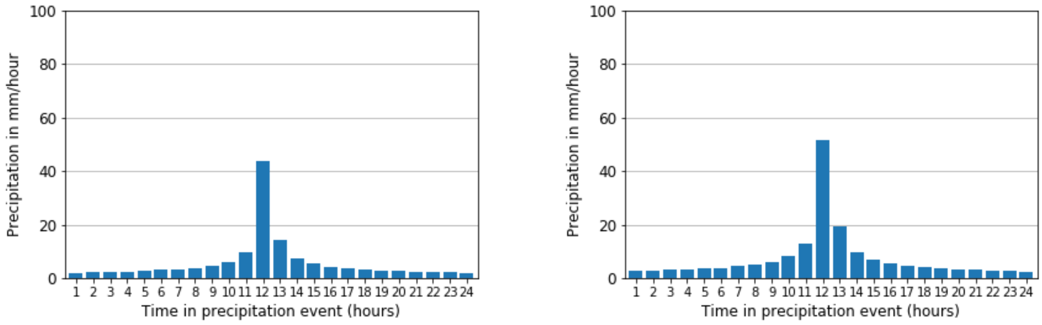
Figure D.9: Failure percentages versus lined and unlined property of canals

E

Input parameters for D-FLOW FM 1D2D

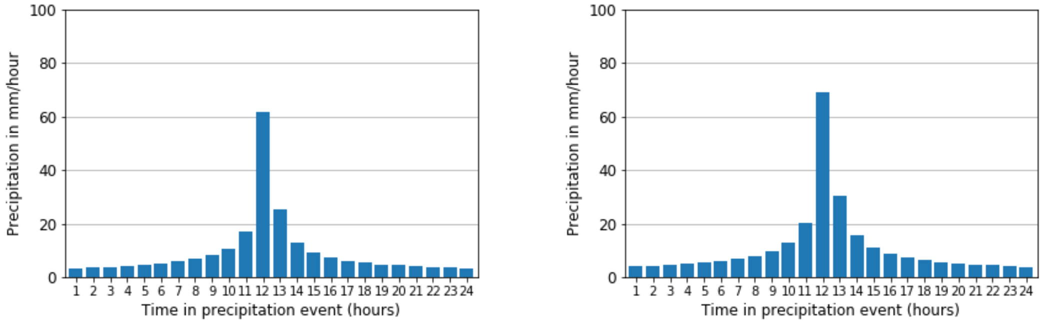
Precipitation events

A total of eight precipitation events are indentified. These precipitation events have a return period of respectively 1, 2, 5, 10, 20, 25, 50 and 100 years. The precipitation events are derived from AIAS et al., 2022 and are presented in figure E.1.



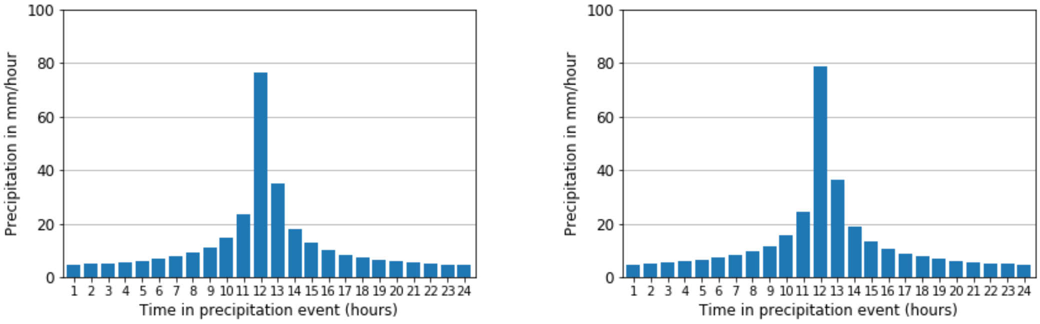
(a) Return period of 1 year.

(b) Return period of 2 years.



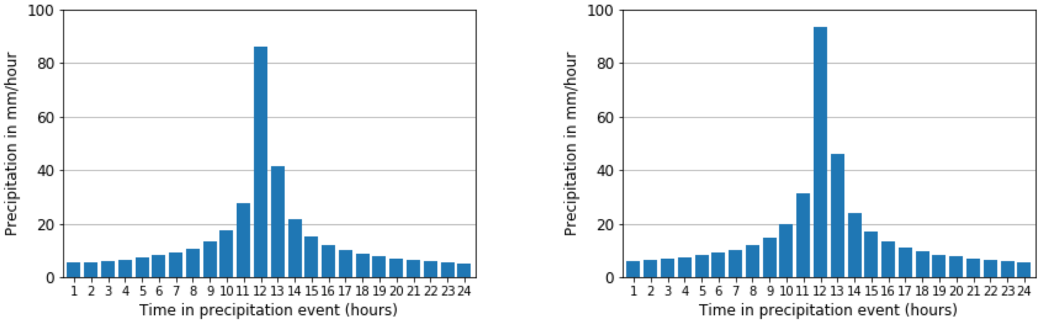
(c) Return period of 5 years.

(d) Return period of 10 years.



(e) Return period of 20 years.

(f) Return period of 25 years.



(g) Return period of 50 years.

(h) Return period of 100 years.

Figure E.1: Precipitation events with the corresponding return periods

Scenario 1: vegetation in canals

This section describes the canals that are affected by vegetation. A map of the locations of the canals that have some degree of vegetation and the associated degree of failure is presented in figure E.2.

Figure E.2: Locations of the cross-sections that are affected by vegetation

Scenario 2: Sedimentation

In the sedimentation scenario, 12 cross-sections are modified to incorporate sedimentation in the model. The locations of the cross-sections and the cross-sections for both the designed and measured situations are presented below:

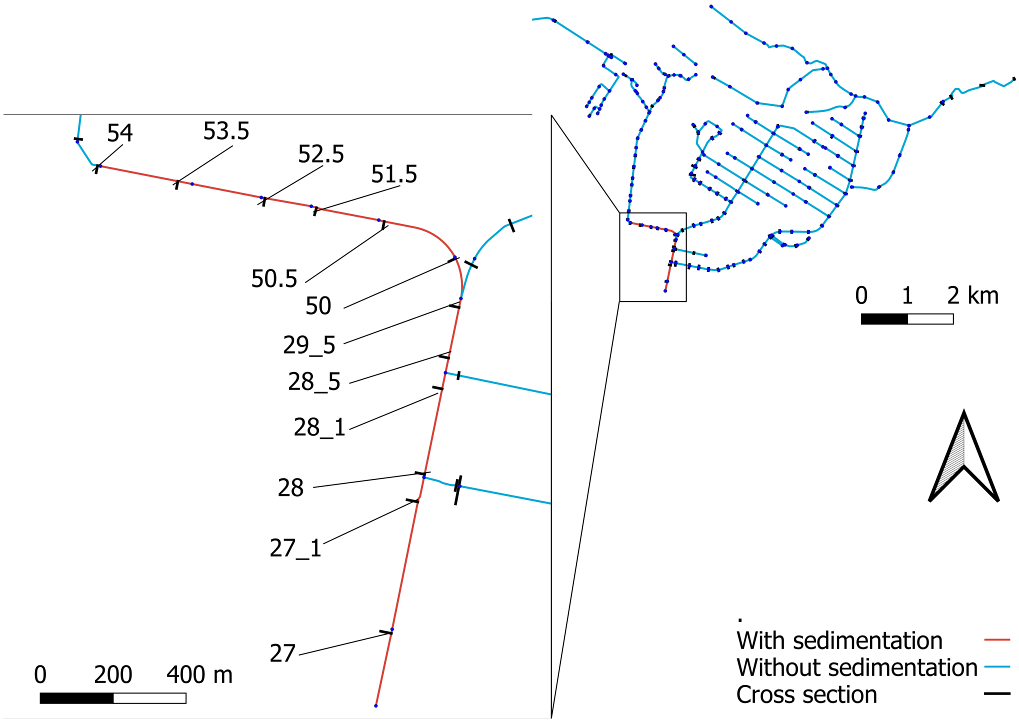
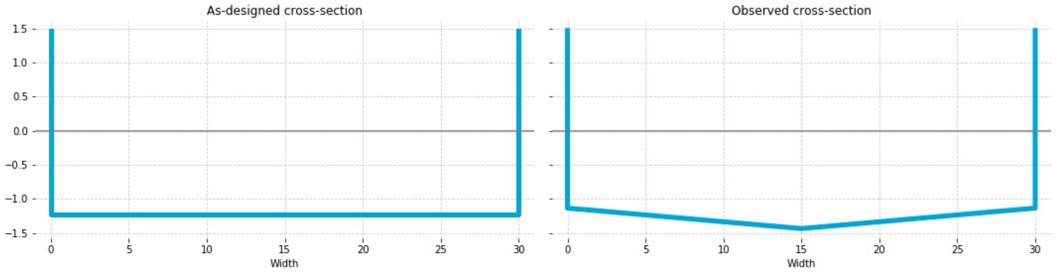
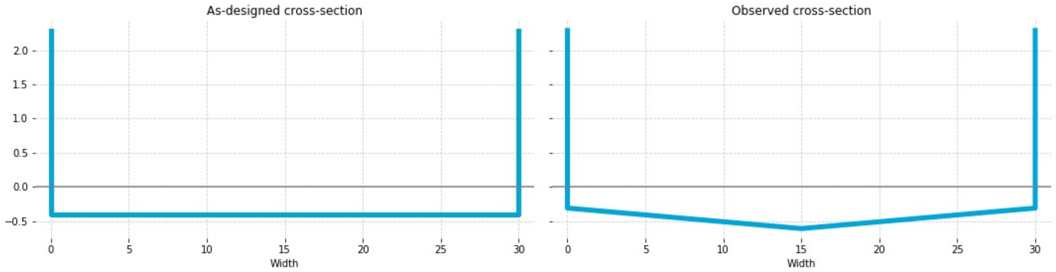


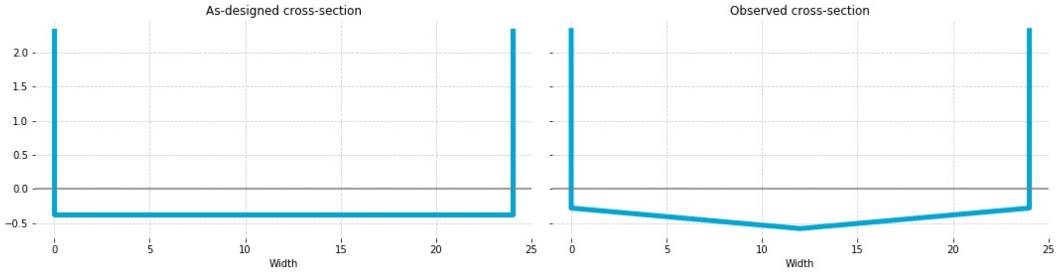
Figure E.3: Locations of the cross-sections that are affected by sedimentation



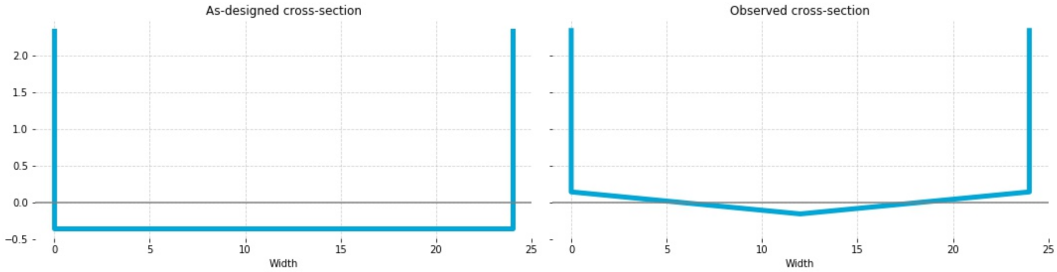
(a) Cross-section canal 27



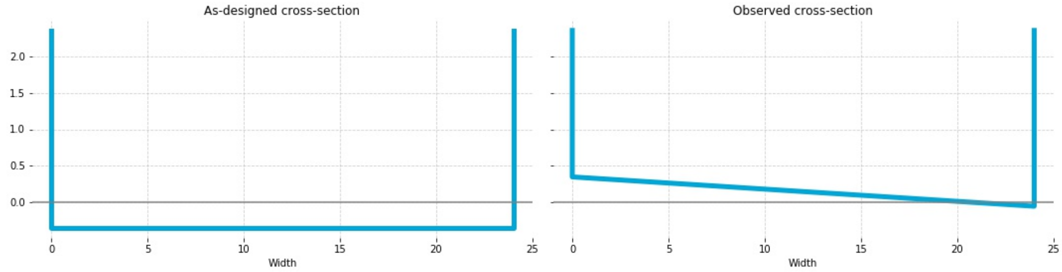
(b) Cross-section canal 27_1



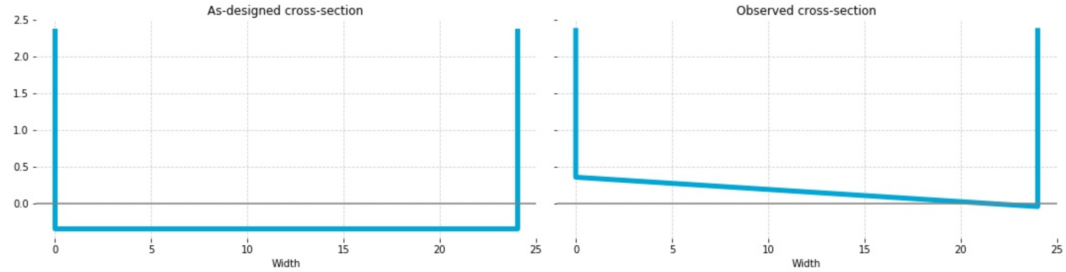
(c) Cross-section canal 28



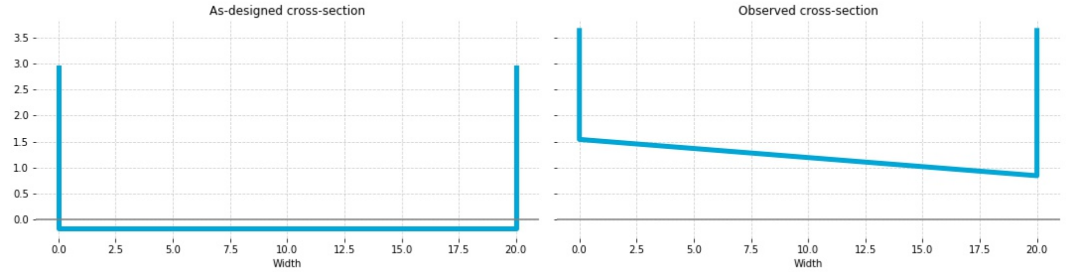
(d) Cross-section canal 28_1



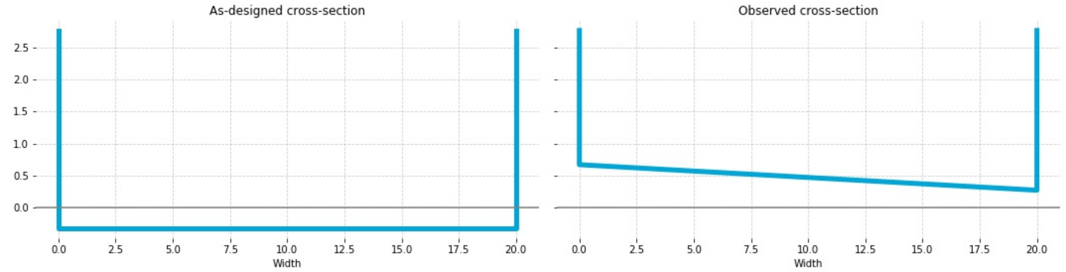
(e) Cross-section canal 28_5



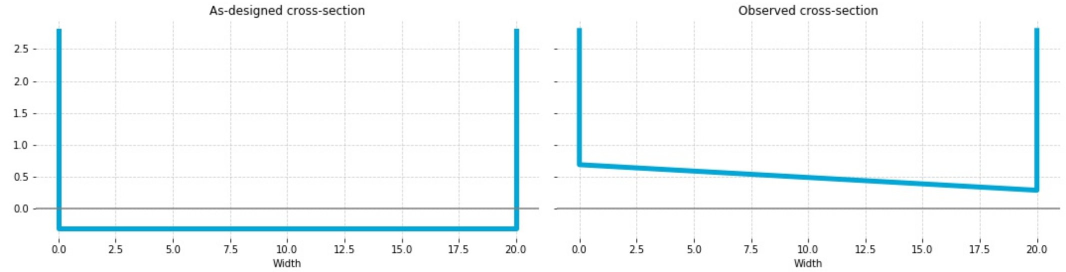
(f) Cross-section canal 29_5



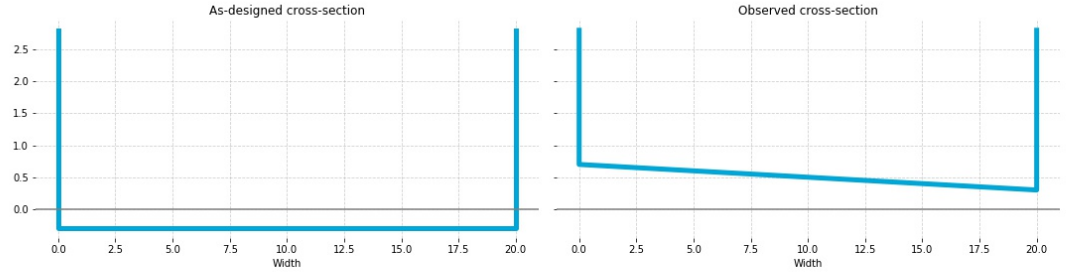
(g) Cross-section canal 50



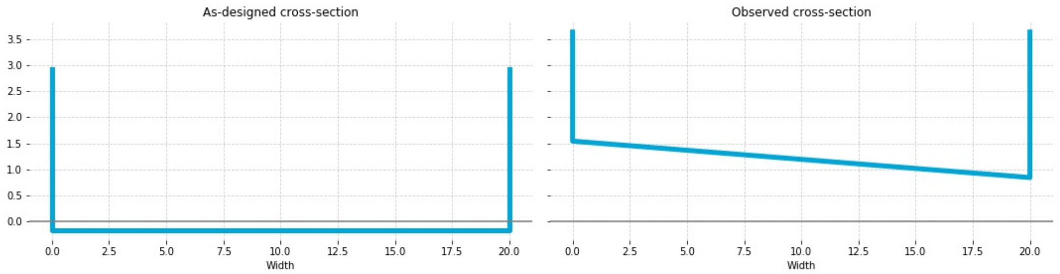
(h) Cross-section canal 50.5



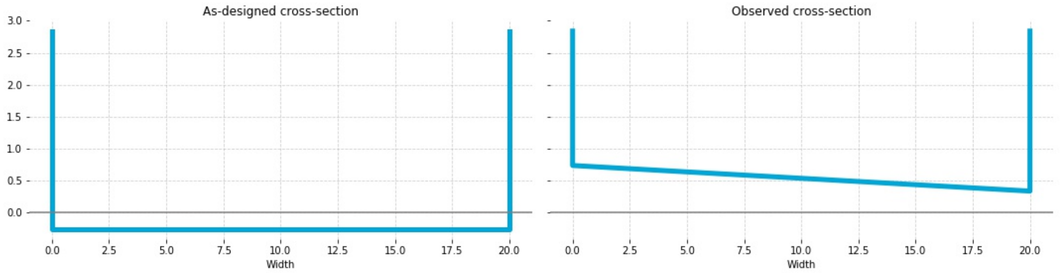
(i) Cross-section canal 51.5



(j) Cross-section canal 52.5



(k) Cross-section canal 53.5



(l) Cross-section canal 54

Figure E.4: Changes made to the cross-sections of the canals caused by sedimentation

Scenario 3: Human Interference

In the human interference scenario, 3 cross-sections are modified to incorporate human interference in the model. The locations of the cross-sections and the cross-sections for both the designed and measured situations are presented below:

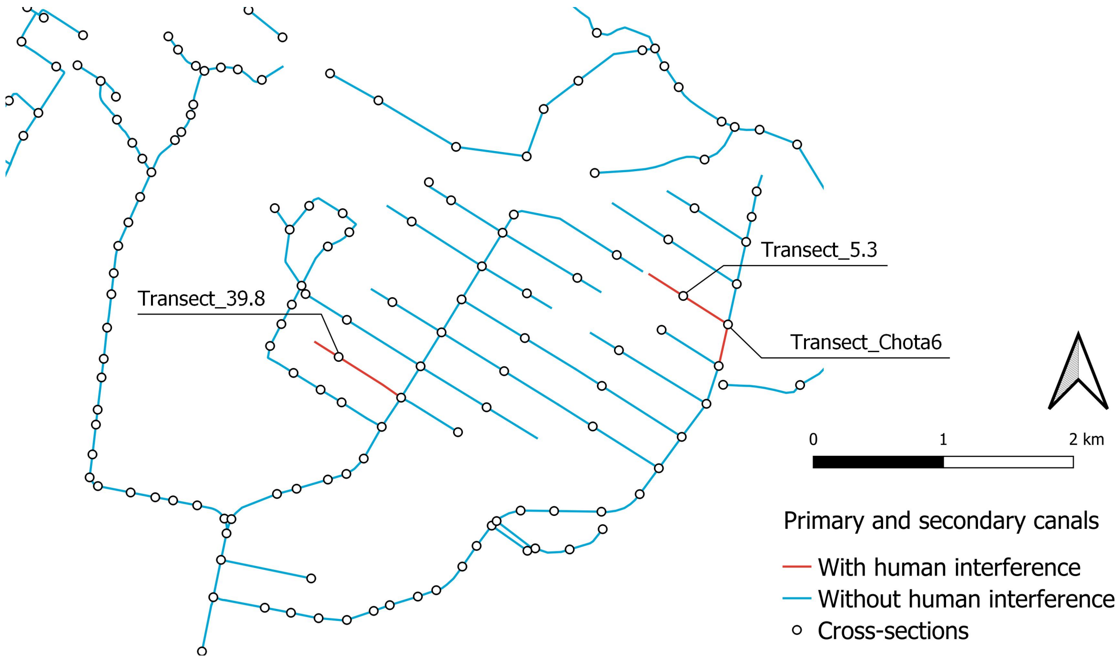
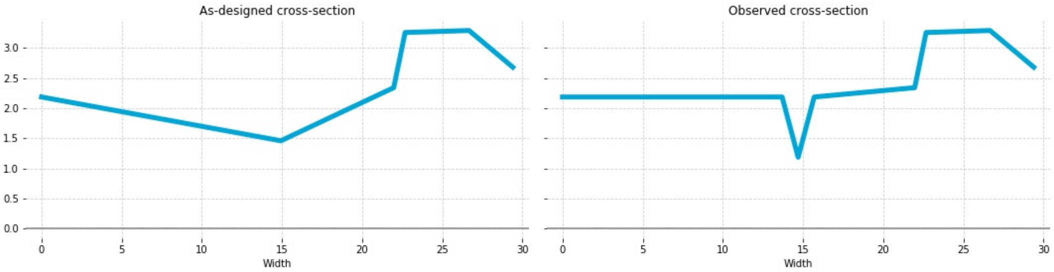
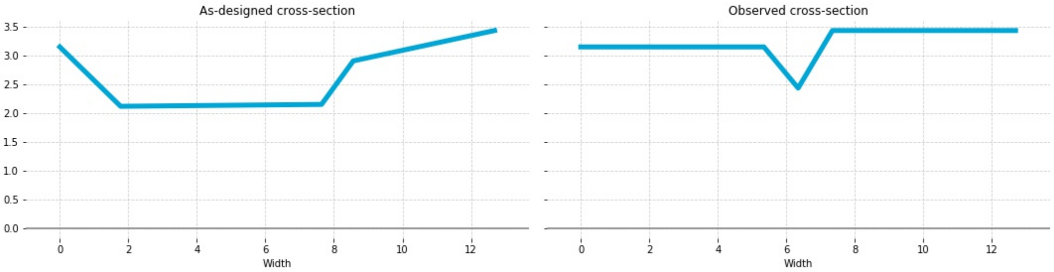


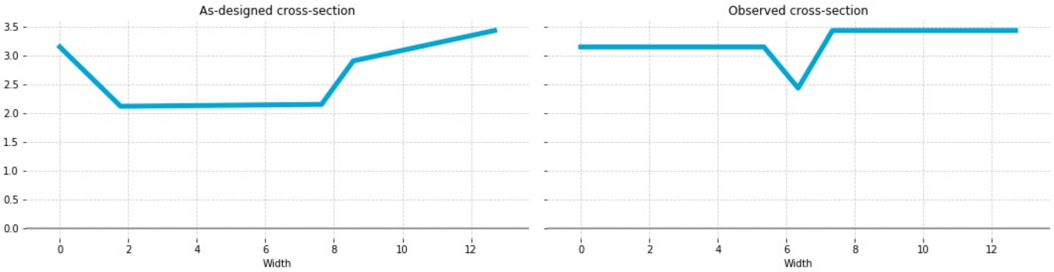
Figure E.5: Canals that are affected by human interference



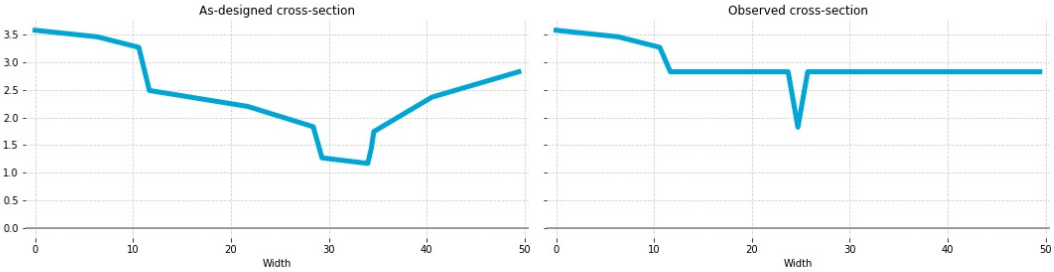
(a) Cross-section canal 27



(b) Cross-section canal 27_1



(c) Cross-section canal 27_1



(d) Cross-section canal 27_1

Figure E.6: Changes made to the cross-sections of the canals caused by human interference

F

Results from D-FLOW FM 1D2D

This appendix chapter holds all results of the hydraulic modeling in D-FLOW FM 1D2D. Table F.1 shows what results are presented in which figures.

Table F.1: Location of results for each failure mode

Scenario	**Figure Number**
Base scenario	F.1
Scenario 1: Impact of vegetation and waste in canals	F.2
Scenario 2: Impact of sedimentation in canals	F.3
Scenario 3: Impact of human interference in canals	F.4
- In the southern Chota neighbourhood	F.5
- In the northern Chota neighbourhood	F.6
Scenario 4: Impact of design issues in canals	F.7
- In the southern Chota neighbourhood	F.8
Scenario 5: Impact of waste in the Palmeiras outlet	F.9
Scenario 6: Impact of blockage of the connections	F.10

Base scenario

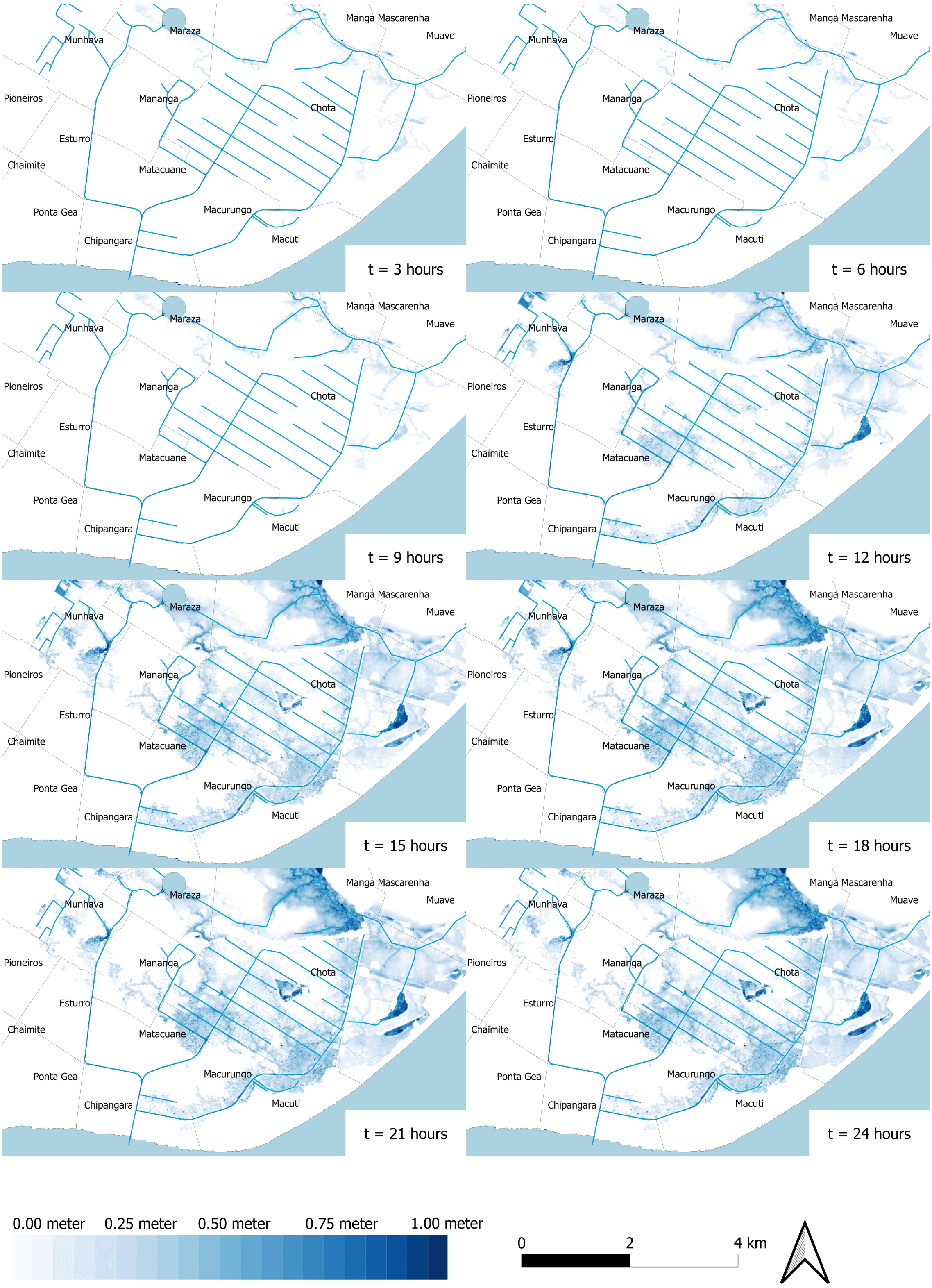


Figure F.1: Inundation depths in base scenario under precipitation event occurring once per 10 years

Scenario 1: Impact of vegetation and waste in canals

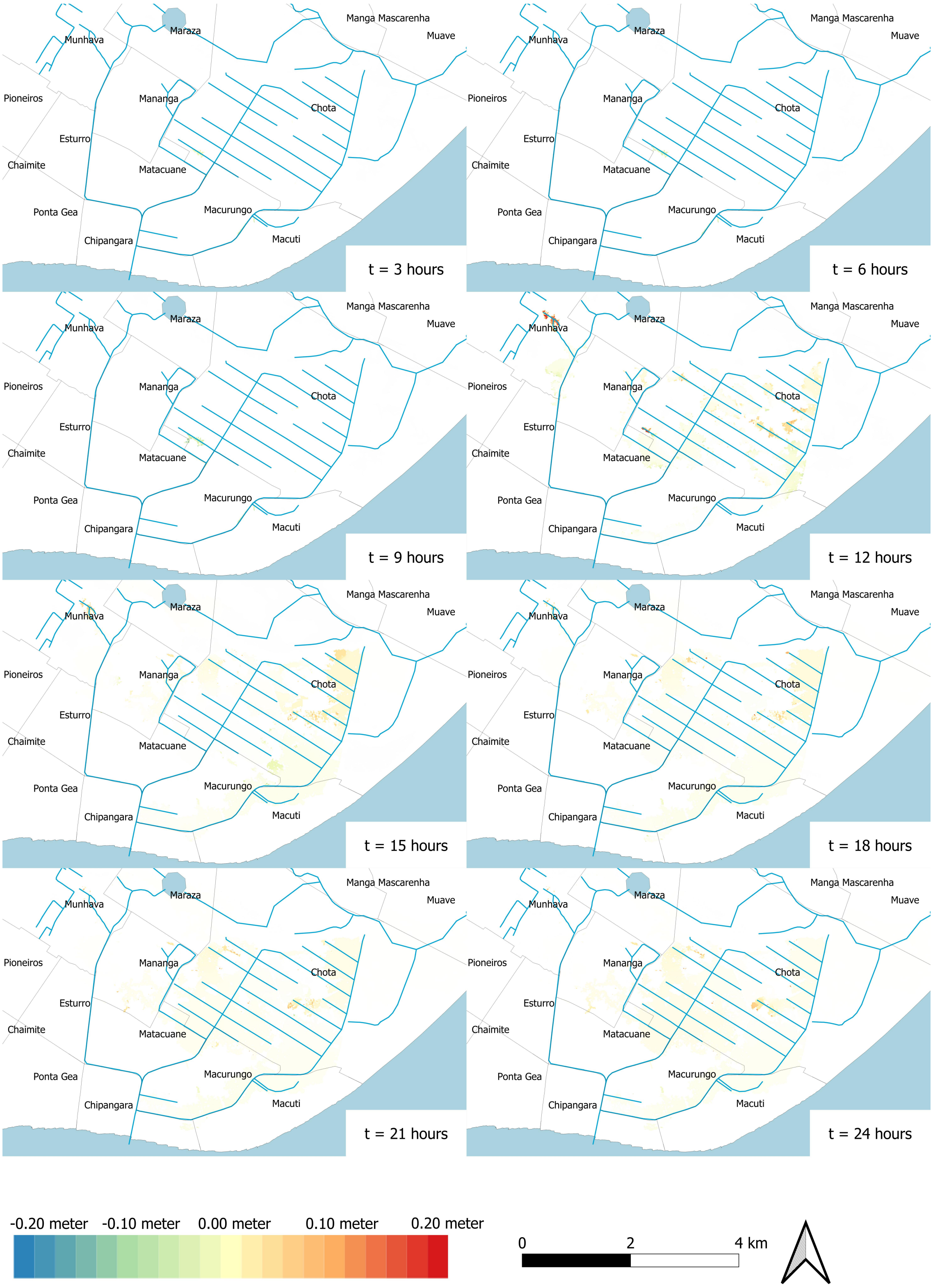


Figure F.2: Inundation depth increases in scenario 1: impact of vegetation and waste in canals under precipitation event occurring once per 10 years

Scenario 2: Impact of sedimentation in canals

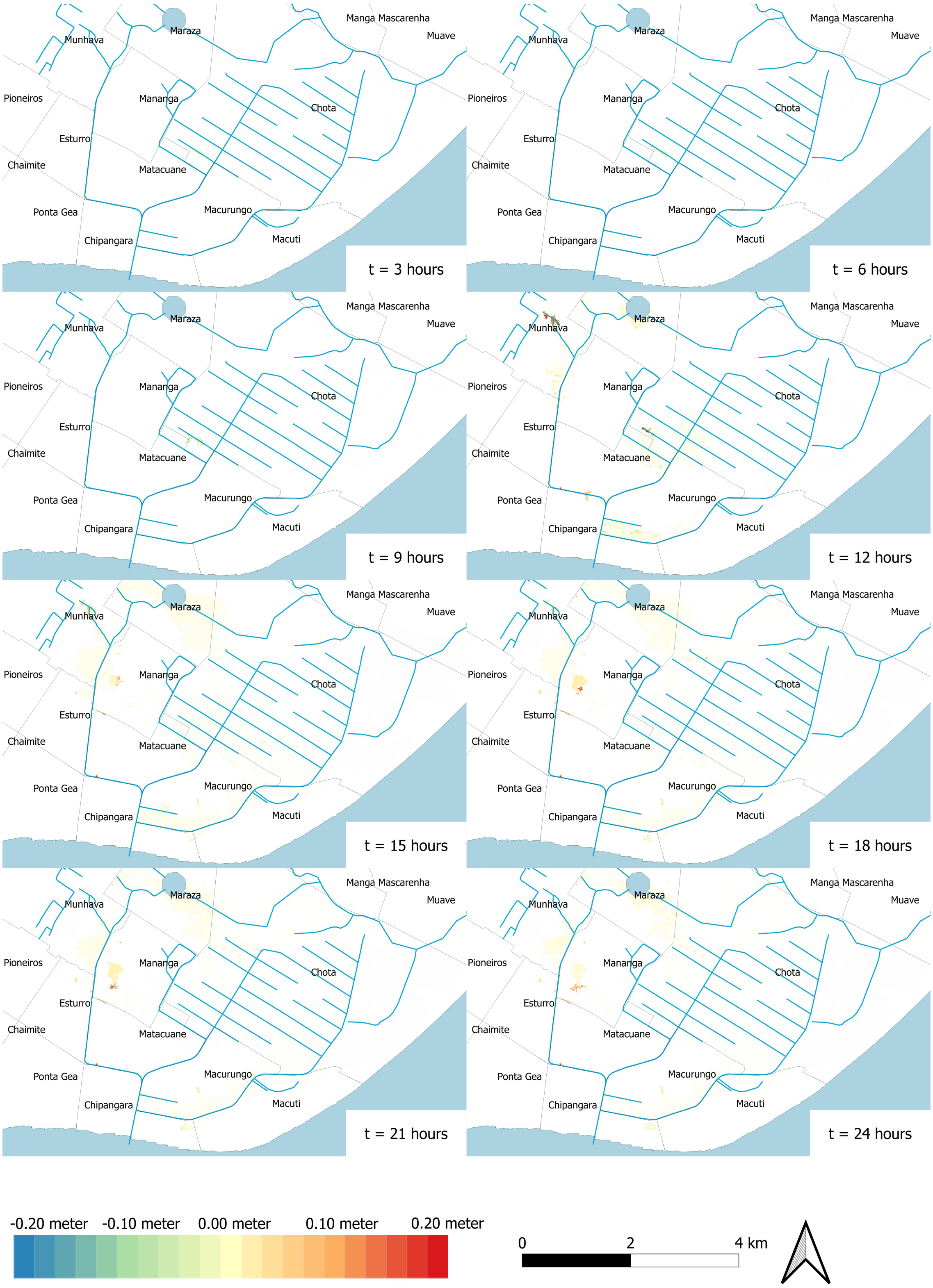


Figure F.3: Inundation depth increases in scenario 2: impact of sedimentation in canals under precipitation event occurring once per 10 years

Scenario 3: Impact of human interference in canals

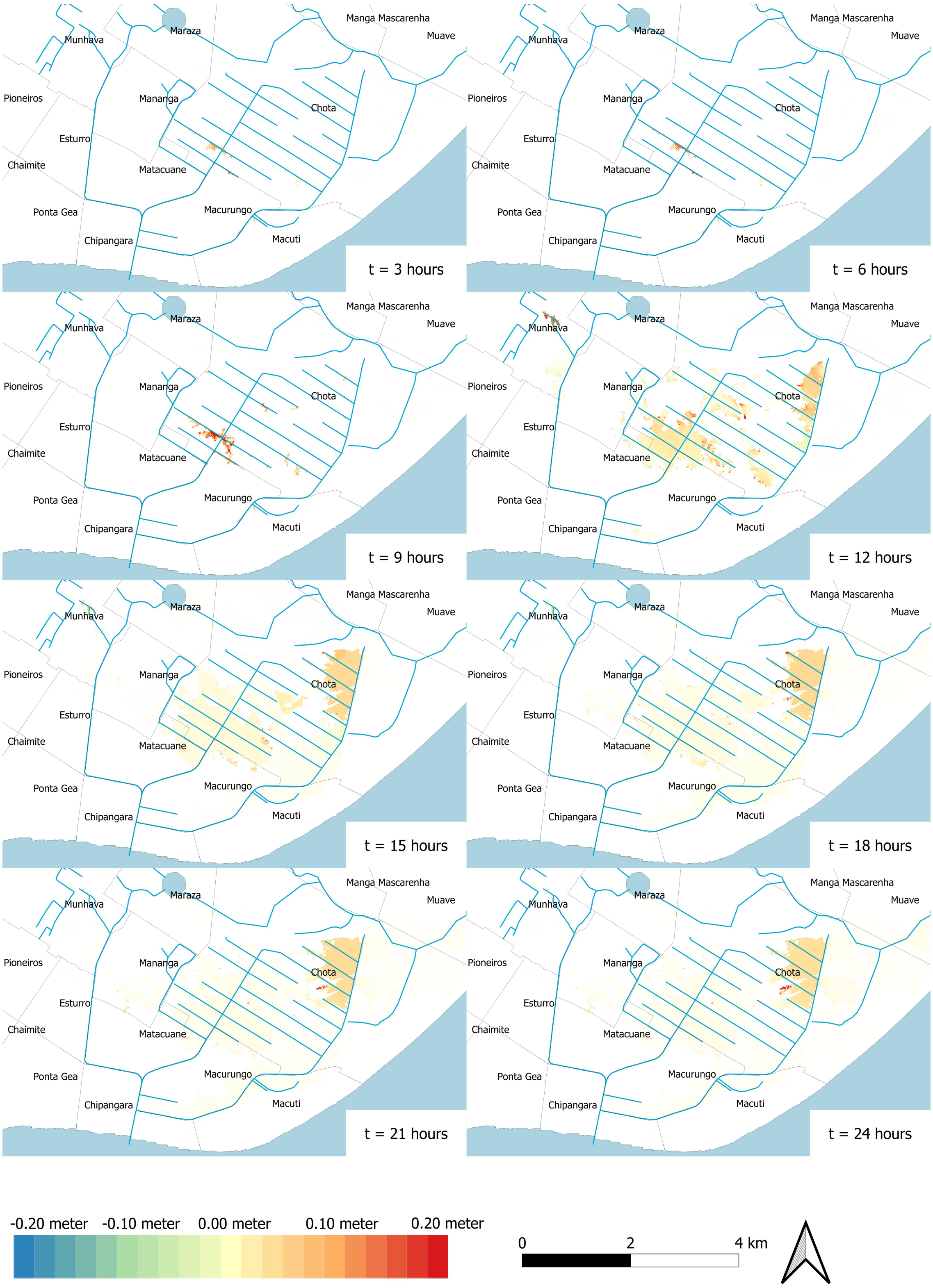


Figure F.4: Inundation depth increases in scenario 3: impact of human interference in canals under precipitation event occurring once per 10 years

Figure F.5: Inundation depth increases in scenario 3: impact of human interference in canals under precipitation event occurring once per 10 years, in the southern part of Chota

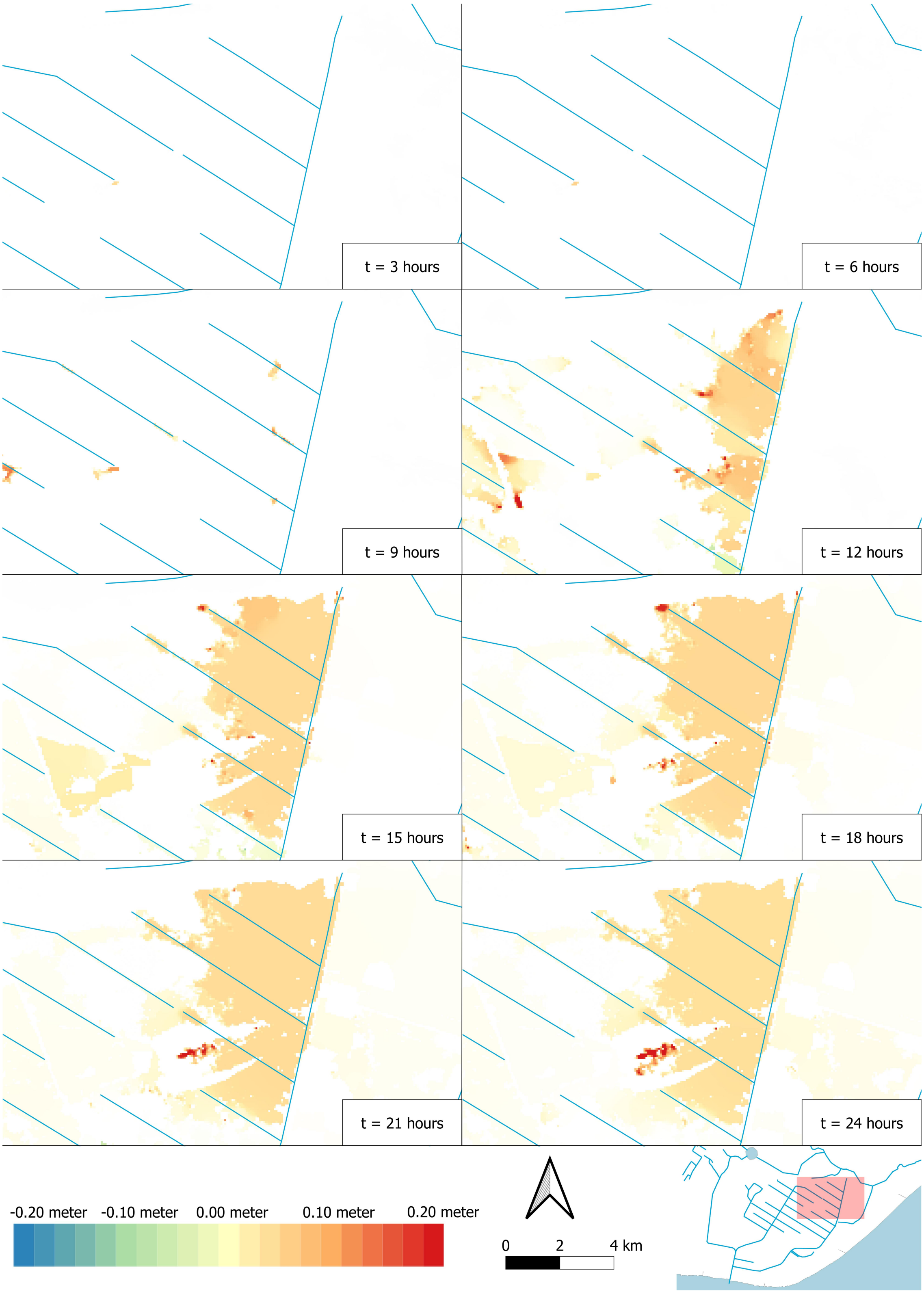


Figure F.6: Inundation depth increases in scenario 3: impact of human interference in canals under precipitation event occurring once per 10 years, in the northern part of Chota

Scenario 4: Impact of design issues in canals

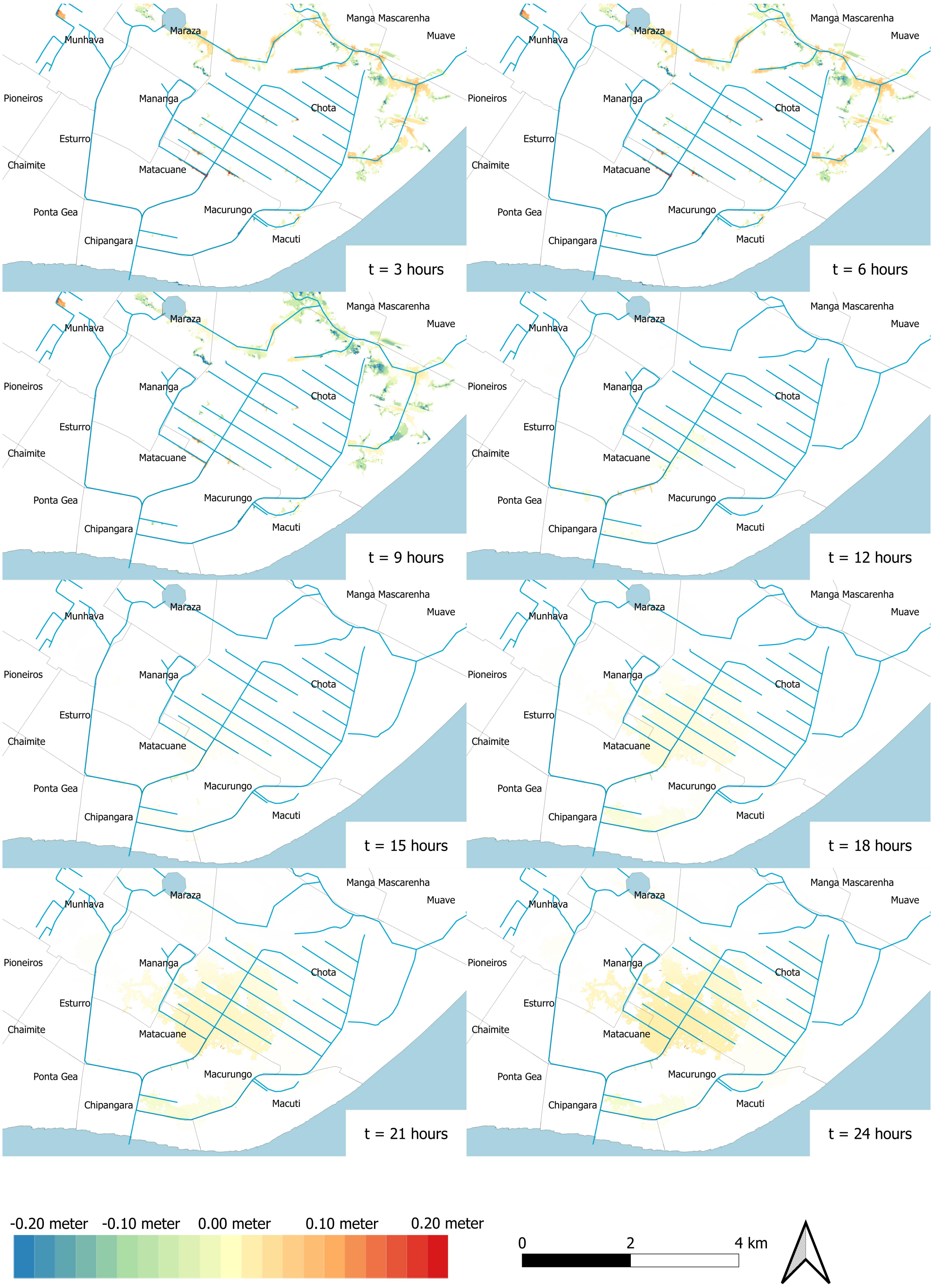


Figure F.7: Inundation depth increases in scenario 4: impact of design issues in canals under precipitation event occurring once per 10 years

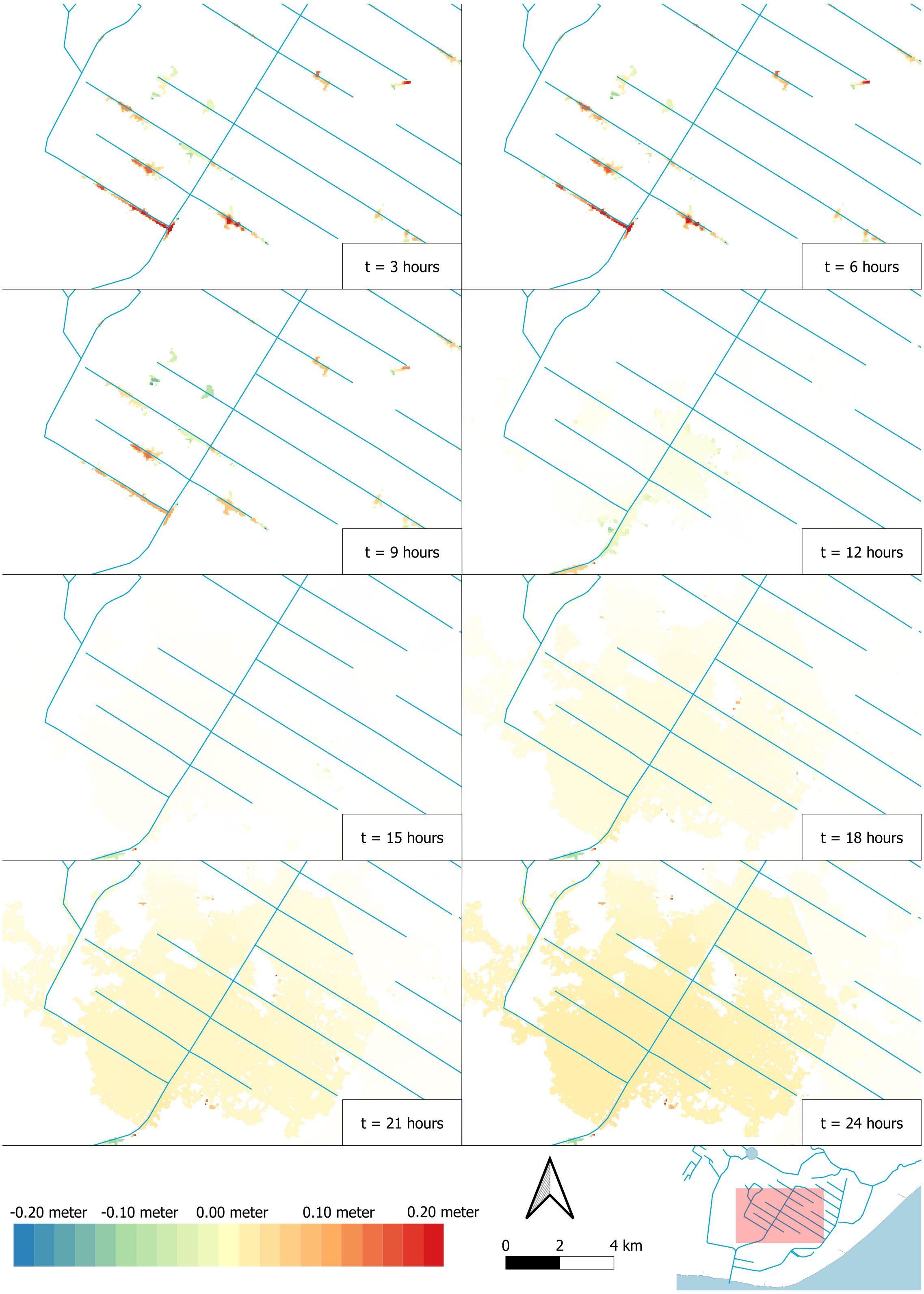


Figure F.8: Inundation depth increases in scenario 4: impact of design issues in canals under precipitation event occurring once per 10 years, in the southern part of Chota

Scenario 5: Impact of waste in the Palmeiras outlet

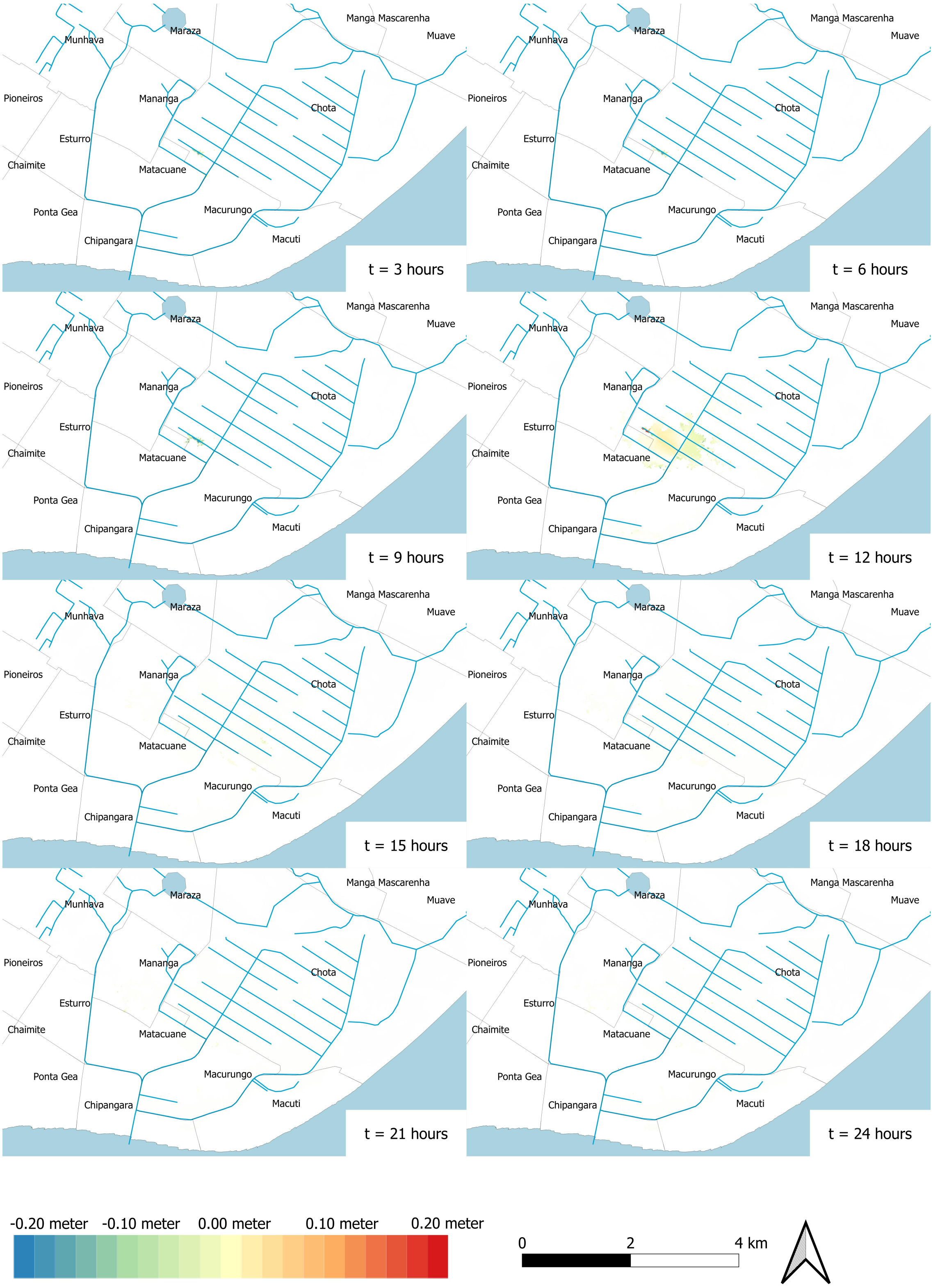


Figure F.9: Inundation depth increases in scenario 5: impact of waste in the Palmeiras outlet under precipitation event occurring once per 10 years

Scenario 6: Impact of blockage of the connections

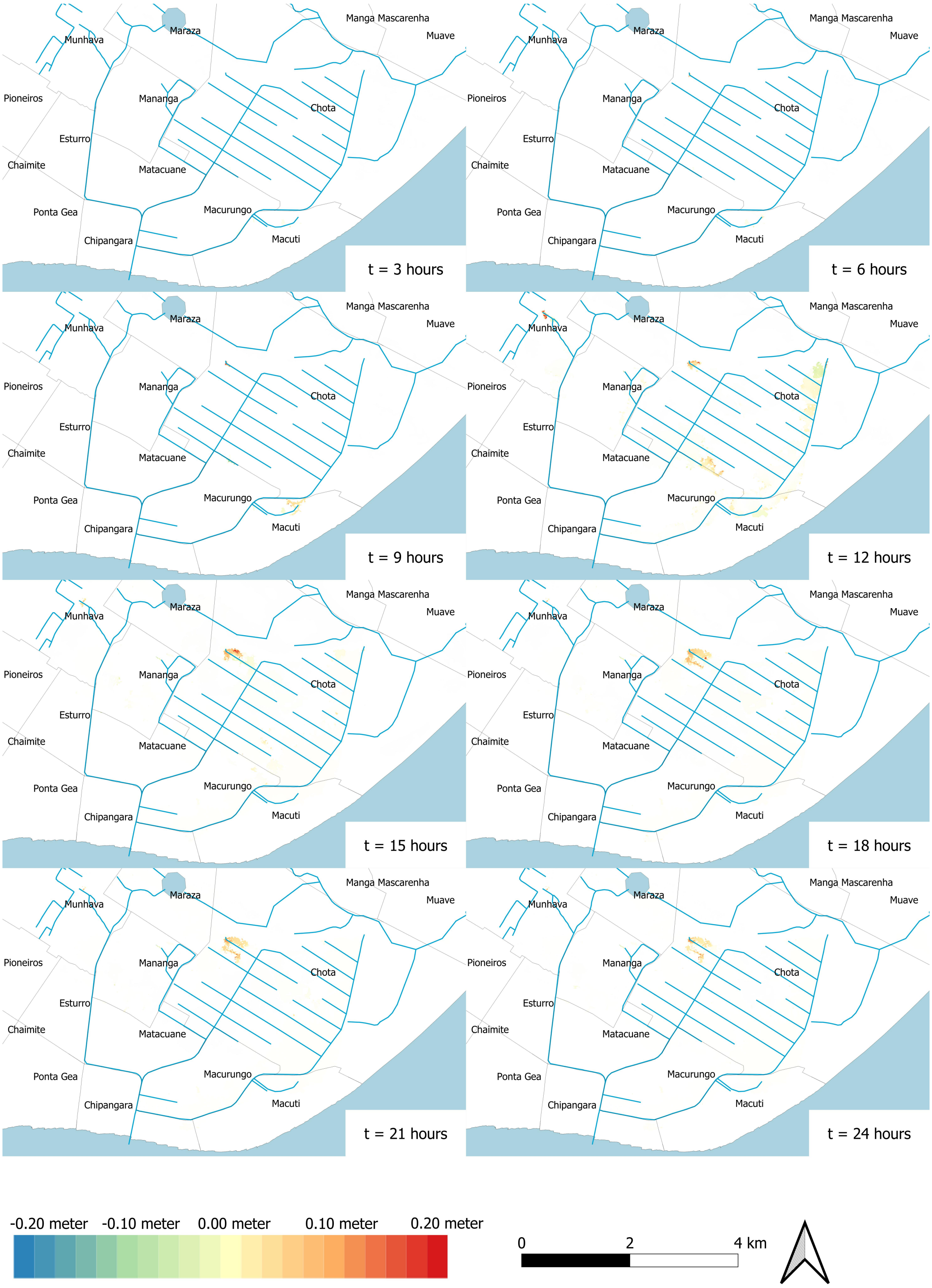


Figure F.10: Inundation depth increases in scenario 6: impact of blockage of the connections under precipitation event occurring once per 10 years

G

Raw data for the state of the system

Assessed connections

This section holds the results of the state of the connections that are assessed. Table G.1 presents these results, with:

- **ID:** An identificator for the datapoint. The first datapoint has an *ID* value of '1', the second datapoint '2', et cetera.
- **Type:** The type of the connection, structure or inlet, as described in table A.1.
- **Canal Type:** The type of the canals that are connected to the one-dimensional point. Can be either *Primary*, *Secondary*, *Tertiary* or *Inlet*. The highest-order canal is noted firstly and the lowest-order canal secondly, with a '-' between the two. For example, a connection between a primary and secondary canal is documented as *Secondary - Primary*.
- **Failtype:** The type of blockage or failure mode in the point. Can be one of the failure modes as defined in section 2.2. Additionally, a point without a failure is noted as *None*. If the failure mode is unknown, *Unknown* is written down in this point. This can also be a combination of multiple failure modes.
- **Fail%:** The percentage of blockage in the connection. Is estimated as the fraction of the available flow area that is blocked. Can be either *0%* (if *Blocktype* is *None*), *10%*, *25%*, *50%*, *75%* or *100%*.
- **Comments:** Comments on the connection that is relevant for qualitative analysis, e.g. the presence of a construction causing a blockage or a person that does regular cleaning of the point.
- **Longitude:** The geographical longitude of the point, in the Coordinate Reference System (CRS) EPSG:2736 (Tete / UTM zone 36S).
- **Latitude:** The geographical latitude of the point, in the CRS EPSG:2736 (Tete / UTM zone 36S).
- **Source:** RAMBLR and Google Photos is used to store the photos that are made. In this attribute, the storage location is defined.
- **Date:** This attribute holds the date of the visit to the point.

Table G.1: Results of the assessment of the connections, structures and inlets

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
1	Open Pit Inlet	Tertiary to Primary	None		695237	7804475	14-6-2023
2	Open Pipe	Tertiary to Primary	Sediment	50	695271	7804627	14-6-2023
3	Open Pit Inlet	Inlet to Primary	None	0	695285	7804680	14-6-2023
4	Sewer Inlet	Sewer to Primary	None	0	695293	7804710	14-6-2023
5	Open Pit Inlet	Tertiary to Primary	None	0	695316	7804784	14-6-2023
6	Open Pipe	Tertiary to Primary	None	0	695346	7804944	14-6-2023
7	Open Pipe	Tertiary to Primary	Sediment	50	695353	7804976	14-6-2023
8	Open Pipe	Tertiary to Primary	None	0	695365	7805039	14-6-2023
9	Open Pit Inlet	Tertiary to Primary	Sediment + Waste	50	695377	7805089	14-6-2023
10	Open Pipe	Tertiary to Primary	Sediment + Waste	75	695395	7805186	14-6-2023
11	Open Pipe	Tertiary to Primary	Sediment + Waste	90	695407	7805225	14-6-2023
12	Closed Pit Inlet	Inlet to Primary	None	0	695417	7805295	14-6-2023
13	Open Pipe	Tertiary to Primary	None	0	695385	7805388	14-6-2023
14	Closed Pit Inlet	Tertiary to Primary	Sediment + Waste	50	695261	7805456	14-6-2023
15	Open Pipe	Tertiary to Primary	None	0	695209	7805463	14-6-2023
16	Bar Screen Pipe	Tertiary to Primary	Waste	25	695085	7805488	14-6-2023
17	Bar Screen Pipe	Tertiary to Primary	Waste	25	695082	7805489	14-6-2023
18	Open Pit Inlet	Inlet to Primary	None	0	694975	7805511	14-6-2023
19	Closed Pit Inlet	Tertiary to Primary	None	0	694864	7805529	14-6-2023
20	Gully pot	Inlet to Primary	Unknown		694857	7805530	14-6-2023
21	Closed Pit Inlet	Tertiary to Primary	Unknown		694792	7805541	14-6-2023
22	Closed Pit Inlet	Inlet to Primary	Unknown		694712	7805555	14-6-2023
23	Closed Pit Inlet	Inlet to Primary	None	0	694654	7805568	14-6-2023
24	Closed Pit Inlet	Inlet to Primary	None	0	694637	7805573	14-6-2023
25	Bar Screen Pipe	Tertiary to Primary	Waste	25	694612	7805582	14-6-2023
26	Closed Pit Inlet	Tertiary to Primary	Sediment	100	694586	7805591	14-6-2023
27	Closed Pit Inlet	Tertiary to Primary	Sediment + Waste	50	694528	7805598	14-6-2023
28	Open Pit Inlet	Inlet to Primary	Waste	25	694477	7805608	14-6-2023
29	Open Pit Inlet	Inlet to Primary	Sediment + Waste + Other	50	694424	7805621	14-6-2023
30	Sewer Inlet	Sewer to Primary	Unknown		694364	7805697	14-6-2023
31	Sewer Inlet	Sewer to Primary	Unknown		694364	7805701	14-6-2023
32	Gully pot	Inlet to Primary	Sediment	50	694369	7805725	14-6-2023
33	Gully pot	Inlet to Primary	Unknown		694372	7805747	14-6-2023
34	Gully pot	Inlet to Primary	Sediment	50	694375	7805770	14-6-2023
35	Gully pot	Inlet to Primary	Waste	25	694379	7805802	14-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
36	Gullypot, no lid	Inlet to Primary	Sediment	100	694382	7805831	14-6-2023
37	Gully pot	Inlet to Primary	None		694385	7805855	14-6-2023
38	Sewer Inlet	Sewer to Primary	Unknown		694376	7805886	14-6-2023
39	Gully pot	Sewer Inlet	Unknown		694376	7805884	14-6-2023
40	Gully pot	Inlet to Primary	Waste	10	694388	7805902	14-6-2023
41	Gully pot	Inlet to Primary	Unknown		694392	7805932	14-6-2023
42	Gully pot	Inlet to Primary	Unknown		694397	7805956	14-6-2023
43	Gully pot	Inlet to Primary	Unknown		694399	7805980	14-6-2023
44	Gully pot	Inlet to Primary	Sediment + Waste	100	694400	7805987	14-6-2023
45	Gully pot	Inlet to Primary	Sediment + Waste	75	694405	7806025	14-6-2023
46	Gully pot	Inlet to Primary	Unknown		694407	7806058	14-6-2023
47	Gully pot	Inlet to Primary	Unknown		694412	7806079	14-6-2023
48	Gully pot	Inlet to Primary	Unknown		694415	7806097	14-6-2023
49	Sewer Inlet	Sewer to Primary	Unknown		694415	7806107	14-6-2023
50	Sewer Inlet	Sewer to Primary	Unknown		694416	7806108	14-6-2023
51	Sewer Inlet	Sewer to Primary	Unknown		694416	7806110	14-6-2023
52	Gully pot	Inlet to Primary	Unknown		694421	7806147	14-6-2023
53	Gully pot	Inlet to Primary	Unknown		694425	7806177	14-6-2023
54	Sewer Inlet	Sewer to Primary	None	0	694430	7806210	14-6-2023
55	Gully pot	Inlet to Primary	Unknown		694431	7806229	14-6-2023
56	Gully pot	Inlet to Primary	None		694435	7806259	14-6-2023
57	Gully pot	Inlet to Primary	Waste	10	694437	7806283	14-6-2023
58	Gully pot	Inlet to Primary	Waste	25	694441	7806310	14-6-2023
59	Gully pot	Inlet to Primary	Waste	10	694443	7806334	14-6-2023
60	Gully pot	Inlet to Primary	Waste	10	694445	7806351	14-6-2023
61	Gully pot	Inlet to Primary	None		694448	7806378	14-6-2023
62	Gully pot	Inlet to Primary	None		694451	7806404	14-6-2023
63	Gully pot	Inlet to Primary	None		694453	7806429	14-6-2023
64	Sewer Inlet	Sewer to Primary	None	0	694457	7806448	14-6-2023
65	Gully pot	Inlet to Primary	Unknown		694457	7806456	14-6-2023
66	Gullypot, no lid	Inlet to Primary	Sediment	100	694464	7806499	14-6-2023
67	Gully pot	Inlet to Primary	None		694466	7806526	14-6-2023
68	Gully pot	Inlet to Primary	Waste	10	694469	7806549	14-6-2023
69	Gully pot	Inlet to Primary	Sediment + Waste	25	694472	7806578	14-6-2023
70	Gully pot	Inlet to Primary	Unknown		694475	7806602	14-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
71	Gully pot	Inlet to Primary	Sediment + Waste		694475	7806645	14-6-2023
72	Gully pot	Inlet to Primary	None	0	694482	7806676	14-6-2023
73	Gully pot	Inlet to Primary	Unknown		694487	7806699	14-6-2023
74	Gully pot	Inlet to Primary	None		694490	7806722	14-6-2023
75	Gully pot	Inlet to Primary	Sediment + Waste	50	694492	7806750	14-6-2023
76	Gully pot	Inlet to Primary	Unknown		694495	7806775	14-6-2023
77	Gully pot	Inlet to Primary	Sediment + Waste	50	694499	7806800	14-6-2023
78	Gully pot	Inlet to Primary	Unknown		694501	7806824	14-6-2023
79	Open Pipe	Tertiary to Primary	None	0	694518	7806828	14-6-2023
80	Open Pit Inlet	Tertiary to Primary	None	0	694509	7806968	14-6-2023
81	Open Pit Inlet	Tertiary to Primary	None	0	694516	7807023	14-6-2023
82	Open Pit Inlet	Tertiary to Primary	None	0	694525	7807066	14-6-2023
83	Open Pipe	Tertiary to Primary	None	0	694533	7807162	14-6-2023
84	Open Pit Inlet	Inlet to Primary	Waste	10	694538	7807200	14-6-2023
85	Open Pit Inlet	Tertiary to Primary	Waste	25	694536	7807226	14-6-2023
86	Closed Pit Inlet	Tertiary to Primary	None	0	694555	7807367	14-6-2023
87	Closed Pit Inlet	Inlet to Primary	Sediment + Waste + Other	50	694560	7807398	14-6-2023
88	Open Pit Inlet	Tertiary to Primary	None	0	694573	7807462	14-6-2023
89	Open Pit Inlet	Inlet to Primary	None	0	694600	7807523	14-6-2023
90	Closed Pit Inlet	Tertiary to Primary	Unknown		694604	7807527	14-6-2023
91	Closed Pit Inlet	Tertiary to Primary	Sediment	75	694625	7807579	14-6-2023
92	Closed Pit Inlet	Tertiary to Primary	Sediment	75	694652	7807633	14-6-2023
93	Open Pipe	Tertiary to Primary	Unknown		694647	7807620	14-6-2023
94	Closed Pit Inlet	Tertiary to Primary	None	0	694686	7807729	14-6-2023
95	Closed Pit Inlet	Tertiary to Primary	Unknown		694706	7807760	14-6-2023
96	Closed Pit Inlet	Tertiary to Primary	Unknown		694719	7807787	14-6-2023
97	Closed Pit Inlet	Tertiary to Primary	Sediment	100	694755	7807854	14-6-2023
98	Open Pipe	Tertiary to Primary	Sediment	100	694762	7807885	14-6-2023
99	Bar Screen Pipe	Tertiary to Primary	Sediment + Waste	25	694780	7807917	14-6-2023
100	Closed Pit Inlet	Tertiary to Primary	None	0	694795	7807964	14-6-2023
101	Open Pit Inlet	Inlet to Secondary	Sediment + Waste	100	694834	7808046	14-6-2023
102	Open Pit Inlet	Inlet to Secondary	None	0	694808	7808091	14-6-2023
103	Closed Pit Inlet	Tertiary to Secondary	Unknown		694778	7808129	14-6-2023
104	Open Pit Inlet	Tertiary to Secondary	Sediment	50	694753	7808179	14-6-2023
105	Open Pipe	Tertiary to Secondary	Sediment	90	694712	7808234	14-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
106	Open Pipe	Tertiary to Secondary	Sediment + Other	10	694693	7808257	14-6-2023
107	Open Pipe	Tertiary to Secondary	None	0	694649	7808334	14-6-2023
108	Open Pit Inlet	Inlet to Secondary	Sediment	100	694624	7808368	14-6-2023
109	Open Pit Inlet	Tertiary to Secondary	Sediment	10	694613	7808376	14-6-2023
110	Closed Pit Inlet	Tertiary to Secondary	Unknown		694596	7808397	14-6-2023
111	Open Pit Inlet	Inlet to Secondary	Sediment	100	694561	7808472	14-6-2023
112	Open Pit Inlet	Inlet to Secondary	Sediment	100	694565	7808479	14-6-2023
113	Open Pipe	Tertiary to Secondary	Sediment	100	694512	7808512	14-6-2023
114	Open Pipe	Inlet to Secondary	Sediment	75	694492	7808533	14-6-2023
115	Open Pipe	Inlet to Secondary	Sediment + Waste	75	694472	7808557	14-6-2023
116	Open Pipe	Inlet to Secondary	Sediment	100	694477	7808575	14-6-2023
117	Closed Pit Inlet	Tertiary to Secondary	Unknown		694460	7808571	14-6-2023
118	Open Pipe	Tertiary to Secondary	Sediment	100	694456	7808597	14-6-2023
119	Closed Pit Inlet	Inlet to Secondary	None	0	694444	7808617	14-6-2023
120	Open Pipe	Inlet to Secondary	Sediment + Waste	100	694441	7808631	14-6-2023
121	Closed Pit Inlet	Inlet to Secondary	None	0	694442	7808661	14-6-2023
122	Closed Pit Inlet	Inlet to Secondary	Unknown		694445	7808678	14-6-2023
123	Open Pipe	Inlet to Secondary	Sediment	100	694445	7808706	14-6-2023
124	Closed Pit Inlet	Inlet to Secondary	Unknown		694443	7808734	14-6-2023
125	Closed Pit Inlet	Inlet to Secondary	Unknown		694464	7808730	14-6-2023
126	Closed Pit Inlet	Tertiary to Secondary	None	0	694426	7808756	14-6-2023
127	Closed Pit Inlet	Inlet to Secondary	Vegetation	50	694404	7808770	14-6-2023
128	Closed Pit Inlet	Inlet to Secondary	Vegetation	100	694383	7808780	14-6-2023
129	Other	Tertiary to Secondary	None	0	694297	7808839	14-6-2023
130	Open	Inlet to Secondary	None	0	694287	7808860	14-6-2023
131	Open Pipe	Inlet to Secondary	Sediment + Vegetation	90	694311	7808847	14-6-2023
132	Open Pipe	Inlet to Secondary	Unknown		694339	7808823	14-6-2023
133	Open Pipe	Inlet to Secondary	Waste	75	694366	7808807	14-6-2023
134	Closed Pit Inlet	Tertiary to Secondary	Unknown		694380	7808802	14-6-2023
135	Closed Pit Inlet	Inlet to Secondary	Sediment + Other	10	694393	7808792	14-6-2023
136	Open Pipe	Inlet to Secondary	Sediment	100	694408	7808783	14-6-2023
137	Closed Pit Inlet	Inlet to Secondary	Vegetation	25	694430	7808771	14-6-2023
138	Closed Pit Inlet	Inlet to Secondary	None	0	694446	7808757	14-6-2023
139	Open Pipe	Tertiary to Secondary	None	0	694476	7808736	14-6-2023
140	Open Pipe	Inlet to Secondary	Sediment	100	694480	7808743	14-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
141	Open Pipe	Inlet to Secondary	Unknown		694484	7808728	14-6-2023
142	Closed Pit Inlet	Tertiary to Secondary	Sediment	10	694496	7808717	14-6-2023
143	Open Pipe	Inlet to Secondary	Unknown		694509	7808703	14-6-2023
144	Open	Tertiary to Secondary	Vegetation	75	694559	7808648	14-6-2023
145	Other	Inlet to Secondary	None	0	694547	7808677	14-6-2023
146	Other	Inlet to Secondary	None	0	694531	7808698	14-6-2023
147	Closed Pit Inlet	Inlet to Secondary	None	0	694541	7808669	14-6-2023
148	Closed Pit Inlet	Tertiary to Secondary	Sediment + Waste	75	694463	7808744	14-6-2023
149	Open Pipe	Tertiary to Secondary	Unknown		694463	7808705	14-6-2023
150	Open Pit Inlet	Inlet to Secondary	Waste	25	694460	7808673	14-6-2023
151	Closed Pit Inlet	Inlet to Secondary	None	0	694459	7808645	14-6-2023
152	Open Pipe	Inlet to Secondary	None	0	694460	7808628	14-6-2023
153	Closed Pit Inlet	Inlet to Secondary	None	0	694464	7808602	14-6-2023
154	Open Pipe	Inlet to Secondary	Sediment	100	694466	7808595	14-6-2023
155	Open Pipe	Inlet to Secondary	Sediment	75	694484	7808565	14-6-2023
156	Closed Pit Inlet	Inlet to Secondary	Sediment	100	694493	7808556	14-6-2023
157	Open Pipe	Inlet to Secondary	Sediment + Vegetation	50	694501	7808545	14-6-2023
158	Open Pit Inlet	Inlet to Secondary	Sediment	50	694523	7808520	14-6-2023
159	Closed Pit Inlet	Inlet to Secondary	Sediment	100	694536	7808505	14-6-2023
160	Open Pipe	Primary to Primary	None	0	694382	7805658	14-6-2023
161	Open Pipe	Primary to Primary	None	0	694386	7805660	14-6-2023
162	Open Pipe	Primary to Primary	None	0	694389	7805662	14-6-2023
163	Open Pipe	Primary to Primary	None	0	694436	7806241	14-6-2023
164	Open Pipe	Primary to Primary	None	0	694441	7806241	14-6-2023
165	Open Pipe	Primary to Primary	None	0	694467	7806476	14-6-2023
166	Open Pipe	Primary to Primary	None	0	694482	7806612	14-6-2023
167	Control Station	Primary to Primary	None	0	694512	7806874	14-6-2023
168	Open Pipe	Secondary to Secondary	Sediment + Vegetation		694549	7808486	14-6-2023
169	Control Station	Primary to Primary	Sediment + Waste	100	695820	7808824	13-6-2023
170	Control Station	Primary to Primary	Sediment + Waste	75	695818	7808826	13-6-2023
171	Control Station	Primary to Primary	Sediment + Waste	100	695814	7808829	13-6-2023
172	Control Station	Primary to Primary	Sediment + Waste	100	695816	7808827	13-6-2023
173	Control Station	Primary to Primary	Sediment + Waste	50	695822	7808822	13-6-2023
174	Bar Screen Pipe	Primary from Secondary	Sediment + Waste	10	695811	7808800	13-6-2023
175	Open Pipe	Primary to Primary	Unknown		696408	7805765	22-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
176	Open Pipe	Primary to Primary	Unknown		696410	7805763	22-6-2023
177	Open Pipe	Primary to Primary	Unknown		696412	7805761	22-6-2023
178	Open Pipe	Tertiary to Secondary	None	0	695986	7805536	15-6-2023
179	Open Pipe	Tertiary to Secondary	Sediment	25	696048	7805313	15-6-2023
180	Open	Tertiary to Secondary	Vegetation + Waste	75	696054	7805285	15-6-2023
181	Open Pipe	Primary from Secondary	None	0	697087	7806794	15-6-2023
182	Open	Tertiary to Primary	None	0	696519	7805925	16-6-2023
183	Open	Tertiary to Secondary	None	0	696553	7806110	16-6-2023
184	Open Pipe	Tertiary to Secondary	Sediment	100	696501	7806143	16-6-2023
185	Open	Tertiary to Secondary	Waste	25	696478	7806159	16-6-2023
186	Open Pipe	Tertiary to Secondary	Vegetation + Waste	25	695802	7806585	16-6-2023
187	Open	Primary from Secondary	None	0	696756	7806320	16-6-2023
188	Open Pipe	Tertiary to Secondary	Unknown		696132	7807048	16-6-2023
189	Open Pipe	Tertiary to Tertiary	Unknown		696139	7807063	16-6-2023
190	Open Pipe	Primary from Secondary	None	0	697069	7806811	16-6-2023
191	Open Pipe	Primary from Secondary	None	0	697067	7806808	16-6-2023
192	Open Pipe	Primary to Primary	None	0	698631	7805608	22-6-2023
193	Open Pipe	Primary to Primary	Vegetation	50	699049	7806177	22-6-2023
194	Open Pipe	Primary to Primary	Sediment + Waste + Vegetation	50	699161	7806338	22-6-2023
195	Open Pipe	Primary to Primary	Sediment + Waste + Vegetation	50	699159	7806339	22-6-2023
196	Open Pipe	Primary to Primary	Sediment + Waste + Vegetation	50	699163	7806337	22-6-2023
197	Open Pipe	Primary to Primary	Sediment + Vegetation	50	699174	7806401	22-6-2023
198	Open Pipe	Primary to Primary	Vegetation	100	699207	7806545	22-6-2023
199	Open Pipe	Primary to Primary	Vegetation	25	699220	7806610	22-6-2023
200	Open Pipe	Primary to Primary	Vegetation	75	699228	7806645	22-6-2023
201	Open Pipe	Primary to Primary	None		699248	7806728	22-6-2023
202	Open Pipe	Primary to Primary	Vegetation	50	699274	7806834	22-6-2023
203	Open Pipe	Primary to Primary	None	0	699279	7806860	22-6-2023
204	Open Pipe	Primary to Primary	None	0	699283	7806860	22-6-2023
205	Open Pipe	Secondary to Secondary	None	0	699094	7806628	22-6-2023
206	Open Pipe	Secondary to Secondary	None	0	699065	7806644	22-6-2023
207	Open Pipe	Secondary to Secondary	None	0	698984	7806693	22-6-2023
208	Open Pipe	Secondary to Secondary	Vegetation	25	698895	7806750	22-6-2023
209	Open Pipe	Secondary to Secondary	Unknown		698868	7806765	22-6-2023
210	Open Pipe	Secondary to Secondary	Waste	25	698853	7806775	22-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
211	Open Pipe	Secondary to Secondary	Human Interference	25	697756	7807450	22-6-2023
212	Open Pipe	Secondary to Secondary	Human Interference	25	697756	7807445	22-6-2023
213	Open Pipe	Primary to Primary	None	0	696950	7804797	22-6-2023
214	Control Station	Primary to Primary	None	0	695240	7804340	3-7-2023
215	Control Station	Primary to Primary	None	0	695238	7804340	3-7-2023
216	Control Station	Primary to Primary	None	0	695234	7804341	3-7-2023
217	Control Station	Primary to Primary	None	0	695231	7804342	3-7-2023
218	Control Station	Primary to Primary	None	0	695228	7804342	3-7-2023
219	Open Pipe	Primary to Primary	None	0	695536	7805459	22-6-2023
220	Open Pipe	Primary to Primary	None	0	695537	7805457	22-6-2023
221	Open Pipe	Primary to Primary	None	0	695538	7805454	22-6-2023
222	Open Pipe	Primary to Primary	None	0	695540	7805452	22-6-2023
223	Open Pipe	Primary to Primary	None	0	695544	7805466	22-6-2023
224	Open Pipe	Primary to Primary	None	0	695545	7805464	22-6-2023
225	Open Pipe	Primary to Primary	None	0	695546	7805462	22-6-2023
226	Open Pipe	Primary to Primary	None	0	695548	7805461	22-6-2023
227	Open Pipe	Primary to Primary	None	0	695549	7805459	22-6-2023
228	Open Pipe	Primary to Primary	Vegetation	25	695745	7806609	22-6-2023
229	Open Pipe	Primary to Primary	Vegetation	25	695746	7806611	22-6-2023
230	Open Pipe	Secondary to Secondary	Vegetation	100	696280	7807505	22-6-2023
231	Open Pipe	Secondary to Secondary	Vegetation	100	696282	7807501	22-6-2023
232	Open Pipe	Secondary to Secondary	Vegetation	100	696121	7807392	22-6-2023
233	Open Pipe	Secondary to Secondary	Vegetation	75	696124	7807391	22-6-2023
234	Open Pipe	Secondary to Secondary	Vegetation	100	696338	7807712	22-6-2023
235	Open Pipe	Secondary to Secondary	None	0	696172	7807824	22-6-2023
236	Open Pipe	Secondary to Secondary	None	0	696169	7807820	22-6-2023
237	Open Pipe	Primary to Primary	Sediment + Waste	100	697265	7807118	22-6-2023
238	Open Pipe	Primary to Primary	Sediment + Waste	100	697272	7807113	22-6-2023
239	Open Pipe	Primary to Primary	Unknown		697268	7807116	22-6-2023
240	Open Pipe	Primary from Secondary	Unknown		697245	7807054	22-6-2023
241	Open Pipe	Secondary to Secondary	Unknown		697386	7806969	22-6-2023
242	Open Pipe	Secondary to Secondary	None	0	697523	7806882	22-6-2023
243	Open Pipe	Primary from Secondary	Unknown		697089	7806797	15-6-2023
244	Open Pipe	Secondary to Secondary	Human Interference	100	697232	7806711	22-6-2023
245	Open	Secondary to Secondary	None	0	697279	7806677	22-6-2023

Table G.1 continued from previous page

ID	Type	Canal Type	Fail Type	Fail Percentage	Longitude	Latitude	Date
246	Open Pipe	Secondary to Secondary	Vegetation	50	697393	7806252	22-6-2023
247	Open Pipe	Secondary to Secondary	Unknown		697204	7806366	22-6-2023
248	Open Pipe	Secondary to Secondary	None	0	697078	7806446	22-6-2023
249	Open Pipe	Primary from Secondary	None	0	696928	7806538	22-6-2023
250	Open Pipe	Primary from Secondary	Unknown		697373	7807332	22-6-2023
251	Open Pipe	Secondary to Secondary	Sediment	50	697331	7807712	22-6-2023
252	Open Pipe	Primary to Primary	Human Interference	100	697637	7807723	22-6-2023
253	Open Pipe	Primary to Primary	Vegetation	10	697640	7807717	22-6-2023
254	Open Pipe	Secondary to Secondary	Vegetation	10	nan	nan	Unknown
255	Open Pipe	Tertiary to Primary	Waste	10	693721	7809440	5-6-2023
256	Open Pipe	Tertiary to Primary	Human Interference	100	693787	7809395	5-6-2023
257	Control Station	Primary to Primary	Waste	50	695824	7808820	13-6-2023

Assessed canals

This section holds the results of the state of the canals that are assessed. Table G.2 presents the results of the assessment, with:

- **ID:** An identificator for the datapoint. The first datapoint has an *ID* value of '1', the second datapoint '2', et cetera.
- **(Un)lined:** Either *lined* or *unlined*. When the canal has a concrete side wall, a canal is considered lined and a canal is considered unlined if the canal does not have a concrete side wall.
- **Order:** The order of the canal, either *Primary*, *Secondary* or *Tertiary*. The definition of the canals is a subject to debate as it is not registered. In this research, it is assumed that the primary and secondary canals are the canals under the maintenance of SASB and these canals are included in the model; the tertiary canals are not.
- **Visited:** Either *Yes* or *No*. Defines whether the canal has been physically visited or not. Some canals are only defined with the help of satellite data.
- **Failtype:** The type of blockage or failure mode of the canal. Can be one of the failure modes as defined in section 2.2. Additionally, a canal without a failure is noted as *None*. If the failure mode is unknown, *Unknown* is written down in this attribute.
- **Fail%:** The percentage of blockage in the connection. Is estimated as the fraction of the available flow area that is blocked. Can be either '0%' (if *Failtype* is *None*), *10%*, *25%*, *50%*, *75%* or *100%*.
- **Comments:** Comments on the connection that is relevant for qualitative analysis, e.g. the presence of a construction causing a blockage or a person that does regular cleaning of the point.
- **Source:** RAMBLR and Google Photos is used to store the photos that are made. In this attribute, the storage location is defined.
- **Date:** This attribute holds the date of the visit to the point.
- **Length:** The length of the canal stretch that has certain properties. The length of the canal stretch is calculated using the *$length* command in the *Raster Calculator* in *QGIS*.

Table G.2: Results of the assessment of the connections, structures and inlets

ID	(Un)lined	Order	Visited	Fail Type	Fail Percentage	Date	Length
1	Lined	Primary	Yes	Sediment/Vegetation	25		427
2	Unlined	Tertiary	Yes	None	0	5-6-2023	89
3	Unlined	Tertiary	Yes	None	0	5-6-2023	17
4	Unlined	Tertiary	Yes	Human Interference	80	5-6-2023	77
5	Unlined	Tertiary	Yes	Human Interference	100	5-6-2023	59
6	Unlined	Tertiary	Yes	None	0	5-6-2023	103
7	Lined	Tertiary	Yes	Waste	50	5-6-2023	98
8	Unlined	Tertiary	Yes	None	0	5-6-2023	36
9	Unlined	Secondary	No	Unknown			322
10	Unlined	Secondary	No	Unknown			338
11	Unlined	Secondary	Yes	Vegetation	25	23-6-2023	79
12	Lined	Primary	Yes	Waste/Sediment	50	13-6-2023	37
13	Lined	Primary	Yes	Sediment	25	13-6-2023	186
14	Unlined	Secondary	Yes	Vegetation	10	13-6-2023	222
15	Unlined	Secondary	No				772
16	Lined	Primary	Yes	Sediment	10	14-6-2023	898
17	Lined	Primary	Yes	Sedimentation	25	14-6-2023	992
18	Lined	Primary	Yes	None	0	14-6-2023	207
19	Lined	Primary	Yes	None	0	14-6-2023	1187
20	Lined	Primary	Yes	None	0	14-6-2023	1221
21	Lined	Secondary	Yes	Sediment	10	14-6-2023	438
22	Lined	Secondary	Yes	Vegetation/Sediment	10	14-6-2023	58
22	Lined	Secondary	Yes	Vegetation/Sediment	10	14-6-2023	35
22	Lined	Secondary	Yes	Sediment + Vegetation	24	14-6-2023	63
23	Lined	Secondary	Yes	Sediment/Vegetation	25	14-6-2023	476
24	Lined	Secondary	Yes	Vegetation/Sediment	50	14-6-2023	145
25	Unlined	Primary	Yes	Vegetation	10	14-6-2023	803
26	Unlined	Primary	Yes	None	0	14-6-2023	114
27	Lined	Secondary	Yes	Unknown			331
28	Unlined	Tertiary	Yes	Vegetation + Waste	50	14-6-2023	149
28	Unlined	Tertiary	Yes	Vegetation + Waste	50	14-6-2023	7
29	Lined	Tertiary	Yes	None	0	14-6-2023	300
30	Lined	Secondary	Yes	Vegetation	25	14-6-2023	339
31	Unlined	Primary	Yes	Vegetation	10	16-6-2023	386

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ID	(Un)lined	Order	Visited	Fail Type	Fail Percentage	Date	Length
32	Unlined	Secondary	Yes	Vegetation	10	16-6-2023	629
32	Unlined	Secondary	Yes	Vegetation	10	16-6-2023	613
33	Unlined	Secondary	yes	Vegetation	25	16-6-2023	395
34	Unlined	Secondary	Yes	Vegetation	10	16-6-2023	272
35	Unlined	Primary	Yes	Vegetation	25	16-6-2023	277
36	Unlined	Primary	Yes	None	0	16-6-2023	303
37	Unlined	Primary	Yes	Vegetation	50	16-6-2023	370
38	Unlined	Secondary	No			13-7-2023	396
39	Unlined	Secondary	Yes	None	0	16-6-2023	221
40	Unlined	Secondary	Yes	None	0	16-6-2023	958
41	Unlined	Secondary	Yes	Waste + Vegetation	25	16-6-2023	102
41	Unlined	Secondary	Yes	Vegetation + Waste	25	16-6-2023	51
42	Unlined	Tertiary	Yes	None	0	16-6-2023	111
43	Unlined	Tertiary	Yes	None	0	16-6-2023	50
44	Unlined	Tertiary	Yes	None	0	16-6-2023	35
45	Unlined	Tertiary	Yes	None	0	16-6-2023	55
46	Unlined	Tertiary	Yes			16-6-2023	61
47	Unlined	Secondary	Yes	Vegetation	25	16-6-2023	240
48	Unlined	Secondary	Yes	Human Interference	90	16-6-2023	488
49	Unlined	Secondary	Yes	Sedimentation	50	16-6-2023	80
50	Unlined	Secondary	No	Human Interference	75		872
51	Unlined	Secondary	Yes	Vegetation + Sedimentation + Human Interference	75	15-7-2023	182
52	Unlined	Secondary	Yes	Vegetation + Sedimentation	75	15-6-2023	171
53	Unlined	Secondary	Yes	None	0	22-6-2023	153
54	Unlined	Secondary	No				466
55	Unlined	Secondary	No				263
56	Unlined	Secondary	Yes	Vegetation	50	15-6-2023	60
57	Unlined	Secondary	Yes	None	0	15-6-2023	55
58	Unlined	Secondary	Yes	Vegetation	50	15-6-2023	118
59	Unlined	Secondary	Yes	None	0	15-6-2023	88
60	Unlined	Secondary	Yes	Vegetation	50	15-6-2023	348
61	Unlined	Secondary	Yes	Human Interference	100	15-6-2023	11
62	Unlined	Secondary	Yes	Vegetation	50	15-6-2023	114
63	Unlined	Secondary	Yes	Human Interference	100	15-6-2023	18
64	Unlined	Secondary	Yes	None	0	15-6-2023	176

Table G.2 continued from previous page

ID	(Un)lined	Order	Visited	Fail Type	Fail Percentage	Date	Length
65	Unlined	Secondary	Yes	Vegetation	50	15-6-2023	52
66	Unlined	Primary	Yes	None	0	22-6-2023	822
67	Unlined	Secondary	Yes	Vegetation	10	22-6-2023	252
68	Unlined	Secondary	Yes	Vegetation	25	22-6-2023	443
69	Unlined	Secondary	No				251
71	Unlined	Secondary	Yes	Sediment + Waste + Vegetation	24	20-6-2023	243
72	Unlined	Secondary	Yes	Sediment	25	20-6-2023	224
73	Unlined	Secondary	Yes	Vegetation	50	20-6-2023	512
74	Unlined	Secondary	Yes	Sediment + Vegetation	24	20-6-2023	132
76	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	214
77	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	205
79	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	167
80	Unlined	Secondary	Yes	Vegetation	50	20-6-2023	349
81	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	220
82	Unlined	Secondary	Yes	Vegetation	10	20-6-2023	27
83	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	59
84	Unlined	Secondary	Yes	Vegetation	90	20-6-2023	675
85	Unlined	Secondary	Yes	Sediment + Human Interference	25	20-6-2023	95
86	Unlined	Secondary	Yes	Sediment + Vegetation	38	20-6-2023	67
88	Unlined	Secondary	Yes	Vegetation	50	20-6-2023	94
89	Unlined	Secondary	Yes	Vegetation	75	22-6-2023	418
90	Unlined	Secondary	Yes	None	0	22-6-2023	27
91	Unlined	Secondary	Yes	Vegetation	90	22-6-2023	365
94	Lined	Primary	Yes	Sediment	25		214
96	Unlined	Secondary	Yes	Sediment + Vegetation	24	20-6-2023	445
102	Lined	Primary	Yes	None	0	22-6-2023	839
102	Lined	Primary	Yes	None	0	22-6-2023	839
103	Unlined	Secondary	Yes	Vegetation	75	22-6-2023	839
107	Unlined	Secondary	Yes	Vegetation	25		646
108	Unlined	Secondary	Yes	Vegetation	50	22-6-2023	1494
109	Unlined	Secondary	No				317
110	Unlined	Secondary	No				1986
111	Unlined	Secondary	No				912
112	Lined	Primary	Yes	Unknown			369

H

Water quality

This appendix presents the longtable of the water quality measurements. It comprehends table H.1, which consists of the following elements:

- **ID:** An identificator for the datapoint. The first datapoint has an *ID* value of '1', the second datapoint '2', et cetera.
- **Nitrate:** The nitrate value measured in the sample, in ppm.
- **Nitrite:** The nitrite value measured in the sample, in ppm.
- **pH:** The pH value measured in the sample.
- **E.Coli:** Whether E.Coli was found in the sample. Can either be *Unknown* if the sample was not tested on E. Coli, *Present* if the amount of E.Coli was more than 1 CFU/ml and *Not found* if the amount of E.Coli was less than 1 CFU/ml.
- **Source:** The type of location where the sample has been sourced. Can be a canal (primary, secondary or tertiary), shallow well to measure groundwater or drinking water from a water tap.
- **Comments:** Comments on the connection that is relevant for qualitative analysis, e.g. the presence of a construction causing a blockage or a person that does regular cleaning of the point.
- **Date:** This attribute holds the date when the sample was taken.
- **Longitude:** The longitude of the location of the sample.
- **Latitude:** The latitude of the location of the sample.

Table H.1: Longtable of the water quality measurements

ID	Nitrate ppm	Nitrite ppm	pH	E.Coli	Source	Comments	Date DD-MM-YYYY	Longitude	Latitude
1	0	0	7	Unknown	Tertiary canal	In drained canal full of waste	05-06-2023	693986	7809402
2	0	0	7.25	Unknown	Tertiary canal	Start of the canal, next to toilet	05-06-2023	693800	7809400
3	0	0	6.5	Not found	FIPAG point	Water tap point from FIPAG	05-06-2023	693854	7809386
4	0	0	6.75	Unknown	Tertiary canal	After toilet in the neighbourhood	05-06-2023	693824	7809416
5	0	0	8.5	Present	Primary canal	Maraza basin	13-06-2023	695809	7809004
6	0	0	8	Unknown	Primary canal	Inlet primary	13-06-2023	695775	7808775
7	0	0	8.5	Unknown	Primary canal	Primary canal	13-06-2023	695725	7808775
8	2	0.15	7.5	Present	Primary canal	Palmeiras outlet	14-06-2023	695228	7804356
9	15	0	8	Unknown	Primary canal	In primary canal	14-06-2023	694511	7806929
10	1	0.15	8	Present	Primary canal	Chota outlet	15-06-2023	695686	7805533
11	0	0	7.5	Unknown	Primary canal	In primary drain	15-06-2023	697261	7807106
12				Present	Shallow well	Pozo Chota 1	15-06-2023	697513	7806176
13	0	0	7.25	Unknown	Secondary canal	In secondary drain	15-06-2023	697645	7806455
14	0	0	6.75	Unknown	Secondary canal	In still-standing water after pipe burst	16-06-2023	696492	7806144
15	2	0	7	Present	Shallow well	Pozo Chota 2	16-06-2023	696064	7806757
16	0	0	7	Unknown	Tertiary canal	in tertiary drain	14-06-2023	694456	7808614
17	1	0.15	7	Unknown	Tertiary canal	In outlet tertiary drain	14-06-2023	694275	7808857
18	0	0	7	Present	Shallow well	groundwater well	15-06-2023	698250	7807515
19		0.15	7.5	Unknown	Secondary canal	In secondary canal	15-06-2023	698511	7806631
20	0	0.15	7.5	Unknown	Tertiary canal	Side canal	19-06-2023	695415	7814328
21	2	0.15	7.25	Unknown	Tertiary canal	In tertiary drain	19-06-2023	694338	7813801
22	2	0	8	Unknown	Tertiary canal	Lake close to Capital Foods factory	19-06-2023	694325	7813882
23	50	0	6.75	Present	Shallow well	Groundwater well. Location is indicative	19-06-2023	694466	7814241
24	20	0.15	7	Present	Shallow well	Location is indication. Groundwater well	19-06-2023	694546	7814433