# Flood Safety Durban

Multidisciplinary Project

CIE 4061-09

MDP 201

## Final Report


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## Preface

In December 2015 we decided to participate in a multidisciplinary project with in total six students from the Delft University of Technology. The goal was to tackle a problem abroad with three different master backgrounds, being Construction Management and Engineering, Transport, Infrastructure and Logistics and Hydraulic Engineering. After analysing several project possibilities all over the world we decided to go to Durban in South Africa, because we considered this project as the most challenging one with respect to all our different backgrounds.

During this project we have learnt to work in an unknown country, dealing with uncertainties, communicating with people from a different country and working with other types of models and data than we were used to. Besides this we have learnt to combine our multidisciplinary backgrounds working towards the same end product.

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## Abstract

Durban is the biggest city of the KwaZulu-Natal province located at the East coast of South-Africa. In South Africa nation wide millions of Rands of damage occur along with tens of casualties as a result of urban flooding. These floods are usually the result of heavy rainfall. In Durban other factors that may contribute to floods are blockage or siltation of the drainage system. The blockage of the drainage system is a result of bad waste management. The continuously rising sea level in combination with a blocked urban drainage system could pose a serious threat. This results in the following main goal of this project: obtain insight in the effects of combined sea storm and high rain/river events on stakeholders and existing transport systems, for regular and more severe events. The scope of the project is the area of Durban from the port up until the Umgeni Business park and from the coast until the hill ridge. This report contains four parts. Part I: Analysis, Part II: Elaboration on Modelling Approach, Part III: Acquiring Results and Part IV: Solutions.

In the first part are analysed: stakeholders, the transport network, the storm water network and hydraulic and hydrological aspects. In the stakeholder analysis several stakeholders are identified that either have a significant interest, or significant power to influence any decisions that will have to be made regarding floods. From the traffic analysis the most important roads and bottlenecks were identified. The only interesting network is the road network, since other infrastructure is not used by many people. The stormwater network analysis showed that in several locations such as the Central Business District (CBD) the tide penetrates far into the network and several outfalls are completely underwater during spring tide. This shows the possible vulnerability of the network to a high water level from the sea. The analysis also showed that external factors such as blockage of the manholes by waste could also affect the functionality of the system. The hydraulic & hydrological parameters that were analysed were rainfall and river discharge from the land side and the water level from the sea side.

In the second part different maps are created which together reveal the most critical areas with respect to flooding. The most critical areas with respect to stakeholders and the traffic network were identified and mapped. Also the drainage model PCSWMM, which has been used to model the urban drainage system of the study area has been described.

In the third part the stakeholder and transport map are combined with a flood map resulting from PCSWMM. The flood scenarios, which are used as input for PCSWMM are based on the likeliness of the combination of occurrence of the sea and land based hydraulic parameters. By the combination of these maps, the consequences of the floods have been evaluated. Because of inaccuracies in the flood map for some regions the focus was laid upon the Central Business District. The consequences of the floods are divided in capital, social and economic costs. Several main roads could get flooded in the CBD which will require the traffic to use other main roads. The exit- and entry ramps of these other roads however are not designed for such an increase in intensity and therefore congestion will arise at these locations. This will cause severe travel time delay and will result in economic costs. With respect to stakeholders, property owners and small businesses will be most affected in some parts whereas in other parts of the area insurance companies will be most affected because of the houses of middle or upper class residents and also business who are all insured for damages caused by floods.

The last part contains four proposed solution strategies which can be used as a starting point in treating floods. Floods can be seen as a risk which consists of the combination of probability and consequences. Therefore four general risk treating strategies are used: Accept, Avoid, Mitigate and Transfer. Four global solutions to deal with floods are constructed each based on these different strategy. The four strategies were evaluated using a Multi Criteria analysis. This showed that all strategies are better than the 0-hypothesis (Accept) but none of the strategies proved to be the

most suitable. Finally some recommendations are given for further research and to improve the PCSWMM model.

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# 1 Introduction

This chapter contains a small introduction to the city of Durban and moreover defines the problem behind what is investigated in this study. This problem will be translated in study goals and objectives and subsequently the used approach will be elaborated.

## 1.1 Area of Interest

The city of Durban, governed by the eThekwini Municipality, is located at the East coast of the KwaZulu-Natal province in South-Africa as can be seen in the figure below (Figure 1.1). The city first started as a trading post for European settlers back in 1824. The Natal Bay as named by Vasco Da Gama when he first arrived on Christmas Day 1497 with his three small ships was on of the few natural harbours available along the east coast of southern Africa between Algoa Bay and Delagoa Bay (now Maputo Bay) [15]. After in 1840 the natural sandbar in front of the port entrance had been conquered, the port rapidly grew to became the busiest general cargo port in southern Africa and one of the largest and busiest container terminals in the southern hemisphere [43].

Durban is the most cultural diverse city of South Africa consisting of 68% black, 20% Indian, 9% white and 3% coloured inhabitants [3]. It has beautiful beaches stretching for 10 km from the marine world Ushaka until the river Umgeni. Along the beach lies the in 2010 built Beachfront Promenade which was constructed for the FIFA World Cup of 2010. Durban has improved a lot since hosting the world cup in 2010. The infrastructure has become much better and by implementing the promenade the criminality has been reduced. Durban has become a world wide known city and focuses on citywide investments and a growing economy.


Figure 1.1: Location of Durban in South Africa

## 1.2 Problem Definition

In South Africa nation wide millions of Rands of damage occur along with tens of casualties as a result of urban flooding. Despite the fact that flood mitigation plans have been drafted, ongoing damage keeps occurring to properties and infrastructure [32]. Floods are usually the results of heavy rainfall in South Africa. In several occasions floods may also happen because of dam breaches or insufficiently designed storm water drainage. In urban areas another factor heavily contributes to the flood occurrence. This is the blockage of storm water pipes or other drainage system infrastructures. This is the result of lacking or below standard waste management and habits of the community. Civilians for instance throw all the garbage on the streets, use manholes to hide their belongs and street cleaners sweep all the trash in the drains (Interview Geoff Tooley Appendix B.5). Due to this problem rainfall often causes more floods than river floods do.

In the end of July 2016 the last floods occurred in Durban and led to nine fatalities [11]. The problem of these floods was the underlying structure of the city. The storm water pipes became obstructed because of solid waste which blocked the culverts and grates and in combination with the high discharge these pipes were not capable of handling the water. This caused the water to back-up rapidly at the obstructions, overtopping barriers, bursting stream banks, disrupting traffic and inundating adjacent properties and dwellings. Structures were destroyed which caused dangerous situations with people that were trapped underneath the rubble [16].

In Durban not only can there be significant rainfall but from the sea side the city is also prone to water related hazards. In March 2007 a cut-off low stationary 500km south-east offshore of Durban caused winds of 60 kts and offshore wave heights of 8.5m at Richards Bay, 100km North of Durban [30]. This event severely damaged the beach front and millions were lost as a result of damages to the tourist industry.

The effects of this particular event were mainly focused on the beach front only and not so much on the hinter laying traffic network and dwellings but one can imagine that there are possibilities for severe events like these to occur simultaneously with heavy rainfall events or significant river discharges. Bearing in mind that blocking of the drainage system is already causing floods that affect the entire city, an interesting question could be what the effect of blocking of the outfalls caused by extreme high water level events from the sea side would be as might occur during these extreme storms. With a continuously rising sea level the effects that sea water level will have on the urban drainage system are also yet unknown and could pose a serious threat.

## 1.3 Objectives

The main goal of this project is to obtain insight in the effects of combined sea storm and high rain/river events on stakeholders and existing transport systems, for regular and more severe events. Moreover an attempt will be made to come up with general solution strategies to limit the negative effects. In order to achieve the main goal several objectives have to be accomplished:

1. Analysis of the system. Part of this system are; the involved stakeholders with their power and interest, the transport network and the urban drainage network.
2. Investigation of parameters considered to be contributing to possible floods with special attention to contributions from the sea side.
3. Creation of a model approach which is capable of indicating the most critical areas with respect to floods and moreover find these areas.
4. Come up with general response strategies in order to deal with floods.

The next section will elaborate on the proposed approach to achieve this objectives and main goal.

## 1.4 Approach

This project is performed with multiple disciplines involved, giving the possibility to investigate the problem from different angles. These angles are however not independent of each other and they should moreover be coupled in order to achieve the main goal of this project. This section will elaborate on the methodology which is used to deal with the multidisciplinary character of this project. Subsequently the structure of the report will be explained.

### 1.4.1 Methodology

The city of Durban might get flooded during certain circumstances causing all sorts of troubles which are relevant to all the disciplines. As mentioned in the previous sentence there are 'certain circumstances' which might cause 'all sorts of troubles'. Apparently there are boundary conditions that, applied to a certain system, can lead to a flood which on his turn will cause troubles. This can be specified as follows: certain rainfall, river discharge and sea water level combinations (boundary conditions) are exceeding the capacity-, or lower the effectiveness, of the urban drainage system (the system) causing damage and traffic delays (troubles).

If this is transferred back to the involved disciplines there is a hydraulic contribution with respect to the boundary conditions and the urban drainage system that might be affected by them. The transport part can be found in the fact that water will cause roads to be closed or less passable causing congestion and traffic delays and the construction management part is found in stakeholders affected by floods. These contributions will be analysed separately to obtain better insight in the behaviour of the system and will be used later in the project to run models and create solutions.

When these analyses are in place the disciplines have to be coupled. This will be done by means of an urban drainage model which, based on the input scenarios from a hydraulic perspective, provides a flood map that can be overlaid by maps containing the critical areas regarding stakeholders and transport. The combined map indicates were the most flood prone area is located. This area will face large problems when a flood occurs. These problems are expressed by means of values which are subdivided into capital-, social- and economical values. Capital values focus on damage to property whereas social values focus on the well-being of humans. Economical values focus more on indirect loss of revenues to companies due to the fact that roads were unavailable or congested which makes it difficult, if not impossible, for employees to go to work. This expression by means of values brings the stakeholder and transport analysis together with as result that the three disciplines are coupled since the hydraulic input was already used to create the flood map.

With the consequences in mind four solution strategies will be proposed based on a theoretical framework used for risk response strategies. These solution strategies will be evaluated by means of a Multi Criteria Analysis (MCA) to indicate the most suitable strategy for the city of Durban. In order to test the robustness of the performed MCA a sensitivity analysis will be performed subsequently.

The above described approach is illustrated in Figure 1.2 below. This figure shows the steps that have to be taken in a rather summarised way. Every block in the diagram can be subdivided in multiple smaller ones which have interdependencies with each other and with other larger blocks. To create structure in this complex system a system diagram has been made which is elaborated on in Appendix A. The reader is referred to this appendix for a more detailed overview of the involved factors, their interdependencies and thus the coherence between the multiple disciplines.

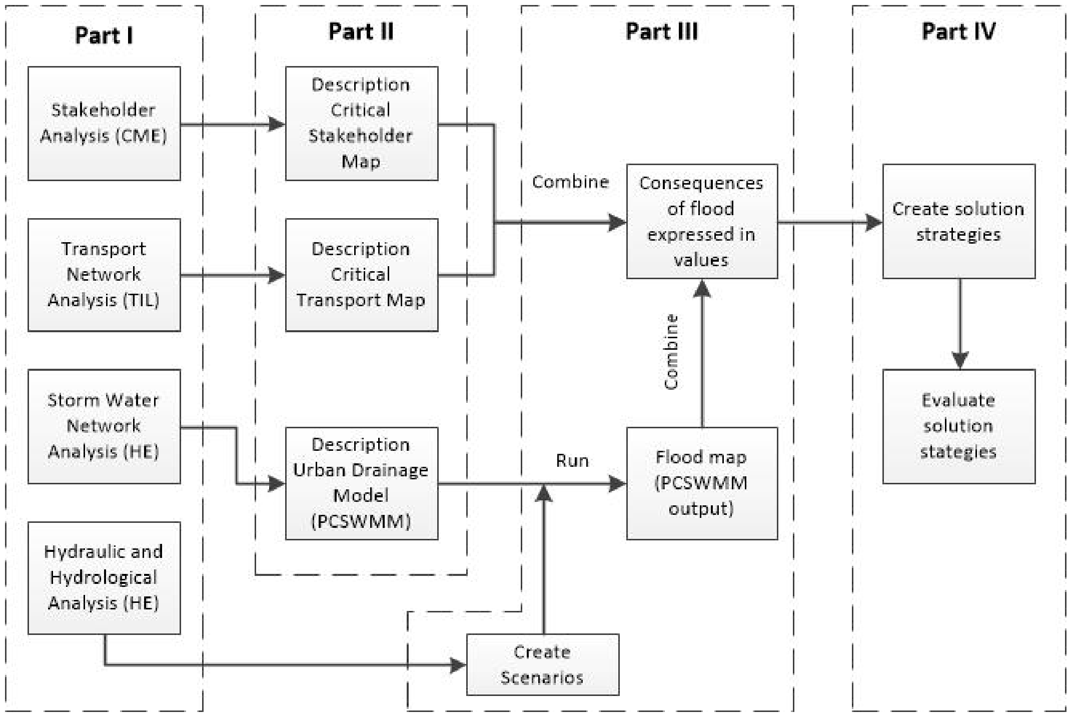



Figure 1.2: Illustration on approach

### 1.4.2 Report structure

As readily can be seen from Figure 1.2 the report is divided into four parts. These parts are:

1. Analysis
2. Elaboration on Modelling Approach
3. Acquiring Results
4. Solutions

The analysis part will be used to investigate the components of the system in more detail in order to increase the knowledge on the whole system. This knowledge will in part II be used to elaborate on a model approach which will be able to indicate the most flood prone areas in Durban based on a combination of a critical stakeholder-, critical transport- and flood maps based on different scenarios. After creating scenarios this model will be used to obtain the consequences of floods and express them in capital-, economical- and social values. Part IV will finally be used to propose solution strategies and evaluate this strategies.

Besides the main part of the report there will be finished with a more general section containing the conclusion and recommendations of the research project.

# Part I Analysis

Part I focuses on the analysis of the area, the stakeholders, the traffic network, the urban drainage network and the hydraulic and hydrological influences on the system. This analysis is needed to obtain more insight in the current situation in Durban regarding people and systems that are affected during flood and the parameters that might have an influence on that. The knowledge is gained by the use of information and data from the municipality, ArcMap (GIS based program), study books, Valuation roll and the web.

## 2 Area analysis

The eThekwini municipality is a municipality with many flood sensitive parts. In every direction there are areas that contribute to floods. At the northern side of the city centre the Umgeni River flows from Drakensbergen into the sea, at the eastern part of the city the Indian Ocean is located, at the southern side of the city centre the busiest port of South Africa is located and at the western side of the city a hill ridge is located. The most important areas to prevent from flooding are the busy and economic active parts of the city which are located in the Central Business District (CBD), Coastline, Umgeni river and the area between the CBD and Umgeni river. That is why the following system boundaries are chosen for this project: on the north side the Umgeni River, on the east side the coastline from the Umgeni river to the north part of the entrance of the port, in the south the northern part of the port and the foot of the hills in the west (see Figure 2.1). All the figures in this report are shown with the North side up. Within this area the stakeholders, traffic and the hydrological & hydraulic parameters are analysed in the following sections.


Figure 2.1: Area of interest

## 3 Stakeholder Analysis

Stakeholders have to be taken into account for having a successful project to mitigate floods [40]. Stakeholders can have unexpected attitudes that can cause risks that could have been prevented.

Therefore an analysis of the stakeholders that are affected by floods in Durban is necessary. For the definition of stakeholders the definition of Nicholas and Steyn (2012) is used who said that stakeholders of a project are "any group or individual who is affected by or having potential influence on the project" [40]. A stakeholder analysis is necessary to take into account during the whole process of a project. This report contains a research project and will give solution strategies that could serve as a start for new research. The parts of the stakeholder analysis that are important for the research project are the stakeholder identification and the stakeholder characteristics. For the elaboration of these solutions the power, interest and attitude of these stakeholders is important to take into account. For this reason the stakeholder identification is made by answering the question: Which stakeholders are affected by floods? The power, interest and attitude of stakeholders is determined by answering the question: What is the power, interest and attitude of stakeholders during a project to prevent floods?.

## 3.1 Stakeholder identification

During a project it is important to know what kind of stakeholders are involved with the problem and the solution of the project. In this chapter the focus will be on the stakeholders that are affected when a flood event occurs. These stakeholders, both directly and indirectly affected by floods, are shown in Table 3.1. The stakeholders that are identified are divided in the categories 1) Authority related, 2) Non Governmental Organisations (NGOs), 3) Organised business (industrial as well as business and commercial), 4) Residential and 5) Recreational. An elaboration of these stakeholders and why they are affected by floods is described in Appendix C.1. This identification is only based on the stakeholders that are affected by floods and not directly have a stake in executing the solution for floods like the construction companies. Reparation of the roads as a result of floods is seen as part of the Transport Authority. At this stage it is not relevant for the municipality to take these parties into consideration.

Table 3.1: Stakeholder Identification

| Category | Stakeholder | Departments |
|---|---|---|
| Authority related | South African government | |
| | National Treasury | |
| | South Africa Maritime Safety Authority (SAMSA) | |
| | Government for KwaZulu Natal Department of Cooperative Government and Traditional Affairs | |
| | eThekwini municipality | eThekwini Electricity |
| | | eThekwini City engineers |
| | | eThekwini Sustainability |
| | | eThekwini Water and sanitation |
| | | eThekwini Transport authority |
| | | eThekwini Economic Development Unit |
| | | eThekwini Business Support, Markets and Tourism Unit |
| | | eThekwini Library Service |
| | | eThekwini Sports and Recreation/Private stadia |
| | | eThekwini Fire |
| | Provincial Department of Health | |
| | Provincial Department of Education | |
| | South African Police Services | |
| | PRASA (Passanger Rail Agency of South Africa) | |
| | KZN Department of Health & private service providers | |
| NGO | Coastal Watch | |
| Organised Business | Insurance companies | |
| | Large businesses | South African Property Owner Assocation |
| | Local businesses | Restaurants |
| | | Shops |
| | | Hotels |
| | | Family stores |
| | | Busses and taxi's |
| | | Surf shops and schools |
| Residentials | Lower class residents | |
| | Higher class residents | |
| Recreational | Tourism organisations | |
| | Ocean users | |
| | Daily visitors focus area | |

## 3.2 Stakeholder characteristics

Every stakeholder has its own impact on the process and should be approached accordingly. If this is done properly it is likely to have a good stakeholder management. Stakeholders have to be satisfied and should have the feeling that their opinion is taken into account. Besides the identification also a power, interest and attitude diagram is part of the good stakeholder management. This diagram can tackle the risks that occur from stakeholders in an early stage. A preparation has to be made to react on negative stakeholders to reduce the time delay, costs and other negative effects on the project [40].

The first figure (Figure 3.1) is only based on the power and interest of the stakeholders. This diagram shows the relation between the stakeholders. In Table 3.2 the stakeholders are defined more generally. They have a high or low level of power and a high or low level of interest. Figure 3.1 shows the differences in power between the stakeholders that are earlier defined as high power stakeholders. This figure can help creating strategies to satisfy the stakeholders and determine the critical stakeholders that need some more attention. Appendix C.2 shows the elaborated version of the stakeholder characteristics. This subsection contains the most important information of this stakeholder characteristics analysis which is used as background information for the project.

In Figure 3.1 the different stakeholders are divided into four groups: Context setters, Players, Crowd and Subjects.

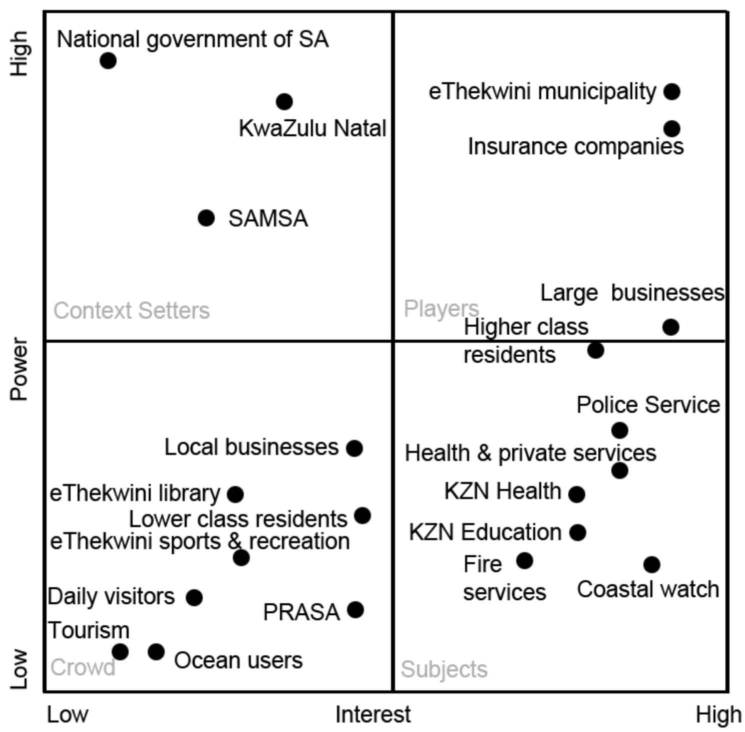



Figure 3.1: Power Interest Grid

The South African government has the most power of all stakeholders, followed by the municipality. The province has a lot of power because of the money distribution they have, in this way they can block the project. Insurance companies also have a lot of power but not as much as the government, province and the municipality. This is because the governmental organisations will organise and lead the project and tell what has to be done in the country, province and municipality when floods occur. Insurance companies are there to help the people to recover as fast as possible but they cannot take the lead.

The difference in interest between the large businesses and higher class residents is that the large businesses have more power available to block the project. The interest of the large businesses is a bit higher because of the economic value and consequences related to floods in large businesses.

For higher class residents these consequences and thus their interest are smaller than the for large businesses.

There are a lot of stakeholders that have little power, the municipality has to keep them informed but put as little effort as possible in them. Especially the stakeholders that have a high interest have to be kept informed. Some of them are part of the municipality or departments of the province, to keep them satisfied they have to listen to them and keep them up to date. Most of the stakeholders that have little interest also have little power. This is because of the authority related background. Authority related stakeholders have more background power and have a team behind them. Local businesses, daily visitors, tourism and ocean users have to give their opinion by themselves. The only reason they have power is because they have a stake in the economic growth of the eThekwini municipality.

The technique of Murray-Webster and Peter is used for Table 3.2 [38]. This power, interest and attitude table shows the power, interest, attitude and the Active Threat and Opportunity Model (ATOM). The ATOM model is useful in order to be aware of the involved stakeholders. Stakeholders with a lot of power and little interest can be very quiet during the project but in the end they can immediately block the project because of their high power. During a project it is necessary to be aware of these risks. An explanation of this model is shown in Appendix C.3. If stakeholders are identified wrongly, risks can occur. These risks have to be taken into account. In Table 3.2 of the power, interest and attitude of stakeholders it seems that there are no real blockers of this project, because of the positive effects of preventing floods. But if some decisions are made during the process of preventing floods they can block the decision.

Table 3.2: Power, interest and attitude of stakeholders [38]

| Stakeholder | Power | Interest | Attitude | ATOM |
|---|---|---|---|---|
| National government and treasury | High | Passive | Backer | Sleeping Giant |
| SAMSA | High | Passive | Backer | Sleeping Giant |
| Government of KwaZulu Natal Department of Cooperative Government and Traditional Affairs | High | Active | Backer | Sleeping Giant |
| eThekwini municipality | High | Active | Backer | Saviour |
| Provincial Department of Education | Low | Passive | Backer | Acquaintance |
| Provincial Department of Health | Low | Active | Backer | Friend |
| eThekwini Library Service | Low | Passive | Backer | Acquaintance |
| eThekwini Sports and Recreation/Private Stadia | Low | Passive | Backer | Acquaintance |
| PRASA (Passenger Rail Agency of South Africa) | Low | Passive | Backer | Acquaintance |
| South African Police Services | Low | Active | Backer | Friend |
| eThekwini Fire | Low | Active | Backer | Friend |
| KZN Department of Health & private service providers | Low | Active | Backer | Friend |
| Coastal watch | Low | Active | Backer | Friend |
| Insurance companies | High | Active | Blocker | Saboteur |
| Large businesses | Medium | Active | Backer | Friend and Saviour |
| Local businesses | Low | Passive | Backer | Acquaintance |
| Lower class residents | Low | Passive | Blocker | Trip Wire |
| Higher class residents | Medium | Active | Backer | Between a friend and a saviour |
| Tourism organisations | Low | Active | Backer | Friend |
| Ocean users | Low | Active | Backer | Friend |
| Daily visitors beach area | Low | Passive | Backer | Acquaintance |

## 3.3 Summary

There are a lot of departments within the government, province and municipality that take care of water. Besides these departments there are a lot of external stakeholders that are affected by floods. The stakeholders that have to be seriously taken into account, as municipality, are the insurance companies, SAMSA, the national government and the KZN province. They have a lot of power that can influence the project and can block or delay mitigating floods. The departments of the municipality are responsible for the execution of the project. For this reason they have to do what the higher level of the municipality wants to achieve. They can say what they think but can not block the process. These stakeholders have to be kept informed. The less affected stakeholders like ocean users, tourists and daily visitors do not need a lot of attention because they have less power and less interest of mitigating the floods.

# 4 Network Analysis

This chapter gives an analysis of the transport network to gain insight in the consequences of floods on transport in the city of Durban. This is done by evaluating and describing the network near the coast and the Umgeni river. This area is probably the most interesting to investigate, because floods are most likely to occur here. The transport network consists of several transport systems (see Appendix D.1) with their own infrastructure, modalities, management and users. A description of these components of the transport systems helps to get more insight in the network. After the description of the transport systems the trip purpose is looked into and a traffic analysis is done to gain insight in the bottlenecks and problem areas of the transport network.

Numbers given in this chapter are, if not otherwise stated, based on the Integrated Transport Plan of the eThekwini Municipality [20].

## 4.1 Transport Systems

There are four main types of transport systems: road, rail, water and air (see Appendix D.1 for more details). These transport systems consist of different kinds of infrastructure and different modalities. Water and air transport are not used within the city and are therefore not taken into account further. The main used modalities in the network are car, walking, taxis (including mini-bus taxis), buses and trains, as can be seen in Table 4.1. These modalities are using the road and rail transport systems.

Table 4.1: Modal Split of passenger transport in eThekwini [20]

| Mode | Percentage |
|---|---:|
| Car | 30.8% |
| Taxi | 30.5% |
| Bus | 10.2% |
| Train | 3.2% |
| Walk | 25.1% |
| Other | 0.1% |
| **Total** | **100%** |

As given in the table above, little over 40% of all trips are done by public transport (public transport includes taxi, bus and train [20]). One of the major public transport nodes can be found in the Central Business District (CBD) of Durban (see Figure D.2). Since a large amount of the trips are done by public transport, these hubs could thus be useful in case of an evacuation (Appendix D.2).

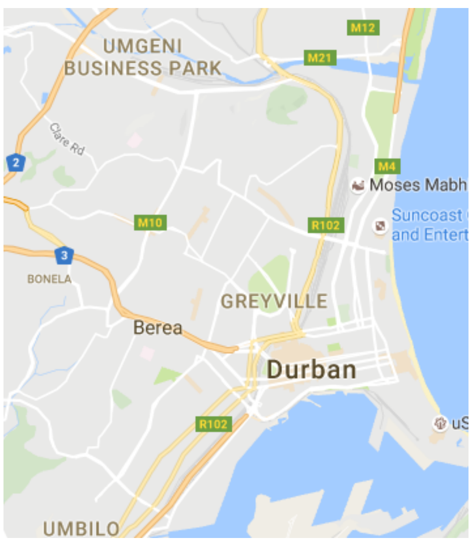
### 4.1.1 Road

There are two aspects of the road transport system that are most important: the roads itself and the modalities on the roads. Roads can be divided in highways and local roads. The most interesting roads are the roads with high capacity since they have the most impact on the network. Roads with high capacity are mostly the main roads going in and out of the city, which are the highways N2, N3, M4 and R102 (see Figure 4.1a). Local roads are less important because they have smaller capacity and play therefore a smaller role in the network. This can also be seen in Figure 4.1b, where the road capacity is given. The thicker lines are the roads with higher capacity, these are partly located near the river, and thus prone to floods.

The modalities for passenger transport that use the road are the private car, (mini-bus) taxis, buses and walking. The most used of these modalities are the private car and the (mini-bus) taxi. Besides passenger transport there is also freight transport, which is on the road done by trucks.

**Private Car**

The most important mode on the road is the private car which is used by almost one third of the road users. This amount of cars can be explained by the fact that only 36.3% of the households have access to one or more motor vehicles, the rest uses other transport modes. According to the Integrated Transport Plan, there were over 240.000 cars in the peak hours in Durban in 2010, with expected increase up to almost 300.000 cars per hour in 2020. Because of this heavy traffic in the peak hours, the municipality discourages the use of private cars by encouraging carpooling [20].




(a) Highways located in the network


(b) Capacity on the roads in vehicles per hour

Figure 4.1: People Mover

**Bus**

Besides cars, buses are also making use of the road transport system. There are three main Public Bus Transport Operators in Durban (Figure 4.2): Durban Transport, People Mover and Mynah [17]. There is one coordinating company, MUVO [39], which makes it possible to travel with the same ticket on different bus companys lines. This is comparable to the OV chip card in the Netherlands.


Figure 4.2: Bus Operators [39]

Durban Transport is the biggest operator of the three. It owns more than 460 buses. It is not only operating in Central Durban, but also in outer regions. This company is operating since 1994 [39].

The people mover is a public bus system operating in the central business district and beach front area of Durban. The people mover has three different lines: Beach Line, City Line and Circle Line (see Figure 4.3b). The frequencies of the buses are four per hour and the operating hours of the people mover are 5-22h [23]. Originally this system is developed for tourists and the FIFA World Cup in 2010.


(a) Area


(b) Routes [17]

Figure 4.3: People Mover

Mynah is the oldest company, it is operating since 1987. At this moment Mynah only has 21 buses [39]. Mynah is operating in the areas around the Central Business District.

**Taxi**
Besides private cars, taxis are a commonly used form of transport by the inhabitants of Durban since there is just a small percentage of the inhabitants that owns a car. In 2010 there were more than 150 metered taxi companies operating in Durban. The total capacity of the legal metered taxis was around 600 cars at that moment [20]. It is unknown how many illegal taxis are operating. The seven most popular metered taxi routes are described in Table 4.2.

Table 4.2: Main metered taxi routes [20]

| Origin | Destination | Average Distance (km) | Time period |
|---|---|---|---|
| CBD | Durban International Airport | 20 | 8:00-19:00 |
| CBD | Pavillion Shopping Centre | 12 | 8:00-19:00 |
| CBD | Gateway Shopping Centre | 14 | 8:00-19:00 |
| CBD | Berea/Overport | 7 | 8:00-22:00 |
| CBD | Sun Coast Casino | 5 | 8:00-00:00 |
| CBD | Internal CBD | 5 | 8:00-02:00 |
| CBD | Residential Suburbs | 25 | 22:00-04:00 |

Besides the metered taxis, there are mini bus taxis. Mini bus taxis are the preferred transport for over 70% of the public transport users. These mini buses do not have particular stops, only designated routes. The routes of these taxis buses have to be known by heart, otherwise it can happen to end up in a totally different place than intended. To get in, the mini buses have to be woven down. The driver's assistants use different hand signals to make clear what the destination of the mini bus [18] is. These mini buses are mainly operating between different cities.

By the introduction of Uber, the taxi industry got even less transparent. Uber is a mobile app which connects travellers with drivers. These drivers use their private cars to transport people through the city. The app automatically calculates the travel fare and transfers it to the driver. There is no data available about the influence of Uber on the metered taxis.

**Walk**
More than a quarter of the population walks to their destination [20]. In this percentage cyclists are also included because there is just a very small amount of people that use a bike. For cycling, the walking ways are used. Most walking trips are made by the inhabitants with the lowest income, and thus happen in the more rural areas of the city. There is a big difference in the amount of people walking during the morning peak and during the evening peak because schools are finished before the evening peak thus these people do not contribute to the evening peak. Most people (more than 80%) feel safe to walk during the day whereas the majority (more than 60%) feel unsafe to walk during night time. An important cause of road traffic fatalities is the conflict between motors and walkers or cyclists [20]. Therefore the aim of the municipality is to improve the walking network: sidewalks, off-road paths, safe crossings, pedestrian bridges etc.

**Truck**
Besides passenger transport there is also freight transported on the roads. For this transport there are three main routes that are used (Table 4.3). These are the N3 West to Gauteng, the N2 South to East London and the N2 North to Pongola. Almost 4500 trucks use the N3 West and the N2 North each day. These roads are connected to the harbour through the CBD, this means that there are a lot of trucks travelling through the CBD.

Table 4.3: Freight transport via road in tons, vehicles per year and vehicles per day [10]

| Network Links | Road tons (mt) | Vehicles/year (million) | Vehicles/day |
|---|---|---|---|
| Gauteng - Durban (N3 West) | 44 | 1,4 | 3836 |
| East London - Durban (N2 South) | 6 | 0,2 | 523 |
| Pongola - Durban (N2 North) | 7 | 0,2 | 610 |
| Total | 57 | 1,8 | 4969 |

There are almost 4000 trucks (see Table 4.3) that have to use the N3 from and to the CBD each day. Since only the traffic volumes in the AM peak are known, some assumptions are made to compare it with the average trucks per day. First it is assumed that there are an equal amount of trucks inbound as outbound, so 2000 trucks in each direction per day. Secondly the trucks are assumed to be spread over the day (8 hours), thus 250 trucks per hour. When one compares this with the capacity and traffic intensity during the AM peak on the N3 (see Table 4.4), it is clear that trucks are just a small amount of total traffic and are therefore not the focus of this report.

Table 4.4: Capacity and AM peak intensity on the N3 [22]

| Roads | Capacity | Intensity |
|---|---|---|
| N3 from CBD | 10000 | 5613 |
| N3 to CBD | 8000 | 7779 |

### 4.1.2 Rail

Next to road, there is a rail network available in Durban. The rail network can be seen in Figure 4.4. The most railways are located alongside the rivers and around the harbour. Because of these locations, they are prone to potential floods. There are several train stations in the area: Congella station, Dalbridge station, Berea station, Durban station, Umgeni station and Springfield Flats station. These stations are connected to each other in this order. Of these stations Durban station is the main and largest station in the area. On these tracks Metrorail [36], owned by PRASA, operates its local passenger trains and Shosholoza Meyl [48] operates its national trains between the main cities in South Africa. During the AM peak hour there are 22.000 inbound passengers, while there is a capacity of 50.000, thus a utility rate is only 44%. During the outbound PM peak hour there is a service capacity of 42.000 whereas there are 17.000 passengers, resulting in a utilisation rate of only 42%. As previous utilisation rates show, the use of this public transport system is far from optimal. The passenger train is therefore highly economically inefficient resulting in unprofitable train trips.

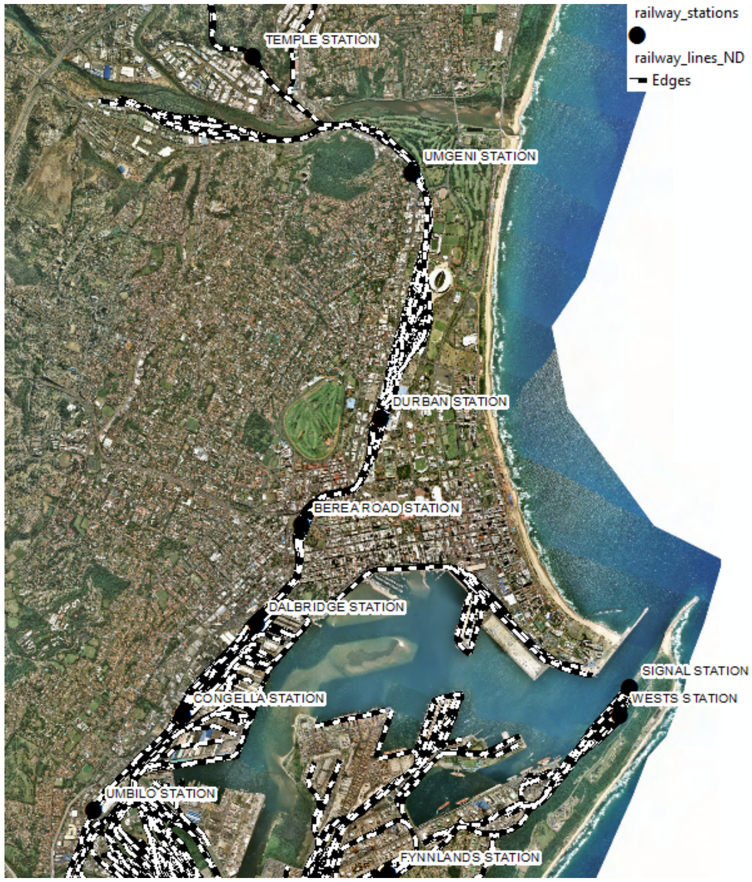



Figure 4.4: Rail network

Besides passenger trains, freight trains travel on the rail network. The freight trains are operated by Transnet [25] and are mainly found around the south side of the harbour. There are three main freight routes from Durban. Table 4.5 shows the amount of freight transported via rail in comparison to road. The rail tracks for freight transport are the same as for public transport. These rail routes can be found in Figure D.2. The Gauteng-Durban link is the most busy link with 24 million tons of freight per year. This link is located south of the N3 and therefore outside of the scope of this project. The remaining freight (5,2 million tons) accounts for only 6% of the total freight transport at the land side from and to the port of Durban. Also rail freight transport is inefficient, unreliable and therefore not cost competitive [20]. Therefore it is considered to be not important enough to focus on in the rest of the report.

Table 4.5: Total amount of freight transport from and to the harbour of Durban by rail and road [10]

| Network Links | Rail tons (mt) | Road tons (mt) |
|---|---|---|
| Gauteng - Durban | 24 | 44 |
| East London - Durban | 0 | 6 |
| Pongola - Durban | 5,2 | 7 |
| Total | 29,2 | 57 |

## 4.2 Trip purpose

People are using the transport systems for different purposes. To gain insight in the problem areas, it is useful to know what the trip purposes are during the morning peak, evening peak and off-peak. The public transport morning peak is from 5:00 until 8:00 and the evening peak is from 15:30 until 18:30 [20]. The car morning peak is from 6:00 until 8:00 and the evening peak is from 15:00 until 17:00 [24]. In Table 4.6 the main trip purposes are shown, the most important origin during the morning peak is home, which is also the most important destination during the evening peak. Work is the most important destination during the morning and the most important origin during the evening. School is also an important destination during the morning. It is thus important to get insight in areas and which origins and destinations can be found where. An important factor which influences the trips is income. The average number of trips per person varies between 4 and 6 per day, increasing with income [20].

Table 4.6: Most important trip purposes

| Trip Purpose | Origin | | | Destination | | |
|---|---|---|---|---|---|---|
| | AM peak | PM peak | All day | AM peak | PM peak | All day |
| Home | 98.1% | 3.2% | 50.1% | 1.8% | 96.4% | 49.5% |
| Work | 1.1% | 83.1% | 22.5% | 45.6% | 2.2% | 22.8% |
| School/College | 0.1% | 9.1% | 22.3% | 48.0% | 0.2% | 22.4% |
| Other | 0.7% | 4.6% | 5.1% | 4.6% | 1.4% | 5.3% |

## 4.3 Traffic Analysis

More than half of the residents encounter traffic congestion problems on their way to work or study [20]. To investigate this congestion, it is important to identify the bottlenecks in the network. In section 4.1 several transport systems within the transport network are described. From now on, the main focus will be on roads since this is most used, and thus most important transport system (see Appendix D.1). The previous paragraph gives information on the capacity of the network, but capacity on its own does not say very much about how busy it is on the network, the load factors are also important. These are given in Figure 4.5, the red lines show the locations with the highest load factors, these are the problem areas in the network. The problem areas are spread over the city.

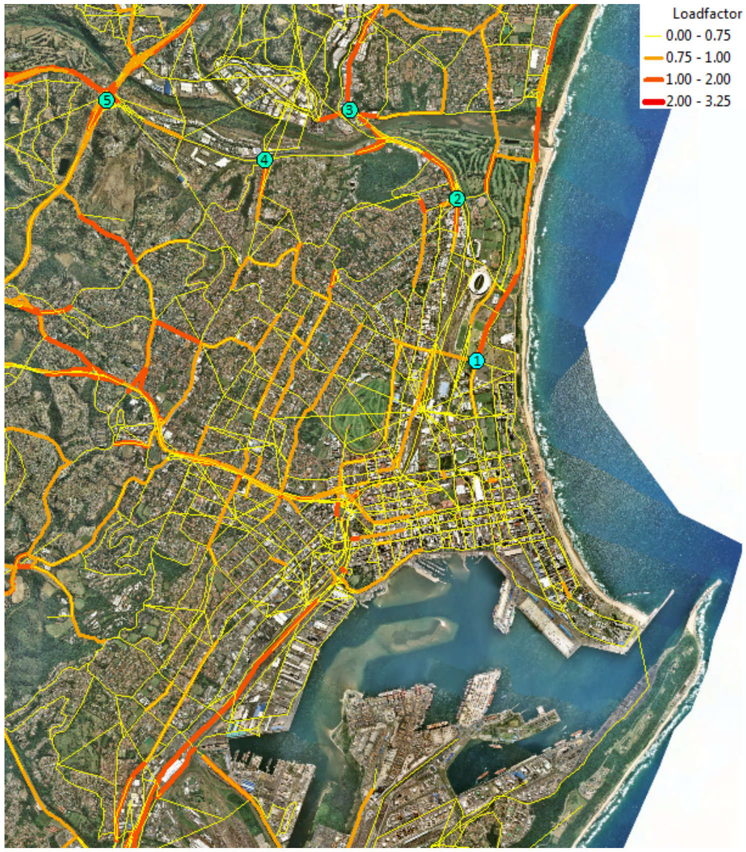



Figure 4.5: Loadfactors of the road network including the most congested intersections in Durban area

### 4.3.1 Bottlenecks

According to Mr. Aucamp (see Appendix B.2 for more details) the biggest bottlenecks in the network are the CBD, the intersections, off-ramps of freeways and signals on one intersections which are not compatible with signals on the next intersection. The most busy intersections according to road statistics [21] can be found in Figure 4.5 as blue dots, these are:

1. Intersection between the M4 and M17
2. Intersection between the R102 and Smiso Nkwanyana road
3. Intersection between the M21 and R102
4. Intersection between the M10 and M19
5. Intersection between the M19 and N2

These intersections in combination with Google Maps Traffic Data (Figure D.3 and D.4) and the load factors of the Emme traffic model determine the bottlenecks of the network (Figure 4.5). The most busy road sections that can be identified from these images are the following:

- Central Business District (north side of the harbour)
- The M4 bridge crossing the Umgeni river

- The crossing of the N2 and N3
- The M10 (especially around the crossing with the M7 and the N3)

In the morning the most traffic flows from the highways to the CBD and Umgeni Business park, where the most companies are located (see Figure 8.1b). In the evening the traffic flows from the business park and CBD to the suburbs where most people live.

The national roads entering Durban are the N2 and N3. The N3 goes from the CBD in Durban to the western suburbs and ends in Johannesburg. The N2 heads along the coast from Cape town in the south of the country to Ermelo in the north. The N2 crosses the N3 in Durban. Besides these national freeways there are metropolitan highways. The M4 heads from the CBD north and south of Durban to the suburbs. The M13 is an alternative road of the N3. Next to the N and M ways, there are provincial main roads. The R102 is an alternative route for the M4. Of course there are also secondary roads and urban streets, but they will not be looked into detail yet.

So the N2, N3, M4, M13 and R102 are the most import roads going out the city center.

### 4.4 Summary

There are two main transport systems in Durban: road and rail. On these transport systems there are both passenger and freight transport. Since the majority of the inhabitants of Durban (over 60%) do not have their own car, they mostly use public transport or walk to their destination. The most used public transport mode is the mini-bus taxi. Most freight is transported via road since the rail network is not used efficiently. Because of the freight trains that happen to drive, a large part of the rail network can be found around the harbour. Also the passenger trains are not efficient and are not used to full extend. Because of the inefficiencies in the rail network, it is not used by a lot of people, therefore the road network is the most important network and thus will be focused on in the rest of this report. During the peak hours the main trip purposes are home, work, and school bound. The traffic analysis shows the most important roads and bottlenecks. The main problem areas are the CBD, the Umgeni Business Park and the M4 to the north.

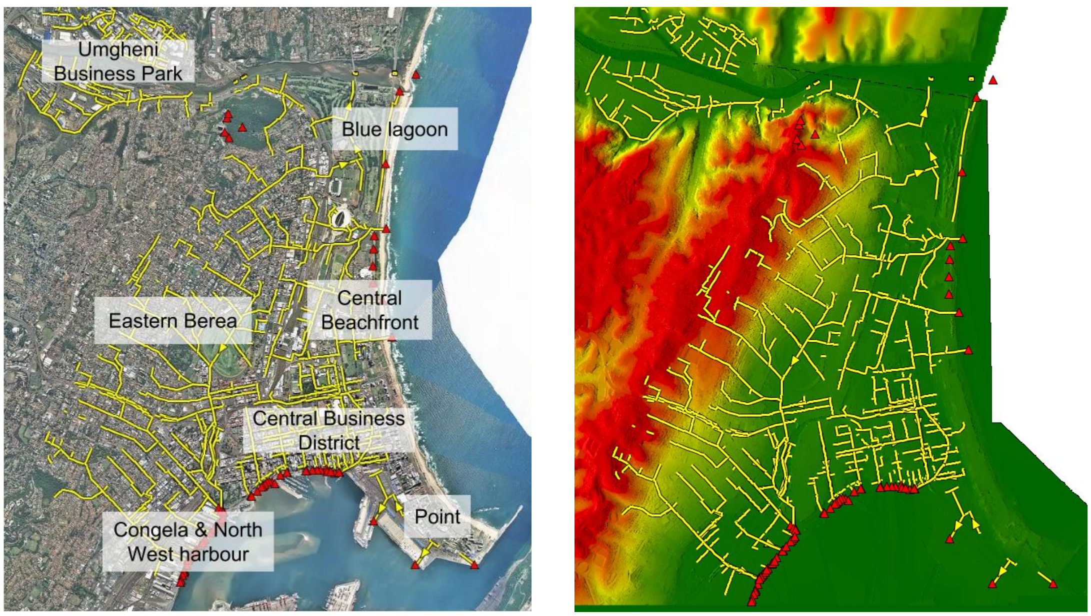
## 5 Stormwater Network Analysis

This part of the analysis is focused on the stormwater network which is in place in the area of interest in Durban. This network is designed to collect and discharge the rainwater which cannot infiltrate into the soil. The area it covers mainly exists of residential and commercial areas and infrastructure. The northeastern part of the area exists of some less developed areas, like sports fields. The system is entirely separated from the sewage network. Most parts of the area are designed to withstand a 1 in 10 years rainfall event, and the Central Business District for a 1 in 20 year rainfall event. More background information can be found in Appendix B.5.

The storm water network is built up by manholes, conduits and outfalls. The water is collected in the manholes, which functions as well as a junction between the conduits. The conduits exist of the stormwater pipes and culverts which transport the water from the catchment areas to an outfall. In total there are about 70 outfalls and 20,000 conduits and manholes in the area of interest. The conduits and manholes are mainly located under the roads in densely built areas, and next to the road in less urban areas. The network discharges the water mainly in the harbour at the south of the area of interest, but also partially at the Umgeni river at the north of the area of interest and in the sea.

## 5.1 Areas within the area of interest

The area of interest has been divided in multiple parts as can be seen in Figure 5.1. A more detailed elevation map can be found in Appendix G. The top of the hill has an elevation of about 150 m and functions as a natural boundary of the system, just as the harbour at the south and the Umgeni river at the North. The hills are fairly steep and end at a level of about 5 to 10 m above sea level. Directly behind the boulevard, which is built at an old dune row, the lowest area can be found at about 2 to 5 m above sea level. This low lying area slopes down from the Blue Lagoon Area towards the harbour. The assumption is made that this has temporarily been the channel of the Umgeni River a long time ago, which could be a reason for the fact that this area is low lying. [50]




(a) Satellite image (b) Elevation map

Figure 5.1: Stormwater network

### 5.1.1 Umgeni business park

The Umgeni business park is built on former flood plains of the Umgeni river, located in the northern part of the area of interest. The Umgeni river confluences with a northern branch in the middle of the area. The area is considered to be flood prone when high Umgeni river discharges are occurring. This is caused by the narrowing of the channel in between this park and the Blue Lagoon area. Multiple measures have been taken to enlarge the cross section at this area, in order to mitigate floods. Smaller local floods might occur when there is a lot of rainfall in this area, but when the rainfall can be discharged in the Umgeni no large problems are expected to occur.

### 5.1.2 Blue Lagoon area

The Blue Lagoon area is located at the north eastern part of the area of interest. It consists mainly of golf courses and only few buildings are located in this area. That is also the reason for the relatively small dimensioned stormwater network in this area. The network does not only discharge its own water, but it is also connected to the more elevated northern part of the Eastern Berea area. There are multiple outfalls which are discharging at the Umgeni river. Furthermore, two smaller outfalls discharge the rainfall of the area at the seaside of the dune ridge. Because the Blue Lagoon area is low lying occasionally floods occur, but this is not regarded as being a large problem because of the undeveloped nature of the area.

#### 5.1.3 Eastern Berea area

This area stretches from the ridge of the hill at the western part of area toward the centre. The area is characterized by its steep slope, which reaches from the top of the ridge. It is separated by the railway tracks from the Blue Lagoon, Central Beachfront, CBD and Congela & Northwest Harbour areas. The northern part of this area discharges the stormwater on the Blue lagoon area and on the sea. The middle and southern part discharge at the northwestern part of the harbour. At the steep hills in the western part not much flooding is expected to occur. The largest problems currently occur at the bottom of the hill, at which the profile of the stormwater pipes and culverts is bending from a relatively steep slope to a very gentle slope from the bottom to the sea. The discharge through the conduits slows down significantly in these areas, which could cause floods if the discharging capacity of the downstream area is insufficient.

#### 5.1.4 Congela & Northwest part of the harbour

This area is the south western part of the area of interest, and stretches from the more residential Eastern Berea area to the harbour. It exists mainly of businesses and is crossed by the railway line and highway. It is located at the bottom of the hill and is low lying, facing potentially similar problems as the Eastern Berea Area. Furthermore, the majority of the water from the Eastern Berea area is discharged at where this area borders the CBD.

#### 5.1.5 Point area

The Point area is the peninsula at the south eastern part of the area of interest. The area exists of residential areas, businesses and tourist attractions. It is mainly built upon an old dune ridge, and is therefore not low lying. This combined with the proximity of the sea and harbour makes this part relatively flood resilient.

#### 5.1.6 Central Beachfront

The Central Beachfront is defined as the area in between the Blue Lagoon area, Eastern Berea area, CBD and the sea. The western part of this area is mainly a residential area, the other areas mainly businesses and sports facilities. The area behind the dune ridge is low lying, at about 3 m above sea level. Three large outfalls discharging at the sea are located in this area. The stormwater of the northern part of the Eastern Berea area also flows through the conduits connected to these outfalls. The outfalls are located at the end of three piers.

#### 5.1.7 Central Business District (CBD)

The CBD is the central and oldest area of the city. It is bound by the railway tracks in the west, the harbour in the south, the sea in the west and the Central Beachfront in the North. The stormwater network of this area is isolated from other parts of the network in the area of interest, and discharges via multiple outfalls on the harbour bay. The eastern part of the area is the lowest part of the city, and is located about 2 m above sea level. The stormwater network is relatively large in this part of the CBD, because of the very small slopes of the conduits. The tidal motion penetrates several hundreds of meters in the network. This effect combined with the small slopes, and consequently small flow velocities lead to siltation problems in the main conduits. Furthermore, the outfalls of the CBD area can get entirely blocked during spring tide, which is expected to limit the discharging capacity. Another large problem is blockage and clogging of the network. The manholes connecting the smaller pipes get frequently blocked by litter and belongings of homeless people who this in trash bags in the manholes.

### 5.2 Summary

Based on this analysis the conclusion can be drawn that the following three problems can occur in the stormwater network:

- The low-lying area behind the dune row is expected to be flood prone during large rainfall events and high water levels at sea.
- The Umgeni Business Park is sensitive to floods caused by large river discharges. The water level in the river could also be affected by water levels at sea.
- The transition from the stormwater network with a large slope at the hill area to the part of the network with a small slope could cause flooding problems.

## 6 Hydraulic & Hydrological Analysis

This section focuses on the gathering of data from a hydraulic and hydrological perspective. The different parameters that are being investigated can be divided into seaside parameters and land side parameters. From the land side rainfall is the most important parameter as it will have a great impact on the severity of the floods in the city. The river discharge from the Umgeni is the other land based parameter that may or may not play an important role in urban flooding. From the sea side several parameters could play an important role in blocking the rainwater outfall system, which is the focus of this project. The occurring tide and possible storm surges will have a clear effect on the water level and also the wave set-up could play an important role. This chapter will be finished with a section on the prevailing weather systems influencing the before described parameters.

### 6.1 General Method for Extrapolating Data

Depending on the type of parameter and the available data a different approach will be applied to obtain relevant input for the construction of the different flood scenarios that will be investigated. For most parameters the goal is to obtain design values for events of different return periods. Based on measured data either a Peak over Threshold (PoT) or Yearly Maxima (YM) method can be applied to extrapolate the data to return periods greater than the period of the measurements. For a data set that spans at least 20 years a YM method can be applied but when this is not the case a PoT analysis should be applied. For the PoT analysis a threshold is set above which all data points are seen as extreme events to increase the number of extreme events with respect to the YM method. From the obtained data points an Empirical Cumulative Distribution Function (ECDF) can be used to fit a stochastic distribution which can then be used to extrapolate to design values for return periods not yet observed. The Cumulative Distribution Function (CDF) is defined as the probability that a random variable $\underline{x}$ is smaller than a certain value $x$ which is denoted by [53]:

$$P(\underline{x} < x) = F_{\underline{x}}(x) \tag{6.1}$$

Depending on whether a PoT or YM analysis is applied different stochastic distributions will be fitted to the CDF yielding the Maximum Likelihood estimates of the parameters of the fitted stochastic distributions. According to the theory, YM observations are distributed by a Generalised Extreme Value (GEV) distribution whereas peak excesses over a threshold occur according to a Poisson process with rate $\lambda$ and are independently distibuted with a Generalized Pareto (GP) distribution [5]. $\lambda$ Is defined as the average number of observations over the threshold per year. Subsequently the $m$-year return value can be found by solving:

$$1 - F_{\underline{x}}(x) = \frac{1}{\lambda_{\underline{x}} \cdot m} \tag{6.2}$$

In case of the YM method there is only one observation per year and therefore $m$ equals 1. For a PoT analysis it is important to make sure that only 1 maxima per event is measured. This is done by only taking peaks, which means that the measured value should be higher than both the preceding and succeeding measurements, and also by applying a minimum peak width. The minimum peak width will make sure that there aren't any peaks measured within a certain distance of another higher peak. Depending on the type of parameter the peak width can differ or can be completely neglected.

To check how well the stochastic distributions fit the empirical distributions use is made of a Normalised Mean Square Error (NMSE) Goodness of Fit test which is given in the equation below:

$$NMSE = 1 - \frac{\frac{1}{N}\Big(X_{REF}(i) - X(i)\Big)}{\left(\frac{1}{N}\Big(X_{REF}(i) - \overline{X}_{REF}\Big)\right)^2} \tag{6.3}$$

Where $X_{REF}$ is the fitted stochastic distribution and $X$ the empirical distribution. NMSE converges to 1 if the fitted and empirical distributions are identical.

Above mentioned procedure will be applied on several variables depending on the data availability and the nature of the variable. For other variables which are not suitable for extreme value analysis another approach will be applied to investigate the probability of occurrence.

## 6.2 Landside Parameters

As mentioned above both the rainfall as the river discharge from the Umgeni will have an effect on the flooding of Durban and are therefore being investigated in this section.

### 6.2.1 Rainfall

For analysing the rainfall in Durban use has been made of 5 rain gauge stations spread around town. These gauges have been gathering data from 1987-2016 and yield measurements every 5 minutes. The gauges are supposed to measure continuously but measurements show that they often show malfunctions which results in missing data. The amount of days that are missing is dependent on the gauge but can be as much as a third of the time. An overview of where the gauges are located is given in Figure 6.1.

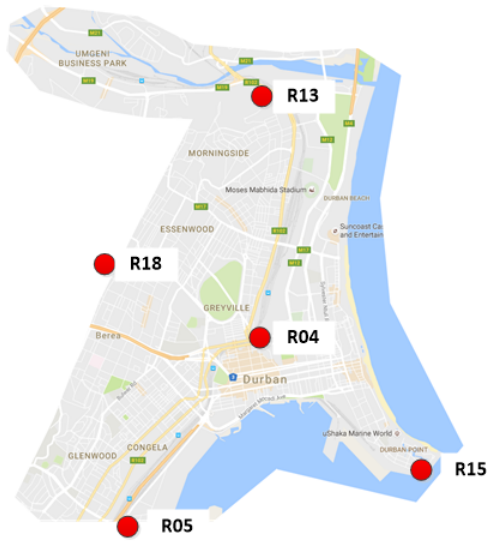



Figure 6.1: Location of the rain gauges in Durban

As can be seen all gauges are either within the field of interest or on the boundary of it. All gauges are located within 10km of each other and therefore all gauges provide important data. The goal is to determine a realistic rainfall event for certain return periods for that is the same for the entire field of interest. Therefore more than one gauge has been used to avoid any negative effects from incorrect measurements and to account for local differences in rainfall per gauge specifically.

For explanation purposes and to avoid repetition only station R18 will be treated here whereas the data for all other stations can be found in Appendix E. The 5 minute interval rainfall data has been summed per day to obtain daily rainfall in millimetres. By doing this the intensity of a single rainfall event is lost from the data and also two subsequent days with a lot of rainfall are seen as separated events. This method was chosen after visually inspecting the daily rainfall and noting there were only a few events where consecutive days had significant rainfall therefore not introducing too many underestimations. Not applying this method would severely increase the difficulty and the time consumption of this analysis and therefore regarding the time span of this study it was opted to apply this method. A plot of the daily rainfall over time for station R18 is shown in Figure 6.2 and the plot for all stations can be found in Appendix E in Figure E.1.

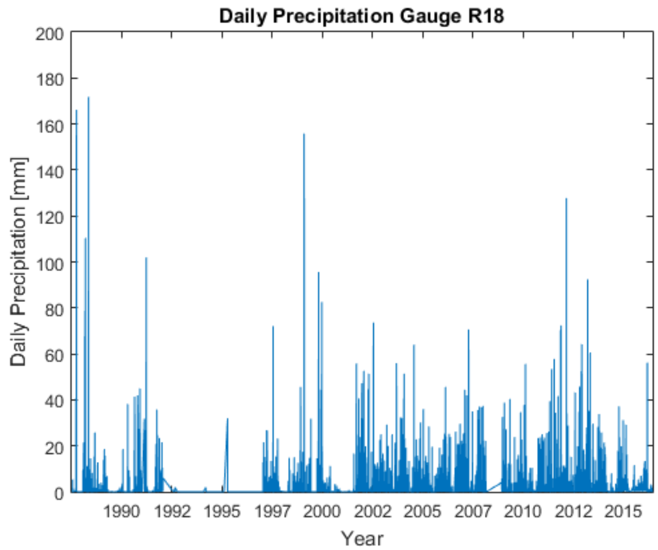



Figure 6.2: Daily rainfall for the R18 rainfall gauge

As can be seen gauge R18 contains multiple gaps where no or very little rainfall has been measured. As said before this is not because there wasn't any rainfall at the time but because of malfunctioning equipment. The data set like all other stations spans from around 1987-1988 until 2015-2016. Because this is almost 30 years both a PoT and a YM method could be applied depending on the amount of gaps and the the best fit. When using a PoT analysis there is no 'best' threshold available. The threshold has to be chosen in such a way that not too many peaks exceed the threshold, as only extreme values are of interest, but also not too little peaks exceed the threshold as more data points result in a more reliable extrapolation. Also the duration that is used in the correction for the intensity of the Poisson process of extreme occurrence is arbitrary in this case because the data set does not cover every day and has multiple gaps of varying sizes. According to assistant professor of Probabilistic Design at Civil Engineering faculty of the TU Delft O. Morales-Napoles there a multiple ways of dealing with this, one way is to exclude the year from the duration if it does not contain any threshold excesses. For the YM method a similar approach was used by excluding a year if the rainfall was significantly lower than all others which would suggest little measurements or malfunctions in the measurements.

As explained above to obtain values for higher return periods the PoT and YM data points should be used to construct a CDF and then fitted by a GP and GEV distribution respectively. The resulting CDFs and fitted distributions for station R18 are given in Figure 6.3 and for all stations in Figure E.2 in Appendix E.

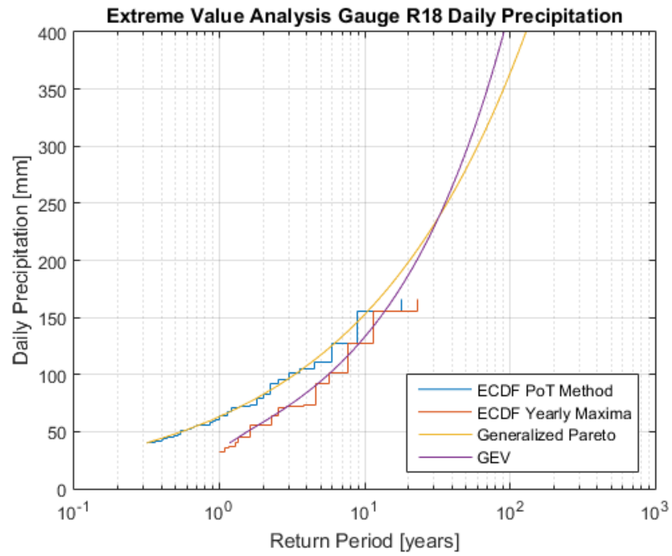



Figure 6.3: Extreme value analysis for the R18 rain gauge

As can be seen from the graph both methods result in slightly different distributions. For both methods the extreme values for larger return periods have been computed and shown in Table 6.1 for all 5 stations including the NMSE Goodness of Fit parameter. Some things can be observed from all the return values. Station R15 yields far lower results for both methods than all other stations. According to Angus Gowar, the rainfall expert at the municipality who operates the gauges, this is the result of exhaust gasses from nearby factories that influence the amount of precipiations that falls at that location. These effects are very local and therefore it was decide to exclude results of station R15 from any further use.

Stations R04 and R05 give very similar results for both methods whereas station R18 and R13 show much higher values for the YM method. Especially for station R13 the YM method results in unrealistic return values. The better NMSE fit for all PoT methods also shows that these results are more reliable which is expected as they make use of more data points. For these reasons the YM results are also excluded for any further use which means that the PoT return values for stations R04, R05, R13 and R18 will be used to construct representative daily rainfall for greater return periods.

Table 6.1: Daily rainfall in mm for extreme return periods per station determined with both a Peak over Threshold and a Yearly Maxima method

| | **R018** | | **R04** | | **R05** | | **R13** | | **R15** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Return Period** | **PoT** [mm] | **YM** [mm] | **PoT** [mm] | **YM** [mm] | **PoT** [mm] | **YM** [mm] | **PoT** [mm] | **YM** [mm] | **PoT** [mm] | **YM** [mm] |
| 2 | 82.5 | 58.3 | 88.1 | 59.7 | 93.1 | 69.1 | 86.5 | 53.5 | 83.2 | 68.2 |
| 5 | 117.2 | 94.2 | 116.1 | 88.0 | 125.6 | 106.2 | 115.7 | 92.8 | 100.3 | 90.9 |
| 10 | 152.6 | 132.8 | 140.5 | 112.6 | 155.6 | 138.2 | 141.7 | 147.6 | 113.0 | 106.4 |
| 20 | 198.3 | 187.1 | 168.2 | 141.7 | 191.0 | 175.7 | 171.7 | 242.9 | 125.6 | 121.4 |
| 30 | 231.1 | 228.9 | 186.1 | 161.4 | 214.7 | 201.0 | 191.2 | 328.8 | 132.8 | 130.2 |
| 40 | 257.6 | 264.3 | 199.6 | 176.8 | 233.0 | 220.6 | 206.1 | 409.3 | 137.9 | 136.5 |
| 50 | 280.1 | 295.6 | 210.5 | 189.7 | 248.1 | 237.0 | 218.2 | 485.9 | 141.8 | 141.4 |
| 60 | 300.0 | 324.0 | 219.8 | 200.8 | 261.1 | 251.0 | 228.6 | 559.7 | 145.1 | 145.4 |
| 70 | 317.9 | 350.2 | 227.9 | 210.6 | 272.5 | 263.5 | 237.6 | 631.1 | 147.8 | 148.8 |
| 80 | 334.2 | 374.7 | 235.1 | 219.5 | 282.8 | 274.7 | 245.7 | 700.6 | 150.1 | 151.7 |
| 90 | 349.3 | 397.7 | 241.5 | 227.6 | 292.1 | 285.0 | 253.0 | 768.4 | 152.1 | 154.3 |
| 100 | 363.4 | 419.5 | 247.5 | 235.1 | 300.7 | 294.5 | 259.6 | 834.8 | 154.0 | 156.6 |
| 110 | 376.6 | 440.3 | 252.9 | 242.1 | 308.6 | 303.2 | 265.8 | 900.0 | 155.6 | 158.8 |
| 120 | 389.1 | 460.2 | 258.0 | 248.6 | 316.0 | 311.5 | 271.5 | 964.0 | 157.1 | 160.7 |
| 130 | 401.0 | 479.3 | 262.7 | 254.8 | 323.0 | 319.2 | 276.9 | 1027.1 | 158.5 | 162.5 |
| 140 | 412.3 | 497.8 | 267.1 | 260.6 | 329.6 | 326.6 | 281.9 | 1089.2 | 159.8 | 164.1 |
| 150 | 423.1 | 515.6 | 271.3 | 266.2 | 335.8 | 333.5 | 286.7 | 1150.4 | 161.0 | 165.7 |
| 160 | 433.4 | 532.8 | 275.2 | 271.5 | 341.7 | 340.1 | 291.2 | 1210.9 | 162.1 | 167.1 |
| 170 | 443.4 | 549.5 | 279.0 | 276.5 | 347.4 | 346.5 | 295.5 | 1270.7 | 163.2 | 168.5 |
| 180 | 453.0 | 565.8 | 282.6 | 281.4 | 352.8 | 352.5 | 299.6 | 1329.8 | 164.1 | 169.8 |
| 190 | 462.2 | 581.6 | 286.0 | 286.0 | 357.9 | 358.4 | 303.5 | 1388.3 | 165.1 | 171.0 |
| 200 | 471.2 | 597.1 | 289.3 | 290.5 | 362.9 | 364.0 | 307.3 | 1446.2 | 165.9 | 172.1 |
| **NMSE** | 0.990 | 0.983 | 0.992 | 0.970 | 0.996 | 0.987 | 0.994 | 0.979 | 0.992 | 0.960 |

To check how well the different stations match each other the mean has been computed for different return periods as well as the percentual deviation from the mean per station. This is shown in Table 6.2.

Table 6.2: Resulting rainfall from PoT analysis and their deviations in % from the mean

| | **R018** | | **R04** | | **R05** | | **R13** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Return Period** | **mm** | **% dev** | **mm** | **% dev** | **mm** | **% dev** | **mm** | **% dev** | **mean** | **mean % dev** |
| 2 | 82.5 | -5.8 | 88.1 | 0.6 | 93.1 | 6.4 | 86.5 | -1.2 | 87.5 | 3.5 |
| 5 | 117.2 | -1.2 | 116.1 | -2.2 | 125.6 | 5.9 | 115.7 | -2.5 | 118.7 | 2.9 |
| 10 | 152.6 | 3.4 | 140.5 | -4.8 | 155.6 | 5.4 | 141.7 | -4.0 | 147.6 | 4.4 |
| 20 | 198.3 | 8.8 | 168.2 | -7.7 | 191.0 | 4.8 | 171.7 | -5.8 | 182.3 | 6.8 |
| 50 | 280.1 | 17.1 | 210.5 | -12.0 | 248.1 | 3.7 | 218.2 | -8.8 | 239.3 | 10.4 |
| 100 | 363.4 | 24.1 | 247.5 | -15.5 | 300.7 | 2.7 | 259.6 | -11.3 | 292.8 | 13.4 |
| 200 | 471.2 | 31.7 | 289.3 | -19.1 | 362.9 | 1.5 | 307.3 | -14.1 | 357.7 | 16.6 |

It is clear that for larger return periods the stations begin to differ more from each other. Especially station R18 starts deviating more when the return periods get larger. On average the deviations are around 5% for return periods up until 20 year and 10-15% for the return periods up to 200 years. Given the data that was available, local factors and equipment malfunctions, this is a very reasonable spread. Because the remaining stations are spread around the area of interest the mean of these stations will be used as representative precipitation for the entire area.

As mentioned before the distribution of the rainfall events was lost when taking daily rainfall. It would be unrealistic to apply the daily rainfall with a uniform distribution into the drainage model and therefore another more realistic distribution should be applied. This is done by using existing design distributions for the area of Durban by an unknown consultancy firm and scaling the total amount of rainfall to the return volumes as determined with the extreme value analysis. The same distribution is used by the municipality for storm water designs. The consultants have fitted a Type II distribution on several rain gauge measurements to obtain the distribution in which the daily precipitation occurs. This distribution is used by the municipality for designs and is therefore considered to be suitable for this study as well. To get insight in what the distribution looks like a random rainfall event of 180mm daily precipitation is plotted in Figure 6.4. As can be seen from the figure the peak of the event is very intense with short duration and most of the precipitation occurs within a 3 hour time span.

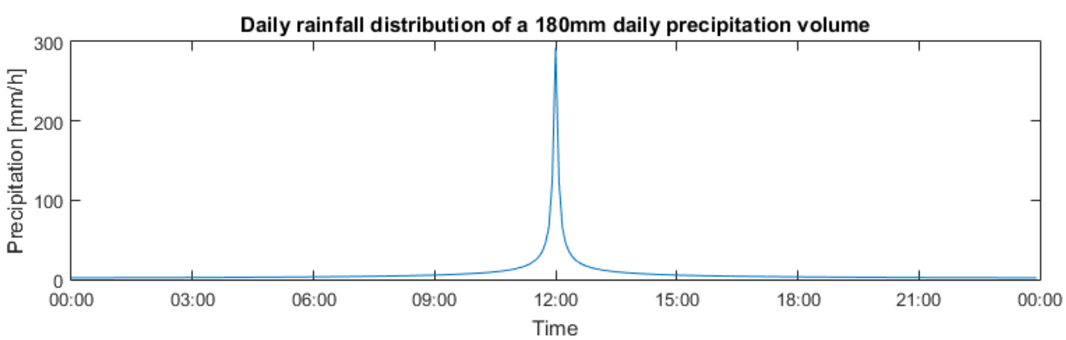



Figure 6.4: Daily distribution of a rainfall event

### 6.2.2 Umgeni River Discharge

The Umgeni river flows along the Northern boundary of the area of interest and flows directly into the sea. The discharge and accompanying water levels in this river could have major effects on the outflow capacities of the drainage system. Combined with a high water level at sea the river itself could also hypothetically flood its banks and cause severe damage. Unfortunately no time series of the discharge was available to perform an extreme value analysis. Therefore the return values for the discharge are obtained from a Flood Risk Assessment Study performed by the Durban Metropolitan Council in 2002 [12]. Besides discharges for several return periods also the discharge in case of a dam break of the Inanda Dam is given in the report.

This is quite an old study but there have been no severe changes in the river catchment since then. In April 2014 contractors started with the canalisation of the Umgeni just East of Connaught bridge for 1km along the Umgeni bussiness park to create more room for the river and reduce the probability of flooding. This was done by widening the river and placing gabion embankments as bank protection. Gabions are steel nets filled with rocks which are widely used as bank or bed protection. The construction was finished in January 2016 but contractors are currently still working on post-assessing the construction. This however has no effects on the river discharge as it does not influence the catchment area of the river. The from the study obtained discharges and accompanying return periods are shown in Table 6.3 for two locations. Connaught bridge is located 2km upstream of the river mouth.

Table 6.3: Umgeni river discharges

| Return period [years] | 2 | 5 | 10 | 20 | 50 | 100 | 200 | Dam Break |
|---|---|---|---|---|---|---|---|---|
| Connaught Bridge [m3/s] | 205 | 645 | 1240 | 2155 | 3890 | 5345 | 6640 | 18873 |
| River mouth near sea [m3/s] | 210 | 655 | 1245 | 2171 | 3905 | 5345 | 664 | 18684 |

## 6.3 Seaside Parameters

The urban flood problem of Durban might be increased by blockage of the outlet system from the seaside. Such a blockage will be induced by a deviation of the water level resulting in a (temporarily) increased water level at the outlets. The remainder of this section will elaborate on the possible contributions of such an increase in water level.

### 6.3.1 Tide

The first expected contributor is the astronomical tide at sea. To be able to say something about the tide at the Durban coast a quick analysis of the tidal signal is performed. This analysis was done with the use of data from a water level gauge which was deployed near the harbour entrance. The data was made available by the Hydrographic office of the South African Navy and contained a period of two years starting from September 2014. The data was loaded into Matlab and analysed with a tidal fitting toolbox [28]. This toolbox returns the name, speed, period, amplitude and phase of a measured signal. Since the focus is on water levels the constituents with the highest amplitude are considered to be most important. A summary of the five largest constituents is presented in Table 6.4 below:

Table 6.4: Summary of most important tidal constituents

| Constituent: | Amplitude [m]: | Angular velocity: [degree/h] | Phase [rad]: | Period [d]: |
|---|---|---|---|---|
| 'M2' | 0.5731 | 28.984 | -1.7321 | 0.5175 |
| 'S2' | 0.3036 | 30.000 | 2.3488 | 0.5000 |
| 'N2' | 0.1070 | 28.440 | -3.0026 | 0.5274 |
| 'K2' | 0.0741 | 30.082 | -1.0265 | 0.4986 |
| 'K1' | 0.0466 | 15.041 | 2.8289 | 0.9973 |

Interested readers can find the complete list of constituents in Appendix F. Despite the fact that these components are obtained with only two years of data they match reasonably well with values found in literature (see for instance [4]).

The found combination of tidal constituents is used to plot the astronomical tide over a longer time span in order to get better insight in the behaviour of the tide at the Durban coast. Figure 6.5 shows the Durban tide for a period of 10 years.

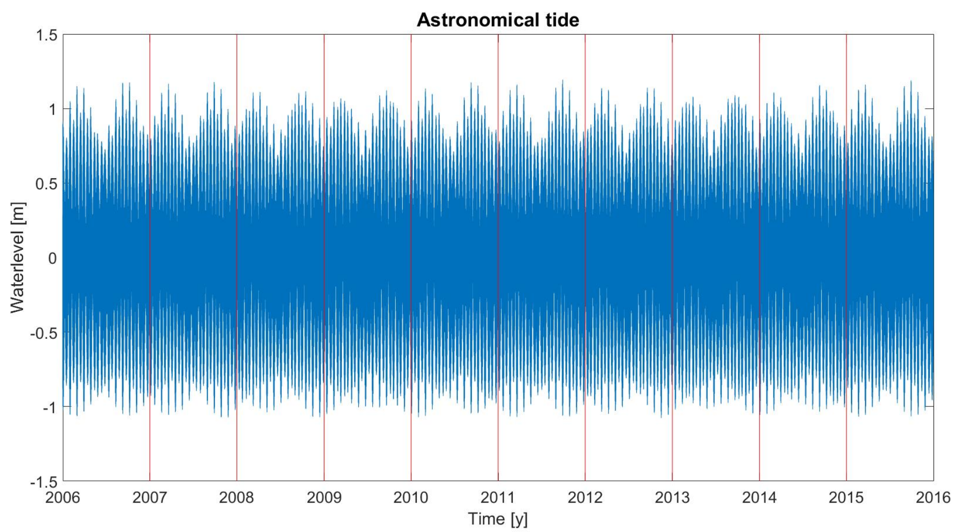



Figure 6.5: Representation of astronomical tide w.r.t. MSL

As can be seen from the figure there seem to be fluctuations of the height of the spring tide within a year. Vertical lines at the first of January of each year are added to be able to check visually whether this phenomenon is in phase with the years or slightly shifts, meaning that the higher spring tides might occur in a different season after a couple of years. Based on this figure with 10 years of tide the phenomenon seems to be in phase. This observation implies that certain distinct periods during the year will face higher spring tides than others. This might be of importance later on when different parameters have to be coupled to scenarios and certain combinations might not coincide due to seasonal variations.

Besides the just mentioned fluctuations on a seasonal time scale, there are also fluctuations on a smaller and larger time scale. The fluctuations on the smaller time scale are caused by the positioning of the moon and sun with respect to the earth and is called spring neap tidal cycle. The spring neap tidal cycle varies with the lunar month of 29.5 days and contains two spring- and neap tides. The large cycle is called the nodal cycle and has a cycle of 18.6 years [2]. In order to come up with realistic water levels forced by the tide the above described fluctuations have to be elaborated further:

**Elaboration seasonal cycle:** In order to get spring tide variations on the seasonal time scale, use is made of the PoT method. For this application the threshold should be low enough to capture all peaks, moreover only one peak should be taken into account per spring and corresponding neap tide. This is achieved by requiring the peak to be at least 14.75 days, being half of the total cycle, wide. The result of this procedure is plotted in the figure below (Figure 6.6):

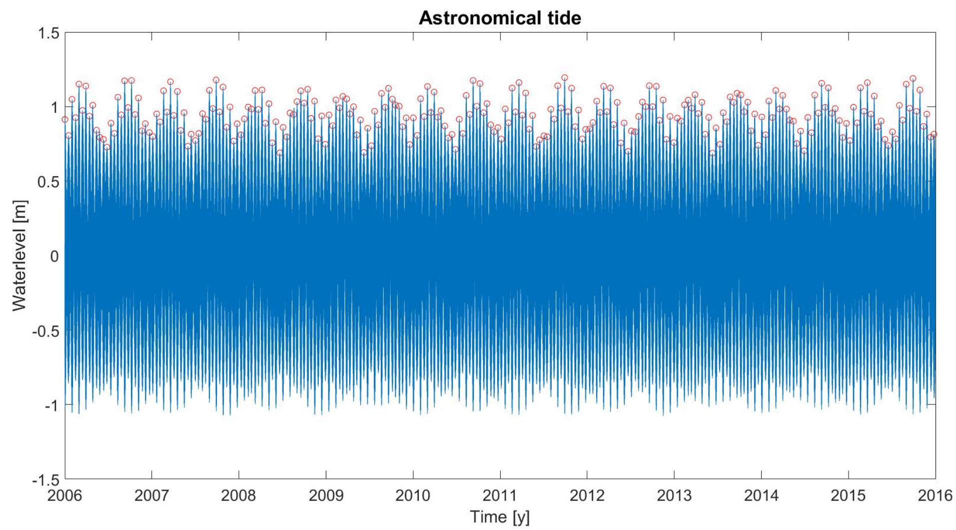



Figure 6.6: Indication of spring peaks in astronomical tide w.r.t. MSL

The red dots in the plot indicate the locations of all the peaks in this domain of 10 years. In total there were found 248 as was expected (248 multiplied by the peak width of 14.75 days divided by 365 days results in 10 years). The water levels of the peaks were analysed by creating bins of water level height and subsequently search for the number of peaks in a certain bin by adopting the height of the threshold. The result of this analysis is showed in the table below (Table 6.5).

Table 6.5: Distribution of spring tide peaks over water level bins

| Range [m]: | Number of peaks: | % of total: |
|---|---|---|
| 0.65-0.80 | 37 | 14.92 |
| 0.80-0.95 | 91 | 36.69 |
| 0.95-1.10 | 85 | 34.27 |
| >1.10 | 35 | 14.11 |
| Total: | 248 | 100 |

As can be seen from the table the peaks are distributed quite equally around a mean of approximately 0.95. In more detail the mean was found to be 0.942m with a maximum of 1.19m and a minimum of 0.69m all with respect to Mean Sea Level (MSL).

**Elaboration neap spring tidal cycle:** To get insight in the differences in high tides within the spring neap tidal cycles again use is made of the PoT method. For this purpose the peak width is taken as 12.25 hours which corresponds to one high-low tide cycle. This approach filters all the high tides in the domain as can be seen from Figure 6.7.

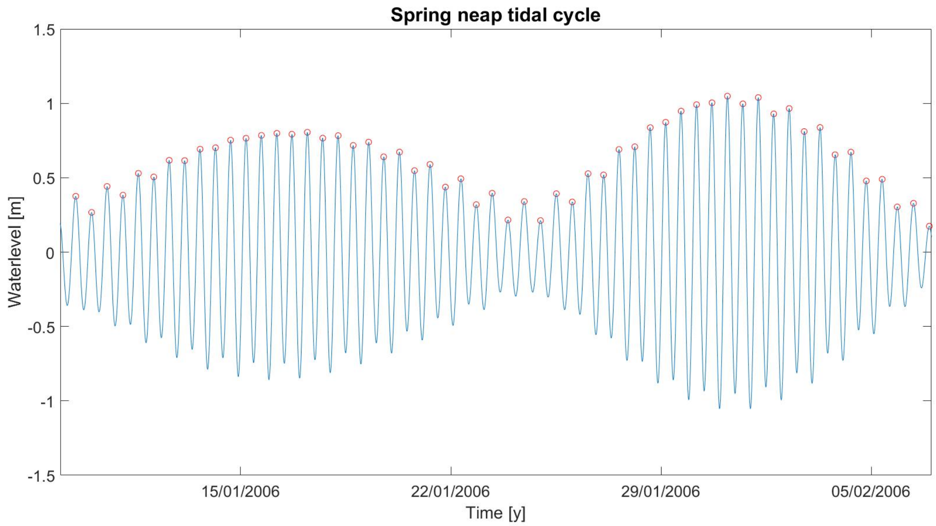



Figure 6.7: Indication of high tides in spring neap tidal cycle w.r.t. MSL

Note that this figure only shows an example of the result of the method on one spring neap tidal cycle but that all high tides in the domain of 10 years are taken into account. After dividing the water levels of the high tides over bins the below table (Table 6.6) can be created. In addition to this table the mean was found to be 0.63m, the maximum 1.19m and the minimum 0.11m.

Table 6.6: Distribution of high tides over water level bins

| Range [m]: | Number of peaks: | % of total: |
|---|---|---|
| 0.10-0.35 | 1166 | 16.52 |
| 0.35-0.60 | 1970 | 27.92 |
| 0.60-0.85 | 2513 | 35.61 |
| 0.85-1.10 | 1339 | 18.97 |
| >1.10 | 69 | 0.98 |
| Total: | 7057 | 100 |

**Elaboration Nodal Cycle** Due to the very long duration of the nodal cycle it was not captured as a tidal constituent in the analysis of the available data of 2 years. Therefore use of literature is made to find a realistic amplitude of the nodal cycle. From [8] it was found that the highest level of this cycle exceeds mean high water springs by approximately 30cm which was also found from figure 4 in [49]. Regarding this, a value of 30cm is expected to be realistic and will be taken into account when creating scenarios. It should be noted that this nodal constituent has a sinusoidal behaviour. The result of this is that there is also quite a long period of time in which this constituent will lower the water level.

The obtained values give insight in the magnitude of water level changes w.r.t. MSL at the Durban coast as a result of the tide on different time scales. Table 6.7 lists all cycles to indicate what relative changes in water level can be expected:

Table 6.7: Summary of phenomenon causing changes in water level (w.r.t. MSL)

| | Min [m]: | Mean [m]: | Max [m]: | Time scale of variation: |
|---|---|---|---|---|
| High tides: | 0.12 | 0.63 | 1.19 | 12.25 hours |
| Spring tides: | 0.69 | 0.94 | 1.19 | Seasonal |
| Nodal cycle: | Mean high water +-30cm | | | 18.6 years |

From the table above it can be seen that the high water level will increase on average approximately 0.30m between a normal high tide and a spring tide. During certain periods in the year this difference is likely to be higher and in the range of almost 0.60m. Based on Figure 6.5 this increased height seems to be most likely around spring and autumn. Besides this there is the nodal cycle with a period of 18.6 years which might add (ór subtract) an additional 30cm to the tide. All these parts together can raise the water level of a high tide up to 0.90m in a worst case scenario.

Several of the outlets are situated within the harbour which potentially would mean that the tidal influence might differ at those locations. Due to the fact that the harbour basin is quite small compared to the length of the tidal wave the small basin approximation is assumed to be applicable. In the past there have been measurements that were searching for potential deformations of the tide in the harbour. Unfortunately this data was not available, but the differences were told to be negligible supporting the small basin approximation.

To summarise: this section on the tide found a way to indicate the range of water level changes due to the tide in combination to a time scale and percentage of occurrence. These components together make it possible to indicate the effect of the tide on the water level in relation to potential blocking of the outlets and can be used in making scenarios.

### 6.3.2 Surge

The next parameter which might be a potential contributor to a high water level is surge. Surge is the phenomenon of increase of water levels caused by atmospheric conditions. Surge is considered to be composed of a part due to wind over long fetches and of a part caused by low atmospheric pressures. For the analysis of the surge again use is made of the tidal gauge data near the harbour mouth. Since this gauge is situated quite sheltered within the breakwater the effect of wave setup on the measurements is considered to be negligible compared to water level differences as a result of the tide and surge. In order words: the measurements contain tidal- and surge information only. In the previous section the tidal constituents of importance were already obtained and used to create a tidal signal. If this tidal signal is created for exactly the same period as the measurements one can look at the differences between the measurements and the tidal signal. This difference is an indicator for the magnitude of water level changes caused by surge due to the fact that the measurements were composed out of the tide and surge only. It should be noted that the residual was measured with respect to Chart Datum(CD) whereas the tide was created around Mean Sea Level. From South African Tide Tables 2016 [42] it was found that the distance from CD to MSL for Durban is 1.11m. Before they can be subtracted the tide was increased with 1.11m to bring them to the same reference level. The measurement vs. tide and the residual is shown in the figure (Figure 6.8) below:

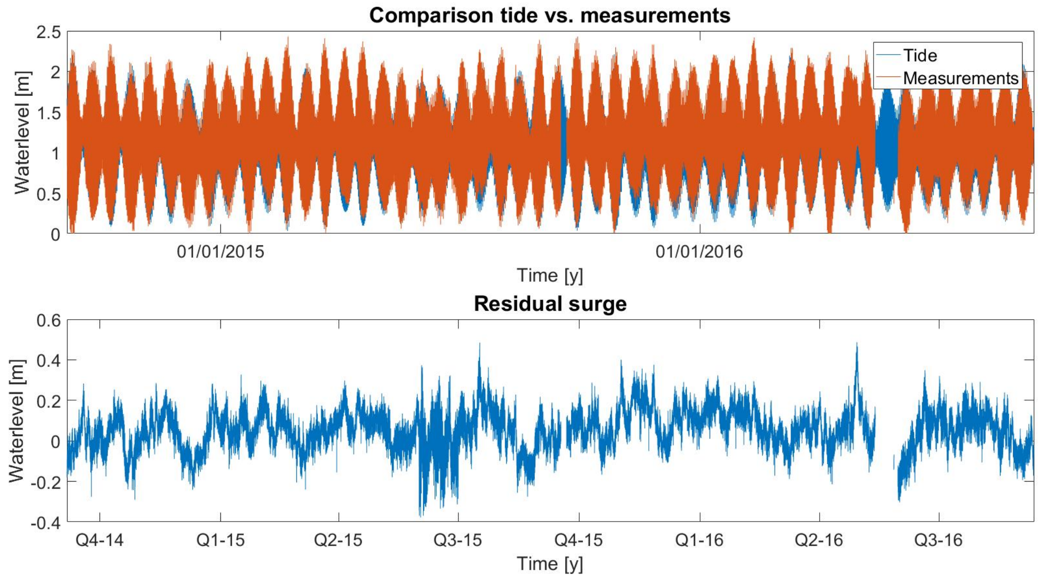



Figure 6.8: Comparison data with tide to obtain surge

As can be seen from the plot on the residual surge there are both positive and negative values. The existence of negative values is quite interesting and supports the idea that changes in atmospheric pressure are of importance as well. From South African Tide Tables 2016 [42] it was found that the atmospheric pressure around the South African coast is 1017.0mb on average and moreover that highs of 1040.0mb and lows of 990.0mb are observed. With an approximate water level change of 1cm per millibar this change could be -23cm for highs and +27cm for lows. From the residual a minimum of -0.38cm and a maximum of 0.49cm was obtained, indicating that other factors play a role as well.

In South African Tide Tables 2016 [42] it was found that ports on the South East coast of Durban have recorded wind piling up the water up to heights more than 30cm for onshore winds underpinning the idea that wind might be a relative big contributor as well. Other factors could for instances be seiches or numerical disturbances due to the fact that the tide was generated based on residuals obtained from a data set of 2 years. Seiches are a resonance phenomenon which can be dealt with by an irregular port lay-out [34]. From the paper of Van der Molen and Moes [52] it was found that the Durban harbour has a fairly irregular lay-out leading to the expectation that the contribution due to seiches is small. Based on the found ranges for water level differences due to pressure drops and wind set-up they together seem reasonably capable of causing the measured residual and therefore they are considered to be the most important contributors.

To investigate the contribution of surge on the water level a PoT approach is applied. This is because the available set of data contains only 2 years of data which is too short to perform a YM approach. The height of the threshold is chosen as 0.25m because this was found to be the highest value that still takes a reasonable amount of points into consideration. The CDF of the data and the fitted GP distribution are shown below in Figure 6.9:

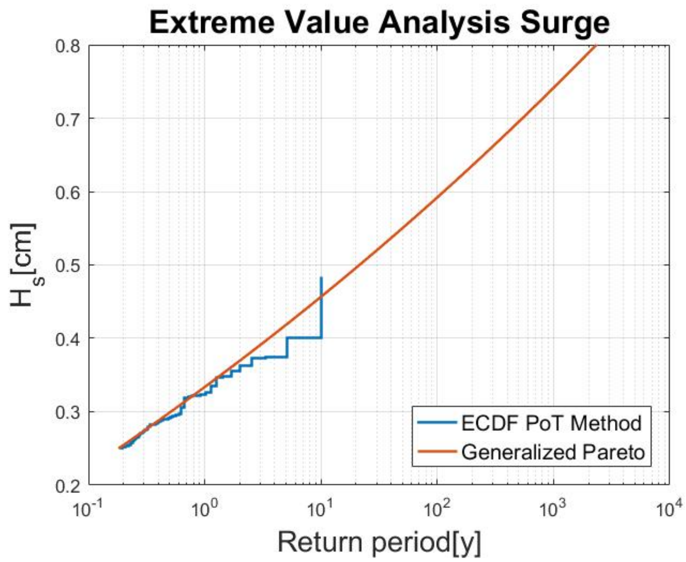



Figure 6.9: Empirical Cumulative Distribution Function and fitted Generalised Pareto distribution for surge Peak over Threshold excesses

The resulting surge height with their corresponding return periods are summarised in Table 6.8:

Table 6.8: Surge level with corresponding return period

| Return periods [years]: | 2 | 5 | 10 | 20 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|
| Surge level [m]: | 0.3694 | 0.4184 | 0.4566 | 0.496 | 0.5499 | 0.5921 | 0.6355 |

Interesting about these values is that they all exceed the water level addition that could be caused by a pressure drop as that was only +27cm. For the lower return periods this difference is quite small and might be explained by the before mentioned seiches or numerical disturbances. These differences start however to become rather large for the higher return periods indicating that wind over a fetch (wind-setup) must play a role. If this consideration is coupled to the orientation of the Durban coast, wind from a North East to South East angle seems to be necessary in order to get the surge levels with high return periods. This might be of importance later on during the formation of scenarios.

To finalise this section on surge it should be noted that performed extrapolation is done with only two years of data. The use of a PoT method made it possible to take more peaks into account, but one could doubt the reliability of the result since the data set is rather short. Towards the end of the project a larger data set was made available but unfortunately it showed quite some unexpected disturbances. Due to the limited time in which this project is performed it was decided to use the above obtained results and focus on other parts. Use of a larger data set is recommended for detailed design purposes.

### 6.3.3 Wave setup

Wave setup might or might not be an important factor in the blocking of the rainwater outlets. Wave setup is the phenomenon of increased water level near the shore caused by the necessity of a force balance between breaking waves and the water level. Inside the surf zone the magnitude of the radiation stress $S_{xx}$ decreases rapidly due to wave breaking which gives a force in landwards direction. To achieve equilibrium the water level on the land side should be higher to create a seaward directed pressure force thus creating wave setup [2]. There are no measurements or data available on the magnitude of the wave setup and therefore a model is used to simulate the waves during extreme events on the coast and thereby computing the wave setup. To accomplish this wave data is required as input for the wave model to compute the setup at the coast. The important wave parameters that are being investigated are wave height, wave period and wave direction. From these three wave height is most important for the magnitude of the setup and therefore the main focus is on wave height maxima. To compute extreme values during storm with greater periods use is made of a PoT analysis. A YM method was not suitable as the available wave data spans only 13 years from 1997-2010 which does not yield enough data points for an extreme value analysis.

For finding the return values for the wave periods instead of also using EVA, the periods are sought after which are linked to the maximum wave heights. These maximum wave heights as found in the PoT analysis and their accompanying wave periods are plotted against each other and based on these points a relation is formed by means of linear regression which can be used to determine wave periods for the greater return period wave heights. For wave direction a similar approach is used where instead of finding the governing wave direction under normal conditions, only the wave direction for wave heights obtained from the PoT analysis are being investigated. The wave data that are available are data from NCEP produced by the WaveWatch III model and are located at a location 22km offshore. For a shorter period from 2002-2006 wave data are available in front of the harbour mouth from an ADCP measurement station.

**Wave height:** As mentioned a PoT analysis will be performed on 13 years of NCEP wave data to obtain the significant wave heights that will occur during extreme events with a large return period. The significant wave height is the average of the 1/3rd highest waves within a time span and is commonly used to describe wave heights [29]. The analysis is performed in the same manner as explained before. First a threshold should be set and a minimum peak width to make sure just one peak per event is measured. In earlier studies by Corbella and Stretch [7] 3.5m significant wave height was proven to be the threshold above which waves with the most energetic spectra occur and therefore for this study the same threshold is applied. The peak width is set at 4 days as nearly all events have a maximum duration of 4 days [6]. The entire NCEP data set including the PoT observations are plotted in Figure 6.10.

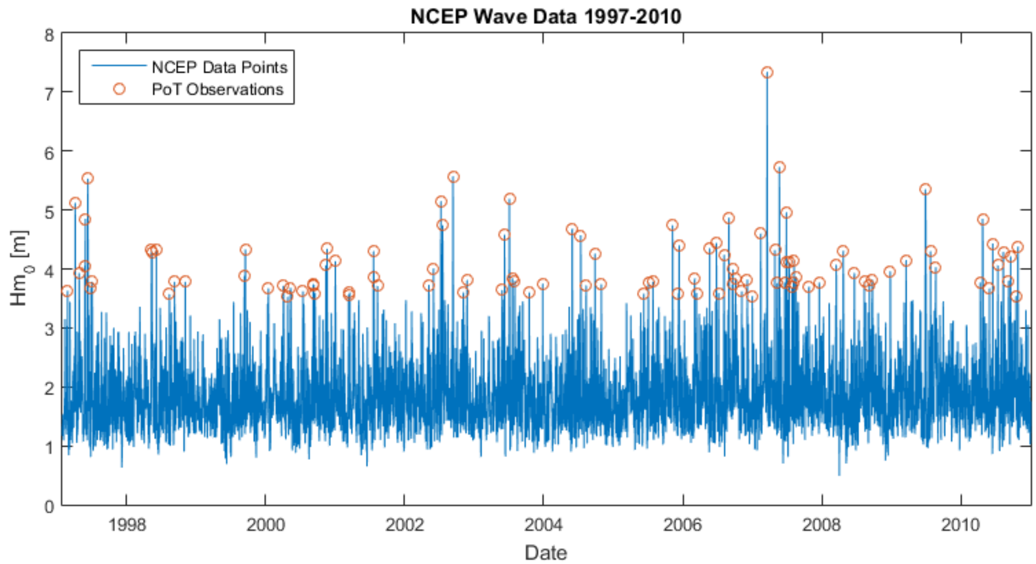



Figure 6.10: NCEP wave data and threshold excesses

Constructing a CDF and fitting a Generalized Pareto distribution on the threshold excesses yields the relation between significant wave height from the WaveWatch III model $Hm_0$ and the return period as can be seen in Figure 6.11. The storm in 2007 had a significant wave height of 7.34m and therefore causes the predictions of large wave heights to be much higher than without the occurrence of this event. An overview of the resulting significant wave height per return period together with matching peak period is given in Table 6.13.

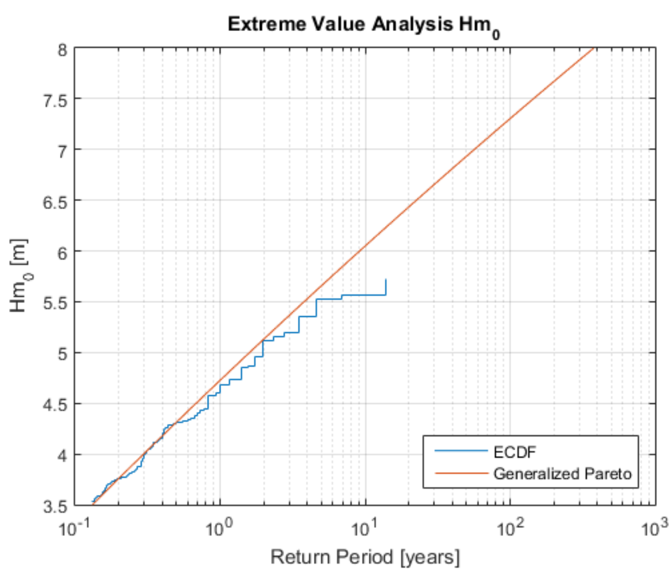



Figure 6.11: Empirical Cumulative Distribution Function and fitted Generalised Pareto distribution for $Hm_0$ Peak over Threshold excesses

**Wave period:** For the wave periods unlike the wave height no PoT analysis was performed. This is because the interest lies in the periods that occur together with extreme wave heights and not in extreme periods in itself. As can be seen in Figure 6.12, the largest peak periods do not necessarily occur together with the highest waves.

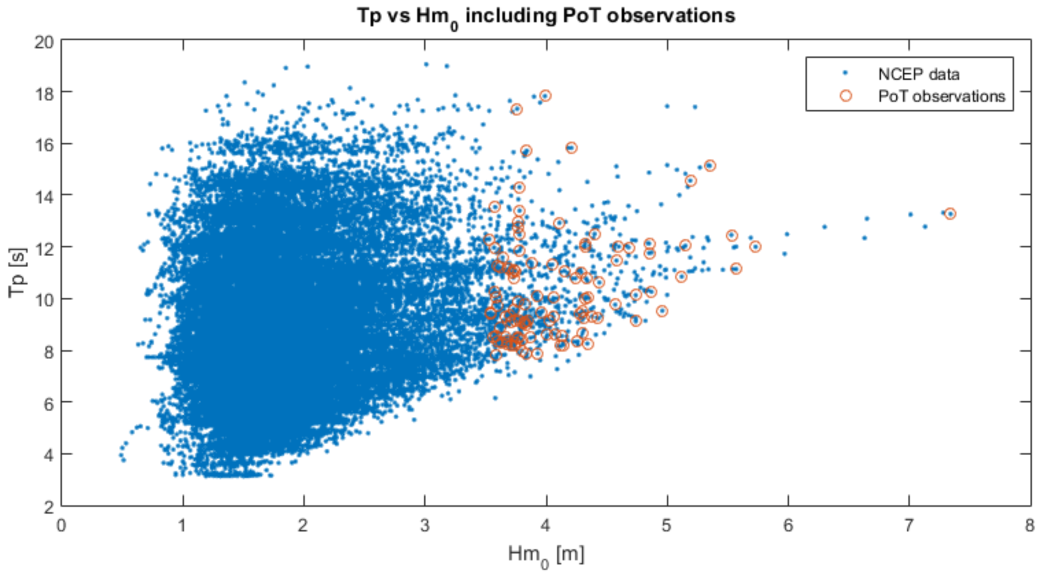



Figure 6.12: Wave peak period $T_p$ vs significant wave height $Hm_0$ including PoT excesses

Therefore to obtain peak periods for larger return periods a relation is made between the PoT wave heights and peak periods by fitting a linear regression line and thus linking the period to the wave height. A plot of the PoT observations and best fit regression line including 95% confidence intervals is shown in Figure 6.13.

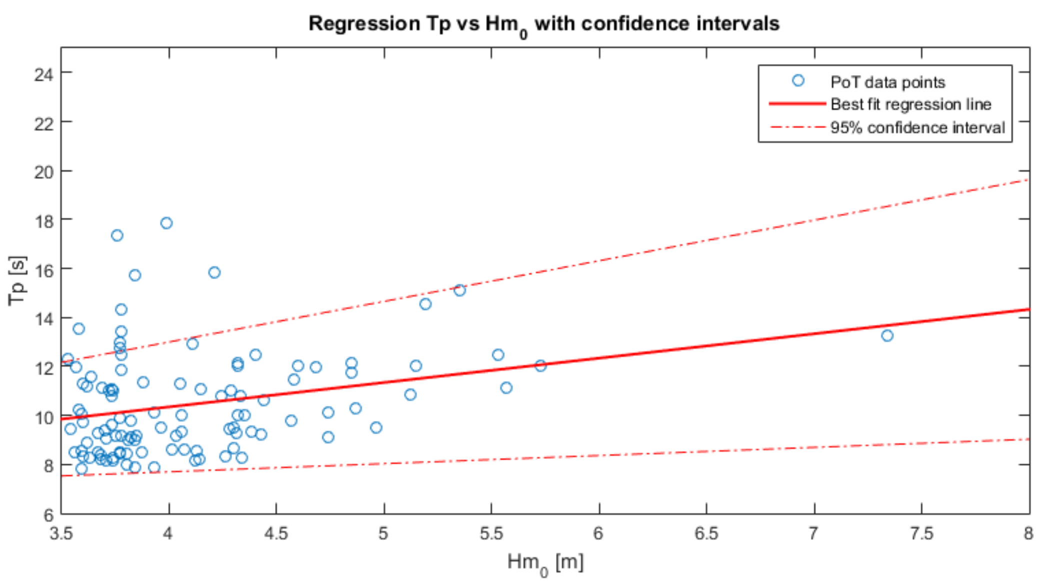



Figure 6.13: Wave peak period $T_p$ vs significant wave height $Hm_0$ for PoT excesses with best fit and 95% confidence interval regression lines

Visually the fitted relation seems to be quite realistic and because of the absence of any other information on the relation between the two parameters this was used to obtain the peak periods during extreme wave events. The resulting peak periods with their wave heights and return periods are given in Table 6.9.

Table 6.9: Wave height and peak periods for larger return periods

| Return period [years] | 2 | 5 | 10 | 20 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|
| $Hm_0$ [m] | 5.13 | 5.66 | 6.05 | 6.43 | 6.93 | 7.30 | 7.67 |
| $Tp$ [s] | 11.47 | 12.00 | 12.39 | 12.77 | 13.27 | 13.64 | 14.00 |

**Wave direction:** For the wave direction just as for the wave period the interest lies in the direction that occurs for the most extreme waves and not for the entire wave climate in general. To get a first insight the wave heights are plotted against the wave direction including the PoT excesses as shown in Figure 6.14. The wave direction is measured clockwise from the North.

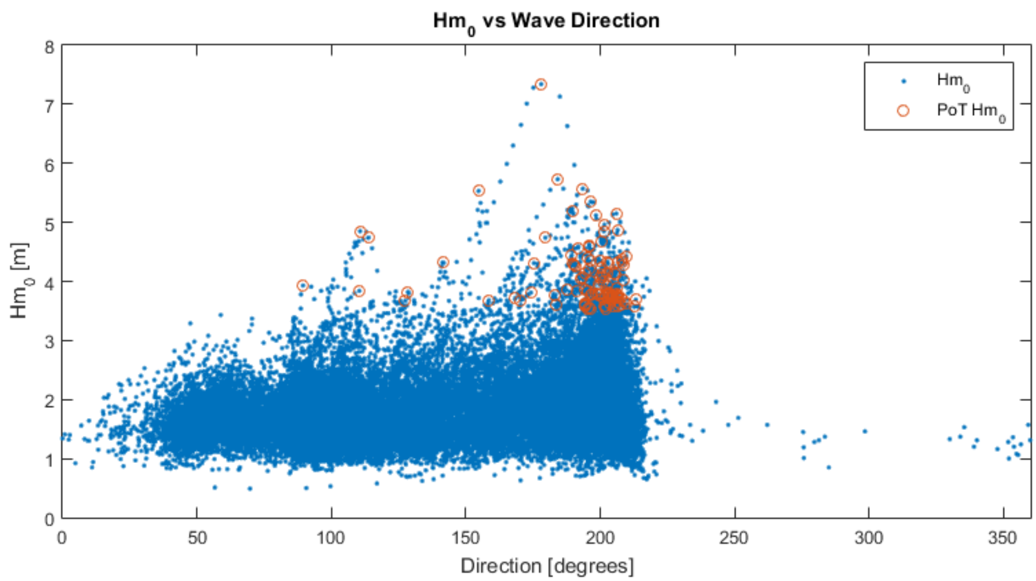



Figure 6.14: Wave height vs wave direction including PoT excesses

As can be seen clearly the dominant wave direction is spread narrowly around 200° so SSW from 190°-210°. The extremely high waves during the 2007 event however had its maximum slightly more from the South starting at 210°, reaching its maximum at 178° and then went below the threshold again at around 140°. 84% Of all threshold excesses are located on the 180°-210° bandwidth but because the biggest historical event had a spread from 140°-210° all these directions will have to be taken into account. Therefore the governing direction will also be based on which direction results in the largest wave setup.

This spread can be reduced even more by taking into account the orientation of the coast. At the northern edge of the domain at the Umgeni river the normal of the coast has a direction of approximately 115° and at the harbour entrance the normal has an approximate direction of 30°. Moreover the harbour breakwater and the bluff protect the coast from waves coming from the South or Southwest. Since the waves will lose height while refracting it can be expected that waves coming from the Southwest will definitely have the smallest setup and all directions greater than 180° are therefore excluded.

**Wave model:** To get from wave height, period and direction to wave setup a wave model is required that will use the known wave parameters as boundary condition and uses them together with the bathymetry to simulate processes like refraction, shoaling, dissipation as well as the wave setup. Because wave setup is only a small part in the entire study the focus was not on having a completely accurate high resolution model but more on getting a global range of what kind of wave setup can be expected for extreme events. The idea was to use an already existing XBeach model and use the computed return events as boundary conditions to obtain results quickly. The Xbeach model however appeared to be calibrated for long term erosion events on a different location and not for extreme wave events and moreover the author of the model did no longer work at the municipality which made it very difficult to get in touch with him.

The other option was to use the wave stand alone version of Delft3D SWAN together with existing grids the municipality is already using provided by Deltares. The problem with the wave stand alone runs was that setup was somehow not computed in the calculations. The problem arose from a to steep grid near the coastline but after refinement of the grid the problem still maintained so therefore another approach was applied. This approach consisted of running the Wave module together with the Flow module and obtaining the changes in water level which would correspond to the wave setup. The problem with this method was that one run would take 6 hours and therefore running all conditions would take quite some time. Reducing the simulation time would however lead to errors because the spin-up time of the model is quite long which means the initial conditions still influence the results which leads to inaccurate results. Therefore three main directions 140°, 160° and 180° were chosen to determine the influence on wave direction and based on that a more specific choice is made where magnitude of the wave setup and likability of occurrence both play a role. This way the number of required runs can be kept as low of possible to cope with the time constraints.

The flow and wave models that were used were already in use by the municipality and run on flow and wave grids created by Deltares. These models are calibrated mainly on erosion events. The grids extend to 20 km offshore to a depth of nearly 400 m which is deep water for all waves under consideration. As a simple check it can be said that a wave starts feeling the bottom at a depth of half its wave length. The wave length depends on its period in deep water by:

$$L = \frac{g \cdot T^2}{2\pi} \tag{6.4}$$

For the 200 year return period the wave period is 14.0 seconds. This yields a wave length of 306m. Therefore the longest waves start feeling the bottom at 153m and the assumption that the edge of the grid lies in deep water is correct. At the northern part of the western edge however the depth is reduced to 80m as can be seen in Figure 6.15.

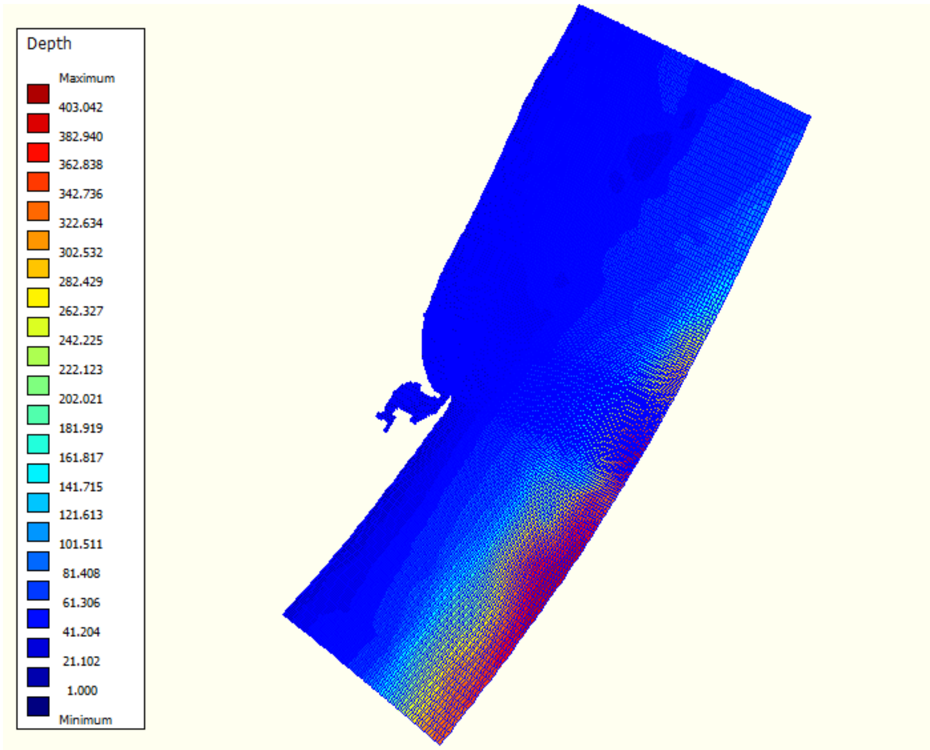
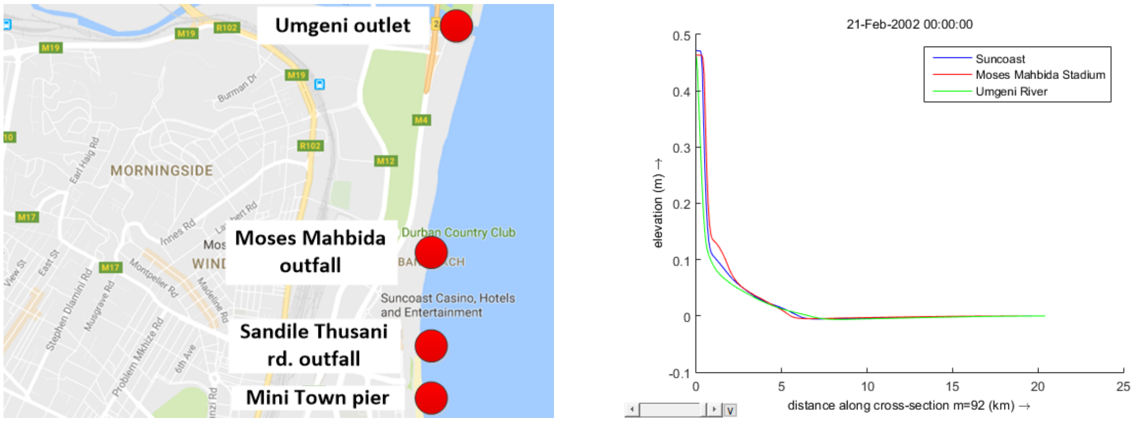



Figure 6.15: Delft3D wave grid and depth

Because the imposed waves are travelling in northern direction and this border is far away from the location of interest the imposed boundary here will not influence the wave setup at the target location. Therefore the use of NCEP wave data as a boundary for the computational grid is also verified and the use of the ADCP data would be incorrect. It was opted not to further calibrate the model solely on wave setup as there are no measurements on wave setup and regarding the scope of this project only the order of wave setup is of importance and slight deviations can be justified.

The wave setup will be used as a boundary for the outfalls in PCSWMM and therefore output is required exactly at these outfalls and the Umgeni river. The outfalls of importance are at Sandile Thusani rd. around the Suncoast Casino, Moses Mahbidah stadium outfall and Mini Town outfall at northbeach which are all located quite close to eachother. In Figure 6.16 the locations of these outfalls are shown together with a cross section of the wave setup around the Umgeni, Moses Mahbida Stadium and Suncoast Casino. PCSWMM also takes a lot of outfalls within the harbour into account, but because the existence of a breakwater the effect of waves in the harbour are considered to be negligible.




(a) Important outfall locations (b) Wave setup at different locations

Figure 6.16: Outfall locations and wave setup

Note that there is only a 1cm setup difference between the three different locations which are investigated. This difference is negligible and therefore an equal wave setup is assumed at all coastal outfalls. The resulting wave setup for the 3 different chosen directions are shown in Table 6.10

Table 6.10: Wave setup for higher return periods at 3 different wave angles

| Wave setup [m] | | | |
|---|---|---|---|
| Return Period [years] | Direction [°] 140 | 160 | 180 |
| 2 | 0.28 | 0.23 | 0.17 |
| 5 | 0.33 | 0.27 | 0.2 |
| 10 | 0.37 | 0.3 | 0.22 |
| 20 | 0.39 | 0.31 | 0.23 |
| 50 | 0.44 | 0.37 | 0.28 |
| 100 | 0.47 | 0.38 | 0.32 |
| 200 | 0.51 | 0.43 | 0.33 |

The first thing that can be noted is that the more the waves come from the East, the higher the setup. This is as expected as the waves will arrive more normal to the shore but now it's also been confirmed by the model. As mentioned most high waves will come more from the South but as was seen in the 2007 storm high waves can also originate from directions as easterly as 140°. Even more easterly directions are excluded as it can be determined visually from Figure 6.14 that extreme events are limited to directions spreading from 140°-210°. If more data would have been available an extreme value analysis could have been performed per wave direction which might have resulted in slightly different return wave heights per direction but unfortunately that was not the case. Therefore and because waves from 140° cannot be excluded this is chosen as the governing wave direction for wave setup and the values as given in the table are used for the purpose of this study.

### 6.3.4 Sea Level Rise (SLR)

Due to climate change the sea level is likely to rise in the future contributing to the possible blocking of the outlets. Dr. A.A. Mather has investigated the sea level rise for the coastal stretch around Durban which was published as a research letter in the South African Journal of Science [35]. Mather used tidal gauge data from 1970 up to 2003 which was provided by the South African Navy to do his analysis. He performed linear regression on both the yearly mean sea levels (YMSL) and the monthly mean sea levels (MMSL) and found values of 2.4 +-0.29 mm/yr for the YMSL respectively 2.7 +-0.05 mm/yr for the MMSL at the 95% confidence interval. Due to the smaller deviation of the value for the MMSL this value will be used in the remainder of this project.

## 6.4 Governing weather systems

As this project aims to predict the effect of combined, weather dependent, parameters it is necessary to gain more insight in the governing systems and their effects on the parameters of interest. Several papers and PhD studies focus on this subject and are used for this purpose. From Corbella and Stretch [7] it was found that there exist three mayor systems which affect the project area:

1. **Cold fronts and coastal lows:** These systems move from west to east which result in wind sea with relatively low wave height and period because of the fact that Durban is situated on the east coast and the fetch to build up waves is therefore limited [7]. Due to the west east movement surge caused by wind over a long stretch is expected to be limited as well. The existence of a low pressure system is considered to be able to give rise to surge due to an atmospheric pressure drop.

2. **Extra-tropical cyclones and cut-off low pressure systems:** According to Schumann [13] a cut-off low results from a mid-latitude trough that is cut-off by a ridge of relatively warm air. From the same source it was found that these systems can cause large rainfall events and therefore have been responsible for many floods in South Africa. Besides this Corbella and Stretch [7] state that cut off lows (in combination with cold fronts) are associated with the majority of waves including the ones with a lot of energy. Since a low pressure system is in place, large surges are likely as well.

3. **Tropical cyclones:** From Schumann [13] it was found that these systems originate North East of Madagascar and are less common but can be very destructive. The more recent paper of Corbella and Stretch [7] states however that recent research suggests that this influence might be less significant as previously thought.

Based on the above descriptions of the three main systems the cut-off lows seem to be the system that is most likely to cause large rainfall events together with high wave setup and surge. There should however be noted that regarding Corbelle and Strtech [7] and Pringle [44] cut-off lows create waves from a South Easterly direction. As stated under number two these waves also contain the high energetic ones giving rise to the expectation to measure high waves from the South East direction. Both sources indeed found this direction to be responsible for the highest waves. The analysis from section 6.3.3 showed however different results. Based on Figure 6.14 the direction causing the highest waves seem to be more from the South to South West. After having a closer look at the paper and PhD study, it was found that they both made use of a Waverider buoy which is located far more onshore than the NCEP data which was used in section 6.3.3 of this report. Depth induced processes like refraction are though to be the cause of the more shore normal South East - East direction of waves closer to the shore. During the final stage of the project the Waverider data became available. This data was put through the same analysis as described in section 6.3.3 to check whether the used method would give the same results as found in the paper and thesis. The result of this process is shown in the figure below (Figure 6.17):

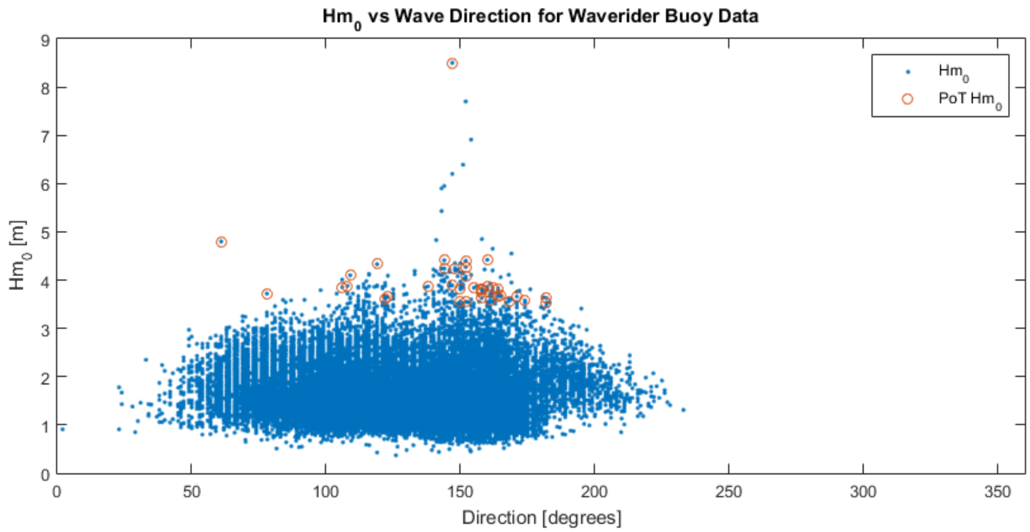



Figure 6.17: Wave height vs wave direction including PoT excesses for Waverider data

The figure shows indeed that larger waves are coming from a more South Easterly direction for the Waverider location validating the method used. Which direction to use in determining the wave setup mainly depends on the grid which is used in Delft3D. Since the data will be used as a boundary condition, the data set which is at the boundary of the grid should be applied. Use was made of a large grid which reached up to the location of the NCEP data so that data should be used as was already done in section 6.17. The model should subsequently change the direction of the waves towards the shore.

## 6.5 Summary

This analysis treated all the parameters that can be of importance to the project regarding the hydraulic and hydrological aspects. A distinction was made between land side parameters, being rainfall and river discharge, and sea side parameters being tide, surge, wave setup and sea level rise. For most parameters data was available which was analysed and extrapolated in order to find values for the higher return periods. For parameters which could not be analysed by means of data, use was made of literature.

The governing weather systems have been used to explain the occurrence of most of the other parameters. From this it was found that the cut-off low systems are capable of producing heavy rainfall together with high wave setup and surge events. Since this project focuses on the combination of them all, the cut-off low seems to be the best candidate to create the combined event.

# Part II Elaboration on modelling approach

This part contains the combination of the different analysis fields of the previous part. There will be searched for an approach which combines the separate contributions in order to tell something about the consequences of a flood and the impact from a coastal perspective on these floods in section III. This part starts with an elaboration on how the urban drainage model PCSWMM can be used to determine a flood map which takes deviations from the sea side into account. Subsequently the creation of the critical stakeholder and transport map will be explained, finished by a conclusion which summarises this part.

## 7 PCSWMM

### 7.1 General background

PCSWMM is the software package used in this project for modelling flooding in the area of interest. The abbreviation stands for Personal Computer Stormwater Management Model. The package is designed for both designing and analysing and evaluating of stormwater, wastewater and watershed systems. In order to model this a lot of processes are included in the model. These include hydrological processes, among others, like rainfall and water evaporation and infiltration. All of these processes can be set to vary in time and space. PCSWMM is as well able to route the rainfall runoff and external inflows through the different parts of the system and surface flow if applicable. All commonly used hydraulic structures and their specific characteristics can be modelled in PCSWMM. The model has different possibilities for flow routing, varying from very straightforward methods to more complex methods. Furthermore, all common types of flow regimes can be modelled as well. All in all PCSWMM is a powerful tool for modelling drainage systems of all types and scales for many purposes [33].

### 7.2 Functioning of a PCSWMM model

This section will give a brief explanation of how the PCSWMM model can be used for urban drainage modelling. At first a rainfall event needs to be defined. The amount of rainfall is varying in time and if desired as well in space. The first important layer is the subcatchments layer. In each subcatchment information like area, type of land use and infiltration rates are defined. The amount and distribution of the rainfall discharged from the subcatchments is not only dependent on the rainfall itself, but also on the characteristics of the subcatchments. The subcatchments route the rainfall to the next layer, the junctions. The junctions represent the manholes which form the starting and connection points of the network. The most important characteristics of the junctions are the invert elevation (level of the bottom) and the rim elevation (level of top side). The junctions are connected by the conduits, which form another layer. The conduits represent the stormwater pipes and culverts. Information about the length, roughness, type and size of cross-section is stored in this layer. The elevation of these pipes is defined by the invert elevation of the manholes. Eventually the water needs to be discharged from the system. These points are defined in the outfalls layer. The most important characteristics are the invert elevation of the outfall, and the type of outfall. This could be a free outfall, but could also be described by a fixed water level or a timeseries like tidal motion.

The above layers are sufficient to model the performance of stormwater network. The water level and flow velocity in all of the conduits can be checked. However, this is just a 1D network model in which possible floods cannot be simulated. An integrated 1D-2D model is required in order the model floods and overland flow. Many additional layers can be used for this, this explanation will be limited to the most important and relevant layers used in cases like this one. At first the area needs to be defined in which floods need to be simulated. A larger layer will require more computational time, so it is advised to only model the areas in 2D in which floods are expected. Based on this layer the 2D Nodes layer will be generated. These nodes form the centre of the 2D cells layer, which needs to be generated subsequently. These cells will eventually carry the information about flooding height. The cells are connected by fictitious conduits, which are there to enable overland flow between the cells. A digital elevation model is required for sampling the elevation of the area to the nodes and cells. Furthermore, an obstruction layer can be used when generating these layers, which makes sure that the cells are not generated at locations where buildings are located. Additionally a downstream boundary layer needs to be used at the edge of the 2D model at which the excess water can flow out. Otherwise the water would pile up at the edge of the model, which is not realistic at boundaries like a sea, river or harbour.

At last the 1D part of the model needs to be connected to the 2D mesh. This is done by another layer, the orifices layer. This layer connects the junctions of the stormwater network to the fictitious junctions of the 2D network, which are generated at the locations of the 2D nodes layer. The fictitious junctions will store the excess water which the stormwater network cannot handle anymore. Based on the area of the 2D cells and the interaction with neighbouring cells, this will be converted into flood depths. If the network has capacity at a later moment, the water will flow back from the 2D layer into the 1D stormwater network.

At the point at which all layers are in place and working correctly the model can be ran for different input and boundary conditions. All water related parameters like flow, depth and velocity can be checked for each element in the system at every time step.

## 7.3 Model setup

### 7.3.1 Preparation of the actual model

The goal of the use of PCSWMM is to set up a comprehensive model of the stormwater network for the area of interest within eThekwini Municipality. This subsection will explain briefly how this model is set up. A more elaborate explanation about the underlying process and steps which were taken can be found in Appendix H.

The necessary comprehensive model was not available at the CSCM department yet. However most of the input data was available in several existing models and the input for the additional 2D modelling was also already partly in place. Multiple separate models had to be merged, expanded and adapted, mainly manually. The Blue Lagoon area south of the Umgeni outlet was missing, and therefore the main network had to be inserted in the model, based on GIS registers, information supplied by employees of the department and building drawings. The Umgeni river was also taken out of another existing 1D model and included in the model.

A 2D model was set up in which the 1D Umgeni channel had to be connected manually. The input data for the 2D model were an elevation map and an obstruction layer, which exists of the buildings in the largest part of the area of interest. At first a rough elevation map was available, but this was insufficient for detailed modelling. At a late stage in the project a very detailed LiDAR elevation map came available, which enabled more detailed and realistic modelling. Furthermore, efforts were made to include blocking of pipes in the model, caused by waste and belongings of people living on the street. Because of the absence of a function in PCSWMM to model this a workaround was found to include this in the model.

### 7.3.2 Input scenarios

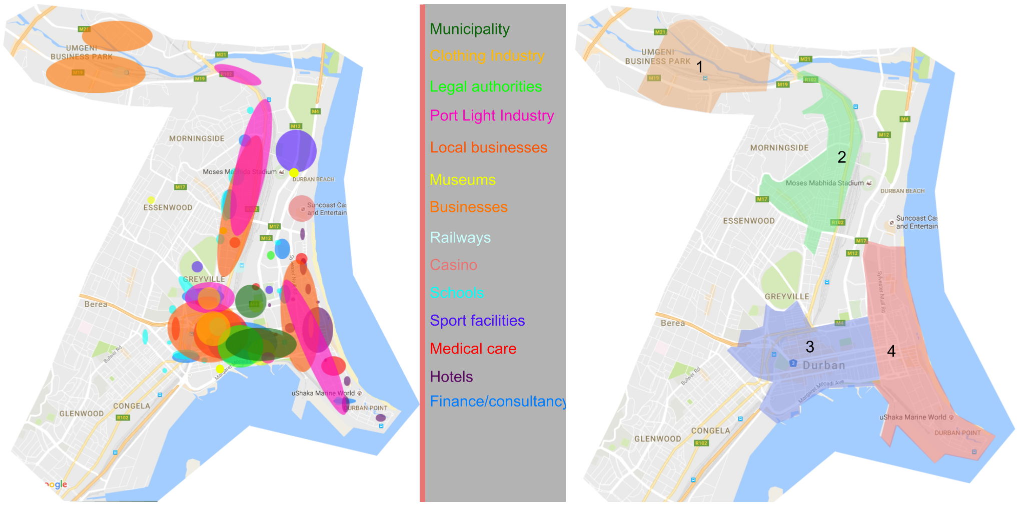
With the model in place boundary conditions are required in order to run the model. These boundary conditions can be composed based on the Hydraulic and Hydrological analysis from Section 6. In this particular section a lot of parameters that might be of influence were investigated. As this project aims to investigate the additional contribution to flood levels as a result of severe conditions from the sea side, several combinations of parameters will be merged in scenarios. Running PCSWMM with different scenarios is expected to result in multiple different flood maps which indicate the relative importance of certain parameters on the urban drainage system. The creation of the scenarios is done in Part III.

# 8 Critical Stakeholder map

The locations of the identified stakeholders are examined in this section and plotted in a map. This map is divided in four areas where a lot of stakeholders are located. For every area the amount of five different categories (roads, vacant land, industrial, business and commercial and residential areas) with their market value is indicated by use of information from the Valuation roll [19]. Amount is seen as the total number of houses, total number of companies (both for industrial and business and commercial), total number of roads and the total number of vacant areas in a certain area. By comparing the amounts and market value of the aspects in the particular areas a conclusion for the most critical areas in eThekwini is made. This map with stakeholder rich areas will be combined with the PCSWMM model to determine the specific flooded area(s) and the consequences of the floods on this area(s) in Section 13.

## 8.1 Location stakeholders in eThekwini municipality

The stakeholders that are found in the stakeholder identification (Table 3.1) are plotted in a map and shown in Figure 8.1a. The location of the identified stakeholders is roughly indicated and the figure only shows the stakeholders that are located in the area of interest. The area with the highest density of stakeholders is taken first and in a later stage more specific parts in an area will be analysed in order to analyse more individual stakeholders. Figure 8.1a shows that the business park around the Umgeni river is an area with a lot of businesses. The area in the Central Business District of Durban is an area with a lot of different stakeholders. Every stakeholder in this figure has its own colour, these colours easily show the stakeholder rich parts of the city. Areas without added colours are mostly residential areas. The same sources as used for the information of stakeholders is used for defining the location of these stakeholders.




(a) Location stakeholders (b) Stakeholder rich areas

Figure 8.1: Stakeholders in the area of interest

There are four areas in eThekwini municipality that seem interesting for examining the effects of floods on stakeholders. Figure 8.1b shows these four areas based on the results of Figure 8.1a. The four areas that contain the most stakeholders are 1) Umgeni Business Park, 2) Windermere and a small part of Morningside, 3) Warwick and Central Business District of Durban and 4) North Beach, South Beach and The Point, see Figure 8.1b.

## 8.2 Valuable parts of eThekwini municipality

It is important to examine which part of the city has the most value to be able to indicate the critical part(s) of the city when floods occur. Value can be described as market value and social value in which market value can be divided into economic and capital value. Social value is the value of social capital as well as the subjective aspects of the well-being of a citizen. Economic value is seen as the indirect values and the capital value is the direct values (See Appendix M.2.1. By calculating the market value the districts and streets within these four areas are combined and divided in the categories vacant land, industrial, business and commercial, PSI and residential. PSI refers to the roads in the areas. The business and commercial sector is seen as retail, offices, entertainment, hotels and restaurants. The Valuation Roll is the most up-to-date data that is available at the eThekwini municipality for making an estimation of the market value of these five categories [19]. The limitation of this programme is that the roads doesn't seem realistic. Therefore, the number of roads in a certain area are found from Google Maps.

**Area 1:** Area 1 is located at the north part of Durban around the Umgeni river. This area contains 64% large industrial companies which cause a lot of economic activity. After the industrial sector the business and commercial sector is the biggest. These two sectors include 83% of all the stakeholders located in this area. For this reason this can be seen as a business area with less residential areas and less vacant land. This information is shown in Table 8.1. The industrial and business and commercial sector are the most important for this area. A less diverse group of stakeholders will be affected by floods in this area but a great amount of industry will be affected that may have a bigger effect on the economic value than in a stakeholder rich area, these costs will be compared later in this chapter.

Table 8.1: Amount of properties and the value of it in area 1 [19]

| Area 1 | Vacant Land | Industrial | Business & Commercial | PSI | Residential |
|---|---|---|---|---|---|
| **Amount** | 11 | 135 | 41 | 24 | 0 |
| **Market value [Million ZAR]** | 35.8 | 1,125.4 | 552.7 | 3.7 | 0 |

**Area 2:** Area 2 consists of the two districts Morningside and Windermere. Due to the location of area 2 there are more residences in this area compared to the first area because area 2 is a residential area and area 1 an industrial area. This is seen in Table 8.2. Besides the large amount of residences in the area, the business and commercial is also very high compared to area 1. In Morningside a lot of restaurants and small businesses are located and there are some well-known streets that a lot of tourists and local people visit. The amount of residences in this area contains 90% of the total amount of stakeholders in Morningside and Windermere. Table 8.2 indicates this high number of inhabitants. For this reason this area can be seen as a residential area. However, the business and commercial sector is, compared to area 1, far more. Therefore, it is important to make sure that the focus point is not only at the residences but also at the business and commercial sector.

Table 8.2: Amount of properties and the value of it in area 2 [19]

| Area 2 | Vacant Land | Industrial | Business & Commercial | PSI | Residential |
|---|---|---|---|---|---|
| **Amount** | 65 | 60 | 467 | 19 | 5699 |
| **Market value [Million ZAR]** | 70.6 | 239.7 | 1,588.0 | 0.6 | 4,178.3 |

**Area 3:** The amount of the residences in the Central Business District and Warwick is predominantly (88%). There are a lot of different sectors and thus stakeholders involved in this part because of the well spread amounts of the vacant land, industrial and roads (See Table 8.3). The stakeholders that are involved are the property owners, business owners and the transport authority. It is important that not only the business and commercial sector gets the attention in area 3 but also the roads, residences and the industrial sector. Without good working roads the business- and commercial sector is also not optimally organised and residents are affected as well.

Table 8.3: Amount of properties and the value of it in area 3 [19]

| Area 3 | Vacant Land | Industrial | Business & Commercial | PSI | Residential |
|---|---|---|---|---|---|
| **Amount** | 78 | 75 | 617 | 79 | 6239 |
| **Market value [Million ZAR]** | 220.3 | 302.0 | 6,943.7 | 2.5 | 2,197.6 |

**Area 4:** As shown in Table 8.4, only 2% of the total of this coastal area 4 consists of business and commercial buildings. This is mainly caused by the tourism near the coast that attracts these businesses like surf shops, small family businesses and restaurants. The industrial sector is also located in this area due to port authorities in the southern part of this area (1%). The coast area consists of a lot of high buildings which are mainly used for residents. Some of the high buildings have apartments for tourists and inhabitants. The amount of residents in the coast area is 96%. The large amount of roads cause small grids in which these high buildings are located. Because of the high amount of residents it is likely that this group is the largest group that is affected by floods. However, mainly the business and commercial sector is located at the ground level of

buildings and the residents are located at higher levels in a building. This means that the capital costs of the residents will be less than for the business and commercial sector. In contrast to this, the economic value is dependent on the water height level at the road. If the residents are able to go to their work the economic value will be less than when floods occur in a grocery store for example and the electricity will not work because of a 5 cm water height, the economic value will be high.

Table 8.4: Amount of properties and the value of it in area 4 [19]

| **Area 4** | **Vacant Land** | **Industrial** | **Business & Commercial** | **PSI** | **Residential** |
|---|---|---|---|---|---|
| **Amount** | 57 | 115 | 251 | 81 | 11484 |
| **Market value [Million ZAR]** | 172.0 | 626.9 | 2,919.2 | 92.1 | 6,553.8 |

## 8.3 Insurances in South Africa

Before drawing a conclusion it is important to take the flood insurances into account because of the damage costs effects of the stakeholders that can result in social impact. If areas with a lot of inhabitants with a flood insurances are affected (high class income inhabitants and large companies), the recovering costs will be less than when an area with inhabitants with less flood insurances will be affected (low class income inhabitants and small companies). This is mainly the case when inhabitants have only a house insurance. The flood damage to the structural elements of a house is included in the house insurance but the damage to the contents is only insured by a household insurance. An examination is done by the flood insurance structure of South Africa and eThekwini that is shown in Appendix L.

In South Africa it is for some people usual to have a flood insurance. If people are not able to have an insurance, the government will pay a certain amount for their flood damage losses (see Appendix L). In eThekwini municipality the Municipal Disaster Management Centre helps the people who cannot afford an insurance, if floods occur they are there from the Ethekwini municipality to assist them in recovering as fast as possible.
People who can afford an insurance mainly have an insurance by private insurance companies. There are several insurance packages with a variety of costs, in this way property owners can choose which insurance fits the best for them [32]. Residents exposed to the most severe floods do see a long lasting impact on the house price. Homes with limited damage seem to be unaffected. In fact insurance companies increase premiums on some homes if the houses submit claims due to the fact that the insurance company have to replace all the appliances, paint and carpets.
For businesses the government does not pay, because they have the opinion that when you can start your own business you are also able to pay for an insurance.

## 8.4 Critical water heights buildings

According to Dharsha Naidoo, one of the city architects of eThekwini municipality, the 1 in 50 rainfall water heights are the advised minimum ground level heights of buildings besides the rule of thumb of a minimum ground level of 20 cm which is the same as in the Netherlands [51]. At this moment it could be that some houses are not regulated in this way and contain the old standards. These buildings will pay more for their flood insurance because they did not everything to prevent floods in the eyes of insurance companies. This can result in no flood insurance because they are not able to pay this insurance. Unfortunately, it is impossible in this time span of eight weeks to determine which areas contain old buildings and which areas contain new buildings. Probably the old districts in eThekwini municipality will be more affected by floods. According to SAPOA, there is no research done before about the ages of buildings and districts. Besides the higher flood insurance costs the bank could also refuse to give a loan for a house, because of the high risks that are involved when floods occur.

## 8.5 Conclusion

Table 8.5 and Table 8.6 show the overview of the amount of the buildings per aspect in a certain area and the market value of these sectors in a certain area. A further elaboration on each category is given below.

Table 8.5: Market value and amount of area 1 and 2 in eThekwini [19]

| | Area 1 | | Area 2 | |
|---|---|---|---|---|
| | **Amount** | **Market value [Million ZAR]** | **Amount** | **Market value [Million ZAR]** |
| **Vacant Land** | 11 | 35.8 | 65 | 70.6 |
| **Industrial** | 135 | 1,125.4 | 60 | 239.7 |
| **Business & Commercial** | 41 | 552.7 | 467 | 1,588.0 |
| **PSI** | 24 | 3.7 | 81 | 0.6 |
| **Residential** | 0 | 0 | 5699 | 4,178.3 |
| **Total** | 211 | 1,717.6 | 6372 | 6,077.2 |

Table 8.6: Market value and amount of area 3 and 4 in eThekwini [19]

| | Area 3 | | Area 4 | |
|---|---|---|---|---|
| | **Amount** | **Market value [Million ZAR]** | **Amount** | **Market value [Million ZAR]** |
| **Vacant Land** | 78 | 220.3 | 57 | 172.0 |
| **Industrial** | 75 | 302.0 | 115 | 626.9 |
| **Business & Commercial** | 617 | 6,943.7 | 251 | 2,919.2 |
| **PSI** | 79 | 2.5 | 81 | 92.1 |
| **Residential** | 9239 | 2,197.6 | 11484 | 6,553.8 |
| **Total** | 10088 | 9,666.0 | 11988 | 10,364.0 |

**Vacant land** The amount and market value of vacant land is important to take into account, but for vacant land it is more important to take the average value of this vacant land. This is highest in area 1 which is in contrast with the numbers that are shown in Table 8.5 and 8.6. For an area it does not matter what the amount of vacant land is because the market value for vacant land is leading in a certain area. If this land is located in a flood vulnerable area, fewer people want to buy the land. For this reason the areas with the most valuable vacant land have to be kept safe from floods. The total amount and value for vacant land is shown in both figures. If the market value of vacant land per area is divided by the amount per area, the average value of one vacant land is calculated. The amount of vacant land for area 1 is 3,256,818, for area 2 108,540, for area 3 2,824,205 and for area 4 3,016,984. This means that the vacant land in area 1 is most vulnerable. This land has to be sold and they have to make sure that this area is flood safe.

**Industrial** For the industrial sector area 1 scores highest at both the amount and the market value. For this reason area 1 is most vulnerable. Even if the average value of industrial is taken into account this area is by far the area with the highest value. Floods can have a negative capital- and economic value impact at the industrial sector.

**Business and commercial** From Table 8.5 and Table 8.6 it can be seen that area 3 predominately contains the most properties of the business and commercial sector, both in the amount of buildings as in the amount of value. However, the average value per business and commercial building is highest in area 1. Mostly this sector is less protected against floods because of the smaller businesses and thus the less money that is available to spend on insurances. The government does not help them by preventing against floods, they have to pay the insurance by themselves. For this reason it is a vulnerable sector. But to examine which area is affected most by floods the areas with the most amount of businesses that are affected is more important than a few businesses with a larger average market value. The differences in total between these two areas is 2 million ZAR. This will be less when more businesses are affected by floods. Floods can have a negative capital- and economic value impact at the business and commercial sector.

**PSI(Roads)** The amount of roads is the same in areas 2 and 4. This means that if there are floods in this area, the chance is high that another road is available. Figure 4.5 shows the amount of roads and the busiest roads in the area of interest. The amount of roads does not always mean that this is the best traffic network. A lot of small roads are located near the coast. Area 3 contains fewer roads but has bigger roads which cause less delay and this means that the traffic network is better organised in this area. Besides this, the amount of traffic that drives through the streets every morning is also important to decide which area is most traffic vulnerable. It does not matter how many roads there are but the amount of cars that pass during one day matters more. This will be elaborated in the next chapter. The delay in traffic results in the economic value.

**Residential** The amount of residences and the total market value is highest in area 4. Also in this area it is necessary to look at what the market value per residence is. One residence has an average market value of 0 in area 1, 733,163 in area 2, 237,861 in area 3 and 570,689 in area 4. These calculations show that the average market value of residences in area 2 is the most. This seems reasonable because the most inhabitants live in area 2 and the houses are often detached. It is likely that the social risks in areas with a lot of residences is higher than in low density areas like the Umgeni Business park. The amount of residents is highest in area 2: Windermere and Morningside.

**Total value** The total market value and the amount of stakeholders is largest in area 4. The numbers do not differ a lot from the market value and the amount of stakeholders of area 3. Area 3 and 4 do not score high at the specific categories but in total they score much higher. Therefore these two areas will be most vulnerable. It is important that less stakeholders are affected and the costs as a result of floods area as less as possible. For this reason it is important to find a solution for the areas where the most stakeholders live and the highest market value is located. It is better to dive deeper in this area and certain districts within this area. For this reason it is important to look per area what solution and strategy sounds best to response to a flood. In section 13 specific parts of area 3 and 4 will be analysed where floods occur and what the effects of floods is in these areas are.

# 9 Critical transport map

Not only the valuable stakeholders play a big role in the determination of critical areas, also the critical transport areas are important. Critical areas for the transport network can be determined by using the critical water heights for the traffic in combination with bottlenecks in the transport network. When it is known what the exact water heights are during a flood and what the exact location is of the flood, they can be used to determine a plan of action for the disaster management.

## 9.1 Critical water heights traffic

Water can cause several risks for transportation. Heavy rain can cause poor visibility, which makes it hard to drive safely. Braking distances between vehicles will increase on wet infrastructure, so the distance between vehicles has to be increased and speed decreased. Standing water on the road can create aquaplaning, which makes vehicles slip off the road. If there is more than 60 cm water on a road, it should not be entered anymore because this water height will float cars. If the water is flowing on the road, 30 cm could already be enough to float cars. For pedestrians 15 cm of fast flowing water can already be crucial to be washed away by the water [1]. Also for small cars 15 centimetres of water with a flowing speed of 1 metre/second can already be enough to float cars [9].

According to Crash Forensics [26], a water height of 1 cm on the road can already cause aquaplaning of cars. This seems a rather small amount of water since this can already happen very fast, and especially in combination with the accuracy of the PCSWMM model as described in Appendix H. Therefore the assumption is made that the amount of water that is needed to have an influence on the traffic is at least 5cm. As described before, the water height at which small cars can start to float and at which pedestrians can have real problems with moving is 15 cm. So for roads with water heights lower than 5 cm it is assumed that they are accessible by traffic. For roads with water heights between 5 and 15 cm it is assumed that traffic has to drive slowly. And to be safe, for example when flow velocities are not known exactly, roads with water heights higher than 15 cm are assumed to be inaccessible for traffic. A summary of the critical water heights can be found in Figure 9.1.

Table 9.1: Critical water heights

| Water height | Consequence for the road |
|---|---|
| 0-5 cm | No impact |
| 5-15 cm | Slow driving traffic only |
| More than 15 cm | Not available anymore |

## 9.2 Location critical areas

For the transport network the critical areas, the areas with the biggest bottlenecks and the main highways, can be defined using the figures from the analysis. There are five critical areas distinguished (Figure 9.1):

1. Umgeni West, a little upstream the Umgeni river, in the Umgeni Business Park there are the N2 and the M19 which are known for their bottlenecks.
2. Umgeni East, around the outlet of the river there are some large entrance roads, for example the M4 north.

3. CBD, the dense area between Berea Road station and the boulevard, in which lots of companies are located.
4. N3 West, the entrance of one of the biggest highways in Durban.
5. M4 South, going south from the CBD along the harbour is the M4.

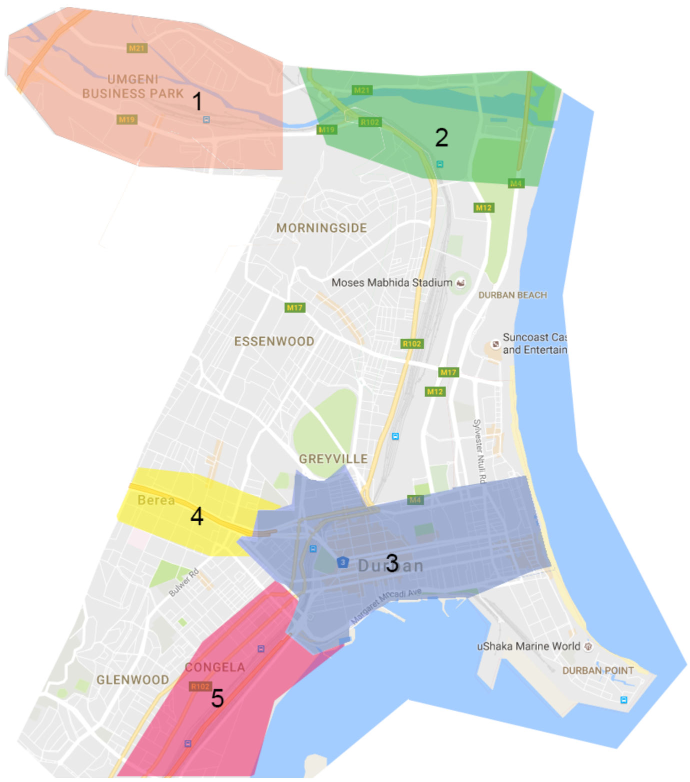



Figure 9.1: Transport important areas

Consequences of floods depend on the areas in which they take place. Thus the impact is different for the different critical areas. In case of floods in area 1, the M19 will not be fully available. The M19 is a road with already several bottlenecks (see analysis), thus in case of a flooding even more problems will occur here. This road has a capacity of 4800 vehicles per hour per direction. The traffic has to use the M21 which also has a capacity of 4800 vehicles per hour per direction or smaller roads. Also the N2 to the North can become unavailable. The N2 is the biggest road going to the North. It is a big national highway. The capacity of the N2 is 8800 vehicles per hour per direction. This will result in a lot of car traffic which has to take smaller roads in area 2. If area 2 is also flooded, there will be no alternatives to go out or enter the city from the north side.

When there are floods in area 2, the M4, M12 and R102 will no longer be available to use, meaning that traffic going north has to change routes and use smaller roads, resulting in possible problems on smaller roads. The only option to go north is by first going west further land inwards, to the Umgeni Business Park.The M4 has a capacity of 6000 vehicles per hour per direction. The M12 and R102 have a capacity of 3600 vehicles per hour per direction. These roads are mainly used for traffic from residents living in the northern suburbs who are working in the CBD.

Floods in area 3 have big influence on both small and big roads. The area is dense and thus already a problem area in terms of bottlenecks. Also traffic going from north to south or the other way around will go through this area. Alternative routes can be found more land inwards. Many companies are located in this area. It will be a challenge to enter and exit this area in case of a flood. The capacity of the most roads in this area divers around 4000 to 5000 vehicles per hour per direction.

Area 4 is the entrance of the national highway, which is unavailable in case of floods. This means the N3 West cannot be used and all traffic has to either use small roads or use the R102 or the M4 to get out or into the CBD. The N3 has a capacity of 10000 vehicles per hour per direction. The N3 is mainly used for traffic from the western suburbs to the CBD (and the other way around).

The last area which is prone to floods is area 5, the M4 and R102 South which can be avoided by using the N3 West and then travelling south. The capacity of the M4 and R102 are 6000 and 4800 vehicles per hour per direction. The N3 has a capacity of 10000 vehicles per hour per direction. The M4 is the main route for traffic from the south to the CBD.

It is also possible that there are more areas that are flooded, for example a combination of area 3, 4 and 5. This will result in even bigger problems since all traffic has to use smaller roads.

# 10 Conclusion Part II

The proposed model strategy is composed out of three maps. Before combining with the flood map there was looked from a stakeholder and transport perspective to the most critical areas with respect to those disciplines. The most critical areas with respect to stakeholders were found to be the Central Business District and the area containing North Beach, South Beach and the Point. From a transport perspective there were found five important areas, but in contrast to the stakeholder map, it was not possible to define a distinct most critical area. With these two maps in place, an urban drainage modelling tool called PCSWMM can be used in order to create a flood map. Be choosing the input scenarios in the right way this map is expected to change between several scenarios making it possible to investigate the impact from combined rainfall/river discharge- and high sea level events on the critical areas. The running of PCSWMM and subsequently overlaying of the obtained flood map by the critical areas will be done in the next part.

# Part III Acquiring Results

With the proposed model strategy in place this part will focus on acquiring results from the models. The purpose of this part is to get insight in different flood scenarios and their consequences. This part starts with creating input scenarios which will be used to run PCSWMM. The output of PCSWMM, being a floodmap, will subsequently be combined with the critical areas regarding the transport network and stakeholders giving the most flood prone areas with the highest impact. This part will be finalised with a conclusion.

## 11 Creation input scenarios

As pointed out in subsection 7.3.2 boundary conditions are required to run PCSWMM. This boundary conditions will be created by the use of the Hydraulic and Hydrological Analysis from section 6 in several scenarios. As was already mentioned in the analysis there is a clear distinction between parameters from the sea- and land side. This section focuses on combining them both in an efficient way regarding computational time and scenario making in order to create realistic input scenarios relatively easy. There will first be elaborated on the coupling which subsequently will be used to create the input.

### 11.1 Elaboration on coupling between land- and seaside

To make the coupling between the land- and seaside there will be looked at the implications of both separately on the PCSWMM model:

#### 11.1.1 Land side

The land side parameters, being rainfall and river discharge, will provide the model with a certain amount of water which has to be discharged through the urban drainage system or the Umgeni river. The distribution of water over the urban drainage system and the Umgeni mainly depends on the catchment areas of both parameters. After taking a closer look at the catchment areas it was found that the catchment of the Umgeni is predominately located relatively far upstream of Durban whereas the catchment of the urban drainage system is predominately around the city. From this it seems correct to make the assumption that the input of water in the river and urban drainage system can be treated separately: The first is provided with water via a discharge resulting from rainfall events far away from Durban, whereas the second is provided with water from rainfall around Durban.

The valuable thing about this assumption is that peak rainfall- and peak discharge events are not necessarily dependent. This assumption simplifies the scenario making from the landward side because the river discharge and rainfall can in principle be chosen in all combinations without having an impact on each other. One should however be careful with applying extreme scenarios on them both simultaneously since there is an area in the model which can be affected by them both during such events. Because of this there is chosen to only apply heavy rainfall with low to medium river discharge and vice versa.

#### 11.1.2 Sea side

The main implication of the sea side parameters with respect to PCSWMM are the blockage of the outfalls by means of an increased water level. In principle one could think of two ways to put this into PCSWMM. The first option is to match the parameters in many different ways by varying return periods of all the involved parameters, subsequently check what water level will be the result and use this level as a boundary for PCSWMM. Because of the number of involved parameters this would result in many different boundary conditions that all had to be checked in PCSWMM requiring a lot of computational effort. To reduce this effort another approach would be to apply predefined water level heights as boundary conditions. PCSWMM will indicate the effect of such a water level in combination with the land side parameters which reduces the involved parameters that directly have to be taken into account in PCSWMM. Apart from PCSWMM one can elaborate on the possible combinations of sea side parameters that might cause one of the predefined water levels. Because of the limited amount of time to run PCSWMM the last option is considered to be preferable and will be used.

In order to make this approach work it is important to define reasonable water levels that are moreover likely to have an impact on the PCSWMM model. The solution to this problem is twofold since it involves both the causal side (possible water level height at sea) as the impact side (blockage of outfalls, possible inundation from inside). As a start there is looked into more detail to impact side:

**Impact side:** To gain more insight in water levels that might affect the drainage system, the position of the outfalls with respect to mean sea level is checked. This is considered to be a first indication for a water level that might cause problems. The height of all the outfalls situated directly on the coast and a selection of the ones within the harbour are listed in the table below (Table 11.1):

Table 11.1: Height of outfalls w.r.t. MSL

| | Elevation bottom w.r.t MSL [m] | Elevation top w.r.t. MSL [m] |
|---|---|---|
| **Coastal outfalls:** | | |
| Umgeni drainage outlet | 2.33 | 3.08 |
| Snell parade pool (north) | 1.14 | 2.04 |
| Moses Mahbida Stadium | 0.04 | 2.44 |
| Sandile Thusi rd. pier | 0.1 | 2.1 |
| Mini town pier | 0.021 | 1.821 |
| | | |
| **Harbour outfalls:** | | |
| OF43 | -1.1 | 1.094 |
| OF44 | -0.35 | 1 |
| OF45 | -0.3 | 1.35 |
| OF47 | -1.5 | 1.95 |
| OF22 | -0.2 | 0.175 |
| OF50 | -3.1 | -0.9 |
| OF51 | -1.128 | 0.372 |

The table only contains a selection of the lowest outfalls in the harbour because there are in total 57 outfalls in the harbour. The outfalls left out of the table have a bottom elevation of 0m w.r.t. MSL and vary in height from 0.3m up to 2.2m. Based on this table the first outfall seems to be blocked around -0.9m w.r.t. MSL (OF50) whereas the last one will start to get blocked around

+3.08m w.r.t. MSL (Umgeni Outlet). This gives a first idea on the range which should be applied on PCSWMM to disturb the system.

**Causal side:** Now that it is known which water levels are likely to cause troubles for the system, it is necessary to check if, and to what extent, the sea is likely to produces such levels. The results from section 6.3 have to be bundled to answer this question. In that particular section the tide, surge, wave setup and sea level rise were analysed. Combining them is very complex, because it is in fact one big multivariate problem with a lot of dependencies and uncertainties. To handle this challenge within the available time span assumptions are required to make the problem less complex. As a start in making these assumptions several considerations are listed:

- The tide can be considered as a deterministic value while the surge and wave setup have a more stochastic character. Sea level rise might in itself be seen as a stochastic process, but since use is made of a fixed value of 2.7mm/y it becomes more or less deterministic for the purpose of this project.
- Because of this surge and wave setup were defined using return period whereas the tide and sea level rise are described more qualitatively.
- The height of the high (spring) tides showed a seasonal variation.

Due to the fact that the tide and sea level rise are considered as deterministic values they can be treated independent of the other parameters. The third bullet point however causes troubles with this approximation because the tide shows a seasonal variation as was described in section 6.3.1. If the higher tides for instance occur in a period in which due to the meteorological situation wave setup or surge are less likely, the combined event is less likely to happen and therefore dependence starts to play a role. To handle this problem more detail should be obtained in the atmospheric circulation patterns causing certain wave and surge events. This is a field of research in itself and out of the scope of this project. Therefore, despite being aware of bullet point three, the assumption is made that any tide can occur simultaneously with the other parameters. The implication of this assumption is that for certain scenarios the proposed water level can be higher than it in reality might be. Since this will lead to a more severe scenario this is considered to be reasonable from an engineering perspective. For the wave setup, being linked to the wave height and period, the likelihood of a combined high spring tide and high setup event can be supported by literature. In [8] exceedance graphs for the significant wave height and peak period were found indicating that the highest wave heights occur during autumn whereas the highest period occurs during winter time, but are also very high during autumn. By saying autumn, months 3-5 are meant which are the South African autumn corresponding more or less with the Dutch spring. The South African autumn was one of the from Figure 6.5 obtained seasons which showed higher spring tidal peaks, so it seems very well possible that the occur simultaneously.

In addition to the above assumption a similar one has to be made with respect to the dependency between surge and wave setup. Wave setup is governed by the wave height at breaking according to [2]. Wave breaking is a steepness induced phenomenon and therefore the period and wave height are considered to be of importance. From section 6.4 on weather it was found that the cut-off lows generate the largest waves both in height and period and therefore cut-off lows are considered to generate large wave setup. Since a low is in place it seems very well possible that the surge will be high as well caused by a drop in the atmospheric pressure. Moreover cut-off lows are able to cause strong onshore winds according to [13], increasing the likelihood of high surge because of wind over a stretch (wind setup). Based on this it seems quite well possible that high surges and high wave setup occur simultaneously as a result of a cut-off low system. Because there are also other systems it is possible that either wave setup or surge is high whereas the other is not. An example of this situation is for instance the described system of cold fronts/coastal lows which could create significant surge due to the low pressure system but is unlikely to create large waves because of the west-east movement. Recall however from section 6.3.2 that surge levels with higher return periods could not be explained by means of a pressure drop only and that wind setup was required to reach to those higher levels. Because of this the occurrence of high surge events without high wave setup is considered to be restricted to surges with the lower return periods. This is because winds strong enough to create significant surge over a long stretch are also likely to create significant waves.

All in all it can be concluded that the the deterministic parameters can be chosen freely with respect to each other and to the stochastic parameters. The two stochastic parameters can have a maximum simultaneously as a result of a cut-off low, but a significant level can also occur separately due to other weather systems. The height of this level is however limited to the lower return periods for the surge because of the requirement of onshore wind to generate surges with high return periods. Regarding scenario making this implies that maxima of the tide (seasonal) can occur simultaneously with high wave setup and surge and that the total water level might get even higher due to sea level rise in the future. Besides this there is the nodal cycle which might add another 30cm in the worst case. To come up with total water level heights the findings from section 6 are summarised in Table 11.2 below:

Table 11.2: Summary of water level contributions from section 6

| **Stochastic parameters** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Return period: | 2 year | 5 year | 10 year | 20 year | 50 year | 100 year | 200 year |
| Surge level [m]: | 0.37 | 0.42 | 0.46 | 0.50 | 0.55 | 0.59 | 0.64 |
| Wave setup [m]: | 0.1 | 0.2 | 0.3 | 0.23 | 0.6 | 0.47 | 0.9 |

| **Deterministic parameters** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time scale: | Hours (tidal cycle) | | | Seasonal (spring tides) | | | Years* |
| Tide [m]: | min: 0.12 | mean: 0.63 | max: 1.19 | min: 0.69 | mean: 0.94 | max: 1.19 | max: MWL +-0.3** |
| SLR [mm]: | + 2.7mm/year | | | | | | |

**Years refers to the nodal cycle of 18.6 years*
***MWL is an abbreviation for Mean Water Level*

If one couples the values from the table with the earlier made assumptions it can immediately be seen that there are a lot of possible combinations. In order to create structure within these possibilities there is first looked at the possible combinations within the stochastic parameters which subsequently will be extended by the deterministic parameters. Note that this approach is possible due to the above made assumption that the deterministic and stochastic parameters can be chosen freely with respect to each other.

The possible water level additions due to the combinations of the stochastic parameters are presented by means of a matrix with the surge level on the x-axis and the wave setup on the y-axis. This matrix is shown in Table 11.3 below:

Table 11.3: Matrix on possible water level increas due to combined surge and wave setup

| | | Surge levels[m]: | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **2y:** | **5y:** | **10y:** | **20y:** | **50y:** | **100y:** | **200y:** |
| **Wave setup [m]:** | **2y:** | **0.65** | **0.70** | **0.74** | 0.78 | 0.83 | 0.87 | 0.92 |
| | **5y:** | **0.70** | **0.75** | **0.79** | **0.83** | 0.88 | 0.92 | 0.97 |
| | **10y:** | **0.74** | **0.79** | **0.83** | **0.87** | **0.92** | 0.96 | 1.01 |
| | **20y:** | 0.76 | **0.81** | **0.85** | **0.89** | **0.94** | **0.98** | 1.03 |
| | **50y:** | 0.81 | 0.86 | **0.90** | **0.94** | **0.99** | **1.03** | **1.08** |
| | **100y:** | 0.84 | 0.89 | 0.93 | **0.97** | **1.02** | **1.06** | **1.11** |
| | **200y:** | 0.88 | 0.93 | 0.97 | 1.01 | **1.06** | **1.10** | **1.15** |

This table shows all possibilities, but regarding the before mentioned considerations and assumptions one can argue how likely some of them are. Based on these considerations and assumptions the idea arises of a certain dependence structure between the surge levels and wave setup. This dependence structure is indicated in the matrix with the bold values and shows a positive correlation meaning that higher values for the surge usually occur with higher values of the wave setup. It should be noted that the band width of the diagonal in the table is rather arbitrary. All the earlier mentioned considerations in this section point in the direction of a dependence structure governed by atmospheric conditions. To really be able to describe this dependence, is way too complex and time consuming for the time span of this project. This approach is therefore a necessary simplification in order to say something about the combined behaviour, but should be used carefully.

To find possible water levels that can occur during extreme events the water levels caused by surge and wave setup should be further combined with possible water levels caused by the tide and the nodal cycle. Because there are endless combinations of these three factors there is a simplicifation required to come up with realistic water levels and an idea of the probability or possibilty of occurrence. This simplification is done by taking for each of the three factors, Surge & Wave Setup, general tide and nodal cycle, a minimum mean and maximum value. For the maximum possible water level in the harbour wave setup is excluded, because wave action in the harbour was assumed to be limited. The minimum, mean and maximum determined values are shown in Table 11.4.

Table 11.4: Minimum, mean and maximum water level setup per contributor

| Water level increase [m] | | | |
|---|---|---|---|
| | Min | Mean | Max |
| Surge | 0.37 | 0.5 | 0.64 |
| Surge & wave | 0.75 | 0.9 | 1.05 |
| Nodal | -0.3 | 0 | 0.3 |
| Tide | 0.63 | 0.94 | 1.19 |

For surge only it has been opted to use the 2, 20 and 50 year return values as min, mean and max values. These are of course not representable values for every day circumstances, but only when looking at extreme events. The combined surge & wave values are determined based on the matrix shown before in Table 11.3. These are determined keeping in mind that there is a strong correlation between both as explained by the existence of cut-off lows. The min, mean and max values have been determined by taking averages of different sections in the matrix. The minimum value can this way be achieved by a combination of a 10 year surge event and a 2 year wave setup event or vice verse and also by a 5 and 5 event. The same goes for the mean and maximum value only higher return values for surge and wave setup would be required in that case.

For the nodal cycle the actual minimum, mean and maximum of the cycle have been used. This is because there is no correlation between the nodal cycle and surge or wave setup and therefore any value for the nodal cycle is just as likely to occur together with an extreme event as any other value. Also the period of the nodal cycle is extremely long and therefore excluding the negative values of the cycle would imply not taking into account 9 continuous years in which many severe storms could theoretically happen.

For the general tide excluding the nodal cycle it is more difficult to determine a minimum, mean and maximum value as there is some dependence between wave setup and the tide caused by a seasonality in the tide which is also present in the waves as mentioned earlier in this section. However, for the scope of this project it has been assumed that all tides can occur simultaneously with extreme sea events. The low tides can be excluded by observing that all extreme sea events have a duration which is longer than 6 hours which will make sure that at least one high tide is present during the duration of the storm. As the interest in this study lies in extreme events which will impose such a water level that it has effect on the drainage system, neap high tides are also excluded from the analysis. Therefore the minimum that will be imposed for high tides that will contribute to an effect on the drainage system is chosen as the mean high tide. The mean is chosen as the mean spring tide and the maximum is chosen as the max high tide which is the max spring tide.

The combination of these minimum, mean and maximum values for the three categories wave setup & surge, nodal cycle and tide will result in 27 scenarios ranging from the combination all minimums to the combinations of all maximums. This is done for surge & wave setup combined as will be present at sea as for only surge which will be present in the harbour. These tables can be seen in Table 11.5 and Table 11.6 respectively.

Table 11.5: Possible combinations of extreme water levels at sea

| Surge & Setup | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | | | | | | | | | Mean | | | | | | | | | Max | | | | | | | | |
| Tide Min | | | Tide Mean | | | Tide Max | | | Tide Min | | | Tide Mean | | | Tide Max | | | Tide Min | | | Tide Mean | | | Tide Max | | |
| Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max |
| 1.08 | 1.38 | 1.68 | 1.39 | 1.69 | 1.99 | 1.64 | 1.94 | 2.24 | 1.23 | 1.53 | 1.83 | 1.54 | 1.84 | 2.14 | 1.79 | 2.09 | 2.39 | 1.38 | 1.68 | 1.98 | 1.69 | 1.99 | 2.29 | 1.94 | 2.24 | 2.54 |

Table 11.6: Possible combinations of extreme water levels inside the harbour

| Surge | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | | | | | | | | | Mean | | | | | | | | | Max | | | | | | | | |
| Tide Min | | | Tide Mean | | | Tide Max | | | Tide Min | | | Tide Mean | | | Tide Max | | | Tide Min | | | Tide Mean | | | Tide Max | | |
| Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max | Nodal Min | Nodal Mean | Nodal Max |
| 0.7 | 1 | 1.3 | 1.01 | 1.31 | 1.61 | 1.26 | 1.56 | 1.86 | 0.83 | 1.13 | 1.43 | 1.14 | 1.44 | 1.74 | 1.39 | 1.69 | 1.99 | 0.97 | 1.27 | 1.57 | 1.28 | 1.58 | 1.88 | 1.53 | 1.83 | 2.13 |

From these tables it can be observed that the water level at sea during extreme events can vary anywhere from 1.08m until 2.54m above MSL. For the water level in the harbour this range is from 0.7m until 2.13m above MSL in the most extreme case. These values are moreover very likely to increase even more over the coming decades as a result of sea level rise.

After investigating the impact- and causal side it now is possible to compare both. Recall from Table 11.1 that for the coastal outfalls the minimum top elevation was 1.82m whereas the maximum was 3.08m. For the harbour outfalls this was -0.9m up to 2.2m. If this is combined with the just mentioned values from the causal side one can readily see that there are water levels possible which will reach to the top of quite some outfalls. Which level to chose depends on the type of scenario one is looking for. The above obtained values will be used in the following section to create the final scenarios.

### 11.2 Combination

High water levels alone will not cause severe flooding in the city whereas heavy rainfall on itself can cause severe flooding. The floods that damaged Durban in the past were always the result of heavy rainfall but the added effect of coastal factors either were not there or have not been noticed. For the Umgeni river the same effect can be investigated. The river banks have been flooded in the past but there are no data on whether this was the effect of extreme discharge or an extreme water level at sea.

To identify this effect several scenarios are constructed which will be capable of pinpointing the difference between damage from heavy rainfall or high river discharge and damage from heavy rainfall combined with blocked outlets or high discharge combined with an extreme sea level. As mentioned the river and the rainfall can be seen separately as the river has a different catchment area than the city of Durban which is affected by heavy rainfall. First for both cases separately a basic scenario will be run which does not take into account the effect from the sea. This is done by applying the 50 year return value for both rainfall and river discharge in 2 scenarios separately together with a water level at MSL. These will serve as the base cases to see what would already be damaged just from the land side if an extreme event occurs.

As this study focuses on what the additional risk of flooding is of a combined rain and sea event compared to just a rain event, the most important results are the differences between the base cases as just explained and the base case combined with an extreme event from the sea. This is done by taking the same 50 year return values for rainfall but now combined with extreme water levels. This extreme water level is not taken as the maximum possible as obtained in the analysis above. Despite the fact that the exact probability of that event can not easily be determined, it can be said that the probability of the combination of all those maxima is very unlikely to happen since it is a combination of multiple components which on its own already have a very low probability. Therefore a water level is chosen which is still very high but can be achieved by multiple combinations of events and circumstances and not just the extremes of these factors thus making it much more likely to occur. Therefore the water levels of +2.0m MSL and +1.6m MSL have been chosen for the sea and harbour respectively. This height will not be reached when the nodal cycle is in its minimum but for other phases combined with either a max tide or surge/setup this level is almost always exceeded.

This results in a total of four scenarios: 2 base cases, one for rainfall and one for river discharge both with the 50 year return values and 2 extreme cases consisting of the same 50 year return values but now with water levels of +2.0m MSL and +1.6m MSL on the sea and in the harbour respectively. An overview of the scenarios is given in Table 11.7.

Table 11.7: PCSWMM input scenarios

| Scenario | Rainfall | River discharge | Water level |
|---|---|---|---|
| 1 | 1/50 yrs | - | MSL |
| 2 | - | 1/50 yrs | MSL |
| 3 | 1/50 yrs | - | +2.0m MSL / +1.6m MSL |
| 4 | - | 1/50 yrs | +2.0m MSL / +1.6m MSL |

One may argue that these scenarios are quite rare, but given the computational time of PCSWMM these four scenarios are considered to give a quick indication of the impact of the several contributions on the system in a relative low amount of runs. Further elaboration can be done on the most severe scenario later on in order to gain more insight in the sensitivity on small changes in that scenario.

# 12 PCSWMM Output

## 12.1 Results of the large comprehensive model

### 12.1.1 Background

The determined scenarios were meant to be analysed using PCSWMM to obtain the flood map of the city for each scenario. These results would then be analysed to determine the effects on the traffic network and on the stakeholders. Unfortunately the model produced many errors which resulted in unreliable results for certain areas or certain scenarios. Elaborate explanation and background of the PCSWMM modelling approach and process can be found in Appendix H.

At the point that all the data was present to set up the comprehensive 2D model it appeared to be unstable. The results were fairly realistic for a large rainfall event, but the instabilities threatened the reliability of the results. The instabilities mainly occurred in the parts of the network at which the stormwater pipes and culverts had a small slope, which are generally the low lying areas. This was mainly relevant for the CBD area, which is an interesting area because of the multidisciplinary nature of the project. The CBD is a low lying area with a lot of buildings and infrastructure. Moreover, the largest problems in the model were the problems in applying a higher water level at the outfalls, which are probably also caused by the instabilities. Applying this effect at the outfalls is necessary for modelling the effect of elevated water levels at sea on the model. Furthermore the Umgeni river channel generated large errors in the model and was therefore unusable. A lot of effort is put in finding the cause of the errors. Potential causes could be inconsistencies in the network, errors in the 2D part of the model and wrong settings. Many attempts have been done in finding a possible source of the errors and instabilities and fix it. This was done together with the CSCM department and eventually as well with the PCSWMM support team, but unfortunately no one was able to find the source of the errors. The complexity of the model and the huge amount of entities could be the source of the instabilities. Other consequences of the complexity were large loading and saving times, low responsiveness and a very long period required to run the model. It took much time to make changes in the model and check whether it helped, which caused delays.

### 12.1.2 Results and validation

As a result the only one scenario which appeared to have fairly realistic results is the 50 year return period for the rainfall combined with mean sea level at the outfalls. This scenario is fully investigated in the following sections in terms of both network and stakeholders. The flood map can be found in Figure 12.1, a larger version can be found in Appendix I. Small floods of 2-10 cm depth are visualized in light blue, medium floods of 10-25 cm in medium blue and larger floods of minimal 25 cm in dark blue.

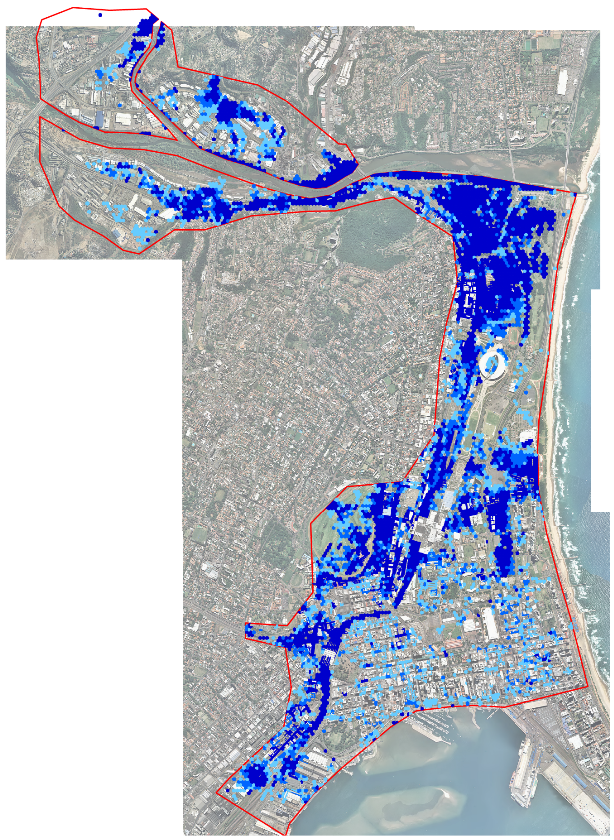


Figure 12.1: Flood map of the area of interest

This model was calibrated with the help of the elevation map (Appendix G) and Geoff Tooley of the CSCM department within eThekwini Municipality. As mentioned before, the results appeared to be fairly reasonable for the most parts of the model. The general characteristics of the distinguished parts within the area of interest are explained in Section 5. The same names for the areas are used as in Figure 5.1 in Section 5. According to the model the following areas are flooded:

- **The Umgeni Business park** (northwest)

  Some floods seem to occur in this area according to the model, however this is not reliable and probably not realistic due to the errors caused by the flow through Umgeni river channel.

- **Blue Lagoon area** (northeast)

  Large floods appear to be present within the Blue Lagoon area, mainly because one of the culverts downstream of the hill area discharges at this area. Due to the fact that the area is relatively uncultivated a lot of water can drain into the soil, however floods are still probable to occur at this area. Floods are not a big problem in this area, because only few buildings are present. When checking the network it appeared that a connection was missing in the stormwater network. This connection was neither present in the GIS register, but according to Geoff Tooley it was there. Furthermore there are some ponds in the area which function as a storage, but these were not included in the model as well. Therefore the floods seem to be somewhat exaggerated.

- **Central Beachfront area** (middle east)

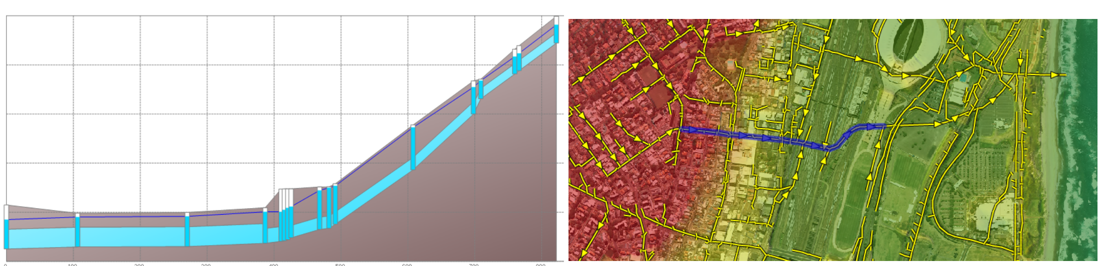
  A lot of floods appear at the Central Beachfront area, mainly at a small distance from the coast behind the dunes. This is caused by the fact that this area is mostly low-lying and the long distance which the rainwater has to travel to the harbour, because part of this area is connected to the outfalls at the harbour. Furthermore there is a large culvert situated in this area which discharges into the sea. This culvert runs underneath the railway tracks and has a very small grade from there up to the sea. This causes problems for the secondary network which is connected to this culvert. Most of the floods occur at the low-lying sports fields in the area, however at some places buildings are affected as well.

- **Railway tracks**

  The railway tracks function as a division between the hill ridge and the low lying Blue Lagoon, Central Beachfront and CBD areas. There appear to be large floods at the railway tracks, all the way from the southwest to the Central Beachfront area more to the north. This is partly because this area is low lying and the railway tracks seem to function as a kind of drain during large rainfall events. The water depth during floods seemed to be slightly exaggerated, although some flooding is not unrealistic. Fortunately the actual railway tracks are elevated by several tens of centimetres from ground level. Small flood depths will therefore not immediately affect train traffic.

- **Eastern Berea area** (west)

  The Eastern Berea area is only partly included in the flood map. This is because floods are not probable to occur at the steep sloping hill. However, at the transition of this hill and the low lying area floods are probable. This is also shown in the model at multiple places at the right of the bounding line at the left. A schematic rendering of such a situation can be found in Figure 12.2. At these places usually the main culverts of the stormwater network are located, which overflow during extreme events. The main roads will be affected by these floods because these larger culverts are often located underneath the roads.



(a) Cross section (b) Location in the model

Figure 12.2: Transition from a hill to a flat area

- **Central Business District** (south east) No large floods seem to occur in the CBD. At many places small floods seem to occur, but no large areas are flooded despite the fact that this area is low lying. The stormwater network appears to be relatively large and dense, which might be a reason for the limited flooding. Unfortunately it was impossible in this model to see the difference between mean sea level and an elevated water level. This might make a difference in the amount of flooding.

- **Congela & Northwest part of the harbour** (south west) In this area floods are occurring as well. This is mostly because of the same reason as described for the Eastern Berea area.

## 12.2 Alternative for the large comprehensive 2D model

### 12.2.1 General approach

Because of the problems with the comprehensive 2D model an alternative had to be found in short term to research the influence of high sea water levels on the performance of the stormwater system. A manual approach was considered to be used which is based on the theory of communicating barrel which is explained in Appendix J. However, the decision was made to use a smaller simplified 2D model of the CBD area and the southern part of the Central Beachfront area. This area is the most interesting considering the multidisciplinary nature of this project. The area is considered to be potentially flood prone when a large rainfall event coincides with high water levels from the sea and the harbour. Furthermore, a lot of buildings and companies are present which makes this area densely populated and leads to a lot of traffic movements. In order to handle the high intensity traffic an extended infrastructural network is present. At last, this area is relatively isolated because it is bounded by the low-lying railway tracks, harbour and sea. Therefore simple boundaries could be used which saved time in setting up the model.

After some problems which had to be solved in both setting up and running the model a working and stable model was created, following a similar process as used for the large comprehensive model. This model fortunately worked properly and did not show any instabilities. Background information about setting up this model and the results can be found in Appendix K. The main differences are the much smaller size of this network and the simplifications which were done at the model. Due to the restricted amount of time which was left it was not possible to analyse these runs thoroughly, but they are sufficient for getting a rough idea on how the stormwater network responds on elevated water levels at sea and at the harbour. The results of these analyses unfortunately came too late to be used in the following parts of the report.

A separate model for the Umgeni River was as well created to analyse the effects of higher sea water levels on the water depth in the river. Unfortunately this generated errors as well and the model was therefore not usable. This could possibly be caused by using an external inflow for a channel, however there was no time left to find and solve these problems. Therefore the choice had to be made to leave this topic.

### 12.2.2 Modelling approach

In order to gain more insight in the performance of the stormwater network multiple runs have been done with different water levels at the outfalls, different rainfall events and both with as without local blockages due to waste in the network. These cases were compared to a base case, which was a less extreme event without an elevated water level at sea and with blockages due to waste.

When processing the results, special attention was paid to the situation around Milnes drain. This is one of the most important drains of the stormwater network of the CBD and located in the lowest lying area. The drain is a culvert with a large diameter and a length of about 1500 m which discharges at the harbour. Problems are expected at this drain because of the very small slope which is 1:2000 at some places and the fact that the outlet is located between -1.1 and +1.1 m relative to MSL. The location of drain is visualized in Figure 12.3 and a cross section is shown in Figure K.3a. In these figures it is visible that this drain is low lying and is influenced by tidal motion.

(a) Location within CBD (b) Location within evelation map

Figure 12.3: Milne's drain

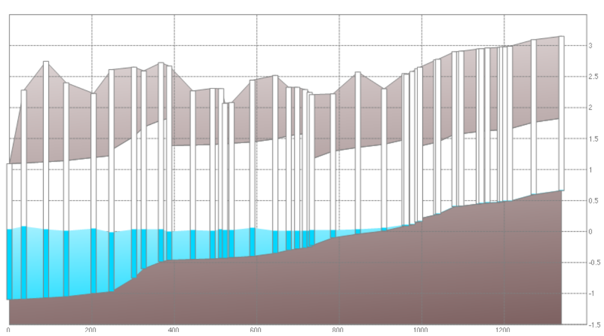


Figure 12.4: Cross section of Milne's during MSL

#### 12.2.3 Results

The flood map for a 1 in 50 rainfall event together with a high water level at the harbour is visualised by figure 12.5. In all of the runs the largest flooding problems occur at the low lying area situated land inward from the dune row, which was already expected. However, most of the floods are local and the depths are usually within a range of 15 centimetres. This could however be a slight underestimation because of the way PCSWMM tries to mimic the actual situation. The approach of PCSWMM does not take account for overland flow directly by rainfall, but routes everything at the manholes and overland flow will only occur if the network has insufficient capacity. Furthermore, the elevation of the cells is sampled from their centre, which is often the middle of a road in the CBD. The sides of the road and the sidewalks are generally somewhat lower. This could also lead to an underestimation of floods. More explanations about these phenomena can be found in Appendix H.

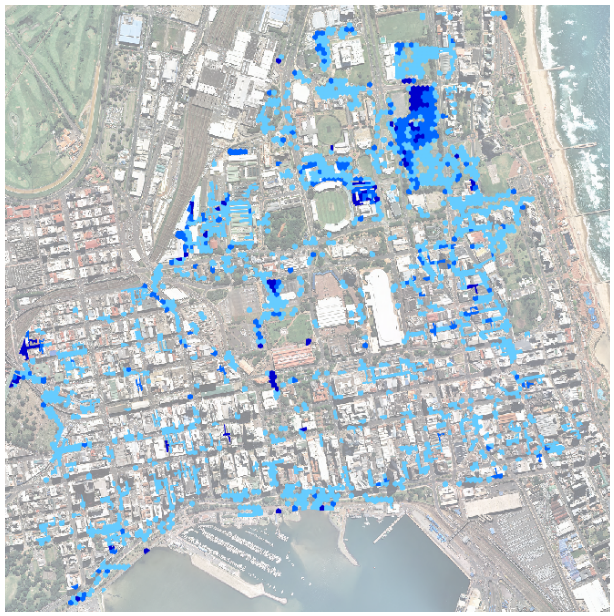


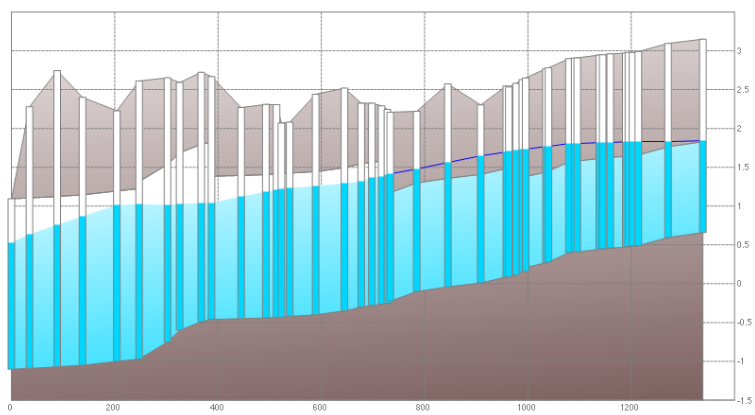
Figure 12.5: Flood map for a 50 year return period rain event combined with high sea water level

Based on comparing the runs with each other the conclusion can be drawn that waste in the network seems to have some effect. However, the difference does not seem to be large for the way it is included in this model. The water probably finds another way quickly in the model via overland flow to another manhole, and therefore does not cause a lot of problems. It is important to state that the approach which was used was somewhat blunt, and therefore probably not entirely in accordance with reality. The main difference is that water often gets blocked when entering the stormwater system. The workaround used for mimicing this in PCSWMM was by blocking stormwater pipes in the system.

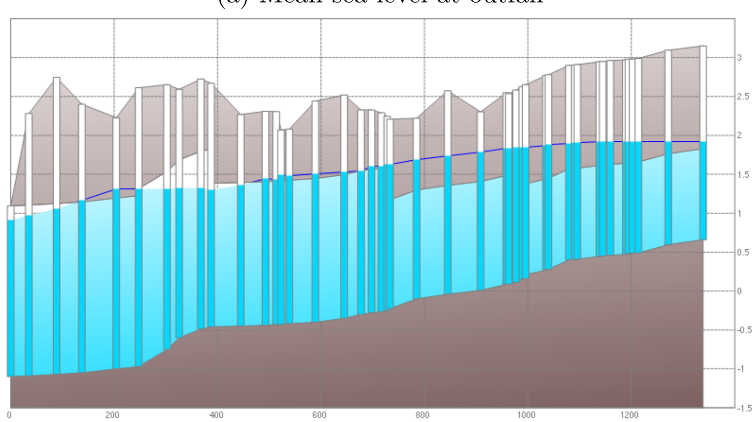
From the results of all the runs which can be found in Appendix K it became clear that the performance is influenced by elevated water levels at the outfalls, however the influence seems to be relatively small. Barely any difference can be seen in the flood maps, however the flood depths are generally somewhat larger. Most of the floods occur at the secondary network which leads to the main drains. The secondary network seems to have difficulties with discharging the water at the main network, which leads to local floods as can be seen by the local character of the floods in Figure 12.5. This occurs for both less and more severe extreme events. In order to check whether the main drains still function with high water levels at the outlet, a comparison is made for the Milnes drain in Figure 12.6. The cross section is visualised for no water level elevation at the outlet (mean sea level), a relatively high water level of 0.9 m above MSL and a very high water level of 1.6 m above MSL. An extreme rainfall event (50 year return period) is used for these of the runs.

From this comparison it appears that the Milnes drain, considered as one of the most critical drains of the network, is still able to cope an extreme rainfall event with very large water levels at the outfalls. An important remark needs to be made about the most upstream part of the drain. In the model in PCSWMM it is defined that there is a water height difference of about 1 to 1.5 m between the top of the drain and ground level. In reality this height difference is only a few decimetres at maximum. This might underestimate flooding, however the top levels of the manholes of the secondary network connected to this main drain seem to be more realistic. The floods in this area are mainly generated by these manholes, while floods would probably occur in reality at the main drain itself. The flood map still seems to be fairly realistic because of this effect.

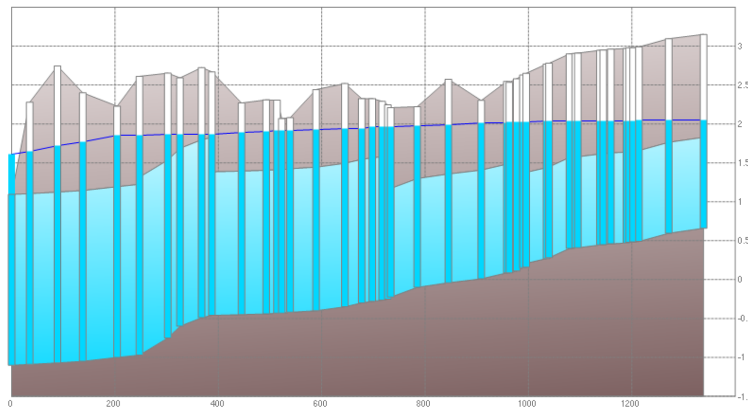
One of the reasons for the fact that no large floods are occurring is that the flow at the largest part of the drain is not extremely large, because the catchment area is limited. The required water head which needs to be built up in order to discharge the flow is therefore only a few decimetres. At some places the network almost overflows, however it is still able to cope. At the location of about 200 m upstream from the outfall there is an inflow from the drain under the Stalwart Simelane St (old Stanger St). This drain has a larger slope because its upstream area is more elevated than at the upstream area of the Milnes drain. At the point of the confluence an offset in the line representing the hydraulic head can be seen. This is because a larger head difference is needed to discharge the increased amount of water. This raises the hydraulic head in the upstream part of Milnes drain, however does not cause large problems.



(a) Mean sea level at outfall



(b) Water level at outfall 0.9 m above MSL



(c) Water level at outfall 1.6 m above MS

Figure 12.6: Peak flow in Milne's drain during a 50 year return period rainfall event

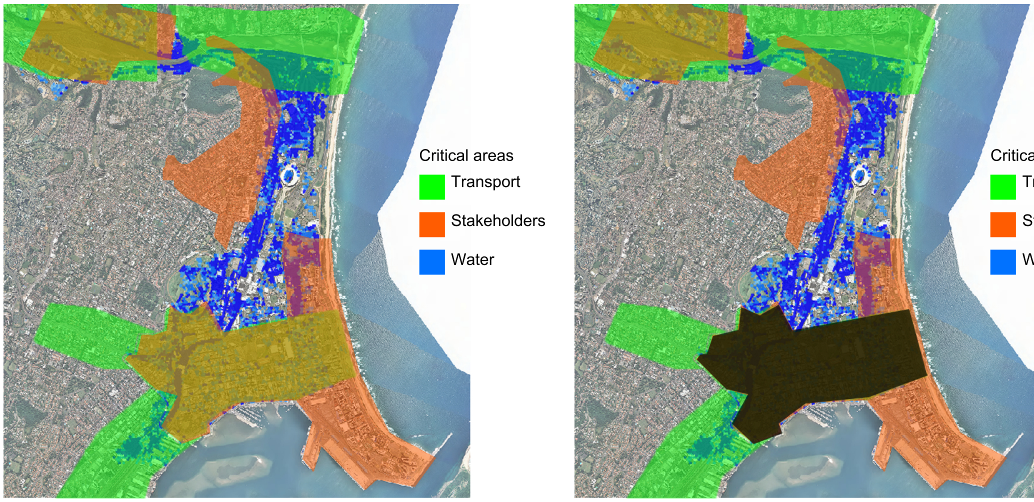
### 12.3 Conclusion

Multiple areas are at risk of flooding during large rainfall events. The floods occur mainly at the transition from a hill to the low lying part of the stormwater network and at low lying areas close to the sea. No large floods are expected at the CBD because of the decently built stormwater network and the limited influence of elevated water levels at the outfalls on the performance of the network. Some places are flooded nevertheless, but these floods are mostly very local and flood depths are limited. The area around the Milne's drain is the most critical part, however the influence from elevated water levels at the outfalls is limited. There is an influence of waste and litter blocking the systems, however this seems to lead mostly to smaller local floods. An important side is that an unrefined approach has been used to simulate this, because there is no possibility for modelling this in PCSWMM. Futhermore, no real calibration data was available for checking the performance of the stormwater network in PCSWMM. There are some reasons explained before why PCSWMM can be expected to underestimate floods. There was general information available about flood sensitive areas, which was in agreement with the results provided. Once the model has been set-up correctly and calibrated it has a large potential. One can easily assess the performance of a stormwater network and determine flood prone areas, for both the current situation as for planned adaptations in the system.

## 13 Consequences of floods

This chapter describes the consequences of the floods in critical areas which are elaborated on in Part II. The transport map and the stakeholder rich area map are combined with the PCSWMM results (see Figure 13.1a) and evaluated. The PCSWMM results were obtained later in the process than expected and therefore as a pre-analysis a short-cut was made which analysed the flood prone areas based on the knowledge at the municipality which can be found in Appendix N.

This section focuses on the results as obtained from the PCSWMM model. There are two main areas, the Umgeni Business Park (1) and from Greyville to South beach which includes the whole CBD (2), these are shown in the yellow parts in Figure 13.1a. Due to the limited results of PCSWMM the focus of this part is on area 2: CBD which is shown in black in Figure 13.1b.




(a) Scenario 1 (b) Focus area

Figure 13.1: Combination three critical maps

## 13.1 General Consequences on Central Business District

The picture below (Figure 13.2) gives a more detailed map of the floods in the Central Business District. The three different shades of blue show different water depths. The middle and darker blue indicate water depths higher than 5 cm, on which the focus will be. In this section will be elaborated on this area.

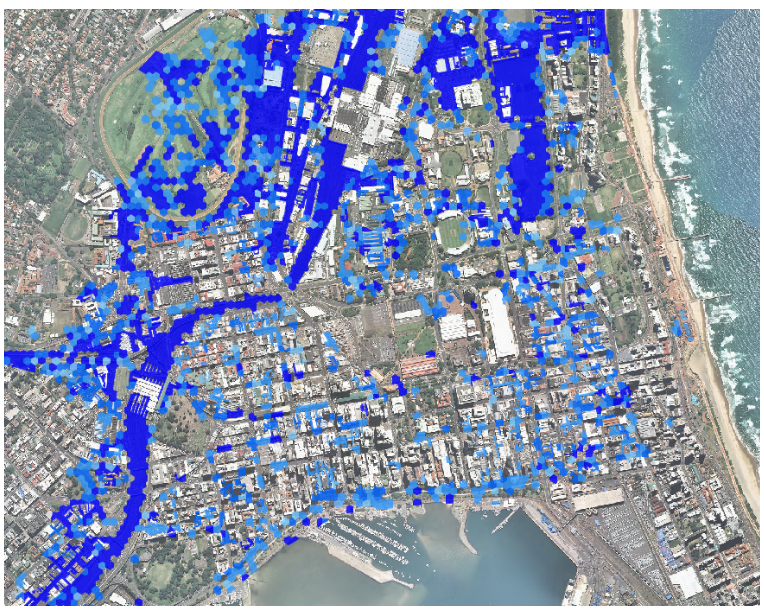


Figure 13.2: Floods in the Central Business District

For the general analysis of the stakeholders that are located in this flooded area and the risks that might occur due to floods, the critical area analysis in Part II can be used together with the risk register from Appendix M.2. To determine both the amount of stakeholders in this particular area and the market value, the whole market value analysis of the CBD can be implemented and expanded by the market value of South beach. This combination is shown in Table 13.1. In this part the industrial-, business and commercial- and residential buildings and inventory are seen as the capital value of an area. These results show that a lot of companies and residents might be affected by this particular floods. In these tables PSI refers to the capital value of road infrastructure, but regarding the limited amount of water this damage is considered to be minor with respect to the just mentioned other capital costs. The same holds for vacant land which refers to open terrain without buildings or other type of structures.

Table 13.1: Market value in Central Business District

| CBD | Vacant land | Industrial | Business and Commercial | PSI | Residential |
|---|---|---|---|---|---|
| **Amount** | 85 | 100 | 644 | 83 | 9590 |
| **Market value [Million ZAR]** | 285 | 405.67 | 7113.066 | 2.457 | 4109.867 |

The general risk register that is shown in Appendix M.2 is made by taking in mind all kind of floods that can occur in Durban. The floods that occur in the CBD are not extreme, which means that it is likely that some of the risks that are determined in the risk register occur in this area, but not all of them. The risks that are less likely to occur in the CBD area, but are shown in Table M.2, are that buildings will fall down, that there is no money available for recovery of the city and the infrastructure is damaged. This is because of the minor amount of water and the relatively good soil conditions in this area. Besides this the buildings in this area are of better material than in other low income class areas like the townships. The risks that are likely to occur are damage to buildings, floods in libraries and museums, basement floods, floods in hospitals, home and office damage and damage to goods. The risks are divided in capital, economic and social risks and might have an effect on the costs. Therefore to determine the capital value these capital risks are taken into account, to determine the economic value these risks are taken into account and to determine the social costs the social risks that can occur are taken into account. In this way it is easy to see which areas contain a lot of risks referred to capital, economic and social values. In the next sections the risks are described that can occur in the CBD regarding the output of the PCSWMM model.

The focus area of this part is the CBD (Southern part of Figure 13.2. It should however be noted that a lot of floods occur in the north of the CBD, especially around the sport facilities. Because of this the northern part is of minor importance regarding capital and social damage but for the transport network, and thus economical losses, it is considered important. Therefore the northern part will be treated in the paragraph on economical value, but will be ignored in the paragraphs on capital- and social values.

## 13.2 Capital Value Central Business District

The capital value is seen as the one-time amount of damage costs in the city (See Appendix M.2.1). As earlier mentioned, the 1 in 50 rainfall water heights are the advised minimum ground level heights of buildings besides the common rule of thumb of a minimum ground level of 20 cm. This means that the heights that are shown in Figure 13.1a are in principle the advised minimum heights of the ground level of buildings, because this was the result of a run with the 50 year rainfall event. This 1 in 50 advise is however very recent and therefore considered to be less suitable to large parts of the area. Therefore the 20cm rule of thumb will be used in examining the capital damages. Regarding the examination one can think of capital damage when the water level exceeds 20cm.

The capital risks that might occur due to floods is shown in Appendix M.2. These capital risks that can result in capital cost for the CBD will be elaborated in this paragraph.

First, damage to buildings might occur in the whole CBD. In the South-west part of the CBD (Greyville) is a high variety of stakeholders because the areas become more residential over there. The market values of the buildings that are located in Greyville are shown in Table 13.2. This table only focuses on this small area which means that there are also a lot of small and short roads. Especially compared to the area in South beach that contains mainly three large and long roads (see Table 13.3 Besides the residents and businesses, also Durban University of Technology, three hospitals, a railway station, entrances to large highways, supermarkets and a bank are located in this area.

Most of the water heights in the residential areas in Greyville differ from 2 to 20 cm for this scenario. Regarding the used rule of thumb which states that the minimum ground level should be around 20cm, this means that the water might reach to the limit. The result of this is that when the advises and rule of thumb of the water department and city architects of eThekwini municipality are not taken into account correctly, these areas are prone to flooding. Besides this, these areas might nevertheless be prone to flooding due to the fact that PCSWMM indicates the height of a cell usually in the middle of the road which is the highest part as was described in subsection 12.2.3. Within this area mostly middle to high class income residents are located. Often they have expensive furniture and equipments in their house. Therefore, a lot of furniture, fridges and other expensive equipments can be lost. Especially in the university and the hospital there is a lot of expensive equipment used for research. Because of this the capital damage when a flood occurs is considered to be relatively high.

The areas around the railways are affected the most by floods because of the water heights which can increase up to 2 metres at some places. The area around the railway has less buildings, but due to the large amount of water some capital damage to the railway structure can be expected. Besides the railway the area is mainly used for markets, which are considered to have a low capital value and therefore a low impact ones a flood occur with respect to capital damages.

The north-east area of the CBD (South beach) is quite different compared to Greyville. South beach is a high density area with middle and low class incomes. This area contains a lot of large as well as small businesses (see Table 13.3). The large companies are mainly located in the north side of the area. Several car rental companies like the world wide known Hertz is located there and in the south of the area a lot of fast-food restaurants like KFC are located. The small businesses, like pharmacies and telephone shops, are mainly located in the southern part where also the inhabitants live (see Appendix N). These small businesses are often located at street level whereas residents live above these companies. Therefore mainly the large companies and these small businesses are considered to be affected in a capital costs way in case of a flood event.

The water heights in this area can be high. With a 1 in 50 rainfall scenario the water heights at the highest part of the road have a minimum height of 5 to 10 cm. This means that the water height at the building location can be more or less 30 cm. Recall that this is because the roads in Durban are above the sidewalk level and that the PCSWMM model generates mostly the height in the middle of the street. This height is above the minimum ground level of 20 cm causing water to enter the buildings.

Regarding the car rentals this is considered to be inconvenient but the damage is likely to be relatively low since a car will not be damaged by 10cm of water. Problems might start to arise for more severe scenarios and the capital damage might go up fast than, because cars represent a relatively high capital value. The current amount of water is considered to cause more damage to the fast-food restaurants and small businesses due to the fact that a lot of electronic equipment is in place. Moreover small business might have a lot of goods in their store that they want to sell or store. If one thinks for instance of a grocery store that needs electricity and water floods the store and shuts down the electricity the products can not be sold anymore leading to capital damages.

Second, floods in libraries and museums might occur that result to damage to art and cultural pieces. The yellow dots in Figure M.1 shows the museums that are located in the area of interest. These museums are mainly located in the middle of the CBD. In this area less floods occur. If the advices of the minimum ground level of buildings are taken into account, less capital damage will occur in these museums and libraries. Precautions are probably necessary to make sure that there will be no damage to books and other cultural pieces. Canals of the water drainage systems are located at the right side of these museums in the map, which means that if there are severe floods the probability will be there that museums floods.

Third, basement floods that result in broken pipes and energy regulator. Figure M.2 shows the several parking places that are located in the area of interest. According to Dharsha Naidoo, Durban has no multiple level basement garages. In Durban the minimum ground water level is 1 meter below the surface, which means that it is very expensive for South Africa to built those parking garages and install several water pumps to make sure that the water will not enter the basement garages. Most of the public garages are half a meter below surface. However, the maps that are available do not show all the basement garages in eThekwini. Some hotels near the coast do have basement garages under the hotel but these are not shown in the maps that are available probably because of the private garages. But the most common way of parking in Durban is at the roof of buildings because of the less costs that are involved compared to basement parking places.

Finally, floods in hospitals that result in loss of important and expensive equipment in Greyville. Two of the three hospitals that are located in Greyville deal with floods in this scenario. At the place where the hospitals are located the water level can rise to 27 cm at one place and 37 cm at the other place with the current rainfall scenario. The capital damage when one of the hospitals flood is considered to be relatively high due to the amount of high tech equipment.

Table 13.2: Market value in Greyville

| **Greyville** | **Vacant land** | **Industrial** | **Business and Commercial** | **PSI** | **Residential** |
|---|---|---|---|---|---|
| **Amount** | 40 | 16 | 56 | 34 | 139 |
| **Market value [Million ZAR]** | 17 | 54.67 | 201.96 | 0.04 | 15.2 |

Table 13.3: Market value in South beach

| **South beach** | **Vacant land** | **Industrial** | **Business and Commercial** | **PSI** | **Residential** |
|---|---|---|---|---|---|
| **Amount** | 7 | 25 | 27 | 3 | 3351 |
| **Market value [Million ZAR]** | 65 | 103.7 | 169.4 | 5000 | 1948.37 |

## 13.3 Economic Value Central Business District

Economic costs are the costs that are of economic value (See Appendix M.2.1). The economic risks that can result in economic costs are shown in Table M.3. The risks that occur in this area are elaborated in this paragraph. The most likely risks are road floods and floods in train stations.

Besides this no electricity will also result in loss of economic value due to not fully functioning of companies. But the main focus will be at the economic value of transport.

The economic damage can be high because of the railway and important roads that are located in this flooded area. The amount of roads that goes to this area is limited. This means that the economic costs caused by travel time delay can be high as well. Companies can not have an insurance for losses that are caused by traffic delay of employees. If employees are not able to access the company, the losses for the company will be high and not covered by insurance companies. For small businesses these impacts are higher than for large businesses because of the larger financial buffer of industrial companies. Since there are a lot of business located in the CBD, the area will be very vulnerable for economic damage.

In the CBD the railway track is vulnerable to floods and floods will thus have a big impact on the rail network. When the tracks are flooded, the trains to and from Berea station (see Section 4) cannot drive anymore, resulting in no rail connection between the centre of Durban and the southern stations. The affected people have to use other infrastructures like road. The resulting impact on the total road network will be very small due to the limited amount of people using the train.

As can be seen in Figure 13.2, the heaviest floods occur on the north, west and south-west side of the CBD. The main roads that will be affected by floods are the N3, M4, R102 and M12. On the N3 going out of the CBD water heights of more than 15 cm can be found and therefore traffic cannot use this road anymore. On the other hand the N3 towards the city is not flooded. On the south western side of the CBD there are floods which block both the M4 and R102: The M4 in both directions and the R102 going out of the CBD. Therefore traffic cannot travel from and to the south. On the north side of the city the R102 and M12 are blocked in both directions, whereas the M4 is still available. Lastly there are floods within the CBD itself. The streets (see Table 13.4) which are most severe flooded are located in the South Beach area and streets going from Greyville to this area. It can also be seen that there are roads that are semi-blocked. There are floods on these roads but with water heights between 5 and 15 cm and therefore the effect is that the traffic can go through but has to drive slower. This information is all summarised in Table 13.4.

Table 13.4: Capacity, normal intensity during AM peak and blockage of roads in case of floods in the CBD [22]

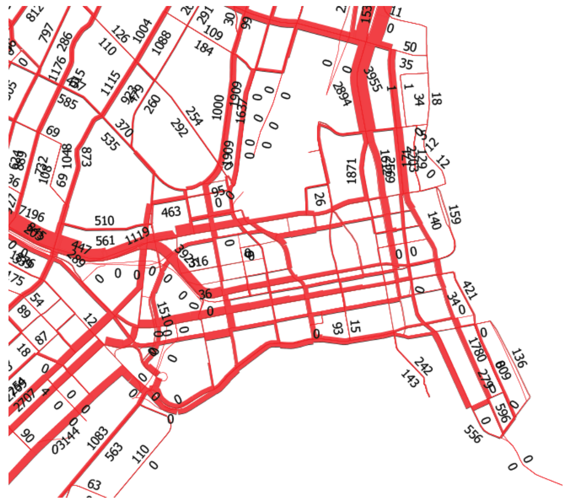
| | roads | capacity | intensity | Scenario 1 |
|---|---|---|---|---|
| West of CBD | N3 from CBD | 10000 | 5613 | Blocked |
| | N3 to CBD | 8000 | 7779 | Open |
| South-west of CBD | M4 to CBD | 6000 | 6344 | Blocked |
| | M4 from CBD | 6000 | 4454 | Blocked |
| | R102 to CBD | 4800 | 2656 | Open |
| | R102 from CBD | 4800 | 2048 | Blocked |
| North of CBD | M4 from CBD | 4000 | 1891 | Open |
| | M4 to CBD | 4000 | 2528 | Open |
| | R102 from CBD | 2400 | 1852 | Blocked |
| | R102 to CBD | 2400 | 2056 | Blocked |
| | M12 both directions | 4800 | 2205 | Blocked |
| CBD | John Milne | 1200 | NA | Blocked |
| | Kearsney Rd | 600 | NA | Blocked |
| | Dr A B Xuma street | 4000 | 3025 | Half Blocked |
| | Monty Naicker Rd | 4000 | 2072 | Half Blocked |
| | Margaret Mncadi Ave | 4000 | 3358 | Half blocked |
| | Dr Pickley Kaseme Rd | 5000 | 3976 | Half Blocked |

It is clear that there are lots of blockages on the network in this scenario, as also can be seen in Figure 13.3 where orange indicates blocked roads and green indicates roads that are still accessible. The blockage of these roads means that almost 15000 vehicles (Table 13.4) have to find another route out of the CBD. They cannot all use the M4 to the south, so there will be heavy traffic jams. There are also almost 9500 vehicles (Table 13.4) that cannot enter the CBD via their usual route.

Figure 13.3: Blocked roads

The blocked roads as shown in the figure above are used as input for the Emme traffic model (see Appendix D.4). The roads are blocked in the model with as result that the traffic is redirected to other roads. Figure 13.4 shows the comparison between normal traffic volumes during AM peak hour (13.4a) and traffic volumes in case some roads are blocked (13.4b). The most obvious difference can be found bottom left in the picture, on the M4. The M4 is completely blocked and can therefore not be used anymore. This traffic is redirected to smaller roads and the N2. Another clear difference can be found a bit above the middle in the pictures, where the R102 is located. When this road is blocked traffic has to use either the M4 or small roads nearby.

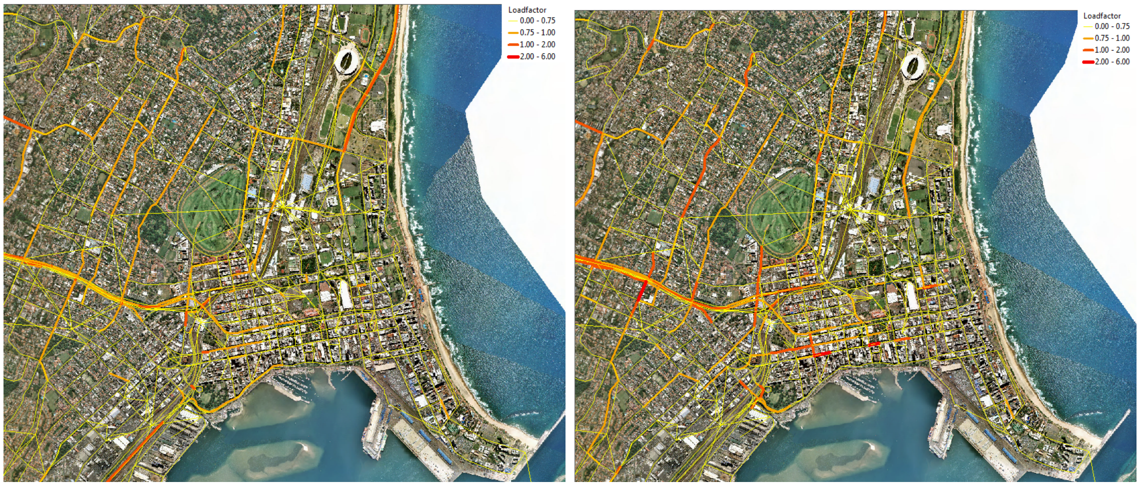
(a) Normal situation (without floods)



(b) Situation with blocked roads (Table 13.4)

Figure 13.4: Traffic volumes in the CBD (AM peak)

The capacity is combined with the traffic volumes in two figures (Figure 13.5) to see the consequences of the blocked roads on the network. There are four colours representing the different load factors. Figure 13.5a shows the load factors of the current transport network, where no roads are blocked. Figure 13.5b shows the load factors in case the roads as mentioned in Figure 13.3 are blocked due to floods. One of the main blockages is thus the M4 to the CBD which is on the north side and around the N3. The M4 road reaches its capacity and is therefore a new bottleneck. The other area that encounters a big impact of the traffic redirection is on the west side of the CBD. This area includes the N3. The main problems of the N3 are not on the road itself, but on its on- and off- ramps. This can be explained by the fact that traffic coming from and going to the south of Durban is redirected because of the blockage of the M4 in the south. This traffic now uses either the N2 (which is outside the scope of this project) or small roads. These small roads eventually enter the N3 which makes the on- and off- ramps very busy. The capacity of the N3 itself is very high (around 10000 vehicles per hour). Compared to this the capacity of the on- and off-ramps are very low (around 1600 vehicles per hour) and cannot always handle the redirected traffic volumes.




(a) All roads open to traffic (b) Some roads closed due to floods

Figure 13.5: Loadfactors of the network

Besides the problem that roads reach their capacity, and thus congestion occurs, there is also delay in travel time. This delay is caused by the fact that traffic has to use other routes than the fastest route. This means more travel time. It is not possible to determine the exact travel time delay, since the origin, destinations or average trip lengths are not known. It is for sure that the travel time delay will result in economic costs, since every second of travel time has a certain economic value.

### 13.4 Social Value Central Business District

Social risks are the risks that are important for the well-being of a human, the risks with a social effect on the environment (See Appendix M.2.1). The social impact and thus the social value in CBD is considered high due to the amount of important public buildings, residences and businesses that are located in Greyville and the less insured property owners in South beach. These social risks that can result in social cost for the CBD will be elaborated in this paragraph.

First, a lot of claims can occur due to home and office damage that result in lots of social costs to insurance companies, houses and companies. Insurances are considered to have a great effect on the social impact of floods on property owners. If people have a well covering flood insurance, the social impact will be less because the insurance company will help them by recovering from floods. When people are not able to afford a well covering flood insurance, the social impact can be high because the recovering costs can be too high for them. However, not only the impact on property owners can be high but also the impact on insurance companies can be high since they have to pay for these costs which can have a large impact on these companies. The money losses due to floods have to be paid. If the property owners do not have to pay for the recovering costs, the insurance companies will have to pay. This is important to take into account when the social impact of floods is being investigated.

The age of a building can be important for the insurance the buildings have. Often when buildings are very old they do not have an insurance because if floods occur the recover costs and recover time will be too high according to Talia Feigenbaum (Appendix B.3). This makes the determination of the most affected areas hard because it is not possible to say which areas contain mainly old buildings and which contain mainly new buildings with the data that is available. This means that it is not possible to say very exact which of the areas are likely to be insurable or not. Another way to obtain information about this matter would be via the South African Property Owners Association (SAPOA), but unfortunately they said that it is not possible to hunt down the amount of buildings that are insured in a certain area in the city. The organisation does not have a map with stakeholders or property owners in the researched area in this report. Because of the described importance of insurances on the social impact it is necessary to make an assumption in order to say something about this. Therefore for the remainder of this section it is assumed that people who have the financial abilities to pay a insurance, will most likely have one.

As earlier mentioned most residents of Greyville are middle- to high income and will therefore, regarding the assumption, have a flood insurance. Most of the businesses an companies in Greyville are considered to be large enough to have a flood insurance as well. The flood insurance for the constructional elements of buildings is included in the house insurance, but people have to be sure that they also have a household insurance for floods to reduce the capital and social costs. Because the people that live in Greyville are middle to high income class residents this is likely to be the case. Even public buildings are mostly well insured as well by the government. Therefore, it seems reasonable to say that the people in this area are well covered by insurance companies and most of the goods that will be damaged can be claimed by the them. The result of this is that the social cost to the inhabitants and companies in Greyville is limited.

Because of this insurance companies have high costs when floods occur in Greyville. Therefore, although the social damage for inhabitants and companies in this area will be low, insurance companies might be a stakeholder which is very keen on lower the flood probability in this specific area. This may be of importance later on in construction the solutions.

Second, as told in the capital value, museums and libraries are located in flood prone areas. The floods that however occur in these areas are not of a high water level. This does not mean that they will not be affected, but they have to make sure that precautions are taken so that the effect will be limited. The floods might be higher than first expected which can cause social damage because art and cultural pieces are damaged.

Third, as earlier mentioned there are three hospitals and a university located in the western part of the CBD of which two hospitals and the university might have to deal with floods for the 1 in 50 year scenario. This means that it will not only affect the people that are living or working in this area but also the students that visit the school and people that need medical care. This can be crucial for the hospital, especially when cars and thus ambulances are not able to drive when a height of 5 cm occurs. The consequences can be enormous as people might drown or die because of delay of emergency authorities at a certain place.

Fourth, sport fields that will not be usable for inhabitants.In the CBD there are no sport fields that are not usable. The main sport fields that are not usable are located in the north of the CBD. Mainly these sport fields are flooded for the reason to keep the floods out of the stakeholder valuable areas so less people will be affected by floods. The sport fields will flood but less buildings will be affected by these floods compared to the CBD, making the expected capital minor. Closed sport facilities might have a social impact, but it is expected that during flood events people are more concerned about their belongings than that they can go sport. Mainly inhabitants that play sports at these sport clubs are affected.

Fifth, it could be that the electricity is unavailable. There are no main electricity areas in the city but there can occur short circuits. Short circuits will result in a dark city and therefore more crime.

This can have effects on the well-being of a human. Besides the lights that are not working, also the emergency buttons in the houses that are often used by high class income residents to prevent crime would not work anymore.

Finally, shops and hotels have to be closed due to water heights that can result in loss of incomes. The water heights in South beach are mostly not higher than 10 cm in the middle of the street. This means that the water heights near the buildings will be more or less 30 cm **See Appendix ??**. The highest water levels occur there where the drainage system blocks. These areas are shown in dark blue in Figure 13.2. The whole area contains a lot industries like restaurants from local restaurants to large fast food chains like KFC. Social impact of floods in this area are mostly the loss of income when floods occur. Smaller businesses have less economic and capital loss as a result of floods than big companies, but the social effect is for a small businesses much higher than for a big company because of the financially stabilised background of big companies. Also in South beach it is not possible to determine the amount of insured companies and the age of the buildings according to SAPOA. It is hard to determine which area is most socially affected because of lack of time and lack of data. There are no hospitals or schools located in this certain area.

## 14 Conclusion Part III

The different parameters that have an influence on the floods in Durban were combined based on reasoning whether or not it is possible and how likely it is for certain events to occur together. This resulted in a range of possible water levels during extreme events in the harbour and at sea. The combination of these water levels with the landside parameters, rainfall and river discharge, formed the scenarios that were put into PCSWWM to investigate the effect of the water level on urban flooding.

The model results were unreliable around the Umgeni and therefore the focus was laid upon the CBD area. From the PCSWMM model it was concluded that no large floods are expected at the CBD because of the decently built stormwater network and the limited influence of elevated water levels at the outfalls on the performance of the network. Some places are flooded nevertheless, but these floods are mostly very local and flood depths are limited. The area around the Milne's drain is the most critical part, however the influence from elevated water levels at the outfalls is limited. Due to the limited results of PCSWMM the focus of the consequences of floods on the network and stakeholders was in the CBD area.

The main risk events that occur due to floods for the capital value are: first, damage to buildings. Second, floods in libraries and museums might result in damage to art and cultural pieces. Third, basements floods that result in broken pipes and energy regulator. And finally, floods in hospitals that result in loss of important and expensive equipment in Greyville.

The consequences due to these risk events for the capital value can be high in this area, the highest capital values will be for the public buildings in this areas, especially in Greyville, that have a lot of expensive equipment that is used for the medical care and learning purposes. The second highest capital value will be for the small companies in the areas. The capital costs have to be paid by someone, if it is not the inhabitants or companies it will be the insurance companies. But the effects of the inhabitants and the companies will be larger. For this reason it is important when looking to the capital value to find solutions for the public buildings to be safe and the companies, especially the smaller companies, to be safe.

The main risk events that occur due to floods for the economic value are flooded roads and railway tracks.

The consequence due to floods is that there are several roads blocked. The traffic that used to take this road has to use other roads now. Some of the big roads are blocked, therefore traffic has the choice to either use other big roads or to use smaller roads. The capacity on other big roads is in many cases enough to cope with the extra traffic. The main problem will be found in the entrances and exits of the main roads since they are small. Congestion will therefore occur on the entry- and exit- ramps of the main roads. This causes travel time delay. Next to the congestion, travel time delay is also caused by the fact that traffic has to take detours, which also takes extra time. The travel time delay results in economic costs, the economic value decreases.

The main risk events that occur due to floods for the social value are: first, a lot of claims due to home and office damage. Second, museums and libraries that can flood. Third, people that drown or die. Fourth, sport fields that will not be usable for inhabitants. Fifth, it could be that the electricity is unavailable. And finally, shops and hotels have to be closed.

When looking at the consequences due to the risk events for the social value, it is considered to be highest for property owners and small businesses in South beach because they mostly cannot afford a flood insurance and for insurance companies Greyville will be more critical. When high floods occur small businesses eventually have to close their company that results in no incomes that can occur in more vulnerable consequences. For property owners it is important to reduce, transfer or avoid floods in South beach.

# Part IV Solutions

Part IV contains the solutions that are created based on the results of Part III. These solutions are compared with each other by performing a Multi Criteria Analysis (MCA). To test the robustness of the results of the MCA, a sensitivity analysis will be performed. It should be noted that the main goal of this project was to find the impact of floods on stakeholders and the transport network and whether this impact could be increased due to severe conditions from the sea side instead of designing detailed solutions. This part is therefore more focused on providing a general framework on how to deal with the problem called floods, instead of really giving a detailed design to limit the impact.

## 15 Creation solutions

To find successful solutions for a certain problematic event it is considered important to think of what the actual problem is. The problem in this case is that there occur floods which cause damage. This problem is largely solved when the probability of a flood is reduced or when the damage during a flood is limited. Based on this notion one can say that the problem is a risk, since risks are defined as the product of probability and consequence (Nicholas and Steyn [40]). In order to deal with the problem there should therefore be searched for ways to response to the risk. A proper solution is thus a risk treater which either reduces the probability of a flood or reduces the impact (or both).

In order to come up with proper responses to these risks, use is made of a theoretical framework as was found in Nicholas and Steyn [40]. The four risk responses that are taken into account are accept, avoid, mitigate and transfer. These four general responses to deal with risk form a starting point in the creation of solutions. The above is summarised in Figure 15.1 below:

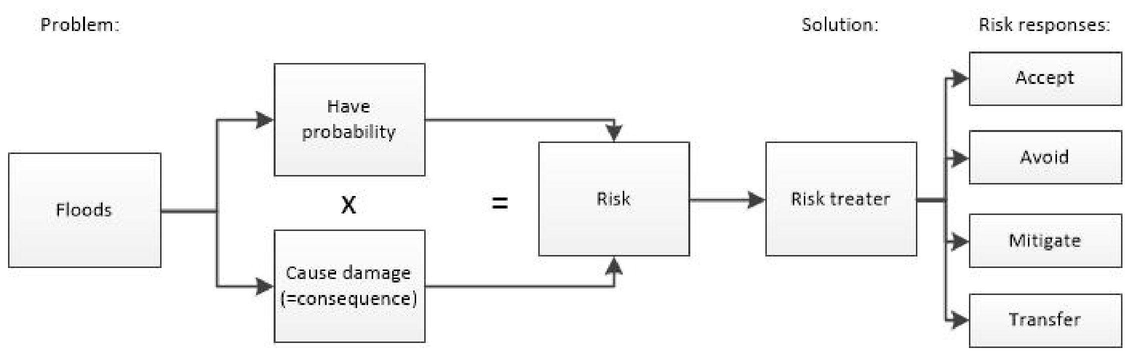



Figure 15.1: Creating solutions

A general description of each of the general solution strategies together with a brief application for the area of interest is given below:

### 15.1 Accept

In Nicholas and Steyn [40] is stated that if the costs of avoiding, mitigating or transferring the risks are higher than the benefits, accepting the risks seems the best solution. Most of the time accepting risks will be done when the consequences of these risks are not high. Although, sometimes it is impossible to response in another way on a risk than accepting it.

**0-Hypothesis** At this moment it is not clear yet if the risks of avoiding, mitigating or transferring are higher than the benefits. Therefore the 0-hypothesis is taken into account just in case the other responses are not feasible in this area. The 0-hypothesis means in this report that nothing will be done to the risks as a result of possible flood events in Durban.

## 15.2 Avoid

Avoid risks can be done in several ways which depend on the project. However, it is not always the case that risks can be avoided [40]. Nicholas and Steyn stated that especially research projects are inherently risky but can end in a lot of advantages in a later stage. Most of the time it is beneficial to reduce the risk instead of avoiding the risks because of the new risks that are involved by avoiding the risks [40].

**Upgrade water drainage system** The floods could (to a large extend) be avoided by upgrading the water drainage system. Preventing floods all together might however be an impossible task or at least not be worth the investments. Avoiding floods means that the water drainage system should be upgraded and subsequently tested to be a proven system that can withstand the most severe conditions. The water drainage system can be upgraded and designed in a way that there is more storage capacity in the system and/or in a way that the water in the system flows faster out of the system than it is currently doing. Pumps might also be a necessity to completely avoid the risks as the water level could get to such a level where, no matter how big the drainage pipes are, they will not be able to discharge quickly enough into the ocean.

## 15.3 Mitigate

Mitigation is defined as reducing the risks. According to Nicholas and Steyn risks are seen as the probability that they occur times the consequences when they occur. If risks have to be reduced it is important to reduce at least one of these two factors. The consequences in terms of budget and costs (economical and capital costs) can be reduced by using a system that is proven and tested for other similar situations. It is important to be sure that this system works, otherwise the risks will not be reduced but increased. This verifying and testing can be done by modelling and assessments of the system [40].

**Change behaviour** One of the problems that causes floods is the bad waste management in the city of Durban. A lot of litter is left on the street which enters the urban drainage system and eventually might lead to blockage. It is a way of behaving that has to be changed. However the solution of changing behaviour sounds realistic, in practice it can be hard. Therefore it is a challenging solution that needs good preparation and good management.

The city of Durban already makes use of early warning systems and it has already proven that it works, especially in the transport network. Since the 2010 FIFA World Cup the municipality used a lot of early warning systems to control the transportation in and around the city. These systems can be used to communicate to inhabitants that floods can occur and for example move their cars to flood safe areas. Besides this, the MDMC already has contact with the weather forecast authorities to communicate when storms can occur or heavy rain will appear in eThekwini. This information can also be used to communicate the information that is gained from these authorities towards the inhabitants.

### 15.4 Transfer

Transfer risk is in this report seen as transferring the risk from a certain critical area to another area that might be less critical than the area that is used in this chapter. It is impossible to transfer the risk to another authority. The eThekwini municipality is responsible for the whole area of interest in which stakeholders always will be affected. The only way in which the risk can be transferred in this report is by reducing the effects which means transfer the event to a less critical area.

**Changing the road system and constructing retention areas** The transfer of the floods can be done by changing the road system. Roads that are prone to floods have to be heightened to let the water flow to other areas instead of blocking that particular road. Roads that should be heightened are the provincial and national roads with bottlenecks in it since the blockage of these roads has the most consequences on the network as was found in section 9.2. The water will thus be transferred to another region which reduces the problems on the roads.

By using areas that do not have much value, like retention areas, the effect of a flood on a city can be reduced. Durban already has certain areas which serve as retention areas but creating even more will further relieve the pressure on the system. One could also think of using basement garages as additional buffer zones.

## 16 Evaluation solutions

As described in Chapter 15 there are four possible solutions created for the flood problems in Durban. These solutions need to be evaluated in order to tell the most promising solution(s). The evaluation of these solutions is done by making a Multi Criteria Analysis (MCA). In order to be able to do an MCA, criteria to test the solutions have been defined, they can be found in section 16.1 together with the weight factors of these criteria. When the possible solutions, the criteria and the weight factors are defined, they will be combined in an MCA. The output of an MCA are the values of the possible solutions, this shows which solution is best. In order to tell with certainty if the outcome is correct, a sensitivity analysis will be shown as well. Figure 16.1 gives an overview of the steps in performing an MCA.

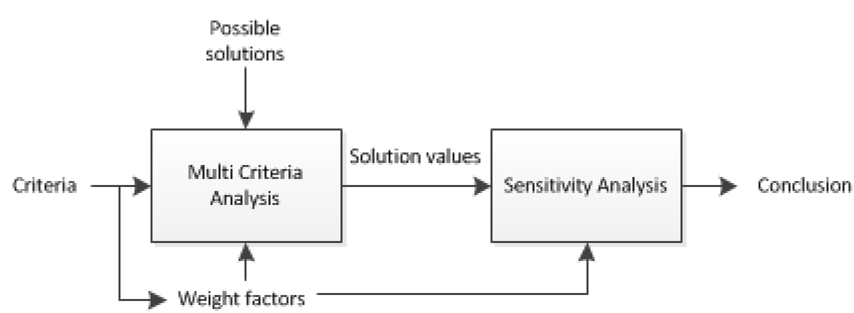



Figure 16.1: Steps in performing a MCA

### 16.1 Elaboration criteria

The criteria are based on the criteria from the system diagram (see Appendix A). In this diagram it was found that the system can be brought back to the criteria: Capital value, Economical value, Social value and Environment. In order to improve the system, improving these criteria is considered important. Besides these system criteria the extend to which the solutions can be implemented in

Durban is thought to be important. This is why the criteria on reliability, implementation costs and implementation potential are included. The final criteria are:

- Capital value: Capital value shows the risks that might occur due to the damage to buildings, infrastructure and other goods like cars.
- Social value: Social value determines to what extend human well-being is affected due to a flood event.
- Economical value: Economical costs are the costs which are the result of the fact that companies can gain less profit due to the floods. For example companies that have to close, or companies that cannot operate because of employees that cannot reach their work. This also includes travel time delay.
- Reliability: Reliability shows how reliable the resources are that are required for the solution, for example traffic lights, dynamic traffic signs, water pumps etc. The reliability also shows to what extent the resources/parties who are involved in the solution strategy can be trusted.
- Environment: The environmental criterion determines the impact of the alternative on the environment and nature. This includes garbage, pollution and damage to nature as fallen trees.
- Implementation: Implementation potential tells how easy it is to implement certain solutions in Durban, taking local organisational problems into account.
- Implementation costs: Construction/implementation costs are the costs that are made to invest in or to construct a certain solution. For example the costs of building new water discharge systems, infrastructure, dams etc.

The criteria have different weight factors. These weight factors show the importance of the weight factors relative to each other. The weight factors are determined by several stakeholders (see Appendix O). The average weight factors of the stakeholders are shown in the table below (Table 16.1).

Table 16.1: Average weightfactors

| | average |
|---|---|
| Implementation costs | 0.13 |
| Reliability | 0.16 |
| Capital value | 0.16 |
| Environmental impact | 0.04 |
| Economical value | 0.15 |
| Social Value | 0.20 |
| Implementation potential | 0.15 |
| Total | 1.00 |

## 16.2 Evaluation solutions

The solutions that are defined in Section 15 are evaluated by the criteria that are defined in Section 16.1. This is done by testing the performance of a solution with respect to a certain criteria. This process is performed based on information of the analyses that are done in Part I, the information that is gained by combining the three analyses in Part II and the determined risk events with their consequences that might occur in the CBD due to capital, economic and social values in Section M.2.1. In the end these results will be summarised by making a Multi Criteria Analysis in which the criteria for a certain solution will get a weight.

#### 16.2.1 0 hypothesis

**Capital value** The capital risks that lead to capital costs in this 0 hypothesis are mainly describe in Section 13. These capital costs will be seen as the capital cost damage that occurs when the 0 hypothesis is applied, thus the reduction in capital value. It might be that these risks are more beneficial compared to the risks that can occur or disappear by implementing the other solutions.

**Social value** The social risk event that can occur caused by floods and their consequences are shown in Section 13. These risks will be the same when the solution will be the 0 hypothesis.

**Economic value** The costs that result from the fact that companies gain less profit due to floods in the current situation are firstly caused by companies that have to close. In the case of accepting the risks of floods, there are several businesses that have to close down, resulting in lots of economic costs. Secondly there is travel time delay when floods occur. When the risks of the floods are accepted, there are many people that have to take detours because fewer roads are available. This results in congestion and thus in lots of travel time delay.

**Reliability** As there are no resources or parties involved in the strategy of accepting the risks there is nothing or no-one to be relied on which means nothing can go wrong and the strategy is completely reliable.

**Environmental impact** In this alternative there is no construction implemented which can have influence on the environment, but there is also no increase of the current environmental impacts. Due to the not good working waste management system a lot of garbage can flow in the sea in case of floods.

**Implementation** This risk response is easy to implement since nothing has to be done. There are no new stakeholders or systems involved by implementing this strategy.

**Implementation costs** There are no implementation costs involved because the risk response is accept the risk event.

#### 16.2.2 Upgrade drainage system

**Capital value** The capital risks and effects that occur or disappear by upgrading the drainage system, compared to the 0 hypothesis will be elaborated.

When the drainage system will be upgraded, the main effect on the capital cost damage will be that the water heights will be decreased or might disappear as a whole in the CBD. This will be most beneficial for the businesses in the CBD and the public buildings and residences in Greyville. Those had the most capital cost damage referred to the capital value of the CBD in Section 13.

The risks that will disappear by implementing this solution for the capital costs is that the damage to the buildings will be reduced. The small businesses can store their products without being afraid that their contents will get lost. The hospitals and schools can do their research and do not have to be aware that the most valuable contents are safe for floods. Besides this, the chance that basements flood will be reduced which means that the capital costs for cars or storage in basements will be mitigated as well.

**Social value** The benefits of avoiding floods by upgrading the drainage system for the social value of the CBD are tremendously high. The risks that have the most social valuable impact in the CBD area are, firstly, shops and hotels that have to close. This means that primary goods are not available for inhabitants and shop owners might lose money by being forced to close the company. For hotels, the economic growth of the city and economic value for the company will decrease by guests that can not stay in the hotels. Second, the hospitals are not accessible which results in people that might arrive in the hospital too late and could die. These risks seems to be tackled when floods will be avoided which means that this solution will have a positive effect on the social value of the CBD.

**Economic value** With an upgrade of the drainage system, the economic costs will decrease compared to the 0-hypothesis. There will be fewer floods because of a better drainage system, meaning fewer companies have to close down. Also employees that have to work will experience less nuisance since roads are not blocked, there is not as much congestion and thus not very much travel time delay.

**Reliability** The reliability of upgrading the drainage network depends on how well this is done. This depends on several factors. Firstly the safety level of the new design of the drainage networks plays an important role. Depending on up to what level the network is improved the reliability differs. If the new network is designed to be capable of withstanding a 1/10,000 years rainfall event it is more reliable than when it is designed for a 1/500 year event. Of course the higher the safety level the more expensive it will be to construct the network which might not be worth the costs. The budget of the municipality is definitely not unlimited which will result in a safety level which is not extremely high.

Secondly, the quality of the work done by the contractor influences the reliability. The work is assumed to be done exactly as planned but any flaw or mistake will reduce the reliability. However it is assumed that the whole system will be post-surveyed once in place and fixed if not everything is up to standard and therefore the new network will be completely reliable in terms of construction quality.

Even though the system is upgraded the system will still be prone to external influences. Even if the system is designed for partial blockage by waste there is always the possibility of even more blockage than designed for or defects in one of the conduits or any other event which might cause the network to function less idealistic. It is not possible to design a system which is capable of handling everything and therefore the system will never be completely reliable.

**Environmental impact** The construction of an upgraded water drainage system does not have a major influence on the environment. Only the exhaust fumes emitted during construction and construction materials like concrete will have a negative influence on the environment. The drainage system is located underground in already built on area, so no new nature has to be destroyed to upgrade the drainage system. By upgrading the drainage system it is also possible to think of ways to upgrade the system in such a way that no garbage will flow into the system. If there is less garbage in the system, less garbage can flow into the sea. This will decrease the environmental impact.

**Implementation** Upgrading the entire drainage network is not an easy thing to do as the network is very vast and comprehensive. First the specific bottlenecks in the network should be identified and designs should be made on how to upgrade them. It might even be necessary to upgrade almost every pipe in the network which would be a major operation.

Once the design would have been made the actual construction should be performed. Since the drainage network lies underground and very often underneath major roads severe construction works would have to take place which would have a huge effect on the traffic network and on the surroundings in terms of noise pollution and general hindrance.

If pumps would be required to reduce the negative effects as much as possible the implementation would be even more difficult. Pumps are not commonly used in South Africa in the drainage network and therefore very little experience exists with designing and operating them. Therefore the implementation of pumps would require a lot of effort, time and money which makes it very difficult.

Besides this, the amount of stakeholders involved in this implementation will also cause some difficulties. As described above, the implementation is a complex project. This complex project will have a direct or indirect effect on inhabitants, transport authorities, construction firms, engineers, the government, municipality, environment groups and businesses. To make sure that all these stakeholders are satisfied a complex stakeholder management is necessary that makes the implementation more difficult.

**Implementation costs** As described in the previous paragraph upgrading the drainage network would require a lot of work and would therefore also require a big investment. The design and especially construction will require a lot of money since the majority of the network lies underground. To replace large conduits entire roads will have to be blocked which brings additional costs and since the network spans the entire city these costs will be extremely high. As mentioned the use of pumps is quite uncommon in South Africa and in itself already a very expensive solution, let alone the costs it would take to hire experts from overseas to do the construction works and operate the network.

### 16.2.3 Change behaviour

**Capital value** The change of behaviour can result in positive effects for the capital value if the implementation is successful. The change of behaviour can be seen as improving the waste management system and using the early warning system. The capital cost damage can be reduced by improving the waste management, in this way the water can easily flow away in the drainage systems. This might result in fewer blocked drainage systems, less water at the surface of the roads and thus fewer floods in buildings if the water heights have reached a critical height for buildings. The early warning system might have a more positive effect on the capital costs of belongings of people because people can take actions before floods occur. In this way they can evacuate their valuable goods and make sure that they are safe. For example an early warning system to park the cars at a higher level in the city. In this way the capital damage to contents will be reduced, but as earlier said, when the implementation is successful.

**Social value** The benefit of mitigating floods by changing the behaviour of people, referred to social value, is that the water heights will be reduced. The effects and results that are written in this paragraph also assume that the implementation will be successful. First the possible effects will be explained when the waste management implication is successful and second when the early warning system is successful.

Implementing the change of behaviour, referred to the waste management, has a positive effect on all the risks that are written in the social value paragraph of the 0 hypothesis. As mentioned above, when waste management is implemented successful the water can flow away easily. The main risks that will disappear are home damage, office damage, not usable sport fields, people that die due to delay of emergency authorities at a certain place or late arrival in the hospital and floating cars.

The main risks that will disappear by implementing successful early warning system are the damage to the contents of a house or company. Precautions can be done by reducing the damage, but the problem is that people have to make sure that they take actions as a reaction on these early warning system. The actions as a result of the reaction on these early warning system will eventually determine how much better this solution will be compared to the 0 hypothesis. The risk that can occur is that the people who throw their bags in the drainage system to make sure that they can find it back the next day will find another place to drop their belongings to make sure that it is safe and will be there the next day. This risk is for now a known unknown risk that might have a negative effect in the future.

**Economic value** The use of early warning systems in case of floods does not have any effect on the companies that are located in the area. The companies still have to close down because they cannot be reached. The travel time delay however can be reduced. The early warning systems provide information on floods, blocked roads and weather forecasts to inhabitants who can then react on it by either taking other routes or changing plans. This means there is less travel time delay and thus less loss in economic value. The change of behaviour of inhabitants in the city regarding the waste management will result in less floods, thus also fewer shops that close down and less travel time delay.

**Reliability** Changing the behaviour of people is not an easy thing and it can be doubted whether everyone is willing to comply. The reason people litter or hide their belongings in manholes or conduits is because it is easy, it does not take any effort and they do not see the negative effects of their behaviour. If their behaviour should be changed there should be an incentive for them to do so. If there are no direct upsides for them it will be very difficult to convince them that it is the correct thing to do and therefore the strategy of changing peoples behaviour can not be seen as a completely reliable strategy.

The use of early warning systems to tell people to move their belongings to a different location because of expected floods will be more reliable as there are no negative effects of moving your car or other valuables other than that it takes some effort. In this case there is a clear upside for them as their belongings will not get flooded which will be enough incentive for them to comply. The system is still not foolproof as the warnings might not come in time or the owner of a car or any other valuable possession is not in the region to move their belongings to a safe location. Moreover there is a possibility that people get sceptic about warnings due to the fact that the system predicted very severe conditions which turned out to be less severe. This might occur due to the complexity of the involved parameters which are mainly weather dependent. Once people start to get sceptic about the warnings, the system might lose reliability.

**Environmental impact** Changing behaviour does not have a physical construction. This means that there is no construction that can have environmental impact. The current environmental impact can be decreased by changing behaviour. If waste management will be increased, there will be less garbage on streets. This also means that there will be less garbage that can flow into the sea.

**Implementation** The implementation of this strategy is twofold. One part consists of changing the habits of people to pollute the streets with garbage and hide their belongings in manholes or conduits and the other part is implementing the early warning system.

As mentioned in the paragraph about reliability it is very difficult to change the behaviour of people. People need an incentive to change and for the people who are causing the problems there are next to none. Therefore a special implementation strategy would be required to convince them to actually change their behaviour. This strategy should come from the municipality and will take a lot of effort and time before proving successful.

On the other hand the implementation of the early warning system will be less difficult. The municipality is already running early warning models and these are already used to inform the public. The only thing that needs to change to improve the efficiency is the magnitude of the warnings and how far they reach and the awareness among the public that these warnings are given and that if they want to save their belongings they should react accordingly.

As mentioned above this implementation is considered to be less difficult for the municipality because of the lower complexity of the solution, this also results in fewer stakeholders involved. The inhabitants are the most important stakeholders to let the solution work. Besides the inhabitants, the Municipal Disaster Management Centre (see also Appendix B.6) of eThekwini and the Cleansing and Solid Waste Unit of eThekwini municipality are the main stakeholders that have to make sure that the solution is executed in a well organised way.

**Implementation costs** The costs to implement this strategy are limited. No actual constructions have to be done or expensive equipment has to be purchased. An extensive strategy or awareness campaign has to be developed by the municipality which will require an investment but will most likely be more time consuming than money consuming. The same goes for the early warning system as no new equipment is necessary to get this system running with high efficiency.

### 16.2.4 Changing the road system and constructing retention areas

**Capital value** Transferring the water to a less critical area might have no advantages or disadvantages for the capital cost damage. If this solution will be implemented it is necessary to analyse the certain area where the water will be transferred to. Almost every area in the centre of Durban contains stakeholders which means that always some stakeholders will be affected by capital damage of floods. However transferring the water to retention areas would be the best solution because of the lack of stakeholders in those areas. In this way the capital costs to buildings and people's belongings will be lowered as much as possible. The risks that will be reduced by transferring the water to a less critical area are damage to (important) buildings, damages to offices, floods in basements, floods in libraries and museums and floods in hospitals. The water will be controlled and moved to the areas that have as less as possible capital cost damage.

**Social value** The social value will be reduced when the water will be transferred in a controlled way. The water will move along the roads and will not affect the buildings or roads when it flows to the best area. The social risk events that still occur after implementation of this solution can be not usable sport fields because it might be used as water storage.

**Economic value** Heightening main roads results in fewer floods on the main entrances and exits of the city. This will result in less travel time delay compared to the 0-hypothesis. Since the water is redirected to areas with few buildings, most companies can still operate. Therefore the impact on the economic value will be low.

**Reliability** Water will always flow downhill and never uphill and therefore heightening the roads will most certainly cause the water to flow to lower lying areas. Therefore heightening the roads can be seen as a reliable method to transfer the water to less important roads. Nevertheless the rain will still fall down on the main roads and in case of very heavy precipitation there might still be a slight water level and significant flow velocities on the heightened roads which will affect the traffic.

Constructing more retention areas is a proven and rather reliable strategy to reduce the negative effects on high value areas. The roads and infrastructure can be adapted in such a way that most of the rainfall is lead towards these retention areas. If the areas are constructed properly they are very reliable and even if the rain is that heavy that the retention basin themselves will overtop, the damage to the other areas will be much lower as a significant amount of water is still retained in the retention basins.

**Environmental impact** This alternative can have environmental impact, since there are roads constructed. If the heights of the current roads is only increased, there will be no additional environmental impact. In this case no nature has to be destroyed for the new roads. If roads are build at new locations it is possible that nature has to be destroyed to build these new roads. This would have a negative impact on the environment.

**Implementation** Heightening the major roads will require blocking these roads first for an extensive period until the construction is finished. This will cause a lot of congestion as these roads are specifically chosen on their importance to the traffic network. The construction process will take time and multiple major roads will have to be adapted which will make the entire operation very troublesome.

The creation of retention basins will be much easier as no major effects on the surroundings are expected during construction works. The locations will be chosen on their relative unimportance compared to other areas and therefore little negative effects should be expected. It might be difficult to identify possible areas which could serve as retention basins as the city is quite densely built and many open fields already serve as retention basins. The implementation is not a complex project which also means that few stakeholders are involved for the implementation. The City Architects, Transport Authority Unit and Coastal Engineering Stormwater Catchment Management Department are mainly involved in implementing this solution. This project can become complex when it turns out that the vacant land that can be used for retention basins is not owned by the municipality. This can cause legal problems. Therefore, research has to be done when this solution seems to be the best for this area.

**Implementation costs** Construction costs to heighten the roads will be very high as a road cannot simply be lifted but will have to be demolished and rebuilt. Moreover the additional costs because of congestion and travel delay will be severe as blocking a major road will have significant impact on the network.

Building a retention basin will cost much less than rebuilding roads since only costs are made with lowering a certain area by digging it out and building levies around it to make sure the water stays inside. Some minor adjustments might have to be made to gutters and occasionally minor changes to the drainage network to make sure the water is redirected towards the new basins. These will however be minor construction works and will not be very expensive.

### 16.3 Comparison alternatives

The criteria of the four solutions as described in the previous paragraph all received a score on a scale of 0 to 10 based on the description given above. For the scores applies that 5 is the current scenario (Accept), 0 is the lowest score and 10 is the highest score. An overview of all scores can be found in Table O.5 in Appendix O. The output of the MCA values combined with the average weight factors is given in the table below (Table 16.2).

Table 16.2: MCA scores of the alternatives including weightfactors

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| Implementation costs | 0.64 | 0.13 | 0.51 | 0.26 |
| Reliability | 0.82 | 1.32 | 0.99 | 1.15 |
| Capital value | 0.78 | 1.24 | 0.93 | 1.40 |
| Environmental impact | 0.22 | 0.18 | 0.35 | 0.18 |
| Economical value | 0.75 | 1.20 | 0.90 | 1.35 |
| Social Value | 1.01 | 1.62 | 1.62 | 1.42 |
| Implementation potential | 0.77 | 0.15 | 0.62 | 0.15 |
| Total score | 5.00 | 5.84 | 5.93 | 5.91 |

It is clear that the scores of the solutions lie very close to each other. The avoid, mitigate and transfer option look like they score almost equally good. Only the accept option scores way lower than the rest. Since the scores of the MCA lie very close to each other it is useful to do a sensitivity analysis. A sensitivity analysis tells if the solutions differ significant from each other. In the sensitivity analysis the weight factors of one criterion are set to 0 to see the effect on the results. This is done for the criteria capital value and implementation costs. The results are shown in Table O.7 and Table O.8 of the appendix. Table 16.3 shows that the order of scores of the solutions differ from the order of the MCA output. Since this difference in ranking and the very small difference between the scores of the different solutions the best option cannot be chosen.

Table 16.3: Normal MCA results compared to sensitivity analyses

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| MCA normal | 5.00 | 5.84 | 5.93 | 5.91 |
| MCA without implementation costs | 4.36 | 5.71 | 5.41 | 5.65 |
| MCA without capital value | 4.22 | 4.60 | 4.99 | 4.51 |

# 17 Conclusion Part IV

To investigate the possibilities of increasing the flood safety of Durban four possible solutions are proposed: Accept the floods and do nothing to prevent them, avoid the floods by improving the water drainage system, mitigate the floods by changing the behaviour of the inhabitants of the city and transfer the floods by changing the road system and the construction of retention areas.

These four possible solutions are evaluated by performing an MCA. The MCA showed that the accept strategy is the worst, whereas the other three alternatives perform better. The MCA showed that these three alternatives score almost equally. Therefore it cannot be said which solution performs best. This is partly caused by the fact that the solutions do not go very much into detail. When one option needs to be chosen the solutions have to be elaborated further. The weight factor need also be investigated thoroughly based on the preferences and power of the stakeholders involved. These solutions and weight factors can then be put in the MCA framework and an option can be chosen. Besides this, not every area in the city is the same which means that the solution for the CBD might not be the best solution for another critical area in the eThekwini municipality.

# Part V Conclusion & Discussion

In this part the final conclusion of the report will be stated and references will be made to the set objectives and goals of this study. The process and results of this study will be elaborated and recommendations will be made on possible improvements and objectives for further study.

## 18 Conclusion

In the introduction (Section 1) the main goal of this study was stated together with four objectives to help achieve this goal. The main goal was to obtain insight in the effects of combined sea storm and high rain/river events on stakeholders and existing transport system, for regular and more severe events. The four objectives to help achieve this goal were:

1. Analysis of the system. Part of this system are the involved stakeholders with their power and interest, the transport network and the urban drainage network.
2. Investigation of parameters considered to be contributing to possible floods with special attention to contributions from the sea side.
3. Creation of a model approach which is capable of indicating the most critical areas with respect to floods and moreover find these areas.
4. Come up with general response strategies in order to deal with floods.

Before drawing a conclusion about the main goal of this study first conclusions will be drawn for the four objectives as mentioned above.

**Objective 1:** The first objective, the analysis of the system, is performed from the three different perspectives as stated in the objective. From the stakeholder analysis several stakeholders were identified that either have a significant stake, or significant power to influence any decisions that will have to be made regarding floods. These stakeholders were the eThekwini municipality, insurance companies, SAMSA, the national government and the KZN province.

From the traffic analysis the most important roads and bottlenecks were identified. The rail network is not used by many people and therefore only the road network is of interest. The main problem areas that were identified are the CBD, the Umgeni Business Park and the M4 to the north.

The stormwater network analysis showed that most of the outfalls discharge into the harbour except for several drains which discharge directly at sea. In several locations flood have occurred, or are expected to be likely to occur. This is mainly the case for the Umgeni Business Park and low-lying areas near the coastline such as the CBD. In this area are tide induced water flows into the network and several outfalls are completely underwater during spring tide. This shows the possible vulnerability of the network to a high water level from the sea. The analysis also showed that external factors such as siltation in the conduits or blockage of the manholes by waste could also affect the functionality of the system.

**Objective 2:** The second objective is performed by investigating the main contributors to floods from a hydraulic & hydrological perspective and from a network perspective as just explained. Siltation and blockage of the network are parameters that can contribute to floods and these were taken into account when modelling the network. The hydraulic & hydrological parameters that were investigated were rainfall and river discharge from the land side and the water level from the sea side. These were investigated by analysing the available data sets for each parameter and extrapolating these data to determine return values during extreme events.

The water level from the sea side was built up of multiple other factors which were the tide, storm surge, wave setup and sea level rise. The tide was split up in the general tide which shows variation through the year, and the 18 year nodal cycle which adds or subtracts a maximum of 30cm from the mean water level. The wave setup was determined by analysing the wave height, period and directions and using these parameters as input in a Delft3D model to compute the wave setup. All sea parameters showed approximately equal importance as each parameter could cause a water level increase of around the same order. Wave setup however does not influence the water level in the harbour since this area is well protected by breakwaters.

**Objective 3:** Objective number three was achieved by creating three different maps that together reveal the most critical areas with respect to flooding. The most critical areas with respect to stakeholders and value and with respect to the traffic network were identified and mapped and subsequently combined with an inundation map resulting from PCSWMM thus identifying the areas with the greatest risk of flooding. The flood scenarios are based on the likeliness of the combination of occurrence of the sea and land based hydraulic parameters as stated in the analysis. This was done by looking at meteorological systems that could cause the simultaneous occurrence of all these parameters.

The floods are most likely to occur at the transition from a hill to the low lying part of the stormwater network and at low lying areas close to the sea. Waste in the network is a large problem and causes floods, however this is difficult to model in programmes like PCSWMM. Within the CBD the area around and north of John Milne Rd are the most vulnerable to floods due to the low ground level, however the influence from elevated water levels at the outfalls is limited. The lack of calibration data made it difficult to validate the model.

The Umgeni business park as well as the CBD were proven very interesting in terms of stakeholders and possible effects on the traffic network because of the presence of main roads. However because of inaccuracies in the inundation map for the Umgeni region the focus was laid upon the CBD. Several main roads could get flooded which will require the traffic to use other main roads that are not flooded. The capacity of the main roads that will not be flooded is still large enough to carry the extra load from traffic that is rerouted to these roads. The exit- and entry ramps however are not designed for such an increase in intensity and therefore congestion will arise at these locations. This will cause severe travel time delay and will result in economic costs.

With respect to stakeholders property owners and small businesses will be most affected in South beach as they are usually not insured and these areas are proven flood prone. Insurance companies are most affected in Greyville because this area houses more middle or upper class residents and also business who are all insured for damages caused by floods.

**Objective 4:** Floods can be seen as a risk which consists of the combination of probability and consequences. Therefore to achieve the fourth objective use is made of the four general risk treating strategies which are: Accept, Avoid, Mitigate and Transfer. Four global solutions to deal with floods are constructed each based on a different strategy. The accept strategy is the 0-hypothesis which means that the situation should stay as it currently is and the current risks should be accepted. The avoid strategy is achieved by upgrading the drainage network to such a capacity where floods will no longer cause damage in the city. To mitigate the risks the behaviour of the people should be changed to make sure that poor waste management will no longer block the conduits and manholes and lead to flooding and also the flood early warning system could be implemented to warn people of predicted floods so that all valuable assets can be relocated to a safer area. The transfer strategy means that the effects of floods should be transferred to a different less critical location. This is done by heightening the main critical roads and constructing more retention basins in areas with low value to relieve the pressure from other more valuable areas.

The four strategies were compared using an MCA based on the criteria: Capital value, social value, economical value, reliability, environment, implementation potential and implementation costs. This showed that all strategies are better than the 0-hypothesis but none of the strategies proved the most suitable.

**Main goal:** Now that the objectives of this study have been met a conclusion can be drawn on the main goal of this study to obtain insight in the effects of combined sea storm and high rain/river events on stakeholders and existing transport system, for regular and more severe events. The effects of flooding by rain on stakeholders and existing transport system have been thoroughly investigated. The extra effect of an increased water level at sea seemed to have little additional effect on the risks of flooding in Durban.

# 19 Recommendations

The section contains the recommendations regarding this report. A distinction is made between detailed recommendations for further research purposes based on this research and recommendations for the municipality regarding flood prevention.

## 19.1 Research Recommendations

Regarding the time span and information available during this study several assumptions had to be made and several aspects could have been worked out in further detail. In this section several recommendations will be made on which aspects would require further attention to further increase the reliability of this research and which continuation studies could be valuable to further investigate the effects and probabilities of floods in Durban. These recommendations will be made separately per Part of this report.

### 19.1.1 Part I

- The tide and surge analysis was performed on a data set of 2 years. This data set can therefore not capture the effect of the 18 year nodal cycle and this might have also slightly affected the outcomes for the other tidal constituents. The obtained tidal signal from this data set was subsequently subtracted from this set to obtain the surge levels. Because most likely the subtracted tide was not a hundred percent reliable, also the surge values are not completely reliable. These surge values were subsequently used in a PoT analysis to extrapolate to higher return values. Since this data set only spanned 2 years the reliability of the EVA is limited and will not be completely accurate. For more reliable results an extended data set should be used to make sure all tidal components can be measured which would result in correct surge values and also make the EVA more reliable as it is based on more data. A longer data set would moreover make it possible to investigate whether surge shows seasonal behaviour or not, which is considered important regarding the possible scenarios.

- The determination of the max wave setup was eventually based on a single direction and the EVA of all wave height data. It was found from Delft3D that the more waves come from the East the higher the wave setup will be. The direction was therefore determined as the most easterly direction that could still produce the extreme events based on visual inspection of the wave directions. A better method to determine the wave setup would be to perform an EVA per directional bin so the return values for the wave height would be different for each direction. All these heights and directions should subsequently be put through Delft3D to determine the wave setup. To do this more wave data than were available are required and also the run time in Delft3D would significantly increase.
- The numbers on transport systems given in the network analysis in Part I apply to the complete municipality. Since the focus of this research is on mainly the CBD, it is advised to find accurate numbers for the CBD area alone since this will differ from the whole municipality.
- The main focus of the transport is on passenger transport via road because the most impact will be on them, but to get a more complete picture it is useful to get insight in the commercial vehicles and the train transportation as well.

### 19.1.2 Part II

- Extension of the investigation of the market value in specific areas. The market value is at this moment gained from the Valuation Roll, but this system sometimes does not seem realistic. For example the number of roads in a certain area are not the same as the roads that are shown in Google Maps. For this reason the market value will also not be correct. It could be that this is also the case for the residences and the companies in a certain area which are most important for this report. Some extension of the investigation of the market value is therefore necessary to make sure that all the numbers are correct that are used. In this report it is mainly used as an assumption.
- Collecting data for the different flood insurances for households and companies in a certain area. Flood insurances have an important role in this report. The social value is very dependent on areas where people have a flood insurance or not. Therefore it would be useful if these numbers are known. Hopefully this data can be gained by insurance companies. At this moment SAPOA, The Planning Initiative and Talia Feigenbaum were asked but unfortunately all of them do not have this information.
- The critical water heights used to decide to block the road are now set to 15 cm in the whole network even though cars can still drive in case the water is standing still. Since it is not researched thoroughly what the water speed is at which location, this is advised to do to get more insight in the necessity of the road closure. The result of this further research would be that there might be roads that could be usable up to higher water heights.
- The following remarks are advised to take into account when modelling cases like this in PCSWMM:
  - Large 2D models tend to become very slow and require large computational times. Therefore it is advised to use 1D models as a first assessment, and based on that use 2D models for specific flood prone areas.
  - It is important to be aware of some bugs in PCSWMM of which some are hard to recognise. In this project this was mainly the case applying changes to entities in the model like assigning other rainfall events and water level elevations at outfalls.

- The model needs to be calibrated in order to get reliable results. This can be done by applying flow or pressure sensors in main culverts and creating detailed reports about flood patterns and depths in case of future floods.
- When more computational power is available it would be helpful to set up a more detailed grid. There is a lot of spatial variability in the cross sections of roads. If this could be modelled a lot more insight can be gained about exact flood patterns on streets.

#### 19.1.3 Part III

- As clearly mentioned in the report the probability of occurrence of combined seaside & rainfall events is a very difficult subject and this study only touched upon the matter lightly. This study investigated whether combinations are possible at all and to some extend which combinations of events are deemed likely. To gain more insight in this matter extended research should be done and even then it seems unlikely that the probability of such events can be put in probabilities of occurrence.

- Determination of the age of buildings. The determination of the age of buildings could be important to gain knowledge about the ground level of buildings. It this way one can determine if they would have taken the minimum heights into account or not. Besides this it is necessary to know the age of the buildings to determine if they would have a mortgage, if it is likely that they do not have a mortgage it is also likely that they do not have a (flood) insurance.

- Collecting data on the amount of basements in eThekwini. The amount of basements could be used for storage of waters. Besides this it is necessary to know where the basements are to execute the solution of the Early Warning System. In this way one can immediately have contact with the areas that are likely to flood to warn them.

- Further investigation of the economic value of travel time delays. This report does not go into depth when looking at travel time delays. Therefore it is useful to gain insight in the expected travel times when roads are blocked. This could also be useful when making an evacuation plan.

- The Emme model should be run multiple times with closure of different roads to see the different effects on the network.

- In order to acquire more realistic results when modelling the stormwater network the following remarks are advised to take into account:
  - There was some ambiguity about the stormwater network, and some data sources are in contradiction to each other. There were doubts as well about at which places a single or double drainage system was in place. It would be helpful to ascertain about this information.
  - The way blocking due to waste and litter was included in the model was relatively crude. No real research has been done into the amount of manholes which are blocked. Furthermore, there are possibly more realistic ways to model this in PCSWMM as done in this report.
  - Building are excluded from the flood map in this model. However, buildings and especially (parking) basements can act as unwanted storages in case of floods. This will have

effect on flood patterns. More insight into ground floor levels and basements of buildings can lead to more realistic flood maps, however it could be challenging to include these correctly in PCSWMM.

– The Milne's drain suffers from siltation problems due to the tidal motion and is crossed by a sewage pipe below Dr Pixley Kaseme St (old est Street). This will have a negative effect on the capacity and should be included in the model for more detailed researches. Furthermore, there seem to be some errors in the data about the rim elevations of the northern part of this drain, which is the most flood prone part.

– Breaking waves at coastal outfalls could lead to an inward mass transport, which could reduce the discharge capacity of the network. More research would be needed in order to assess whether this effect is large.

#### 19.1.4 Part IV

- An extensive stakeholder analysis should be performed on the parties involved with the solutions. It is necessary for every new solution to do a new stakeholder analysis to make sure that the analysis is in more depth. It is likely that there are a lot of other stakeholders involved by for example upgrading the water drainage system.

- Examining which negative risks can arise by implementing the solutions. For now rough research is done about the risks that will be gone by implementing the solution and roughly thinking about negative risks that can occur but at this moment there were no negative risks that were likely to occur. But there will certainly occur negative risks. For this reason a more in depth research has to be done about the negative risks.

- Defining the solutions in more detail. To give a good advice about what would be the best solution for the eThekwini municipality the solutions should be defined in more detail. This detailed level is required for a reliable result of the MCA. Based on the results of the reliable MCA, the best solution could be chosen.

- Get more insight in the possibilities for emergency help and evacuation options. The appendices contain several interviews that could be helpful to determine which parties are involved. The combination of this knowledge and the flood prone areas can make emergency services get to their destination faster and make evacuations possible in case they are needed. Coordination between several parties often seems to be a problem.

### 19.2 Recommendations for eThekwnini Municipality

This section consists of the general recommendations for eThekwini Municipality which are based on the insights that are gained during the project. The recommendations are divided in three parts: preventing floods, acquire more insight in flood patterns and at last minimise damage which occurs during floods. Note that the strategies as proposed in Section 15 are a general framework, whereas this recommendation should be considered as a first practical step within this framework to improve flood safety in Durban. It therefore uses parts from Section 15, but does not elaborate a complete strategy.

#### 19.2.1 Preventing floods

The main cause for floods is an excess of water caused by extreme rainfall events. The storm water network in the researched area seems to suffice for relatively extreme events, however problems appear to be present nevertheless. Waste and litter in the system is a problem in the city and probably an important source for the problems. Reducing the waste in the system is considered to be helpful in the prevention of floods. Another measure which can be taken in order to prevent floods is to further encourage the construction of green areas and roofs in the city, in order to delay the discharge of the rainfall and mitigate the floods. For that matter, the current efforts which are already made regarding this development within eThekwini Municipality are helpful.

### 19.2.2 Acquire more insight in flood patterns

Another recommendation is to gain more insight in the occurrence and patterns of floods. A lot of information about the storm water network is already available, however this is mostly used for other purposes than researching flood risk. The models set up for this project are a first step, however refining and calibration is necessary. It is advised to create detailed reports of floods, which can be used for calibrating the models. Furthermore the exact scale and impact of waste on the system has not been researched, despite the suspicions that it has a lot of impact in the systems as stated before. At last verification is desired for the presumption that elevated sea water levels only have little impact on the performance of the storm water network. Regarding this water levels it is also recommended to further investigate the probability of occurrence of a certain water level as a result of the combination of seaside parameters. The university of Kwazulu Natal already covered some of this combinations in PhD studies but to eventually come up with a probability more research is required. A collaboration between the municipality and the university is considered to be the most convenient option if one is willing to tackle this problem.

### 19.2.3 Minimise damage

Besides preventing floods and acquiring more insight in floods, steps can also be taken in minimising the damage caused by floods as proposed in the mitigation strategy. It is advised to share information about possible floods to businesses and residents, the transport department and emergencies department of eThekwini Municipalities. Businesses and residents can then insure themselves appropriately for flood risk. The transport department can use the information about flood prone areas when constructing new roads or carrying out maintenance on roads in these areas. For the emergency services it is relevant to have information about roads which are less or not accessible at all, in order to arrive on their destination as soon as possible. Good communication between the municipality and the emergency services is thus very important to make sure the consequences of floods are dealt with in the best possible way. In addition to the above, Forecast Early Warning Systems (FEWS) are considered to be valuable for mitigating strategies. This is because such systems can inform the inhabitants in time that an event is coming, so that the have time to secure their valuables.The municipality is already busy with these kind of systems for water quality assessments. Further expansion of them with for instance the PCSWMM model might significantly increase the ability of flood mitigation.

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# Appendix A System diagram

This appendix elaborates on the relationship between different factors of flood events in Durban. The factors of the three different disciplines: Construction Management and Engineering (CME), Transport Infrastructure and Logistics (TIL) and Hydraulic Engineering (HE) come together to one system in which floods events are included. In general one can think of factors which have an influence on the system and are governed by external factors. Moreover a lot of these internal factors have connections with each other. All these factors can eventually be brought back to several criteria which can be used to test proposed solutions be means of a Multi Criteria Analysis. These three elements of the system are listed in Figure A.1 below:

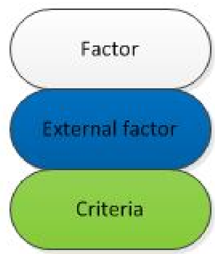



Figure A.1: System diagram legend

Due to the amount of involved disciplines the project covers a wide scope leading to a complex situation with a lot of factors affecting each other. Figure A.2 shows the relationships between all factors in the system in order to create structure in the complexity. For an optimal functioning system there are several criteria, these criteria are highlighted in green. As stated before the system can be brought back to these criteria, so if one is willing to change the system these criteria should be taken into account. Besides criteria there are also external factors, which can not be influenced, but will influence the internal factors of the system.

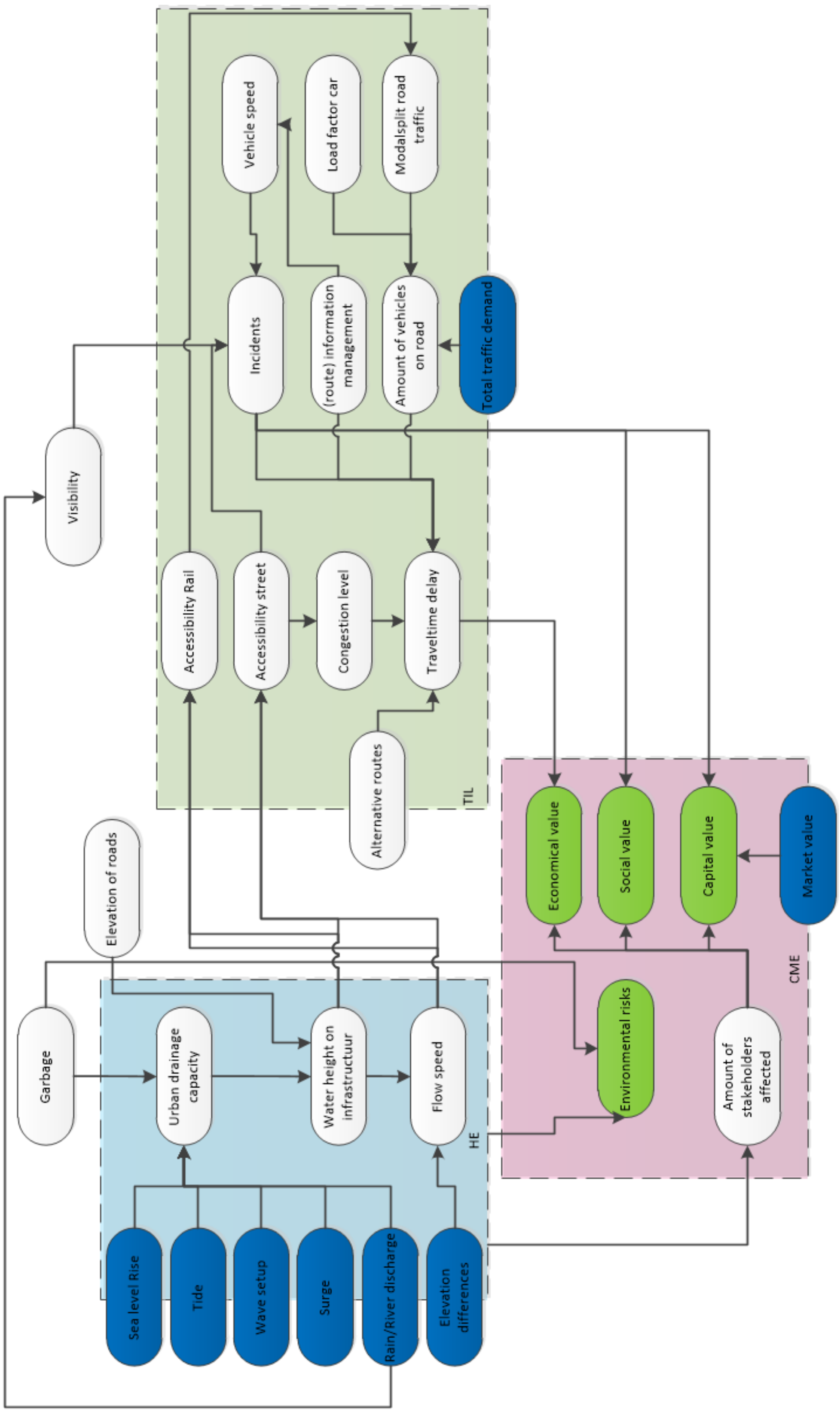



Figure A.2: System diagram

Several factors contribute to the occurrence of a flood. As mentioned before a division can be made between internal (system) factors which can be controlled and external (weather) factors which can not be controlled. This is shown in the Hydraulic system diagram (Figure A.3) below. In principal one can describe a flood event as an event in which the amount of water which enters the system cannot leave the system in time or can be stored sufficiently within the system. From this statement it can readily be seen that the rain and river discharge which enters the system are of importance. To handle this amount of water an urban drainage system is in place which might or might not be able to treat all the water.

Regarding this urban drainage capacity several internal and external factors might be of influence. The first is garbage which enters the system and lowers the capacity. This might seem as a factor with minor influence but according to several people at the Coastal, Storm water and Catchment Management department this is a serious problem. Besides blocking of the system from the inside by litter this might also occur from the outside by the sea. The drainage system discharges at sea and if due to certain circumstances the sea level is higher, this will not be possible. Factors influencing the water level from the sea side are: Sea Level Rise, Tide, Wave Setup and Surge.

These factor together determine whether water will start to flow over the roads or not. In order to determine the impact on the Transport System and the Stakeholders it is important to know the water height and flow speed of the surface water. The flow speed is considered to be determined by elevation differences where higher differences will lead to higher flow velocities. The water height on the infrastructure depends on the elevation of that infrastructure. If a road is for instance positioned higher it is considered to flood less early.

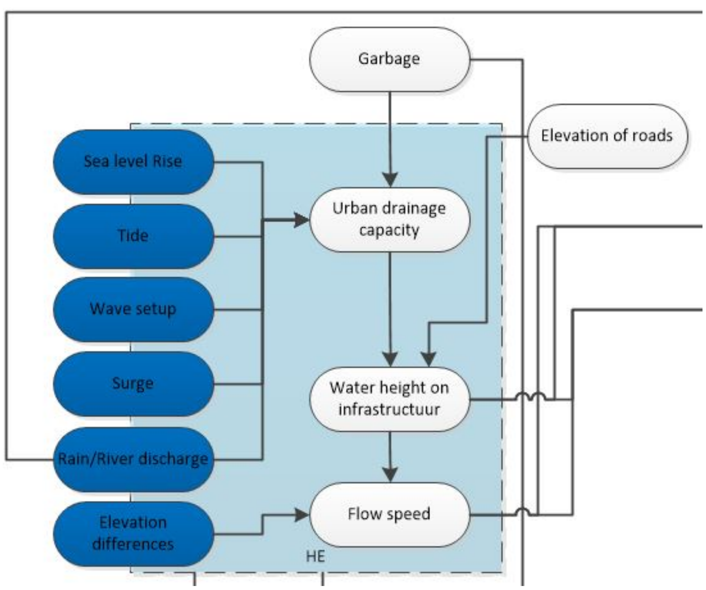



Figure A.3: Hydraulic system diagram

During floods the accessibility of the transportation network can be influenced. Factors influencing this accessibility are captured in the Transport system diagram (Figure A.4). Water heights and water flow speeds determine how much the system will be affected. If the railways are flooded, there will be no different railroads which can be used. The consequence of this is that the people that normally use the train have to switch to other modes. This will probably increase the amount of road traffic. The more road traffic, the more congestion there will be if the capacity of the roads is not enough. Congestion results in travel time delay, which ends in economical costs. Congestion is not only influenced by the amount of cars on the road, but also by the amount of incidents on the roads. If the visibility on the roads decreases by rain, it is more likely that incidents will happen. Also driving through water can make cars uncontrollable and cause incidents. Incidents can result in social costs for injured or dead people. It can also lead to capital damage.

There are also factors that can improve the transportation system. If there are enough alternative routes which can be taken in case a road is flooded, there will be less congestion. Route information and traffic management can help. Human signs (for example police) can block roads and give directions, to prevent using flooded roads. Traffic lights can also be managed in such a way that some routes will get preference above others. Dynamic traffic signs can give dynamic traffic speeds and route information. Also navigation systems (like google maps) can give information about which roads are blocked and the less congested roads.

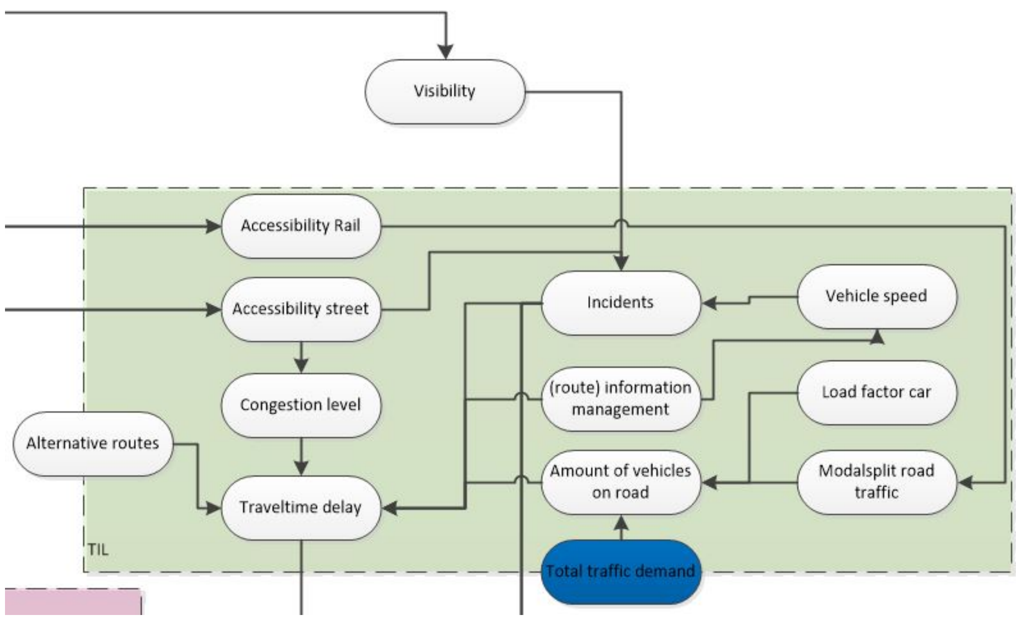



Figure A.4: Transport system diagram

Floods will affect a lot of stakeholders. The way they are affected can differ in several ways and is divided in Economical-, Social- and Captical costs or values. The connection between the involved factors is shown in Figure A.5 below. Economical costs are the costs of business who gain less profit during floods, or employees who can not reach their work. As readily be seen from this definition economical costs are to a large extend determined by the effects of floods on the transport system. Social costs focus on the impact of a flood on the well being of the stakeholder. Moreover buildings and other things like cars and infrastructure can get damaged by floods which is captured in capital costs. The market value determines the value of areas. The more market value an area has the higher the capital costs will be if this area is affected by floods. All these costs and damages have to be minimal to reduce the impact of floods on the system and therefore are concerned as good criteria to test solutions.

Besides these three there are some factors within the system that might cause environmental risks. One of the mayor factors to this risk is the garbage. As explained before this might cause blockage of the drainage system resulting in urban flooding. As such a situation occurs this garbage will eventually end up in the ocean polluting the environment. Moreover water that flowing over roads might get polluted due to for instance oil spill. Lastly large amounts of water might be capable of uprooting trees and other vegetation destroying the urban environment.

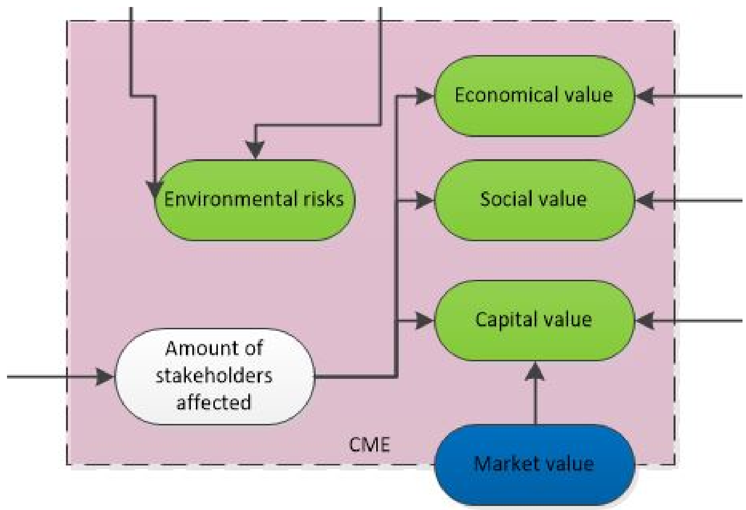



Figure A.5: CME part system diagram

# Appendix B Interviews

This appendix contains several interviews which are used to get more insight in the current situation in Durban. The interviews are used to help get a better idea of the way things work and to help with the research.

## B.1 Interview Sandra Graham

29 August 2016
Sandra Graham (eThekwini Transport Authority)

Sandra Graham is the Road Safety Co-ordinator of eThekwini Municipality. She coordinates between different parties which have to deal with road safety. Some of these organisation are the following:

- Ambulance
- Fire department: a very well organised department, owned by the government. Most of the time they are the first people to arrive at an accident.
- Police: There are three different Police organisations operating in Durban
- SAPS (South African Police Service): national police. This is a big, efficient organisation. It doesn't control traffic, but only accidents.
- Road traffic inspectors: controlling of the national and provincial roads. Not a big group, but works well for the amount of staff.
- Metropolitan police: does not cooperate very well with the government. They say that they are there to protect the citizens, so they do not want to do traffic management. There are around 400/500 police men. Good cooperation between them and the municipality could lead to an improvement of the road safety.
- Disaster management: this department deals with the management of disasters. Brenda Ndlovu is the head of this department. A meeting with her will be scheduled to get more information about this department.

Sandra told that there are many structures for road safety created, but legislation is not approved yet by the government. She also told that because of the World Soccer Cup of 2010 there are signs used that redirect traffic when e.g. roads are flooded, but due to the police that does not want to cooperate and the severe conditions of the floods this does not work out very well.
Sandra invited us to a meeting with several parties on the 31st of August.

### B.2 Interview Andrew Aucamp

29 August 2016
Andrew Aucam (Urban Traffic Control of ETA)

Andrew Aucamp is Senior Manager (Urban Traffic Control) at the eThekwini Transport Authority and lecturer at the University of KwaZulu Natal. Andrew gave a lot of information regarding the UTC (Uraban Traffic Control) and other departments involved in traffic management. First of all the aim of the UTC department is to create a SMART city, a city with IT technologies. For this a portal is used in which GIS layers are loaded which give information about signals. Secondly the department is interested in what happens in case of floods, they tried to get more information about floods in combination with the environmental department, but unfortunately this did not work out well. Thirdly, in the municipality there is a disaster management department which contains IT services and gives information to police and fire department to come into action when something happens. This department currently develops evacuation plans. And as last there is an incident management system on national freeways. On the secondary roads the incident management system does not work that well since this is only reactive, not proactive.
The department UTC focuses on two systems to control the traffic:

- Controlling signals: there is communication between the control center and 500 of the 800 signals. There is contact with 150 controllers via fibre and the rest uses GPRS. The control center monitors congestion and communicates to the change the timing of the traffic lights. There is thus variation possible in the traffic light timing. In case of evacuation a pro-active reaction is thus possible, but it is not yet used since there is input needed to finalize these plans.
- Freeway management systems: there are 12 variable message signs on the arterial network, but there are only 6 of them working right now due to vandalism. This system focuses on the major arterial roads.

Next to the variable message signs on on the freeways, there are also other signs, which are owned by another company. This company gets its data from TomTom. TomTom tracks the speed of the traffic using radar to give real-time information to the traffic. This information could possibly be used in case of an evacuation. This system is only used on national roads.
The main problems in Durban are topology issues, think about hills and rivers. The main bottlenecks are the following:

- intersections
- CBD (Central Business District) area
- off-ramps of freeways
- signals: the signal timing should be efficient and compatible with each other. Automatic fault detections is used to reduce the incidents resulting from signal faults.

According to Andrew the main problem in the municipality is the lack of inter-department communication.

### B.3 Interview Talia Feigenbaum

30 August 2016
Talia Feigenbaum (Economic specialist at Urban-Econ)

1) What is the interest of stakeholders on floods?
Interests of Stakeholders is how to response on damages. The ability to pay (household income/insilliance) and what the response is from the city (1. speed, 2. efficiency (politics)).

2) How much are the costs of the municipality to floods?
Talk with the eThekwini sustainability, safe cities and issues around sustainability. Ask the Disaster management centre to know how much damage there is in the city.

3) How does the port react when floods occur?
The port is still available if floods occur, they do ad hoc maintenance when something goes wrong. But the ships are still able to enter the port and thus they will not be affected that much.

4) Is there a flood insurance that people can have?
People can insure themselves for floods. Insurance is mandatory if you have a mortgage. If you have an old house and the mortgage is paid than a lot of people are not insured anymore. This is the same for public buildings of the municipality.

5) Is there are great difference between high and low class residents?
Yes, there is a high difference between the two groups. Mostly the lower class residents cannot afford an insurance.

6) Is the flood insurance the same for every class residents?
No, there are different flood insurances you can chose. If you have a house insurance you are also insured for floods but the amount you are insured varies. You are not insured for goods with this insurance only are only insured if something is damaged of the construction of the building.

7) Is there are certain programme that defines the value of businesses?
Voor de valuable parts kijk dan naar de Valuation Roll. The value of a business is more about how old a building is. And if they have some insurance. It takes longer to recover.

8) Where are the electricity areas located in the city?
Look to eThekwini water, eThekwini electricity and eThekwini sanitation. Take the map that we have found were some floods are and lay them above the other map. In this way you can see what kind of electricity is affected. Ask to generate map.

## B.4 Road Incident Management System Steering Committee Meeting

31 August 2016
Sandra Graham (eThekwini Transport Authority)
Rona Ranidhani (eThekwini Transport Authority)
Police
Firefighters
Paramedics
Tow Truckers

During the eThekwini Road Incident Management System meeting several involved parties were present. The meeting was about how the road incidents are managed currently and how they could be improved. The involved parties are the following:

- Government
  - eThekwini Transport Authority
  - Department of Health: Emergency Medical Services
  - Cross Border Road Transport Agency
- Police
  - South African Police Service (SAPS)
  - Traffic Police
  - Metro Police (not attending even though they are an important party in this concern)
- Firefighters: owned by the government
- Paramedics
  - Public party:owned by the province (EMRS): mainly used by poor people
  - Private parties (Citimed, Metcare...)
- Tow truckers: there are several private parties

The private sectors dominate the government/authorities. During the last period there is a legislation developed which gives guidelines to road incident management, but it is not passed by the government yet. One of the problems of the large amount of different parties involved in incidents is that they only have their own data and do not share it with each other. The Emergency Control Center (ECC) should collect the data of the different parties and combine it to get more insight in incidents. There is no data about how many people die in or just after traffic accidents. The different parties that are involved in the emergency have to be called individually, so there are different phone numbers for private and government owned ambulances, police, firefighters etc. The result of this is that not always the closest ambulance to the incident is called.

Travel time and delay
There has been done research to the travel time and delay during the morning and evening peak between the residential areas and the Central Business District. The most important residential areas are the following:

- Phoenix

- Umlazi
- KwaMashu
- Tongaat
- ..

There is a distinction made between incidents and accidents. Incidents are for example break downs (traffic lights), animals on the roads and pedestrians on the road. Accidents are the collisions between cars etc. During rainy weather conditions the travel time on one route increased from 40 minutes to 59 minutes.
During the last flooding a sinkhole appeared on Dicksen road [37] and nothing has been done to repair it yet, another example of the not so well working collaboration between different parties.

## B.5 Interview Greg and Geoff

September and October 2016
Greg Williams (Stormwater Engineering)
Geoff Tooley (Catchment management)
This section is a report of the information acquired from Greg Williams and Geoff Tooley during multiple meetings. Both are working at the Coastal & Stormwater Catchment Management department of eThekwini Municipality. They have been working for a long time at the municipality and have a lot of knowledge and experience.

**General background about the Durban stormwater network** There are different types of rainfall events in and around Durban. The long rainfall events will cause problems at the rivers. Short heavy storm events cause mainly run-off problems at urban areas. Most outlets discharge in the harbour, so these outlets are not really hindered by much wave impact. Furthermore, there are three large and five small outlets at the beachfront. The large outlets are located at Somtseu Road, Sandile Thusi Road and seaward of the Moses Mabhida Stadium. The area under consideration for this project is bounded by the Umgeni River at the north. Major floods occur every 20 to 30 years. Heavy storm and rain events generally occur in a cycle of every 7 to 9 years. The city is insured up to 10 million for floods, which is meant to be used for water related infrastructure.

The stormwater network is designed for a 10 year return period, except for the CBD which is designed for 20 year return period storms. The most vulnerable areas are expected to be the low lying parts of the city which are mostly located at a few hundred meters from the coastline, right behind the former dune row at which the boulevard and many hotels are built. Other vulnerable parts of the system are the transition from steep sloping pipes at the hill area to the more gently sloping pipes of the lower part of the city. The water discharges can generally get much larger at steep pipes than at the gently sloping pipes, which can lead to floods in case of large discharges.

There are no real maintenance policies regarding the stormwater network. When parts are broken or operation insufficiently they will be replaces or repaired, but there is no long term strategy regarding replacement of the network. The main focus within the department is on construction new systems in new or developing urban areas within the city, which are generally different areas than the area of interest defined for this project.

**Recent floods**

- 26-10-1999: This was the latest big Umgeni flood, caused by a long period of rain in the upstream catchment area.
- 2007: There was a large storm causing high waves, coupled with rainfall. However, the rainfall was not significant during high tide.
- 2008: Floods at the highway flood following several large rain events
- 2009: Several large rain events causing local floods
- May 8th, 2016: Severe rainfall, leading to flash floods in higher areas
- July 25th, 2016: Comparable situation as at May 8th in 2016

**Runoff problems caused by waste** A common problem in eThekwini municipality is the blockage of the storm water network. Blockages are caused by cleaners who sweep trash in the stormwater network. Another cause are street kids, homeless people and cardboard collectors who store their goods and belongings in the manholes. The trash is partly blocked by grids which are placed in front of the inlets of the manholes.This is especially the case for areas with a lot of pedestrians and homeless people. The blockages mainly occur near the manholes of the smaller network. The larger pipes and culverts will not block normally, because an object which could cause blockage will always flow downstream, and the further downstream, the larger the pipes and culverts get. Therefore, the blockage will mainly be in the smaller branches which discharge at the main branches. Homeless people and street kids store their personal belongings in a (garbage) bad in the manholes. When the bag blocks an outlet pipe in the manhole, local floods can occur easily. The water will eventually find its way to another manhole, but especially in the flat areas this leads to small floods and reduces the capacity of the network. The estimate has been made that 25% of the manholes connecting pipes with a diameter smaller or equal than 0.3 m get blocked.

**Milne's drain** The most important drain in the low-lying area in the east of the CBD the Milnes drain, located under John Milne Rd (Figure B.1). This drain is about 1250 m long and discharges at the harbour. One of the problems is that the drain is prone to siltation due to the very small gradient, which is at some places as small as 1:2000. The siltation is caused by the tidal motion, and mainly occurs in the middle part of the drain. The more upstream part is less influence by the tide, the downstream part is as well less affected because of the larger flow velocities due to the tidal motion. Recently maintenance was done to this drain and up to 60 cm of silt was removed. Another problem with this drain is that the top half of sewage pipe with a diameter of 75 cm crosses the drain under Dr Pixley Kaseme St (former West st). There syphon which is constructed to keep the cross section does not work, because this is prone to siltation.

The Hunter street which crosses the Milnes drain already has problems with discharging rain water during spring tide. This is one of the lowest areas in this part of the network. Inundation could theoretically be prevented by constructing the drainage system at a higher level, but the drain are generally constructed at the highest possible level already.

Figure B.1: Milne's drain (blue)

## B.6 Interview Disaster Management eThekwini municipality

27 September 2016
Zamani Mtshali (Disaster Management)
Stephen Hendrickse (Disaster Management)
Jamila Ndovela (Disaster Managment)
Malcolm CanHam (Disaster Management)
Charles Khumalo (CC TV department)
Allan Pillay (Management Information System)
Brenda Ndlovu (Emergency Control Centre)

Most of the time the eThekwini municipality has flash floods, the rain falls and runs down the hill towards the sea and the port. Because of the fast growing urbanisation of the city the drainage systems in the city are too small and have to increase, there is a lack of maintenance of the culverts which destroys the ways because of the blocked stand water. But most of the floods are gone in one day. The flash floods cause a lot of infrastructural damage and the rush of the water causes land slides. Most of the time in residential low income areas because of the bad buildings materials that are used for the construction of the buildings. This results in damages in millions of rands. For the future the storm water drainage systems have to be upgraded, especially because of the fast increasing sea level rise. The blocked culverts is the main reason for standing water floods.

Most of the people in the centre of eThekwini municipality have a house insurance. The inhabitants in the rural area of eThekwini municipality are not insured. Most of the time they are located in flood plains, they do not have a lot of money and these areas are very cheap. But they have a risk, they often flood which means that the houses also become affected by floods. The Municipal Disaster Management Centre (MDMC) helps those people who are not able to recover after a disaster happened, in this report a flood disaster. They mainly help people that cannot help themselves. The MDMC do not buy stuff but they assist them temporarily and are more focused on the residents.

There are two types of insurances, namely the house insurance and the household insurance. The house insurance means that the construction of your house is insured and the household insurance means that the properties within the house are insured like furniture and fridges. An insurance is for the lower income class gambling with money, if they take the risk that no floods occur and they do not spend money on an insurance or do spend money on an insurance and hope that no floods will occur. Most of the people have an insurance for their house and not for the household. If a municipality builds a new house and the house will be damaged in five years within the completion the rental or owner of the house will be insured within these five years. The government does not pay for the insurance of local businesses because they have the opinion that when you can start your own business you are also able to take an insurance.

There are three layers in which the MDMC operates. The ground level (bronze level), silver level and the strategic level. The bronze level contains of SAPS, fire authorities etc. The silver level is the Transport authority for example and the strategic level is where the MDMC operates. When roads collapse they have to make the area safe and have to maintain the road immediately. If the municipality does not have the money to maintain it they have to inquire for budget. If there are not sufficient funds then they have to try to receive money from the KZN province. If they also do not have sufficient funds than they have to try to receive money from the National Government. If they receive the fund or not depends on which road is damaged. If a municipal road is damaged they are responsible to maintain it, if a governmental road is damaged they have to maintain the road and the same for the national roads and the government. If there is only one road to a certain district and this road is damaged or not available anymore, then there are emergency grant funds that give some money, the road has to be repaired within three months with this fund. Besides the emergency grant funds there is a rehabilitation fund which means that the road has to be maintained within eight months. The rule of thumb is that if there is heavy rainfall and floods occur, the people have to be safe. They can evacuate the people but only when it is really needed because of the great amount of things that have to be organised when this happens. When floods occur the MDMC is responsible to coordinate the authorities that are responsible for the maintenance of for example a road. The MDMC always makes reports of the floods, they have to give an overview of the damage costs of a disaster. The municipality has to know if they can deal with the damage costs of the floods, if they cannot deal with it they have to get funds to cover the costs.

The floods of 25-26 July 2016 have cost 85 million Rands. Mainly the informal groups were affected by the floods. There are several lower income groups that locate their house in flood plains of the river, this means that the chance is high that their house will flood but the government has to help the people that do not have an insurance and make sure that these people are safe. For this reason they do not need an insurance in their eyes because they receive the help of the government and municipality. To prevent this the MDMC goes to the schools and other public buildings to make the children and inhabitants aware of the risks of living in an area where the risks for floods are very high. The problem of the floods of 25-26 July 2016 were because of the heavy rainfall combined with the high sea levels during the rainfall. The water of the rivers was not able to flow into the sea.

In case of disasters MDMC informs inhabitants by radio. They give information about which roads have to be blocked by the metro police. The metro police has to block the roads for the safety of inhabitants. The transport authority is responsible for informing people about the duration of a road block and directions to use other roads. If people have to be evacuated the municipality has 'City Fleed', cars for evacuation.

In case of an emergency people can call the call centre to which they tell what happened and the location where it happened. The call centre then dispatches the information to the right level to get the right emergency response. The police, fire department, ambulances and provincial services are contacted using radio communication. These organisations go to the location and handle the situation. People can thus call the emergency call centre in case of an incident, but Durban is also monitored all the time by Closed Circuit Television (CCTV). There are several cameras trough out the municipality. MDMC is also warned by the early warning system which works together with weather forecasts and besides that they receive provincial alerts. When a disaster is major the Disaster Operation Centre (DOC) is activated. The DOC is a big room in which all important stakeholder can come together and make important decisions. The room consists of a big screen on which camera footage of the disaster location can be shown.

Roads with construction and lower laying roads are often flooded.

# Appendix C Stakeholder Analysis

This appendix mainly contains an elaboration on the earlier mentioned analysis. First the stakeholder characteristics are elaborated, second the stakeholders are described and in the end an elaboration is given on the power, interest and attitude diagram.

## C.1 Stakeholder description

The stakeholders that are identified are shown in Section 3.1. This appendix contains background information of the identified stakeholders and why they are affected by floods.

**South African government:**
The national government of South Africa is responsible for the safety of their country. South Africa is the 30th driest country world wide. This means that there are a lot of authorities that focus on water management. The government acts through these water authorities. The department 'Water and Sanitation' is responsible for the water and owns the money if something has to be done referring to water and sanitation. South Africa is a democracy in which the national, province and regional levels have their own legislative and executive authority. The national, province and local levels are distinctive, interdependent and interrelated. The national government makes laws and sets policies for the entire country which is divided into nine provinces. During this project the KwaZulu-Natal province will be the focus area. They are involved in this project because the national government regulates the money and their task is to make South Africa safe. Floods disturb the safety of the country.

**National Treasury:**
The National Treasury is part of the South African government and is responsible for managing the finances of this country. One of the main key goals of the African Government is having a growing economic development. The National Treasury is an important aspect of getting a growing economic development, in this way all the finances are located at and organised from one place in the governmental system. In this way the money is organised quite well and there is a better view on the in- and outcomes of the government. In this way not only the economy will be growing but also the standard of living for the inhabitants of South Africa will rise. There is an overarching organisation that examines the National Treasury on transparency, accountability and financial control. This is important for this project because national roads can be destroyed by floods, if these roads have to be repaired money is needed from the government. The National Treasury takes care of this money and could fund national infrastructure. Besides the national infrastructure, it can also fund the Disaster management or fund money for rebuilding. See Appendix B.3.

**SAMSA:**
SAMSA is the abbreviation of the South African Maritime Safety Authority, this is a young organisation that is established in 1998. The SAMSA takes care of the safety of life and property at sea, prevent and combat pollution from ships in the marine environment and they promote the Republic's maritime interests. SAMSA is involved in this project because it takes care of the maritime safety, when floods occur some dangerous situations can occur near and in the coast. For this reason it can be affected by floods.

**Government for KwaZulu Natal Department of Cooperative Government and Traditional affairs:**

The KwaZulu-Natal province has its own legislative and executive authority. This province is divided into eleven districts. Each of the nine provinces in South Africa has their own portfolios and priorities that it wants to fill in. The KwaZulu-Natal province is conducted with everything that is going on in that province. For this reason they have their own departments that are responsible for water or for traffic. The KwaZulu-Natal province is divided into eleven municipalities. One of them is the eThekwini municipality, the focus point of this project of the KwaZulu-Natal province. The KwaZulu Natal province is affected by floods because of the interrelations with the eThekwini municipality. The KZN province has to take care of the development and safety of the municipalities within the province.

**eThekwini municipality:**
The eThekwini municipality is situated at the east coast of South Africa. In total there live more or less 3 442 400 people over an area of 2297 km2. Because of the rich history the city knows a lot of cultural differences. This can be seen in the social, economic, governance and environmental aspects. EThekwini municipality wants to strive for a safe environment for everyone and wants to meet the needs of an ever increasing population. The eThekwini municipality contains several departments that are focusing on floods, especially the Coastal department of the City Engineers of the eThekwini municipality. The Transport authority of the eThekwini municipality is also aware of the effects of floods on the transportation network. The eThekwini municipality owns several buildings in the city like the uShaka marine world, if something happens with that building they lose a lot of money because of damage to the building, tourism and visitors. The eThekwini municipality has its own insurance for flood damage to their buildings. Besides the City Engineers and the Transportation Authority the following departments will also be affected by floods: eThekwini Electricity, eThekwini Sustainability, eThekwini Water and Sanitation, eThekwini Economic Development Unit and eThekwini business support, markets and tourism.

**Provincial Department of Education:**
The schools that are affected by floods are located in areas that are sensitive for floods. It depends on the height of the water in what extent these schools are affected. Education is very important in South Africa. The national government wants to have a high educated, skilled and highly developed population. The first step is having good education, this education is not possible if the buildings are damaged by floods and not available anymore. A solution has to be found to make education possible for the children if the buildings are not available and accessible. The Provincial Department of Education is the overarching organisation of eduction in eThekwini Municipality, when damage occurs the provincial department of education has to search for solutions and/or take care of the losses.

**Provincial Department of Health:**
South-Africa knows a lot of diseases that can spread very fast. Several health care centres are located in flood sensitive areas. If floods occur, it is possible that hospitals are not able to care for people who need care, people can die or a disease can be spread very fast. In South-Africa it is important that people go to the hospital as soon as a disease is recognised or the symptoms are there. The health care centres in the province want to prevent diseases, poverty and want to get a better life for everyone. It is important to develop and implement a health care system for everyone based on the Primary Health Care approach through the District Health System [45].

**eThekwini Library Service and Museums:**
South Africa has a rich history that is seen in a great collection of artifacts and books in several museums and libraries in and around the city. [46] Books have played an enormous role for the

education of thousands of people. Nowadays the libraries have a collection of over a million items and more or less 593 000 members. [47] It is important that the rich history remains intact when floods occur and are safe. These departments need money to secure these items when floods occur. Otherwise the affect of floods on this department and indirect the whole nation will be immense.

**eThekwini Sports and Recreation/Private stadia:**
The eThekwini Sport and Recreation department is responsible for development of the sports and recreation, they want to improve the quality of life for inhabitants of eThekwini. [41] A lot of sport facilities are located near the coast, the Umgeni river and the city centre of Durban. The probability of floods in the sport facilities are likely. For this reason they are also affected by floods and games can not be played.

**PRASA:**
PRASA is the abbrevation for Passanger Rail Agency of South Africa. This organisation is part of the National department of Transport. PRASA wants to achieve a good transportation network in which commuters can easily travel from place to place. PRASA is a government driver entity which causes that the government is a strategy driver for the organisation. The train stations in Durban can be flooded which causes that the trains might not run anymore. For this reason they are taken into account.

**SAPS and eThekwini Fire:**
SAPS is the abbreviation for The South African Police Service. This is a national organisation that is affected by floods because they maintain public order in the city, protect and secure the residents of the country and thus the inhabitants of the eThekwini municipality which results in a safe and secure environment. In general and during floods they want to make sure that every inhabitant of the country is safe and bring them to hospitals where possible and needed.

**Coastal watch:**
The coastal watch is in Durban a Non Governmental Organisation that protects and manages the coastline of the province. The coastal watch works together with nation wide organisations. These nation wide organisations are not named in the stakeholder identification because it will not affect them by floods of the eThekwini municipality. The Coastal watch is involved in this project because they want to make sure that the coastline is safe, if floods occur a dangerous situation can occur near the coast.

**Large businesses:**
Entrepreneurs are divided into large businesses and local businesses. Large businesses are seen as international, national and large firms. Most of the time they are part of the South African Property Owner Association. This association is also called SAPOA and is responsible for the property owners of the city and represents, protects and takes care of their interests in the property industry. The amount of insurance for floods is for a lot of people too high. For large businesses this causes less problems than for local businesses. Insurance is most of the time relevant by new or relatively new building, if the building is payed off they normally do not choose for a flood insurance because the time of recovering is higher. If economic value is also taken into account a great difference between large and local businesses occurs as well. Large businesses are affected by floods because there are two business areas in Durban, one in the Central Business District of Durban and one near the Umgeni river. The chance that floods occur near the river and in the centre of Durban are high because of lowlands areas.

**Local businesses:**
Local businesses are seen as small shops or firms, most of the time family shops. The problem with these shops is when floods occur they often have damage because they can not afford the newest buildings or newest materials to prevent damage. In South Africa the insurance is of such a high amount that not everyone is able to insure themselves for floods. This means that local businesses are sensitive for floods.

**Insurance companies:**
Insurance companies determine their probability of losses by analysing historical data and try to transfer them into the future, in this way they try to predict the losses of the future. The amount of uncertainty of the owners has to be reduced by insurance companies. The economic burden of loss will be spread among members of the insured group. Flood insurance does not prevent loss but assists the person with the flood insurance of the financial burden in the event of a loss occurring. [32] Insurance companies play an important role in the project of reducing and managing flood risks, they adapt and take some measures to the policy holders and want to avoid development in high risk areas [32]. When the government takes decisions that are not in line with the insurance companies, they can change their rules in such a way that the it will end in the best solution for the insurance company. This can have negative effects for the municipality. When the premiums will be higher, there are less residents who can pay the premiums and the municipality has to take care of them or they will change rules to block the municipality in the project or in another way.

**Lower and higher class residents:**
The difference between lower and higher class residents is very essential when we look to floods. It not only depends on where the areas are of these residents. It also dependents on how high the insurance can be of these people. A lot of people in Durban are not able to pay a flood insurance. Besides this, there is also a division in how old a building is. If the building is old and you already payed the building off, they often do not choose for a flood insurance anymore. This is also the case for companies that are located in these buildings or authority related organisations like the municipality, museums etc. This can also be affective for the economic value of an area in the city. Therefore certainly a division have to be made between the lower and higher class residents. Their difference is very dependent on the results of the project.

**Tourism organisations:**
Durban is a place that attracts more and more tourism and wants to make tourism as the key contributor to the local economy. When floods occur it can be possible for tourism to choose for another destination than Durban. Durban will loose a lot of money by tourists that have to leave the hotel because of floods or choose last minute to go to another part of South Africa instead of Durban.

**Ocean users:**
Ocean users are affected by floods. If floods occur they cannot go into the water because the waste of the streets will go back to the ocean and the current will be too strong into the ocean. The ocean in Durban is an attraction for tourists and inhabitants. A lot of surfers and inhabitants make use of the ocean. If floods occur they cannot use the ocean anymore and the effects will be there for several days. Ocean users are therefore mainly socially affected.

**Daily visitors focus area:**
It depends on the height of the water if daily visitors can enter the area or not. If there is a height of ten centimetres the roads will already not be available for visitors. Daily visitors can choose to go to another area than Durban, which means that the city will loose money by less visitors.

## C.2 Stakeholder characteristics

**National government and treasury:**
The national government and treasury has a high power because it is the highest organisation in the country that regulates the country. If something happens with the country they are responsible for the amount of money and the recovery of the country. They have a low interest by preventing floods. This is because of the several layers that are below them. Every municipality is responsible for the safety of their own municipality. For this reason the national government is less pro-active by preventing floods than municipality for example.

**SAMSA:**
SAMSA is the South African Maritime Safety Authority which has a high power. They want to make sure that everything at and surround the sea is safe. If a party wants to make some changes to it they have a high power to block the project for example, but their interest is passive. This authority is more related to the water quality and the safety for animals and people. Floods are not the main interest for them. The result of floods can be bad water quality in which they are a stakeholder that is affected by floods.

**Government for KwaZulu Natal Department of Cooperative Government and Traditional affairs:**
The government of Kwazulu Natal has the same high power and low interest as the national government of South Africa. They also have a high power because they can block the programme and have to give an approval for the projects and for where the money goes to. But they also have low interest for the project because the municipality is the responsible party for the safety of the inhabitants and should take care that everything runs properly.

**eThekwini municipality:**
The municipality has a high power and an active interests by preventing floods. They are responsible for what has to be and can be done in the municipality. They are responsible for the distribution of the money within the several departments and for the safety of the municipality.

**Provincial Department of Education:**
The provincial department of education has low power and passive interest. They are responsible for the content of the education and that the education is equal for every inhabitant in KwaZulu Natal. The interest on preventing floods is low because this is not their main goal. Their power can be high to make sure that education still runs also when floods occur. But in this case listening to the stakeholder and searching for an easy solution can be good enough.

**Provincial Department of Health:**
The provincial department for health has low power but an active interest. It is really important that the medical care keeps going on when floods occur. Even more when people can drown, for this reason it is important that there are some hospitals available in the area that have enough capacity to give the people who need it medical care. The municipality has to listen to them but their power is not that high that they can block the project. They stand behind the municipality to prevent floods so there is less medical care needed and the medical care that people need can just go on without being interrupt by floods.

**eThekwini Library Service:**

The eThekwini library service has low power and passive interest. South Africa has a rich history with a lot of artifacts of the history. It is important that these artifacts are safe when floods occur, but they do not have enough power to block the project. Their interest is also passive because they want to prevent the floods as well. In this way they stand behind the project to mitigate floods.

**eThekwini Sports and Recreation/Private stadia:**
The power of the eThekwini sport and recreation is low. It is important that people can play sports but it is not that bad if sports can not be played for several weeks because of floods. The effects will not be that high for the municipality. For this reason they have a low power towards the project. They also have a passive and low interest. They want to make sure that the sport activities continue as soon as possible, for this reason they want to prevent floods as well. But their interest is not that pro-active as for the health department for example.

**PRASA:**
The power of the PRASA is low because the rails are not often used in KwaZulu Natal. This transportation is not really common for the most people. The interest of PRASA is to organise the best transport possible by train. Only 3% of the people in Durban use the train. Their interest is passive because of the small amount of trains that run during a day. For this reason not a lot of trains will be affected.

**SAPS and eThekwini Fire:**
SAPS and the eThekwini fire have low power. They are part of the municipality and highly affected by floods. They do not have the power to have any influence on the project but they definitely are necessary to search for a best possible solution. For this reason they have low power but a high interest in the project.

**KZN Department of Health and private service providers:**
The KwaZulu Natal Department of Health and private service providers have low power and an active interest. Besides the hospitals in the area, also the ambulances are taken into account. They have to do their work while floods occur, they have to be available and roads have to be accessible for them. Same as the SAPS and eThekwini fire they have to be listened to to get a lot of feedback and get a better solution for the problem but they do not have enough power to block the project. They want to have the most safe situation as possible.

**Coastal watch:**
The coastal watch has low power, they want to create a safe situation near the coast but do not have enough power to be very critical for the municipality. The municipality has to listen to them but they can not influence them a lot.

**Large businesses:**
Large businesses do not have low power and not high power but intermediate power. Large businesses are good for eThekwini municipality because of the economic value that they will bring in the city. They have to make sure that the large businesses keep running while floods occur. The large businesses have a lot of money which they can use to increase their power. Beside the intermediate power they have an active interest, the businesses have to move forward and it is necessary to run the business to work every day. There will be a lot of economic losses if the businesses do not work for one day.

**Local businesses:**

Due to less money available for local businesses and the size of the businesses their power is low. They are not able to have a great influence on the municipality. Their interest is also passive because the consequences for the local businesses are smaller than for example large businesses.

**Insurance companies:**
Insurance companies have a high power and have a very active interest. They have to pay the flood damage to property owners that are insured. They will get affected the most and want to pay as little as possible. For this reason they have a high interest. Their power is high because they have a lot of money and they help the people to recover after a flood. They pay them to help the community. If the people do not have money to help themselves the government takes care of them.

**Lower class residents:**
The power of lower class residents it not high at all. They have little money to care for themselves and their priority is not making the area flood safe. The government pays them a certain amount to recover if floods will damage their services or houses. For this reason they have little power and a passive interest because of the services they receive of the municipality.

**Higher class residents:**
The power of higher class residents is intermediate. They pay a lot for their house and insurance, for this reason they have more influence on the problem. Most of the higher income class wants to have the best for their money, for this reason they will let the municipality know what they want to have and will do the best to get what they want to have. For this reason they are active and have a high interest.

**Tourism organisations:**
The power of tourists is low and passive. It is very important for the eThekwini municipality to have a lot of tourists in their city. They are important for the economic growth of the city. Because the tourists do not stay for a long time in Durban they are passive. They do not have a high interest by preventing floods. The municipality will make sure that the tourists are safe and have the best time in Durban but the tourists are not a problem for the municipality during this project.

**Ocean users:**
Ocean users often come to Durban because of the warm coast which is very attractive for ocean users. This results in a high interest on preventing floods. Their power is low, for this reason the municipality has to listen to them but it is not necessary to take it very serious.

**Daily visitors focus area:**
Daily visitors in the focus area come to Durban for one day and probably spend some money in the city. When floods occur and the city is not well accessible, these visitors will stay at their home which causes less economic growth in the city. They have low power because they come here for one day in a flood event which is not really effecting the municipality as we compare it with the annual economic growth of the eThekwini municipality. Because they visit for one day their interest is also low.

## C.3 Stakeholders power, interest and attitude

To identify the stakeholders power, interest and attitude towards the flood safety project the technique of Murray-Webster and Simon is used. It is necessary to identify these three aspects of stakeholders because stakeholders can have an unexpected influence on projects. By using this technique the aspects power and interest are set against each other and interest and attitude. By combining these two combinations with each other a 3D graph appears which is shown in C.1. [38]

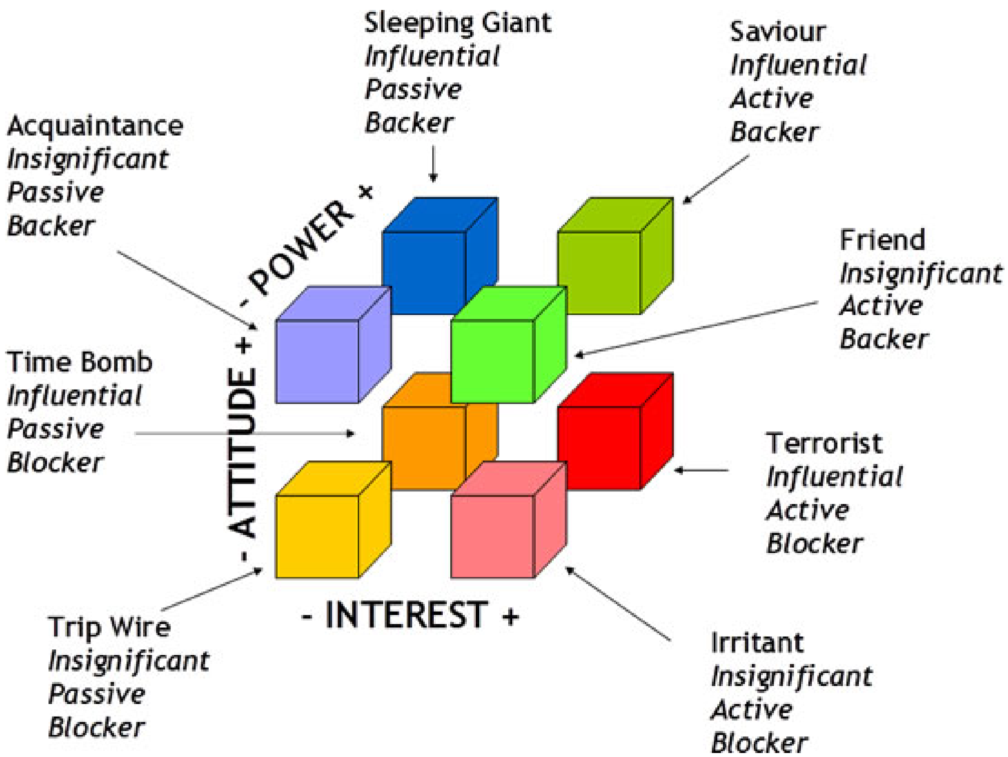



Figure C.1: 3D Graph power, interest and attitude

Saviour - powerful, high interest, positive attitude or alternatively influential, active, backer. They need to be paid attention to; you should do whatever necessary to keep them on your side - pander to their needs.

Friend - low power, high interest, positive attitude or alternatively insignificant, active, backer. They should be used as a confidant or sounding board.

Saboteur - powerful, high interest, negative attitude or alternatively influential, active, blocker. They need to be engaged in order to disengage. You should be prepared to lean-up after them.'

Irritant - low power, high interest, negative attitude or alternatively insignificant, active, blocker. They need to be engaged so that they stop 'eating away' and then be 'put back in their box'.

Sleeping Giant - powerful, low interest, positive attitude or alternatively influential, passive, backer. They need to be engaged in order to awaken them.

Acquaintance - low power, low interest, positive attitude or alternatively insignificant, passive, backer. They need to be kept informed and communicated with on a 'transmit only' basis.

Time Bomb - powerful, low interest, negative attitude or alternatively influential, passive, blocker. They need to be understood so they can be 'defused before the bomb goes off'.

Trip Wire - low power, low interest, negative attitude or alternatively insignificant, passive, blocker. They need to be understood so you can 'watch your step' and avoid 'tripping up'.

# Appendix D Transport analysis

## D.1 Transport system

Figure D.1 gives insight in the most important aspects that can be found in the transport system.

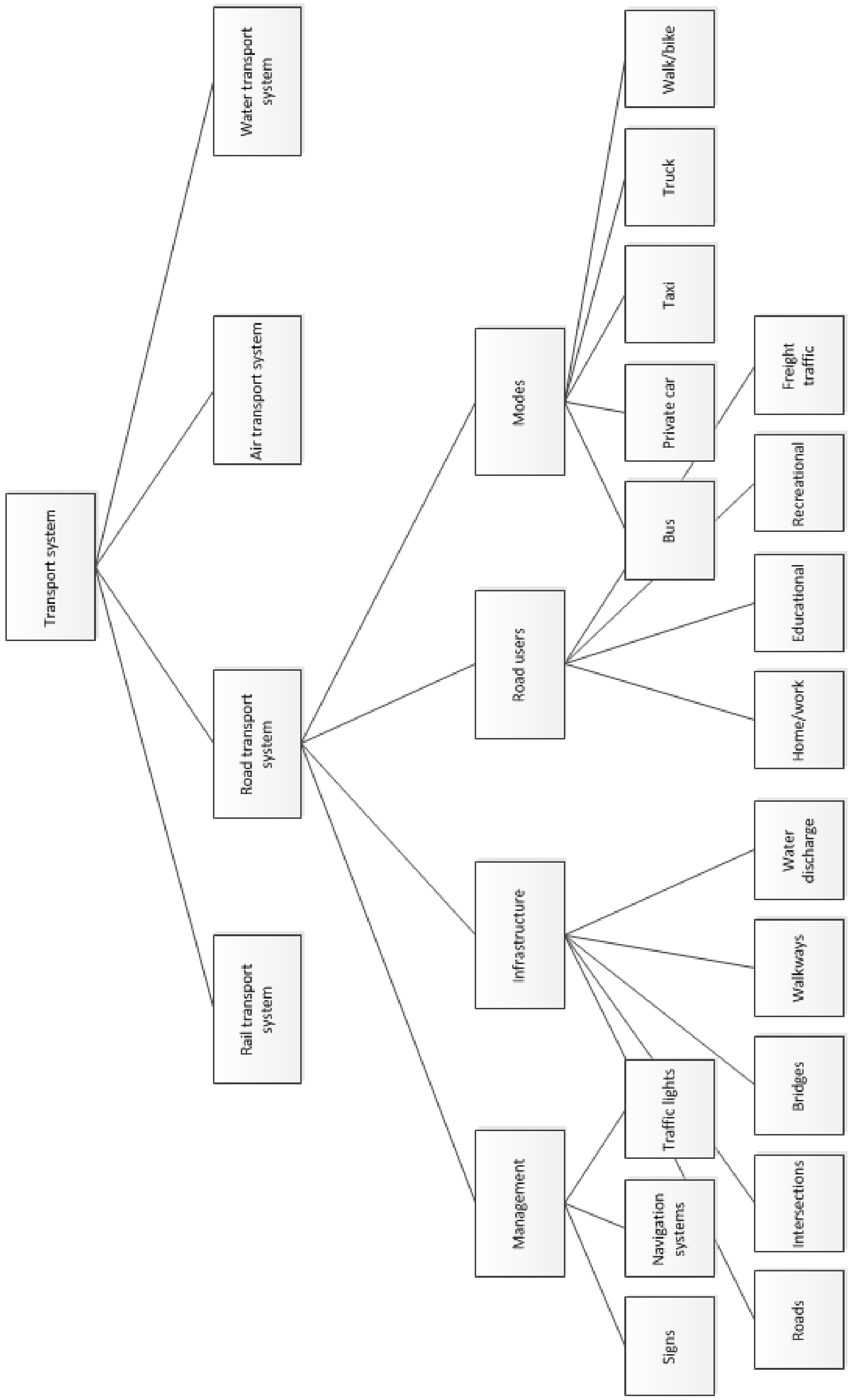



Figure D.1: Components of the transport system

The transport system consists of four subsystems; rail, road, air and water transports systems. Within the city road transport and a little train transport are the only used modes as can be found in Table 4.1. The flood focus area does not contain any airport thus the air transport system is not taken into account. The focus area does contain the harbour and the Umgeni river, but since the water transport is not used within the city, it is not considered as useful transport systems. Then there are only two transport systems left on land; rail and road. There is only one route available for rail, as can be seen in Figure 4.4, whereas there is a big transport network for road transport. For this reason, the main focus will be on road transport. The road transport system is a big system which contains all components that play a role in the transport network. The road transport system can be subdivided in four categories: management, infrastructure, road users and modes. As described in Chapter 4, five main modes can be found on the road network: bus, private car, taxi, truck and walk/bike. These modes can be used for different purposes, and by different users. Most users have as trip purpose home/work, education, recreation or transporting freight. All these road users use the infrastructure of the road network. The infrastructure mainly consists of roads, intersections, bridges, walkways and water discharges. Because of the combinations of these parts of the infrastructure, there is some management needed to let the traffic flow through smoothly. This management consists of signs, navigation systems and traffic lights.

## D.2 Major Public Transport Nodes

In case of an evacuation it might me useful to know where major public transport nodes are to gather people. The major public transport nodes are given in Figure D.2. As can be seen one of the major nodes is located in the CBD of Durban which is in the area of interest.

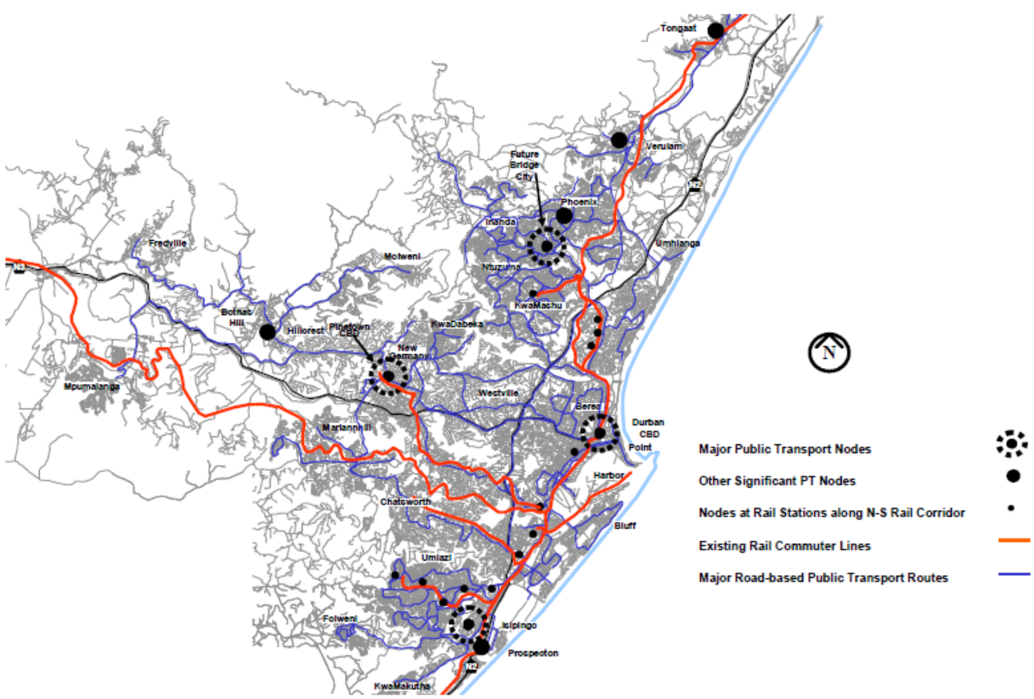
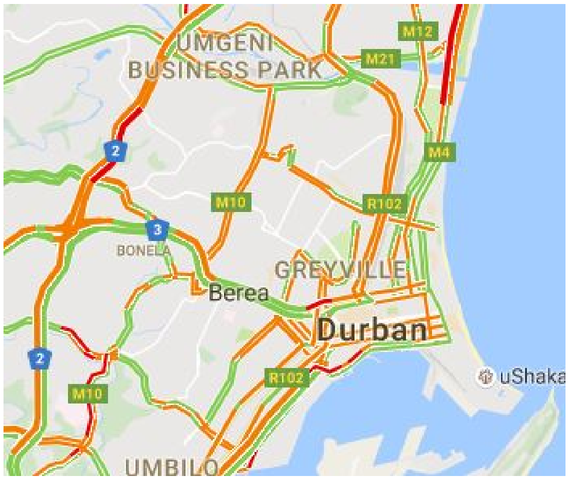


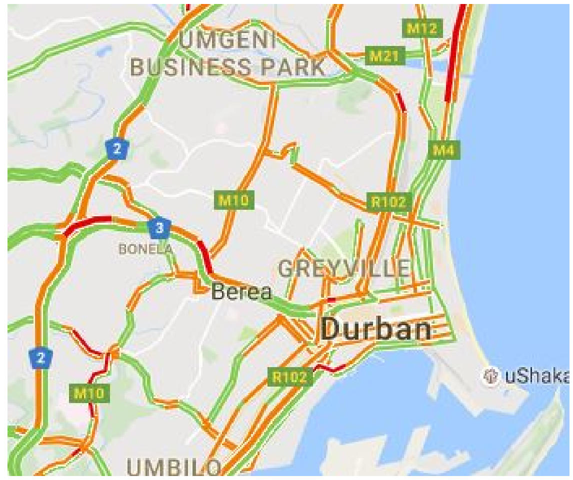

Figure D.2: Major Public Transport Nodes

### D.3 Google Maps Traffic Data

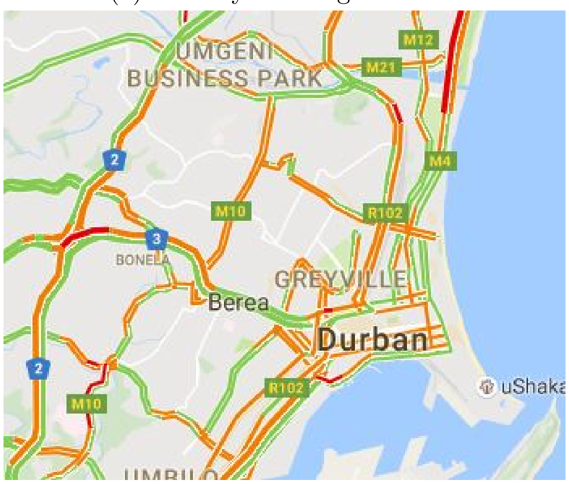
Google collects data about traffic in Durban. This data is used in Google Maps [27] to show live traffic and typical traffic during the day in the city. This data can be used to tell which roads are most busy during specific times of the day. Most congestion occurs during the morning and the evening peak. Figure D.3 shows the typical traffic during the AM peak (7.30 AM). Figure D.4 shows the typical traffic during the PM peak (5 PM). The colours of the roads, ranging from green to red, give the speed of the traffic. Green means traffic can drive fast whereas red means traffic is driving very slow, or even standing still. This thus shows where the bottlenecks are at that moment. As can be seen in all figures below, during the peak hours traffic often has to drive slow.



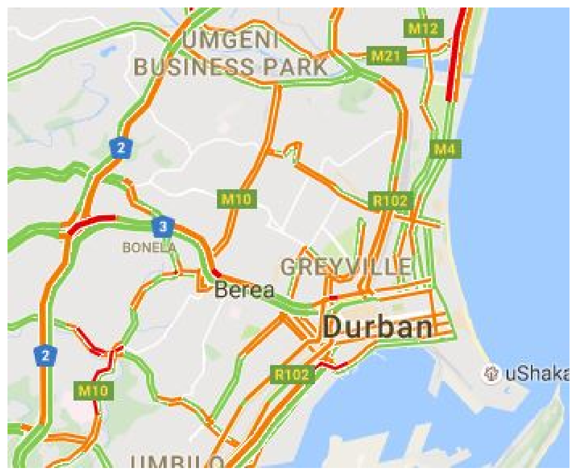

(a) Monday morning 7:30 AM



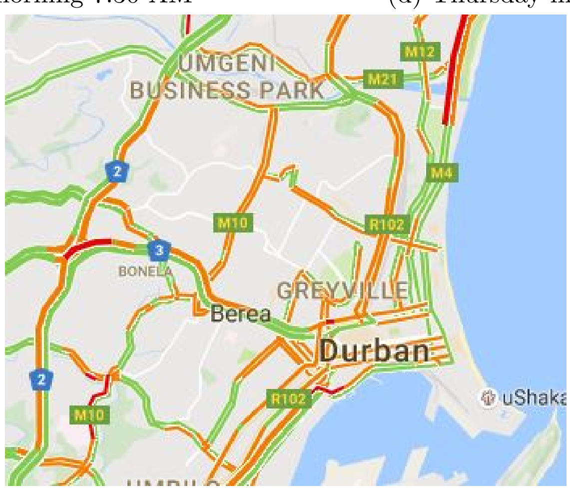

(b) Tuesday morning 7:30 AM




(c) Wednesday morning 7:30 AM




(d) Thursday morning 7:30 AM

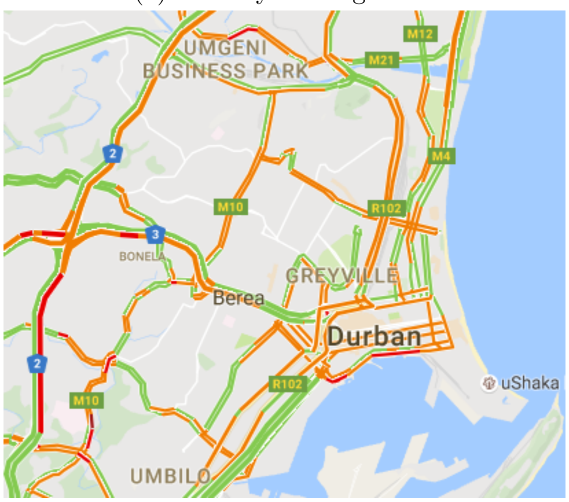



(e) Friday morning 7:30 AM

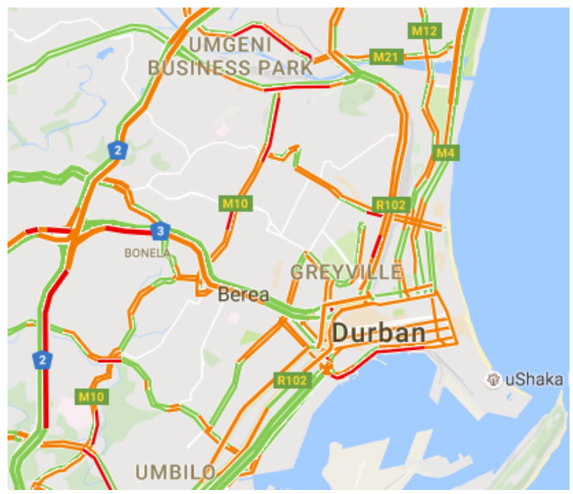
Figure D.3: Morning peak 7:30 AM


(a) Monday evening 17.00

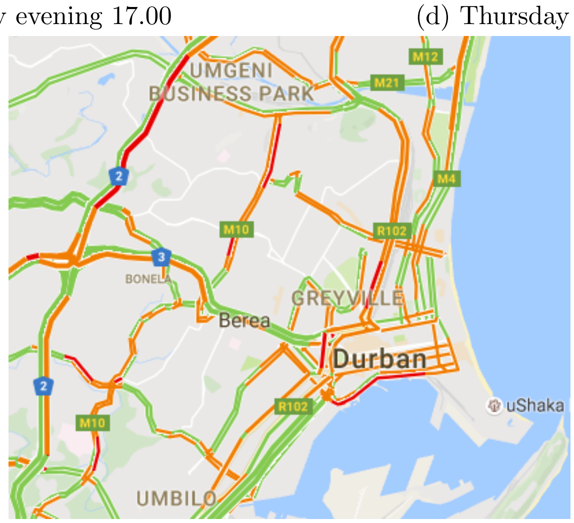

(b) Tuesday evening 17.00




(c) Wednesday evening 17.00




(d) Thursday evening 17.00




(e) Friday evening 17.00

Figure D.4: Evening peak 17:00

## D.4 Traffic model

The Emme transportation forecasting software [31] is a travel demand modelling system that is used by the eThekwini Transport Authority (ETA) to forecast transportation in the city of Durban. The model uses origin-destination matrices to assign traffic to the roads in the network. This model can only be used by the employees of ETA. The origin-destination matrices are not available to the public. The Emme model is based on AM peak hour data. First the model is used to determine bottlenecks in the transportation network in the study area. The results of these runs are the Emme 2015 data [22] which are put into ArcMap. By using ArcMap, the traffic volumes, capacities and load factors can be visualised.

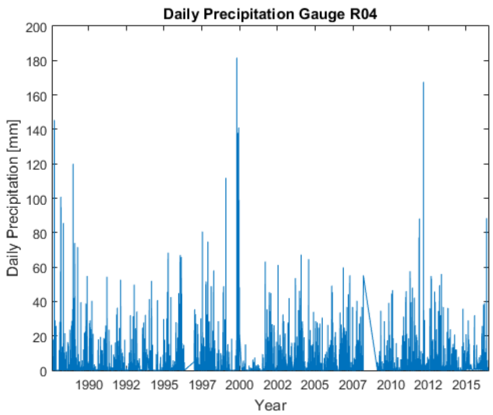
ArcMap is part of ArcGIS [14]. This is used to visualise GIS shapefiles and explore and edit datasets. Several layers of different elements can be combined to create a map for the study area. The used layers for this project are: a satellite picture of Durban as background, road links and traffic data from the Emme model. A layer can have several attributes. Important attributes in the Emme layer are:

- ID: This is the number of a link (road). This number is used to identify the links. The ID is based on the numbers of two nodes which are connected by the link.
- MODES: This attribute determines which models are allocated to a link.
- LANES: The number of lanes of a link are determined by this attribute.
- DATA2: This is the capacity of a link.
- TOTAL: The total traffic volumes on the link.

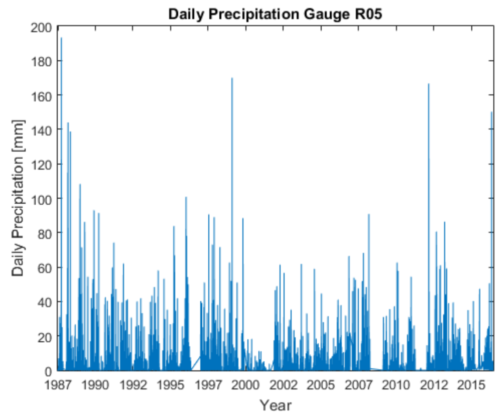
Besides the above attributes, the attribute 'Load factor' is added to the dataset. This factor determines the difference between the traffic volume and the capacity of a link. So Loadfactor=TOTAL/DATA2.

After identifying the bottlenecks in the network, the model is used to see the difference between the normal traffic and the case where roads (links) are closed due to floods. This is done by not allowing the road traffic to use the specific links any more. The traffic of the blocked roads will use other routes to get to their destinations. So the traffic volumes on other roads will increase. To determine which roads have to be blocked PCSWMM is used. All the roads which will be flooded with more than 15 cm (see paragraph 9.1) are decided to block. After running the adapted traffic model by ETA, figures with traffic load factors are given by them to evaluate the network.

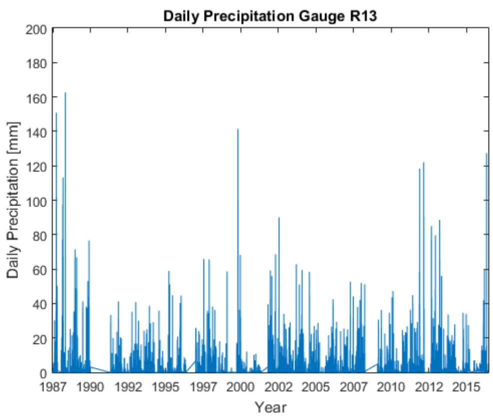
# Appendix E Rain Gauges



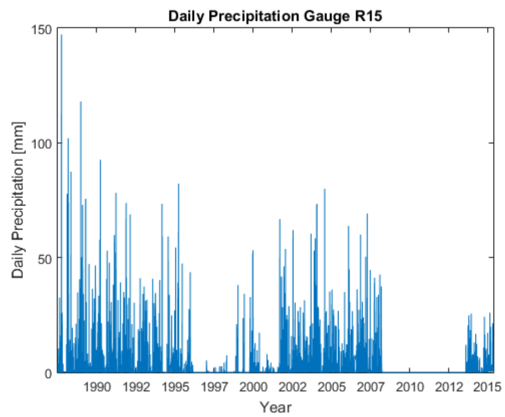

(a) Gauge R04



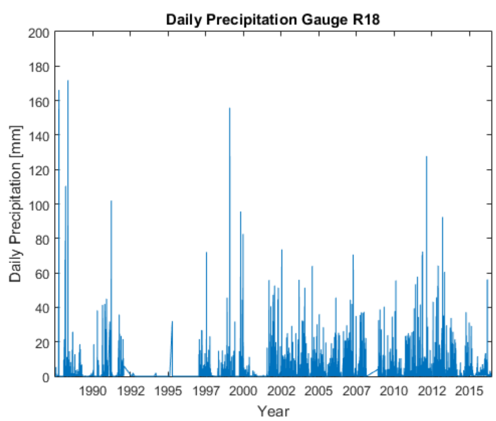

(b) Gauge R05




(c) Gauge R13

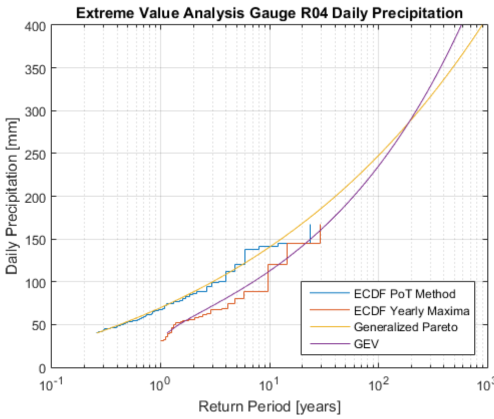



(d) Gauge R15

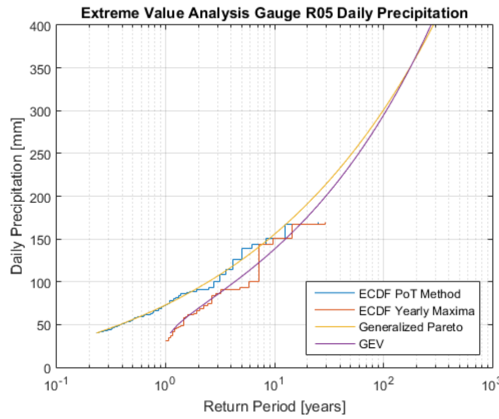



(e) Gauge R18

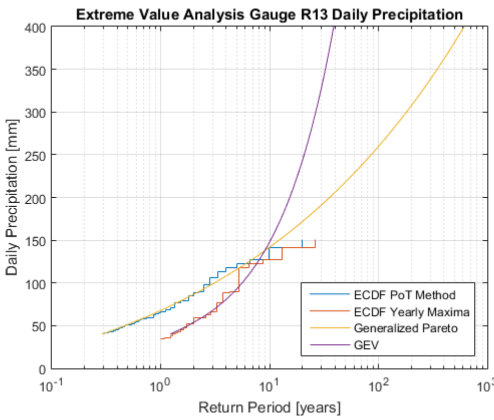
Figure E.1: Entire data sets off all 5 rain gauges



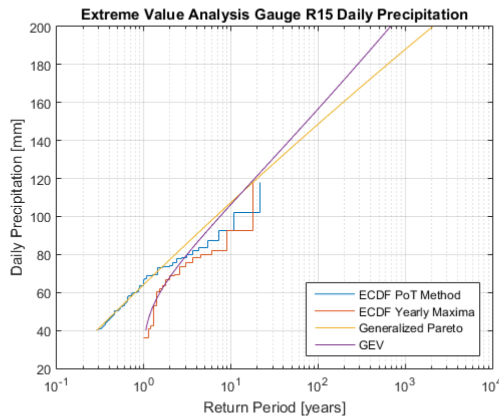

(a) Gauge R04



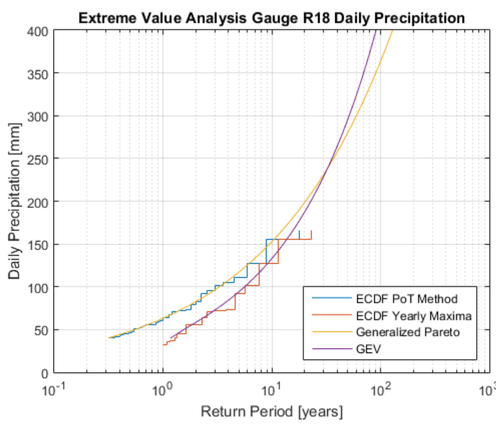

(b) Gauge R05




(c) Gauge R13




(d) Gauge R15




(e) Gauge R18

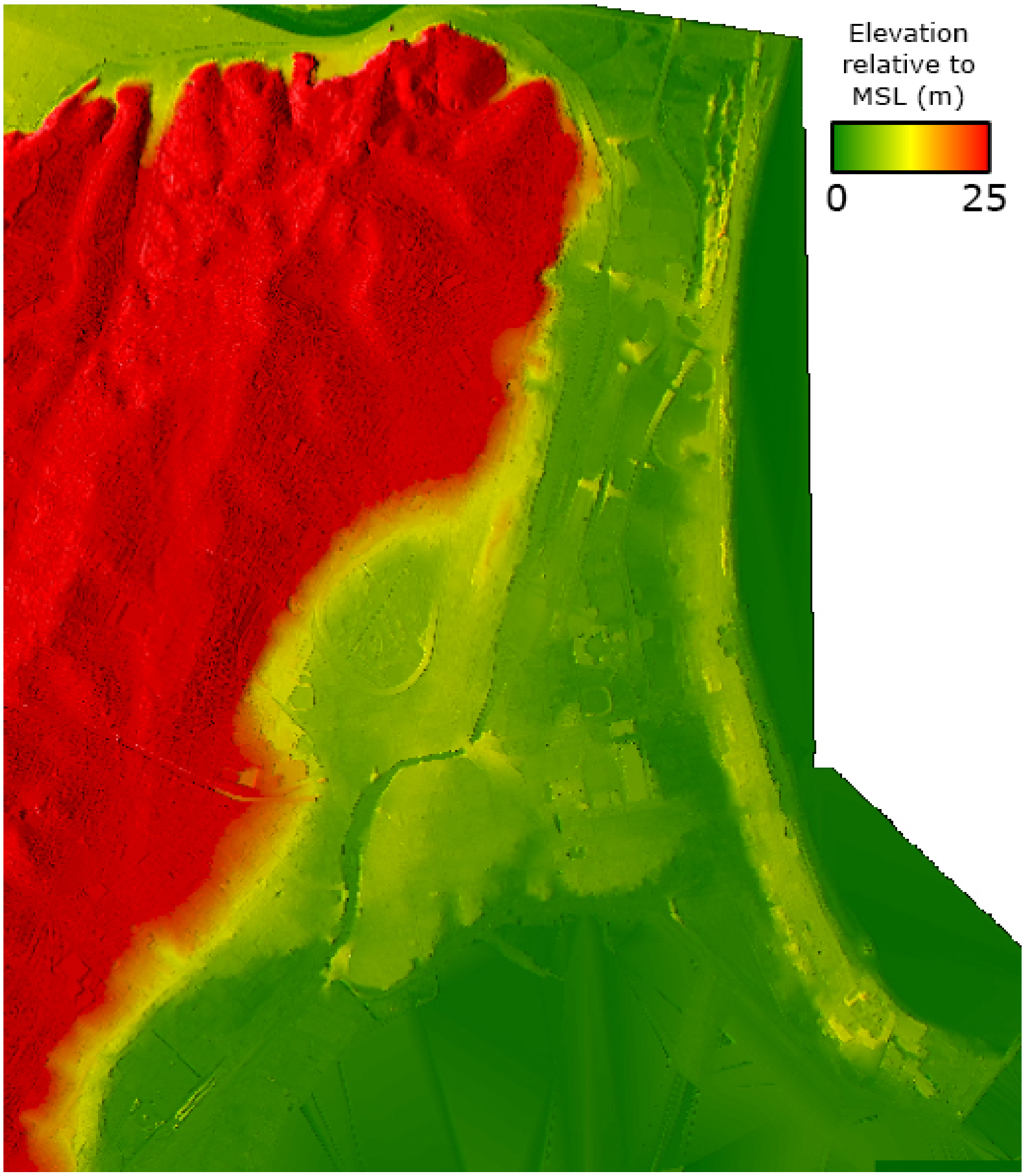
Figure E.2: Extreme value analyses off all 5 rain gauges

# Appendix F List of all tidal constituents

Table F.1: Complete list of tidal constituents

| Constituent: | Amplitude [m]: | Angular velocity [degree/h]: | Phase [rad]: | Period [d]: |
|---|---|---|---|---|
| 'M2' | 0.5731 | 28.984 | -1.7321 | 0.5175 |
| 'S2' | 0.3036 | 30.000 | 2.3488 | 0.5000 |
| 'N2' | 0.1070 | 28.440 | -3.0026 | 0.5274 |
| 'K2' | 0.0741 | 30.082 | -1.0265 | 0.4986 |
| 'K1' | 0.0466 | 15.041 | 2.8289 | 0.9973 |
| 'SSA' | 0.0398 | 0.082 | 2.4953 | 182.6211 |
| 'T2' | 0.0230 | 29.959 | -2.9062 | 0.5007 |
| 'L2' | 0.0223 | 29.528 | 2.7026 | 0.5080 |
| 'MU2' | 0.0187 | 27.968 | 0.8952 | 0.5363 |
| 'NU2' | 0.0174 | 28.513 | 2.2807 | 0.5261 |
| 'P1' | 0.0165 | 14.959 | 2.8902 | 1.0027 |
| 'MF' | 0.0162 | 1.098 | 0.0001 | 13.6608 |
| '2N2' | 0.0162 | 27.895 | 2.1156 | 0.5377 |
| 'MM' | 0.0146 | 0.544 | -1.2226 | 27.5546 |
| 'S1' | 0.0134 | 15.000 | -2.2022 | 1.0000 |
| 'O1' | 0.0116 | 13.943 | 2.3235 | 1.0758 |
| 'Q1' | 0.0078 | 13.399 | 0.8568 | 1.1195 |
| 'R2' | 0.0073 | 30.041 | 2.5837 | 0.4993 |
| 'MSF' | 0.0068 | 1.016 | 2.9061 | 14.7653 |
| 'M1' | 0.0055 | 14.497 | 2.4766 | 1.0347 |
| 'J1' | 0.0041 | 15.585 | -1.5572 | 0.9624 |
| 'M4' | 0.0039 | 57.968 | -1.9154 | 0.2588 |
| 'LAM2' | 0.0038 | 29.456 | -2.8004 | 0.5092 |
| '2SM2' | 0.0030 | 31.016 | -2.3325 | 0.4836 |
| 'MN4' | 0.0030 | 57.424 | 2.2984 | 0.2612 |
| 'M3' | 0.0030 | 43.476 | 2.1242 | 0.3450 |
| 'OO1' | 0.0024 | 16.139 | -1.9870 | 0.9294 |
| 'RHO' | 0.0017 | 13.472 | 0.3965 | 1.1135 |
| '2Q1' | 0.0015 | 12.854 | -1.0437 | 1.1669 |
| 'M6' | 0.0014 | 86.952 | 0.8203 | 0.1725 |
| 'MK3' | 0.0011 | 44.025 | -0.3305 | 0.3407 |
| 'S4' | 0.0010 | 60.000 | -2.6613 | 0.2500 |
| 'S6' | 0.0008 | 90.000 | 0.2708 | 0.1667 |
| '2MK3' | 0.0008 | 42.927 | 1.9236 | 0.3494 |
| 'MS4' | 0.0006 | 58.984 | 2.6156 | 0.2543 |
| 'M8' | 0.0003 | 115.936 | -1.9844 | 0.1294 |

# Appendix G Detailed Elevation Map Durban



# Appendix H Elaboration on modelling process PCSWMM

PCSWMM is a program with a lot of modelling possibilities and is equipped with an extended user interface. There was no experience within the group regarding this software program or similar programs, which lead to the need of following multiple tutorials to get familiar with PCSWMM.

## H.1 Setting up the 1D model

The base model which was used as a starting point is a large 1D model which is built up for modelling the stormwater discharges of the catchment area upstream of the harbour. This model is very large because a lot of stormwater outfalls are situated at the harbour. The needed area in was taken out of the model and formed the southern part of the desired model for the area of interest. A ridge forms a natural border between the city center and neighborhoods outside the center. In Figure H.1 all outflows and their upstream areas have been selected (blue and red) which discharge in the northern part of the harbour.

The middle part near the beach of this model is linked to the network discharging at the harbour, however there were no conduits included in this part, the subcatchments were directly routed onto the harbour. This is done because the network was not really relevant for the scope of this model, which is mainly water quality. However, in reality part of this network is discharging on the sea rather than the harbour. Another model is used as a replacement for this area, in which a network is included and which is closer to the actual situation.

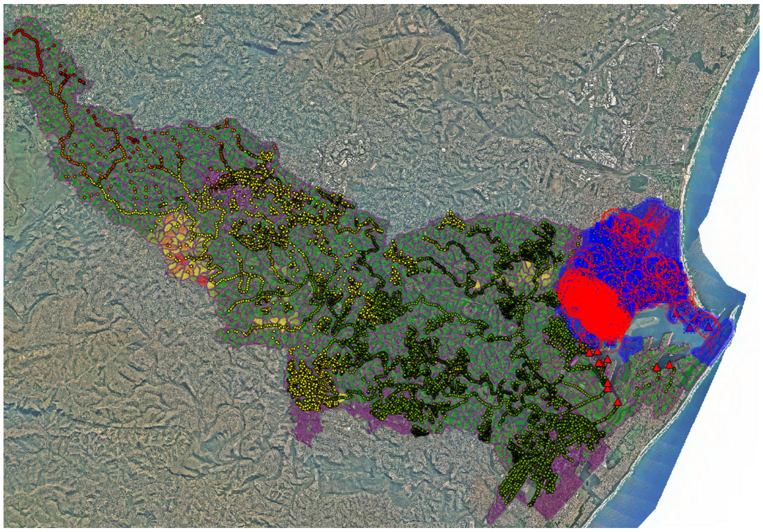


Figure H.1: Large PCSWMM basis model

The northern part of the project area is obtained by using multiple smaller models. The GIS information had to be imported in PCSWMM, and subsequently in the model which was used as a basis. Figure H.2 shows one of the smaller blocks of which the model is built up. During the merging operations some of subcatchments appeared to be partly overlapping, and in some places subcatchments were missing. The overlaps had to be cut off or merged, and the gaps needed to be filled in, both manually. Furthermore, the conduits needed to be linked to eachother manually. Next to that the outflows of the small models had to be removed and connected to the other models. Otherwise the drainage water would disappear out of the model.

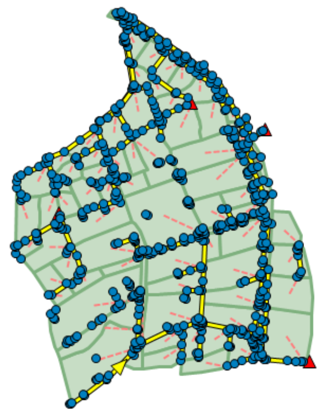


Figure H.2: One of the smaller blocks

One area in the model situated south of the Umgeni outlet, called the Blue Lagoon area was missing. This area is a very interesting area, because it is low-lying and in between the Umgeni river, sea and hill area land inward. Unfortunately this area was not yet modelled in PCSWMM, and also not present in the main GIS database of the municipality. After searching in other databases the GIS files were found, however some information like the invert elevation of the outfalls was still missing in this model. Furthermore, there seemed to be some inconsistencies which had to be checked with the help of colleagues and building drawings of the culverts at the outfalls.

All in all this led to a 1D model, which is shown in Figure H.3. The following layers are the minimal requirement for a 1D model. General explanation about these has already been given in section 7. If applicable, one can also apply more specific hydraulic structures like weirs, pumps and storages, but these are either not present or not of significant relevance in the stormwater system in the area of interest.

- **Subcatchments** (green planes)
  These entities collect the rain fall and direct the amount of water which is unable to infiltrate to a discharge point, which are generally the junctions. The following characteristics need to be assigned to these entities:
  - Location
  - The applicable rainfall time series
  - The area and its characteristics like, among others, slope, impervious area and infiltration rate
  - The junction or other subcatchment at which the subcatchment discharges
- **Junctions** (blue dots)
  These entities are the connections in the model between the subcatchments and the conduits, and as well between conduits. They mainly represent the manholes in the stormwater system. The excess water of the subcatchments is routed onto these items. The most important characteristics of these entities are as following:
  - Location
  - The elevation of the bottom (invert elevation) and the top (rim elevation) of the junction. The pipes are generally connected at the bottom of a manhole, and the rim elevation is usually at ground level.

- **Conduits** (yellow lines)
  These entities represent the pipes, culverts and channels of the stormwater network. The main characteristics are as following:
  - Inlet and outlet nodes (junctions)
  - Shape and dimensions
  - Slope
  - Hydraulic roughness
  - Type of cross-section and dimensions
- **Outfalls** (red triangles)
  These are the points at which the water leaves the 1D network and the model. The main characteristics are the location, invert and type of outfall. This could be free, but as well a fixed or varying water level.

Figure H.3: The comprehensive 1D model

Other problems and challenges which were encountered when setting up the 1D model are listed below:

- Some of the conduits had a negative slope which is probably caused by merging the models. These had to be tracked and fixed.
- There was some confusion within the department about the actual network. Some of the employees stated that the network in the model was duplicated, and therefore not true. These duplicates were taken out of the model, however some others stated that there is actually a dual network at these places in reality.

## H.2 2D Modelling

In order to set up a combined 1D-2D model, the following layers had to be obtained for the 2D part:

- **Elevation map of the area (LIDAR)**
  From the beginning on there was already a Digital Elevation Model available, however the accuracy of this map was limited to 0.25 m, and some deviation seemed to be present. This map sufficed for a first estimate on flooding, but lacked accuracy for a decent and reliable inundation map. At the end of the 6th week of the project the LIDAR map was present, which is reliable and accurate to the cm. This map can be found in Appendix G.
- **Obstruction layer** (Figure H.4)
  In this layer the buildings of the area are included as obstacles. These buildings will be excluded from the flooding layer. This layer was already available for Durban, although the more outer parts of the area of interest are not included. Unfortunately the Umgeni Business park is also not included in this layer.

Figure H.4: Obstruction layer

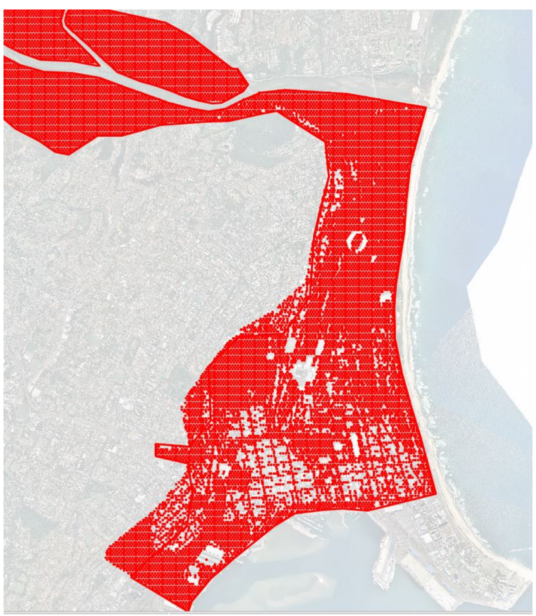
With the use of these layers the 2D layers necessary for the model were generated:

- **Bounding layer** (Figure H.5a)
  This layer defines the extent of the 2D model. The choice was made to exclude the hill (west) and point area (southeast) from the 2D model, because these areas are not flood prone. This will save computational time, which is very much desired for a large model like this. The 1D part will still be modelled in the excluded areas, only floods cannot be simulated. The spatial resolution of the 2D model also needs to be defined in this layer.

- **2D nodes** (Figure H.5a)
  The 2D nodes layer is a point layer which defines the junctions of the 2D network. The elevation of the points is sampled from the elevation map, the LIDAR in this case.

- **2D cells** (Figure H.5b)
  This layer is used to define the cells of the 2D network, which are necessary for displaying information about the flood depth. The common layout of these cells is hexagonal, however other options are possible as well.

- **Downstream layer** (Figure H.5b)
  The downstream layer is used within the 2D model to define boundary outfalls which cannot be described as a point. In this model this layer was used for the area adjacent to the coastline and the harbour. If this layer would not have been defined, water would pile up at these areas which is obviously unrealistic.



(a) Bounding (red outline) and nodes (red dots)

(b) 2D cells (blue hexagonal planes) and downstream layer (dark red line)

Figure H.5: Layers required for 2D modelling

When setting up the 2D cells layer PCSWMM as well creates fictitious junctions and conduits. These are in the same layers as the junctions and conduits of the stormwater network, but are distinguished by different tags. The junctions are nodes which represent the actual 2D cells in the model and carry the information about flood depth, which is used by the 2D cells layer. The conduits are the fictitious channels which allow flow between the fictitious junctions, which represents the overland flow. The fictitious conduits are shown in detail in Figure H.6 in the next paragraph by the thin black lines, and the fictitious conduits by the grey dots.

## H.3 1D-2D model interaction

The only thing missing for a working integrated 1D-2D model is a connection between the 1D and 2D parts. The Orifices layer needs to be generated in order to connect the models. Orifices are the fictitious openings in the model connecting the manholes of the 1D model to the fictitious 2D junctions, which are the information source of the 2D cells which show the flood depths.

The working principle of the interaction will be explained on the basis of Figure H.6. The first step is that the rain falls down at the subcatchments, which are visualized as the more or less square planes with green outlines. Each of them routes their discharge to the closest manhole (junction, blue dots), this connection is indicated with the red dotted line. As the water has entered the network it will be discharged via the stormwater pipes (conduits, yellow lines). In case of too much rain or an insufficient network flooding will occur. When this applies, the orifices (pink lines) will be used to discharge the excess water from the manholes (blue dots) to the fictitious junctions (grey dots). The junctions are located in the center of the 2D cells (blue hexagonals) and have the same elevation and area as the cells. The cells will carry and display information about the flood depth which originates from the fictitious junctions. The buildings are excluded from this layer and can be recognized by the non-blue areas where the mesh is wrapped around. When there is local flooding, water can flow to other spaces or flow back in the network, or a combination of those. Overland flow happens via the fictitious conduits (black lines) in between the fictitious junctions (grey dots). The flow back into the network takes place again via the orifices, only then in opposite direction.

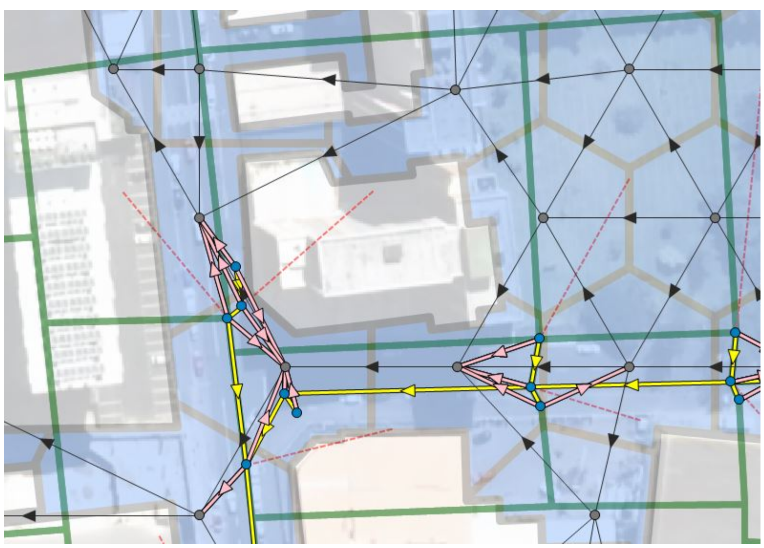


Figure H.6: 1D-2D interaction

## H.4 Modelling the input and boundary conditions

### H.4.1 Umgeni River

The Umgeni river is an important boundary for the comprehensive model. The eThekwini Municipality already had several models in which Umgeni river and its catchments are modelled. The main channel was taken out of the model and placed in to the model. The main channel of the river was therefore kept out of the 2D layers. The channel of the Umgeni river was not in the elevation map, because this cannot be measured by LIDAR techniques. If it would have been in the elevation map it could be included in the 2D mesh. One of the challenges was to connect the 1D river channel correctly to the integrated 1D-2D model. The connections between the river and the outfalls and the 2D cells had to be established manually. Furthermore the cross sections of the river had to be adapted to minimize gaps or overlap between the channel in 1D and the 2D mesh. In Figure H.7 a part of the river can be found. The stormwater network outfall is connected by the orifice (pink line) directed from the embankment to the river channel. If the water level at the river becomes too high, the flow will be the other way around. The orifices directed from the river channel towards the fictitious junctions representing the 2D layer can enable flow towards the embankments and hinter lying area if the water level at the river exceeds the elevation of the embankment.

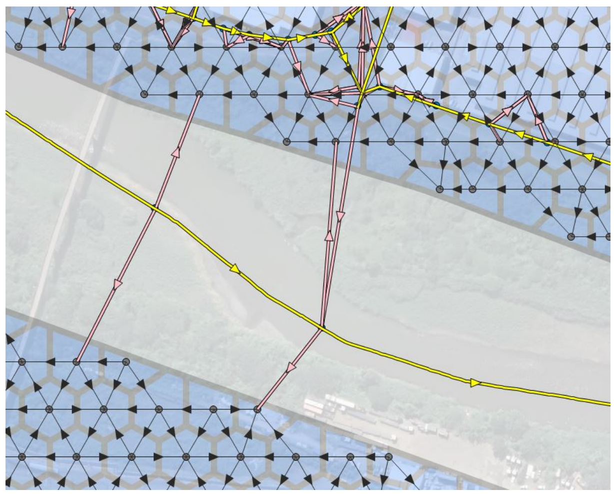


Figure H.7: 1D-2D interaction at the Umgeni river

### H.4.2 Rain gauges

The data and insights acquired in the hydrological analysis (Section 6) was used as input for PCSWMM. The CSCM department uses a specific distribution for the rainfall. The peak of this distribution is thought to be somewhat too spiky. However, because this is used in all simulations the decision has been made to use it for the model for this project as well. This distribution has been used together with the acquired data about rainfall amounts, and scaled to the values obtained in the analysis. During modelling it an error in PCSWMM appeared which prevents the user from changing the rainfall event. In order to fix this, the main file of PCSWMM had to be opened in a simple text processing program like Notepad and the reference to the old rainfall event had to be deleted. An example of a rainfall intensity distribution for a 50 year return period is shown in Figure H.8.

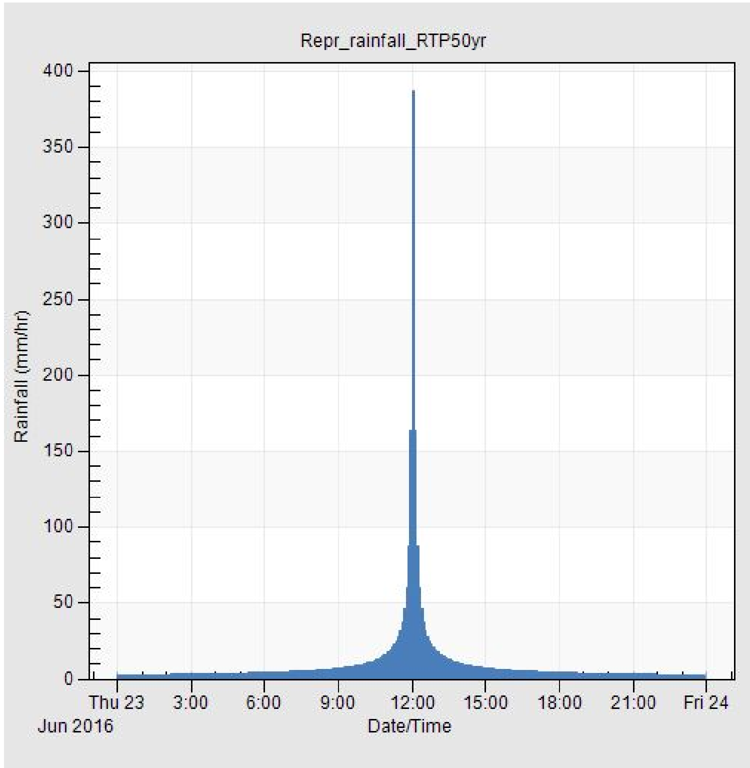



Figure H.8: Example of a rainfall intensity distribution

### H.4.3 Elevated water levels and tidal movement

As stated before, PCSWMM is also able to model the performance of a network with an (elevated) water level at the outfalls. Multiple choices can be made, the one which is preferred is a fixed stage. Although this is not entirely realistic because of the tidal movement, it makes comparing the easiest. The runoff time of a design storm is not larger than about 2 hours, which allows the use of a fixed level. Unfortunately this induced errors, because the invert elevation of many manholes is below the water level which was applied. In reality there would be an inflow, but PCSWMM could not model this. A common solution is to select all manholes with a low invert elevation and apply an initial depth, but this didnt work either. In the end a time series was used in which the water level was built up gradually, which appeared to work.

### H.4.4 Blockage in the system caused by waste

As explained in section 5 waste in the stormwater network is considered to be a large problem. The estimation has been made that 25% of the manholes of the smaller network is blocked by waste in the CBD area (more background information in Appendix B.5). Unfortunately there is no possibility in PCSWMM to model this, so a workaround was made for getting insight in the consequences for floods due to this problem. In PCSWMM all conduits with a diameter of 0.3 m or smaller were exported from the model to an Excel file. These are the smaller pipes, as the larger pipes are improbable to block because of their size. An amount 25% of the selected conduits was blocked by reducing the diameter to 10% of its original value. The conduits which were getting blocked were randomly determined, and imported back into to the model as a replacement. Unfortunately there was no time left to deepen out this problem further, therefore this rather blunt approach was used.

An impression of the blocked conduits in the southeast of the CBD is given in Figure H.9. When looking carefully it is visible that only the smaller branches are blocked.

Figure H.9: Blocked conduits (blue colour)

## H.5 Problems with the large comprehensive model

With all the input data, boundary conditions and a comprehensive model in place everything should be ready to run multiple scenarios of the model. However, as explained in section 12 this was unfortunately not the case. The following problems in the modelling occurred:

- Some conduits were generating errors. This was mainly the case for conduits in low-lying areas, like the CBD. This could be caused by the very small slopes of some of the pipes and culverts in the network. This could generate errors, however the model should in principle be able to handle it. The following changes have been tried in order to repair these errors:
  - The time step was lowered to a very low value, but this did not make a real difference.
  - The model was checked for conduits with a slope of 0. This will cause instabilities, because the flow in a conduit is partly determined by its slope. However, the errors were still remaining after forcing a slope at all of the conduits.
  - The conduits of the model were all set to have a minimum length of 5 m. Too small conduits together with a too large time step could cause problems, because the water could then travel faster through the network than that the information is updated. However, this did not help either.
  - Employees of the CSCM department and the PCSWMM support team also looked into the model, however no one was able to find the cause of the error. All in all the most probable cause of the errors is the complexity of the model. A lot of small conduits and branches were present in the model. Because of the large size of the model, it was impossible to inspect the whole network manually. Unfortunately the automated functions to search for error causes did not help out either.
- The time needed to use and run the model was very large. Opening the model took about 15 minutes, the program responded very slow and the time needed to run the model was about 10 hours. This made it very time intensive to adaptation and check the model. To check the effect of an adaption of the model at least a night of waiting time was needed.

- The Umgeni river channel modelled in the area caused large instabilities, also for small discharges. The idea was to apply initial discharges at the two points where the river entered the model, however this caused as well problems. Due to the limited amount of time there was no possibility to have a deeper look into this problem.

- It was impossible to model an elevated water level at the outfalls. This is necessary for modelling the effect of a high water level at sea on the model. This problem could be caused as well by the instabilities, however there could also be another unknown cause for this problem.

Despite the problems a flood map was generated for a 50 year return period storm without elevated water levels at the outfalls. This map can be found in appendix I.The model was checked with Geoff Tooley, and despite the problems it seemed to be fairly realistic. The floods in the low-lying part of the CBD were expected to be larger for a 50 year return period design storm. Explanation about this flood map can be found in section 12.

#### H.5.1 Alternative for the large comprehensive model

An alternative had to be found in short term to research the influence of high sea water levels on the performance of the stormwater system. Therefore the network of the CBD and a part of the central beachfront was taken out of the large model, simplified and again expanded with the 2D layers. The stormwater network of this area is isolated because it is enclosed by the railway, harbour and sea, which are easy to model as boundary conditions. The 1D part of this model can be seen in Figure H.10. The approach for setting up the model was similar as for the large comprehensive model, except for the simplifications. The simplification was done by merging conduits of the same size in the network. This leads to a reduction of the amount of manholes in the model, however less entities also generally means a more stable network. The instabilities fortunately disappeared and this model could be used for researching the influence of the boundary conditions on this smaller part of the area of interest. There were some challenges in applying different water levels and rainfall events, however this eventually worked. The results of the runs with this model can be found in Section 12 and Appendix K.

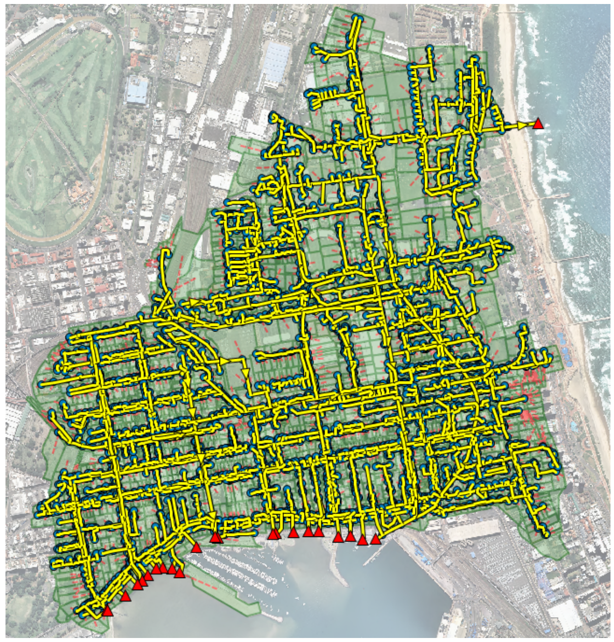


Figure H.10: 1D part of the CBD model

## H.6 Recommendations on modelling comparable cases with PCSWMM

The following recommendations are relevant when using PCSWMM for modelling at the area of interest in Durban or for comparable cases:

- Acquire information about underground spaces and the exact elevation of ground floors of buildings. This will give more insight in whether buildings get flooded, and if this is the case, the flood depths will be smaller than currently estimated by the model. When floods reach a level of more than 5-10 cm, depending in the location and type of buildings, water will start flowing into the buildings. The buildings then act as an unwanted storage and reduce the flood depth, which is not taken account for in the model. There is a possibility to used storages, but then it will be necessary to research a flood sensitive area very detailed.

- When flood sensitive areas are located, use a more detailed mesh to get more insight in the exact flowing patterns. It is not advised to use a large comprehensive model from the beginning, because of the slowness of such a model and the difficulty in finding possible errors.

- Roads normally are constructed in such a way that the middle of the road is the highest point. The sides are lower, and the pedestrian area or berm is often higher than the sides, but often lower than the middle. The model samples the elevation of the center of the cells, which could be any of these height. This results in differences between the elevations of neighbouring cells, whilst thats not per se necessary. The pattern of cells is therefore a bit bumpy, which does not represent the actual situation. An example of the sampling of the elevation can be seen in figure H.11. There are options in the program to tilt the cells, which could partly solve this, mainly with a very small cell size and wide streets.

- It is important for the department to know precisely if there is a dual network at some places. The presence or absence of a dual network makes a lot of difference regarding discharging capacity, and thus potential flooding.

- A factor which is not taken into account is the effect of breaking waves at coastal outlets. Large mass transport can occur at breaking waves, which could cause even an inflow of sea water in the network because of this effect. The interaction is probably relatively difficult, however this effect should be kept in mind when analyzing or designing a stormwater network.

- It is hard to calibrate such a model, which is partly caused by the fact that the CBD has not flooded severely recently. It is advised to create detailed reports about flood depths in case of flooding. This will help a lot in calibration models which are already existing or yet to be built.

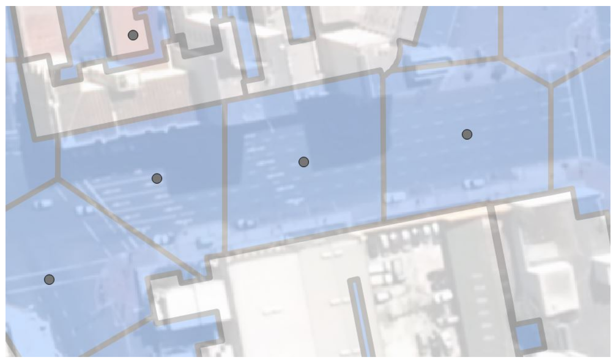
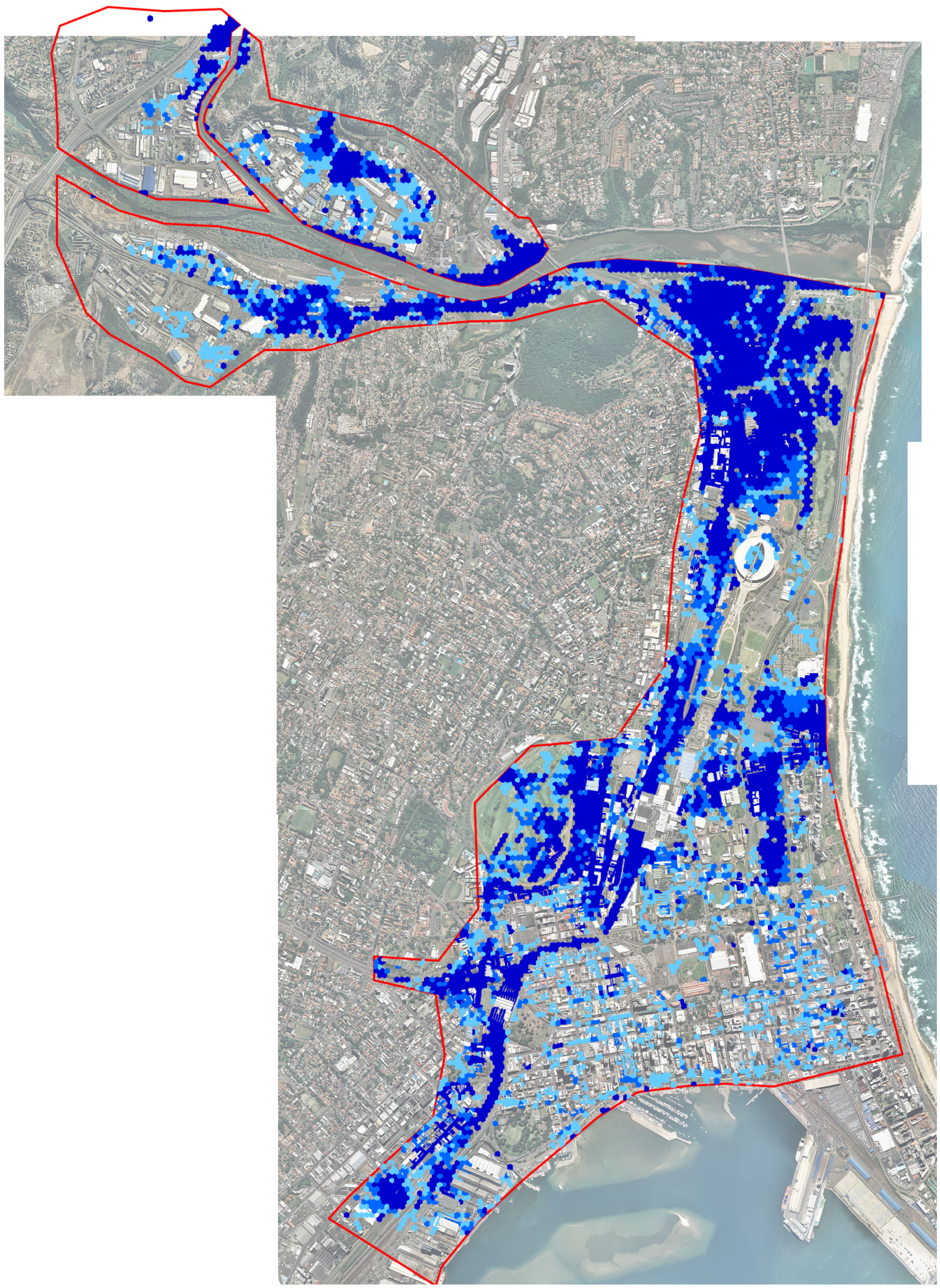


Figure H.11: Cells with the location at where the elevation is taken from (grey dots)

Another factor which should be kept in mind is a shortcoming of PCSWMM regarding modelling floods. As explained in section 7 the model is a combined 1D-2D model. In short, all runoff of the rain which does not infiltrate is directed to the stormwater network. When this network cannot cope anymore, manholes will overflow and subsequently overland flow will occur. In reality rain could already cause small floods and overland flow before entering the stormwater network. This is mainly the case at sloping areas. The overland flow generated by the model will be underestimated at places at which the network suffices, and overestimated at places where the network is insufficient. This is caused by the phenomenon that at these places more water is present in the network in PCSWMM than in reality, because of the overland flow at upstream locations. This unwanted effect could maybe be resolved when calibrating the model further.

# Appendix I PCSWMM Flood map

This map is the flood map of the compehensive large model. Small floods of 2-10 cm depth are visualized in light blue, medium floods of 10-25 cm in medium blue and larger floods of minimal 25 cm in dark blue.



# Appendix J Theory of communicating barrels

To be able to say something about which areas will be affected when applying an increased water level a different, more qualitative, approach is used. From the results of the 50 year return rainfall scenario one can already identify the areas that are prone to flooding even without blocking of the outfalls. More prone areas can be identified when the height of the urban drainage network is taken into account. Earlier in Table 11.1 the height of the outfalls were already mentioned to show that the drainage system could possibly get blocked. But if one wants to investigate blockage further, besides the height of the outfalls, also the height of the connected urban drainage system is considered to be of importance. This is because the urban drainage system, and therefore water in the system, most likely is positioned higher than the outfalls w.r.t. mean sea level. Water in the system with an higher elevation than the water level at sea is considered to create a pressure near the outfall pushing water into the sea despite the fact that the water level at sea might have reached the top of the outfall. In other words: as long as there is water in the urban drainage system with an elevation higher than the sea level, rain water is likely to be discharged onto the sea. One can think of this phenomenon as two barrels which communicate with each other and eventually will find equilibrium when the water levels are the same. This is illustrated in Figure J.1 below:

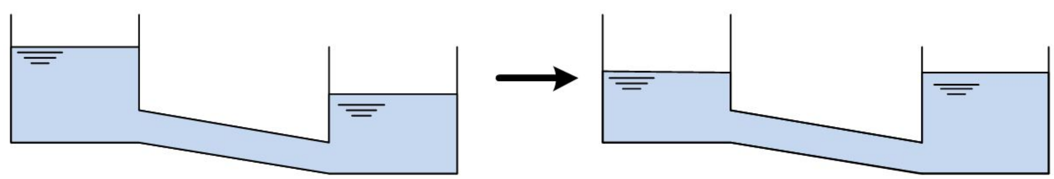


Figure J.1: Illustration on communicating barrels

It should be noted that for this specific situation the water levels in reality might differ slightly between the barrels for a state of equilibrium. This is because the density of the rain water in the drainage system is expected to be lower than the mixture of rain and sea water on the sea side. Moreover waves breaking directly on the coastal outlets might cause an additional pressure force from the sea side.

Due to the before mentioned fact that water is likely to be discharged onto the sea when the elevation in the urban drainage system is higher than the sea level it is interesting to see what the elevations of the drainage network are. The idea behind this is that, following the just described line of reasoning, real blockage will occur for that part of the system where the water level has the same elevation as a certain water level at sea. More insight into vulnerable areas in the system can be gained by plotting different colour at low-lying manholes.

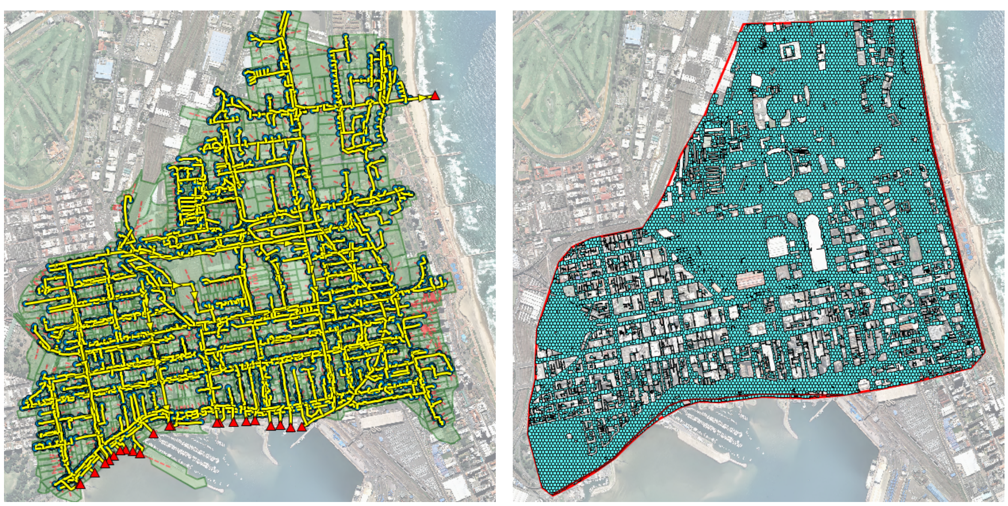
# Appendix K PCSWMM CBD Modelling

## K.1 Approach

In order to model floods and the influence of elevated water levels at sea, an alternative had to be found for the large comprehensive model. Therefore the choice was made to set up a separate model for the low lying CBD area. The stormwater network of the CBD area was taken out of the large model and simplifications were done by merging conduits in the network which have the same diameter and approximately the same slope. These steps reduced the amount of entities in the model, for example the amount of conduits is 5,000 instead of 20,000 in the large comprehensie model. which has the following advantages:

- The model becomes more responsive which saves time
- Instabilities are less likely to occur
- The time required for running the model becomes smaller

Too drastic simplification might result in an unrealistic model. However, modelling the actual network in PCSWMM is often far more detailed than necessary for modelling the performance of the main stormwater network and flood patterns. In figure K.1 the 1D model and 2D are shown which were used.



(a) 1D network model

(b) 2D cells (blue) and bounding layer (red outline)

Figure K.1: PCSWMM CBD model

## K.2 Modelling

In order to gain more insight in the effect of elevated water levels at the outfalls multiple scenarios have been used with different rainfall events and both with and without waste. The rainfall events which are used have a return period of 20, 50 and 100 year. The water levels which are used are as following:

- Mean sea level (0 m)

- A water level of 0.9 m which is about comparable as the maximum water level during spring tide
- A high water level of 1.3 m above MSL
- An extreme water level of 1.6 m above MSL
- An extreme water level including 100 years of sea level rise, which ads 27 cm, leading to a total level of 1.87 m abov MSL

There is a bug in PCSWMM which prevents changes in the model to be used in the actual runs. The only way to change this is opening the main PCSWMM input file in a text processor and remove or adapt all references to the old input settings. This had to be done for the rainfall events and different sizes of the conduits, which was used for modelling waste. The fixed stage elevation which is meant to be used for modelling a elevated water level at outfalls still did not work. A workaround was used by using a timeseries at which the water level was gradually built up to the design water level. This resulted in the right water level in the network at the moment that the rainfall peak occured.

## K.3 Results

### K.3.1 Floods

After running the scenarios a check has been done how large the area is within the model which were flooded at least 5 cm. The floods in these areas are summed. The results of these checks for the different runs can be found in Table K.1. The rainfall event with a 2 year return period rainfall event and without elevated water levels at the outfalls was used a base case. Due to small errors in the model there are multiple places where the water piles up, but this is not necessary the case or not considered as a problem. Therefore these flood are not of large relevance. The most relevant parameter when comparing scenarios is the relative flooding compared to this basecase. The results give some insight in the sensitivity of the system to the different input conditions. The next step would be more runs, calibration and validation of these results is very important, however this was not possible anymore considering the limited amount of time left. Only preliminary conclusions can be drawn from these results.

A floodmap is shown as well in Figure K.2. Small floods smaller than 10 cm are visualized in light blue, medium floods between 10 and 25 cm in medium blue and more severe floods of at least 25 cm in dark blue. Differences between the floodmaps are present, however they did not appear to be large. The more severe the scenario, the larger and more outspread the floods became. Only one map is shown because the differences between the scenarios appeared to be relatively small. It is hard to estimate from this preliminary research whether this is realistic, which as well stresses the importance of good calibration and validation.

Table K.1: Add caption

| Water level at sea (m) | Water level at harbour (m) | Return per. rainfall event (yr) | Blocking due to waste | Flood area (ha) | Flood area (ha) rel. to basecase | Flood amount (m3) | Flood amount rel. to basecase (m3) |
|---|---|---|---|---|---|---|---|
| 2 | 1.6 | 100 | yes | 22.4 | 16.2 | 24245 | 13264 |
| 2 | 1.6 | 100 | no | 21.8 | 15.6 | 23839 | 12858 |
| 2.27 | 1.87 | 50 | yes | 19.7 | 13.5 | 23791 | 12810 |
| 2 | 1.6 | 50 | yes | 18.8 | 12.6 | 23435 | 12454 |
| 1.5 | 1.3 | 50 | yes | 18.2 | 12.0 | 23145 | 12164 |
| 2 | 1.6 | 50 | no | 18.0 | 11.8 | 22837 | 11856 |
| 1 | 0.9 | 50 | yes | 17.9 | 11.7 | 23005 | 12024 |
| 0 | 0 | 50 | yes | 17.7 | 11.5 | 18908 | 7927 |
| 0 | 0 | 50 | no | 16.7 | 10.5 | 18404 | 7423 |
| 0 | 0 | 20 | yes | 13.6 | 7.4 | 17105 | 6124 |
| 0 | 0 | 20 | no | 12.5 | 6.3 | 16417 | 5436 |
| 0 | 0 | 2 | yes | 6.2 | | 10981 | |

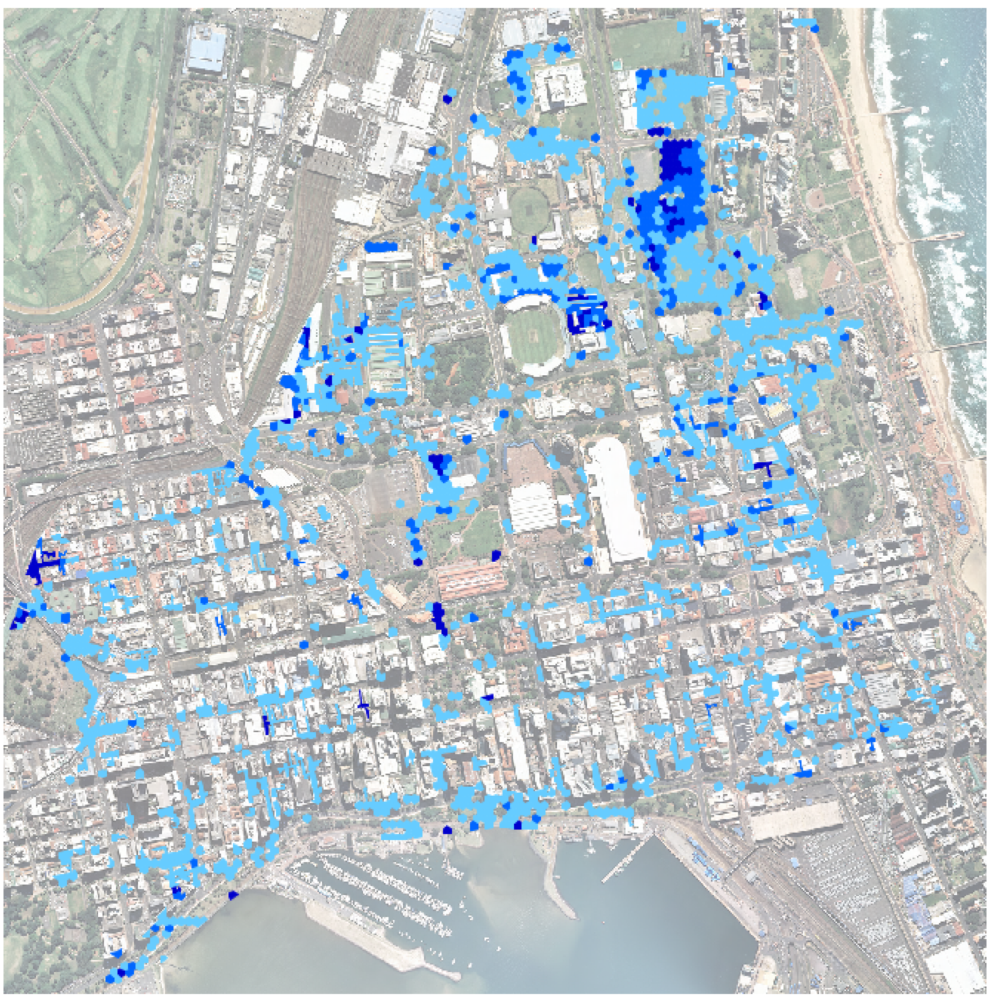
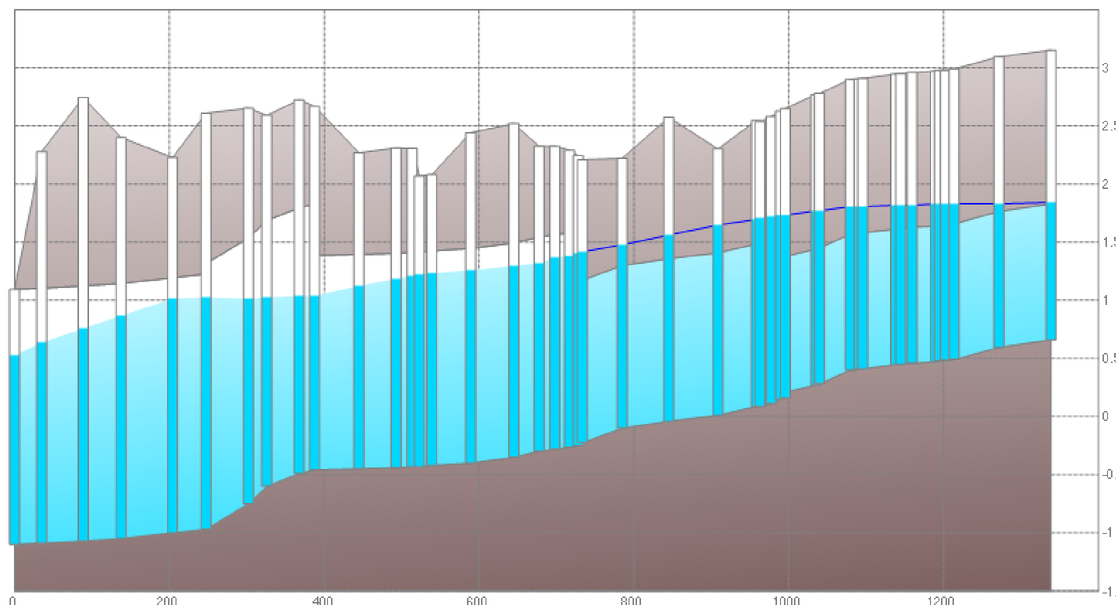


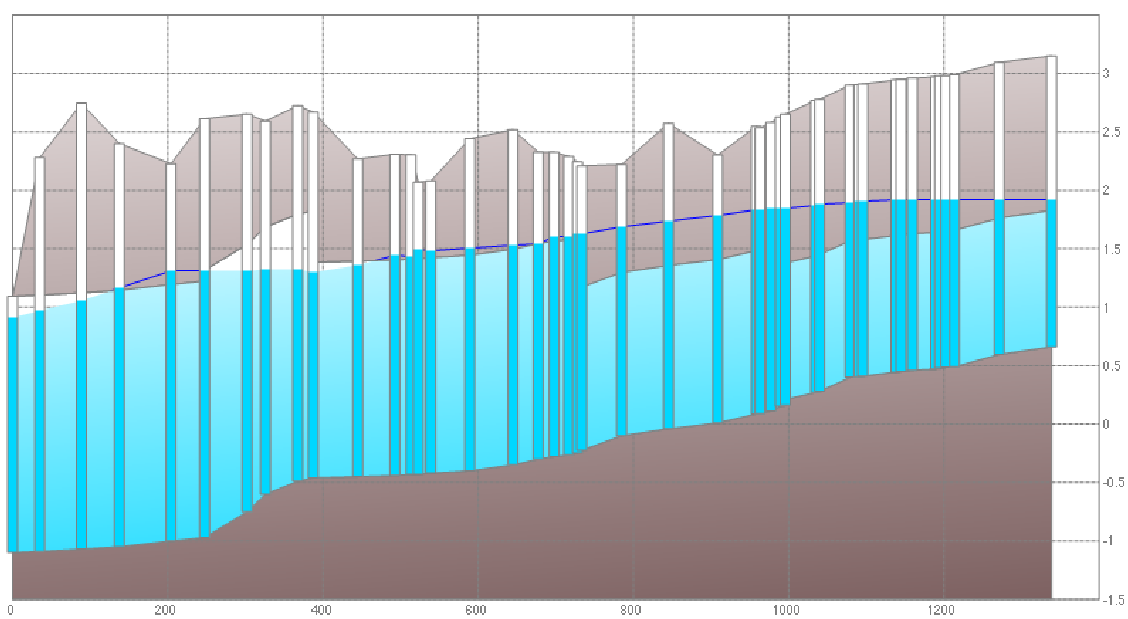
Figure K.2: Flood map for 50 year ret. period storm and high water level at harbour (1.6 m above MSL)

### K.3.2 Milne's drain

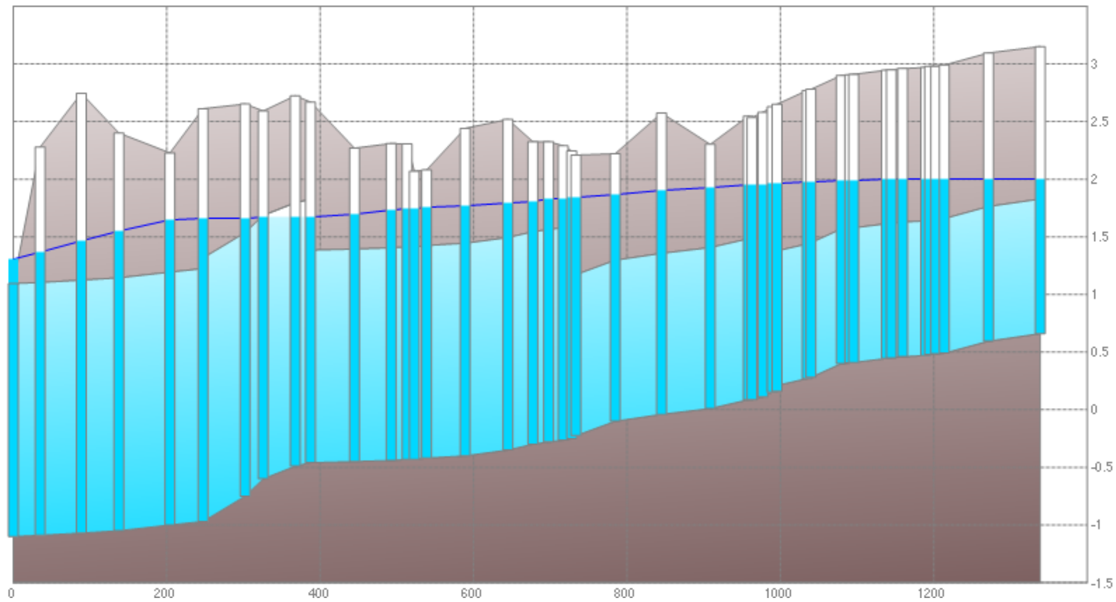
The cross sections of the Milnes drain are visualized for a 50 year return period rainfall event together with water levels at the outfalls of MSL, 0.9 m, 1.3 m and 1.6 m. Figure K.4 shows drain during no rainfall event and MSL as a reference.



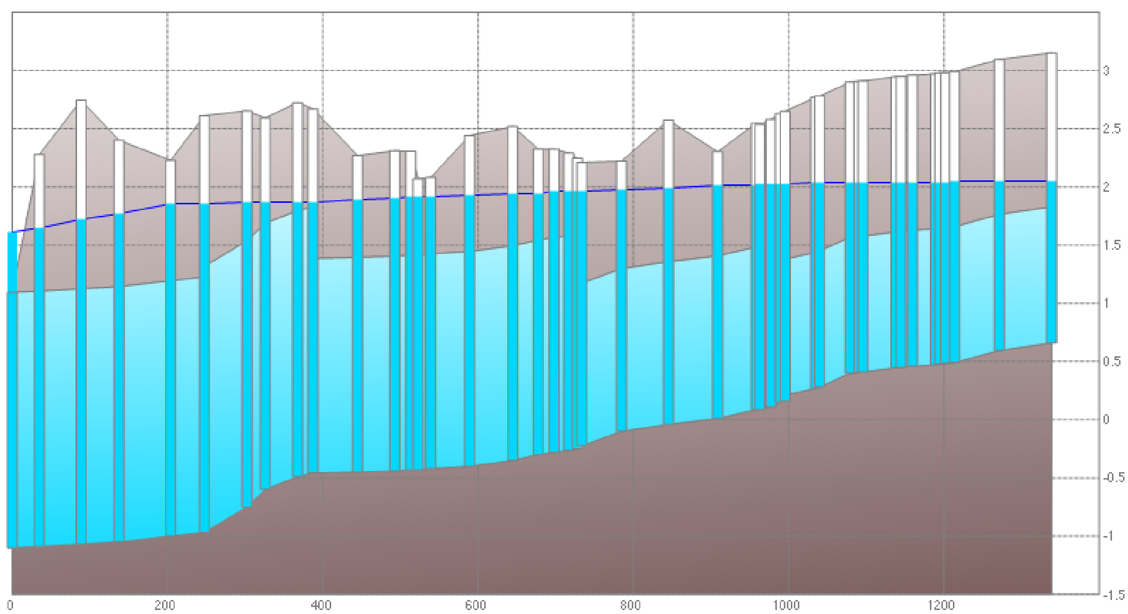

(a) Mean sea level at outfall




(b) Water level at outfall 0.9 m above MSL




(c) Water level at outfall 1.3 m above MSL




(d) Water level at outfall 1.6 m above MS

Figure K.3: Peak flow in Milne's drain during a 50 year return period rainfall event

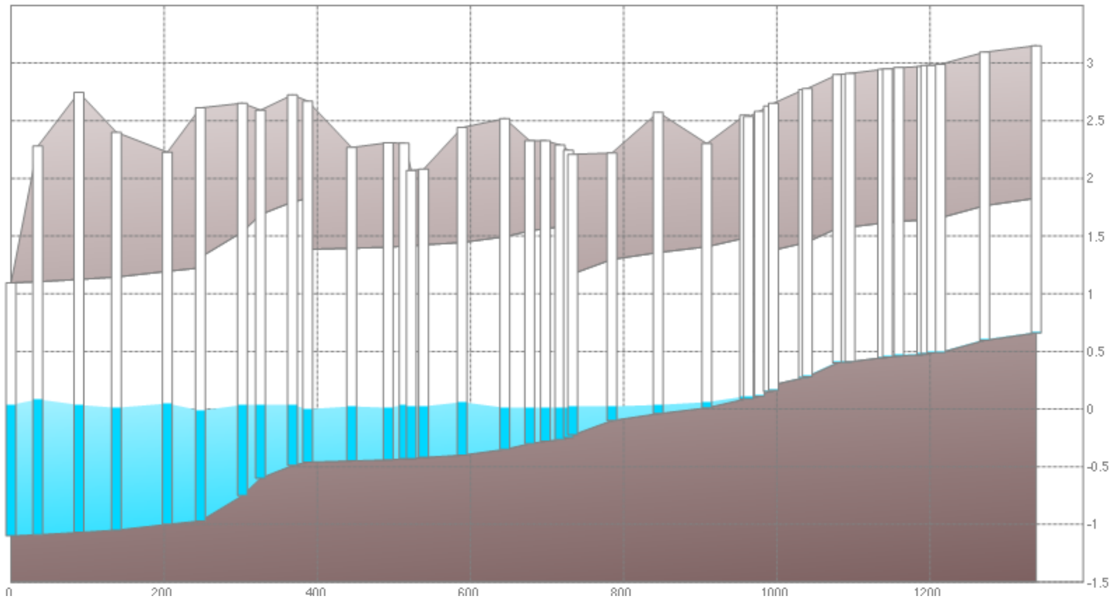



Figure K.4: Milne's drain without rainfall at MSL

# Appendix L Insurance

This chapter will dive into the different insurance organisations in South Africa. Due to the certainty that insurance companies can give property owners it is important to take this into account by examining the critical parts in the city.

Damage losses for floods have a direct or an indirect impact on insurance impositions and payouts. Floods are a major natural disaster which can cause a lot of troubles. Therefore people can insure themselves against floods for example. In every country these insurance companies are different organised. Because insurance companies can play a positive role during floods by reducing the damage losses a research is done about the insurance companies in South Africa.

**South African insurance structure**

In South Africa a lot of rainfall is seen in spring and summer seasons which cause a lot of floods. Flood insurances are in this report seen as an insurance that protects property owners from the damage losses to their properties as a result of floods or high water. Besides flood insurances there are re-insurances that reduce the risks for the insurance companies. By this method, the insurance companies buy an insurance to insure themselves against high costs and losses [32]. Re-insurance companies have avoided accepting a heavy concentration of liability on one area.

Insurance companies measure the amount of damage by mapping direct and indirect effects of floods, the amount and type of goods affected by floods and the extent of affected goods. The SAIA (South African Insurance Association) does not has specific guidelines for covering the losses caused by flood damage. The SAIA is the umbrella of the South African insurance industry. It represents almost all of the short-term insurance companies in South Africa.

When South African insurance companies determine what the extent is of the losses affected by floods they take the next aspects into account:

- Depth of water
- Water velocity
- Transportation of debris
- Speed of rise
- Inundation periods

The last years, the government helps the people that can not afford the flood insurances because private insurance companies only compensate insurance policy holders. Besides the governmental insurances there are private insurance companies for additional support during floods but these are mostly for the middle and higher income classes. For this reason low income classes are left with inadequate government intervention after floods[32].

Middle and higher income classes that are not dependent of the government can choose what kind of insurance they want to have, within the flood insurance there are different sub-insurances. This is done to meet the requirements of all different residents in South Africa and varies in costs. The different flood insurances that people in South Africa can choose are:

**Building property coverage** This includes the insured building, electrical and plumbing systems, furnaces, water heaters, centralized air conditioning system, cooking stoves, refrigerators, built-in appliances, window blinds and debris removal.

**Personal property coverage** This includes the loss of personal belongings, curtains, air conditioners, washing machines and dryers, portable microwave ovens and dishwasher, food freezers, and carpets.

**Price distribution for flood insurance policyholders** This insurance is based on the type of construction, size and location of the building. The insured value of the property is the rate per rand of insured value.

**Determinable probability distribution of flood insurance** The determinable probability distribution for losses within a reasonable degree of accuracy.

**Flood insurance on property** Only those property owners, who are aware of being exposed to floods frequently, and with severe consequences, may consider purchasing insurance.

**Government subsidising flood insurance premiums premiums** People who develop property in flood plain areas do not pay the full costs associated with the development. The insurance is only available to residents who have taken appropriate safety precautions that will help to reduce the expected loss.

Most of the people in the centre of eThekwini municipality have a house insurance that includes a flood insurance. The inhabitants in the rural area of eThekwini municipality are not insured. Most of the time they are living in flood plains, because they do not have a lot of money and these areas are very cheap to live in. They are nevertheless exposed to a risk, because the flood plains often flood which means that their houses are likely to be affected by floods. As told in section 6.2.2 the Umgeni river could flood its banks and cause severe damage. This situation might even get worse if high water levels in the river occur simultaneously with high water levels at sea. The problem at this moment is that poor people consciously move to areas where often floods occur. They have to pay less money to build their house at flood sensitive places. When floods occur, their house floods and at that moment they are not able to pay for insurance. The aim of the Municipal Disaster Management Centre (MDMC) is to help people who are affected by a disaster and need assistance. When floods occur in these areas the MDMC has to help them, in this way they even do not need an insurance. They will not help them financially but they help them with shelter. The Municipal Disaster Management Centre (MDMC) helps those people who are not able to recover after a disaster happened, in this report a flood disaster. They mainly help people that cannot help themselves. The MDMC do not buy stuff but they assist them temporarily and are more focused on the residents. (See appendix B.6)

The information that is used in Table L.1 is received from Talia Feigenbaum (see appendix B.3. These costs show the amount on miscellaneous services that is seen as the costs for insurances. If the total costs are divided by the amount of households the obtained average costs per household for miscellaneous services was 9,680 ZAR in 2010 , 9,906 ZAR in 2011, 10,502 ZAR in 2012 and 10,876 ZAR in 2013 (Table L.1). This is for a lot of people too much. For this reason they prefer not paying for an insurance and hope that their house will never flood.

Table L.1: Costs per household for miscellaneous services in Million ZAR

| Year | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|
| Miscellaneous services [million Rand] | 9,434 | 9,866 | 10,563 | 11,047 |
| Population | 3,608,763 | 3,665,407 | 3,702,890 | 3,740,479 |
| Households | 974,504 | 995,929 | 1,005,795 | 1,015,690 |

# Appendix M Risk register

## M.1 Risk Management

Risk management can only be done if you are aware of the risks [40]. For this reason a risk identification is done by making a risk register. After the risk register is made the risks are divided into capital, economic and social risks (see Appendix M.2.1). These risks have different consequences which are necessary to determine what area is most valuable for the eThekwini municipality if floods occur. This is done by taken all the risks and consequences into consideration. In practice these risks cannot be divided in such a way because damage can lead to no office accessibility(economic value) but also to costs to repair the situation(capital value). For this reason risks can be taken into account twice, as well for the capital costs as for the economic costs. Risk events can lead to different consequences, in this risk register the most common consequence of a risk is described otherwise the situation will become too complex.

## M.2 Risk Register

This risk register is made for identifying the risks, this is necessary to manage these risks because they can cause serious delay for the project. At this stage it is necessary to examine what kind of consequences occur when floods occur. In this way the need for a solution is more clear. In this appendix all potential impacts of the floods are taken into account, as well for the natural as for the man-made environments. Risks can be positive or negative, both of them are shown in the risk register. By analysing reports of floods in the past of the eThekwini municipality some risks are identified. Several parts of the eThekwini municipality flood very often but is not part of the research area of this report. For this reason some incidents and damages that occurred in previous floods are not taken into account. This report focus on the stakeholder and residence rich areas. By making the risk register the following sentence is used: As a result of definite cause, uncertain event may occur, which would lead to effect on objective(s).

Table M.1: Risk Register

| Nr. | Category | Cause | Risk event | Consequence |
|---|---|---|---|---|
| 1 | Capital risk | Floods | Basement floods | Broken pipes and energy regulator |
| 2 | Capital risk | Floods | Electricity area floods | No electricity |
| 3 | Capital risk | Floods | People that cannot leave their house | People in danger situations |
| 4 | Capital risk | Floods | Holes in roads | Traffic accidents |
| 5 | Capital risk | Floods | Damage to buildings | A lot of loss in money |
| 6 | Econcomic risk | Floods | Floods in train station | Trains will not drive |
| 7 | Econcomic risk | Sewerage constipation | Roads floods | Roads not available for traffic and passengers |
| 8 | Economic risk | Floods | No tourism in eThekwini municipality | loss of money |
| 9 | Social/capital risk | Floods | Floods in hospitals | No medical care possible |
| 10 | Social/capital risk | Floods | Home damage | Homeless people |
| 11 | Social/capital risk | Floods | Office damage | Workless people |
| 12 | Social risk | Floods | Closed shops | No primary goods available |
| 13 | Social risk | Floods | Closed hotels | loss of money of hotels |
| 14 | Social risk | Floods | Floods in libraries and museums | Damage to art and cultural pieces |
| 15 | Social risk | Floods | Closed grocery stores | No food |
| 16 | Social risk | Floods | People drown or die | Damage claim |
| 17 | Social risk | Floods | Not usable sport fields | Cancelled sport activities |
| 18 | Social risk | Floods | Delay of emergency authorities at a certain place | Too late at their destination, fatalities |
| 19 | Social risk | Floods | Floating cars | Damage |
| 20 | Legal risk | Floods | People have to leave their home | Pillage, more crime |
| 21 | Environmental risk | Floods | Bad water quality by fuel | People and animals can get poissoned |
| 22 | Environmental risk | Floods | Ocean and city becomes one | A lot of waste in the ocean and the city |
| 23 | Environmental risk | Floods | Trees falling down | landslips, damage to buildings, road blocks |
| 24 | Black Swan | Floods | Lots of damage | Insurance companies go bankrupted by too much claims |
| 25 | Black Swan | Floods | Buildings falling down | People die |
| 26 | Black Swan | Floods | No money available for recovery of the city | The city becomes a poor ghost city |
| 27 | Black Swan | Floods | Erosion | landslip, roads will be damaged |
| 28 | Positive risk | Floods | Infrastructure damage | New and better infrastructure |
| 29 | Positive risk | Floods | A lot of fresh water near the coast | This can be stored and transfer into drinking water |

### M.2.1 Capital impact

Capital costs are in this report seen as the one-time amount of damage costs in the city. The risks that are shown in M.2 have a more underlying consequence which is very important for this project.

Table M.2: Capital risks that lead to capital costs

| **Risk event** | **Consequence** |
|---|---|
| Damage to buildings | Capital cost damage |
| Floods in libraries and museums | Damage to art and cultural pieces |
| Basement floods | Broken pipes and energy regulator |
| Floods in hospitals | Loss of important and expensive equipment |
| Home damage | Damage to personal belongings |
| Office damage | Damage to equipments |

### M.2.2 Economic impact

Economic costs are the costs that are of economic value. If an office can not run for one day the costs will not immediately be seen but it is expressed in economic value. Also travel time can be of economic value. The longer it takes to transport freight, the more this will cost. Also for travellers travel time has an economic value, which can be calculated using a value of time. The economic impact is an important result of flooded roads.

Table M.3: Economic risks that lead to economic costs

| **Risk event** | **Consequence** |
|---|---|
| Roads floods | Road not available for traffic and passengers |
| Electricity area floods | No electricity, buildings that not fully function |
| People that cannot leave their house | People cannot go to work |
| No tourism in eThekwini municipality | Loss of money for the economic growth of the city |
| Floods in trainstations | Trains will not drive |

### M.2.3 Social impact

Social risks are the risks that are important for the well-being of a human, the risks with a social effect on the environment.

Table M.4: Social risks

| Risk event | Consequence |
|---|---|
| A lot of claims | Insurance companies go bankrupt by too much claims |
| Electricity area floods | No electricity, more crime |
| People that cannot leave their house | People in dangerous situations |
| Floods in libraries and museums | Social damage to art and cultural pieces |
| People drown or die | Damage claim |
| Home damage | Homeless people |
| Office damage | Workless people |
| Not usable sport fields | Cancelled sport activities |
| Delay of emergency authorities at a certain place | Too late at their destination, fatalities |
| Floating cars | Damage |
| People have to leave their home | Pillage, more crime |
| Closed shops | No income |
| Closed hotels | Loss of income for property owner |

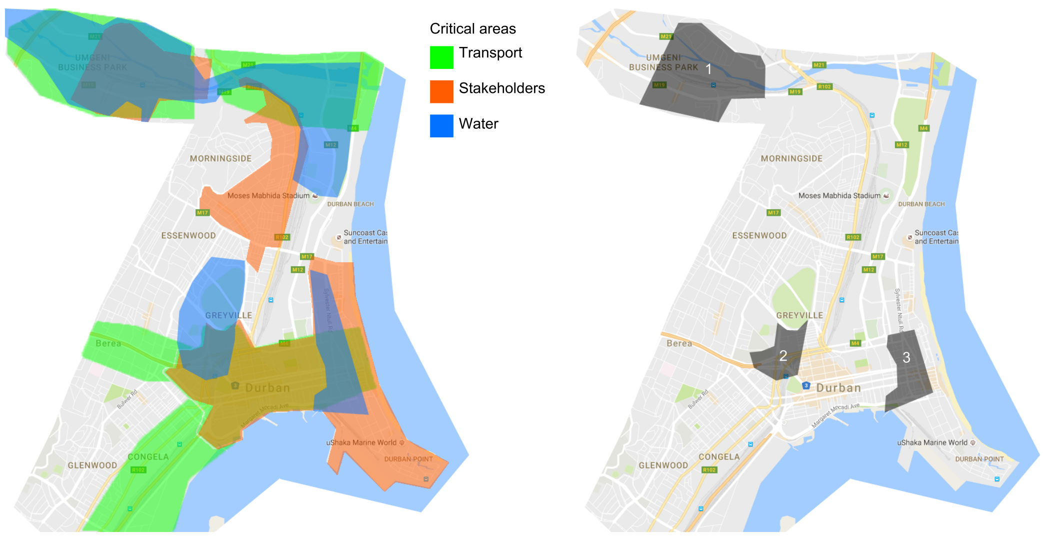
### M.2.4 Additional figures


Figure M.1: Museums and libraries in eThekwini municipality


Figure M.2: Parking garages in eThekwini municipality

# Appendix N Short-cut

This section is made because of delay in the PCSWMM model. Results of PCSWMM were obtained later in the process than expected and therefore as a pre-analysis this short-cut was made and used, for as far as possible, in Chapter 13. The focus of this section is on the analysis of flood prone areas based on the knowledge at the municipality. The current knowledge of the municipality is used to create a map of the probable flood prone areas. This map is combined with the map of the stakeholder rich areas (Figure 8.1b) ad the map of the important transport areas (Figure 9.1). This results in the figure given below (Figure N.1a), where the transport map is given in green, the stakeholder map is given in orange and the flood map is given in blue.




(a) Rough map of combined critical areas

(b) Focus areas of the short-cut

Figure N.1: Combination three maps

There are three places where the maps of the three critical areas overlap and can be found in Figure N.1b. These are the Umgeni Business park (area 1), the CBD/Greyville (area 2) and CBD/South Beach (area 3). The impact of floods on the stakeholders and the transportation system in these areas is discussed in more detail below. By making the short-cut the problem for the less amount of residences in area was not yet found. For this reason the residential numbers are not the same as in the main report. Because the numbers of the residences were not correct at this moment, the percentages were wrong as well.

### Area 1: Umgeni Business park

For area 1 it is already determined what kind of stakeholders are located in this area and the biggest stakeholder group that will be affected by floods, the market value of this area is also shown in Chapter 8.1. In this area 65% of the market value consists of industrial and 32% of Business and commercial. In total it means that 96% of the amount of market value consist of business (the amounts are shown in Table N.1. All the businesses of this area are located in the flat part of the district near the rivers, this means that when floods occur this whole area will be affected. This chance is very likely because the floods in July 2016 were caused by rainfall in combination with the high sea level at that moment, see Appendix B.6. The government thinks that if people are financially able to start their own business they are also financially able to take an insurance for their business. For this reason the assumption is made that most of the people that are located in this area have an insurance. There are several flood insurances that can be chosen, it could be that the local businesses choose the cheapest flood insurance and the larger business the more expensive and extensive insurances. According to the MDMC (see Appendix B.6), it is not possible to know how many people are insured in a certain area. The only thing that could be known is the amount of money that a household per year pays for an insurance. But there are people who do not pay an insurance and people who do pay a high amount to insure them. Besides this it is likely that not every household is included in this amount of insurances.

Table N.1: Market value in area 1

| Area 1 | Vacant land | Industrial | Business and Commercial | PSI | Residential |
|---|---|---|---|---|---|
| Amount | 11 | 135 | 41 | 24 | 0 |
| Market value [million ZAR] | 35.825 | 1,125.391 | 552.66 | 3.698 | 0.0 |

Because of the industrial focused area less people live in this area. This means that there are fewer people that have to be able to enter and leave the house several times a day. But there are a lot of companies that have to run five days a week. The economic consequences on this area are high, it is not possible to determine the exact amount of economic cost damage that occur from floods. Most of the floods do not occur for longer than a couple of days. This means that the maximum economic loss will be the economic loss of more or less three days. It can also be that floods occur for a couple of hours and if they are lucky the floods will be during working hours which means that employees can drive to their work and back. Most of the time businesses are insured by private insurance companies which means that the capital costs will be covered mostly by insurance companies. According to SAPOA it is not possible to hunt down the amount of buildings that are insured in a certain area in the city. The organisation does not have a map with stakeholders or property owners in the researched area in this report. For this reason an assumption can only be made by the effects of floods in a certain area. Besides this, a train station is located in this area and the M19 runs through this area. The train tracks are located lower than the roads, the train track is thus the first infrastructure that is affected by floods. Depending on where exactly the floods are, the effect on the infrastructure will be mere or less severe. If the floods occur around the crossing of the M19 and the R102, then the connection between Durban and the north is blocked. This means that the train experiences lots of problems. But in case only the train station Springfield Flats is blocked, the consequences are smaller; the Umgeni Business Park is the only impacted area. The train is used by a very small amount of people, the impact is thus limited in comparison with floods on roads. Therefore it is more important to look into roads. Presumably the M19 and the M21 are most prone to floods. If one of the roads is blocked, it is a good idea to redirect the traffic to the other road. The consequence of a detour is that more traffic has to use one road. Table N.2 shows the capacity and the amount of traffic on one road in case of a detour. As can be seen, a detour from the M19 east to the M21 east results in too much traffic on the detour route M21 east, resulting in congestion. In west direction the impact is less severe, and the capacity is not exceeded. The detour the other way around, the exact same amount of traffic is directed to use the detour.

Table N.2: Capacity, normal intensity and detour intensity in case of blockage of the M19 [22]

| | Capacity | Normal intensity | Detour intensity |
|---|---|---|---|
| M19 west | 4800 | 2654 | 0 |
| M19 east | 4800 | 2938 | 0 |
| M21 west | 4800 | 1055 | 3709 |
| M21 east | 4800 | 1974 | 4912 |

Since the M19 and M21 both are located at almost the same distance from the Umgeni river, there is also a change that both roads are flooded, resulting in even more detours that have to be made. In this case, all traffic has to be redirected to the M45 which is located north of the focus area, and to the M17 which lies between Morningside and Essenwood.

**Area 2: CBD/Greyville**

This area is area 3 and a part of area 4 of the stakeholder map that is shown in Figure 8.1a.

In this part of the area there is a high variety of stakeholders. The market values of the buildings, roads and vacant land that are located in area 2 are combined and shown in table N.3. Besides the residents and businesses, also Durban University of Technology, three hospitals, a railway station, entrances to large highways, supermarkets and a bank are located in this area. This means that it will not only affect the people that are living or working in this area but also the students that visit the school and people that need medical care. A lot of business and commercial companies are located in this area who are most of the time insured. The people that live there are middle income class residents who mainly are insured for floods. Public buildings are also good insured, for which the capital costs damage by floods will be less for this area. Unfortunately the social impact is high in this area due to the amount of important public buildings, residents and businesses that are located in this area. The amount of roads that go to this area is also limited. This means that the economic costs can be high as well. Smaller businesses have less economic loss by floods than big companies but the social effect is for a small business much higher than for a big company because of the stabilised background of big companies. Also in this area it is not possible to determine the amount of insured companies and the age of the buildings according to SAPOA.

Table N.3: Market value in area 2

| Area 2 | Vacant land | Industrial | Business and Commercial | PSI | Residential |
|---|---|---|---|---|---|
| Amount | 3 | 12 | 43 | 14 | 19 |
| Market value [million ZAR] | 1.12 | 27.59 | 195.695 | 0.001 | 39.74 |

In this area the railway track is vulnerable to floods and floods will thus have a big impact on the rail network. When the tracks are flooded, the trains to and from Berea station cannot drive anymore, resulting in no rail connection between the centre of Durban and the southern stations. The affected people have to use other infrastructures like roads. The impact on the total road network will be very small due to the limited amount of people using the train. The main roads that will be affected by floods are the N3, M4 and R102. In case the N3 is not usable anymore, the traffic has to be redirected towards the M4 and R102. Normally there are three ways in/out of the CBD; north, south and west. When the N3 is blocked, the west entry/exit is blocked which results in people either using the north or the south route. The change of route from the N3 to M4 and

R102 is given in table N.4. The original traffic from the N3 is diverted over the other two roads. It is of course also possible that not the N3 but the other two roads are blocked, in that case all traffic has to use the N3.

Table N.4: Capacity, normal intensity and detour intensity in case of blockage of the N3 [22]

| | | Capacity | Intensity | Detour |
|---|---|---|---|---|
| West of CBD | N3 from CBD | 10000 | 5613 | 0 |
| | N3 to CBD | 8000 | 7779 | 0 |
| South of CBD | M4 to CBD | 6000 | 6344 | 8289 |
| | M4 from CBD | 6000 | 4454 | 5857 |
| | R102 to CBD | 4800 | 2656 | 4601 |
| | R102 from CBD | 4800 | 2048 | 3451 |
| North of CBD | M4 from CBD | 4000 | 1891 | 3294 |
| | M4 to CBD | 4000 | 2528 | 4473 |
| | R102 from CBD | 2400 | 1852 | 3255 |
| | R102 to CBD | 2400 | 2056 | 4001 |

**Area 3: CBD/South Beach** Area 3 is mainly the South Beach district of eThekwini municipality, see figure 8.1. This area is a high density area with middle and low class incomes. Table N.5 shows that there are only 6 residential buildings, this is not the case for this area. Therefore the amounts and market values of residents are not high weighted in this report. Besides the business and commercial the industrial sector is also big in this area. Those are mostly insured but because of the old buildings the costs of recovering can be high. This contains large as well small businesses. The large companies are mainly located in the north side of the area. Several car rental companies like the world wide known Hertz is located there and in the south of the area a lot of fast-food restaurants are located like KFC. The small businesses, like pharmacies and telephone shops, are mainly located in the south part where also the inhabitants live. A lot of small businesses are located at street level and residents live above these companies. Therefore mainly the businesses will be affected by floods in a capital costs way. This area has some hotels due to the coast which is one block away. This area contains a lot of crime, especially when it is dark. Therefore the most tourists will go to Umhlanga or the hotels that are located near the Boulevard which is defined as safe. Area 3 is not seen as a highly developed area and a lot of Nigerian people live there, they often have a small business to earn money. The roads in this area are worse because of the people that have to move from the beach front to the CBD and because of the high amount of residents in this area that have to go to their work. A lot of tourists make use of the roads through this area to go to their hotels or to go to the tourist attraction Ushaka Marine World in The Point below this area. This area does not include train tracks. There are multiple roads and routes which can be taken within the area. The roads in this area are only local roads, therefore it looks like the impact on the transport network will not be very high, but because of the large amount of buildings, streets and traffic going through these streets, the impact of floods on this area can still be quite severe. In case of floods, all streets can be blocked, which means people are stuck and cannot get out of this area.

Table N.5: Market value in area 3

| Area 3 | Vacant land | Industrial | Business and Commercial | PSI | Residential |
|---|---|---|---|---|---|
| Amount | 7 | 34 | 34 | 17 | 6 |
| Market value [million ZAR] | 64.8 | 123.125 | 242.69 | 0.005 | 12.31 |

Unfortunately it is not possible to say which areas contain mainly old buildings and which contain mainly new buildings with the data and contact details of persons examined, so it is not possible to say which of the four determined areas are the oldest and newest. The age of a building can be important for the insurance the buildings have. Often when buildings are very old they do not have an insurance because if floods occur the recover costs and recover time will be too high according to Talia Feigenbaum. According to SAPOA it is not possible to hunt down the amount of buildings that are insured in a certain area in the city. The organisation does not have a map with stakeholders or property owners in the researched area in this report.

# Appendix O Multi-Criteria Analysis

## O.1 Weight factors

The weight factors are based on three different expert groups with a TIL. CME and Water background. The weight factors of these three groups are given in the tables below (Table O.1, Table O.2 and Table O.3). Table O.4 gives an overview of the weight factors of the three different expert groups and, resulting from that, the average weight factors. These average weight factors will be used for the MCA. The weight factors are scaled between 1 and 5. The different criteria are compared pairwise to each other. If a criteria is more important than another criteria, the value will be more than 1 up until 5. 1 means that two criteria are equal important. If a criteria is less important than another criteria the value will be one divided by the extend in which it is less important (between 2 and 5).

Table O.1: Weightfactors TIL

| | Implementation costs | Reliability | Capital value | Environmental impact | Economical value | Social Value | Implementation potential | **Total** | Normalized |
|---|---|---|---|---|---|---|---|---|---|
| Implementation costs | 1 | 1 | 1/3 | 3 | 1/3 | 1/4 | 1 | 7 | 0.08 |
| Reliability | 1 | 1 | 1/3 | 2 | 1/4 | 1/5 | 1/2 | 5 2/7 | 0.06 |
| Capital value | 3 | 3 | 1 | 4 | 2 | 1/5 | 3 | 16 1/5 | 0.19 |
| Environmental impact | 1/3 | 1/2 | 1/4 | 1 | 1/5 | 1/5 | 1/5 | 2 2/3 | 0.03 |
| Economical value | 3 | 4 | 1/2 | 5 | 1 | 1/5 | 3 | 16 2/3 | 0.19 |
| Social Value | 4 | 5 | 5 | 5 | 5 | 1 | 3 | 28 | 0.33 |
| Implementation potential | 1 | 2 | 1/3 | 5 | 1/3 | 1/3 | 1 | 10 | 0.12 |
| **Total** | | | | | | | | 85 7/9 | 1 |

Table O.2: Weightfactors CME

| | Implementation costs | Reliability | Capital value | Environmental impact | Economical value | Social Value | Implementation potential | **Total** | Normalized |
|---|---|---|---|---|---|---|---|---|---|
| Implementation costs | 1 | 1 | 1 | 4 | 1 | 1 | 1 | 10 | 0.17 |
| Reliability | 1 | 1 | 3 | 3 | 2 | 2 | 1 | 13 | 0.22 |
| Capital value | 1 | 1/3 | 1 | 3 | 2 | 1/2 | 1 | 8 5/6 | 0.15 |
| Environmental impact | 1/4 | 1/3 | 1/3 | 1 | 1/3 | 1/3 | 1 | 3 3/5 | 0.06 |
| Economical value | 1 | 1/2 | 1/2 | 3 | 1 | 1 | 1 | 8 | 0.13 |
| Social Value | 1 | 1/2 | 2 | 3 | 1 | 1 | 1 | 9 1/2 | 0.16 |
| Implementation potential | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 0.12 |
| **Total** | | | | | | | | 60 | 1 |

Table O.3: Weightfactors Water

| | Implementation costs | Reliability | Capital value | Environmental impact | Economical value | Social Value | Implementation potential | **Total** | Normalized |
|---|---|---|---|---|---|---|---|---|---|
| Implementation costs | 1 | 1/2 | 1 | 4 | 1 | 1 | 1/2 | 9 | 0.14 |
| Reliability | 2 | 1 | 1 | 5 | 2 | 2 | 1 | 14 | 0.21 |
| Capital value | 1 | 1 | 1 | 3 | 1 | 1 | 1/2 | 8 1/2 | 0.13 |
| Environmental impact | 1/4 | 1/5 | 1/3 | 1 | 1/3 | 1/3 | 1/5 | 2 2/3 | 0.04 |
| Economical value | 1 | 1/2 | 1 | 3 | 1 | 1 | 1/2 | 8 | 0.12 |
| Social Value | 1 | 1/2 | 1 | 3 | 1 | 1 | 1/2 | 8 | 0.12 |
| Implementation potential | 2 | 1 | 2 | 5 | 2 | 2 | 1 | 15 | 0.23 |
| **Total** | | | | | | | | 65 1/7 | 1 |

Table O.4: Average weightfactors

| | TIL | CME | Coastal | average |
|---|---|---|---|---|
| Implementation costs | 0.08 | 0.17 | 0.14 | 0.13 |
| Reliability | 0.06 | 0.22 | 0.21 | 0.16 |
| Capital value | 0.19 | 0.15 | 0.13 | 0.16 |
| Environmental impact | 0.03 | 0.06 | 0.04 | 0.04 |
| Economical value | 0.19 | 0.13 | 0.12 | 0.15 |
| Social Value | 0.33 | 0.16 | 0.12 | 0.20 |
| Implementation potential | 0.12 | 0.12 | 0.23 | 0.15 |
| Total | 1.00 | 1.00 | 1.00 | 1.00 |

## O.2 MCA values

The consequences of each alternative on the criteria are described in Section IV. These consequences are scored as can be found in Table O.5. The scoring is done on a scale between 0 and 10. The base alternative 'Accept' scores a 5 for every criterion, because this is the reference alternative. The higher the value, the better a solution scores on a criteria compared to the base alternative. After scoring the alternatives, the average weight factors are assigned to the scores. The result of multiplying the scores by the average weight factors can be found in Table O.6. 'Mitigate' has the highest total score, but all the scores of the different alternatives are very close to each other. The only thing that can be taken from this analysis for sure is that all the alternatives will be better than not doing anything.

Table O.5: MCA values of the alternatives

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| Implementation costs | 5 | 1 | 4 | 2 |
| Reliability | 5 | 8 | 6 | 7 |
| Capital value | 5 | 8 | 6 | 9 |
| Environmental impact | 5 | 4 | 8 | 4 |
| Economical value | 5 | 8 | 6 | 9 |
| Social Value | 5 | 8 | 8 | 7 |
| Implementation potential | 5 | 1 | 4 | 1 |

Table O.6: MCA values of the alternatives including weightfactors

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| Implementation costs | 0.64 | 0.13 | 0.51 | 0.26 |
| Reliability | 0.82 | 1.32 | 0.99 | 1.15 |
| Capital value | 0.78 | 1.24 | 0.93 | 1.40 |
| Environmental impact | 0.22 | 0.18 | 0.35 | 0.18 |
| Economical value | 0.75 | 1.20 | 0.90 | 1.35 |
| Social Value | 1.01 | 1.62 | 1.62 | 1.42 |
| Implementation potential | 0.77 | 0.15 | 0.62 | 0.15 |
| Total score | 5 | 5.84 | 5.93 | 5.91 |

## O.3 Sensitivity analysis

A sensitivity analysis is performed to test the robustness of the MCA. This can be done by giving less or more weight to a criteria. The main question that needs to be answered to tell the robustness of the MCA is thus the following: Is there a difference between the previous results of the MCA and the results of the MCA if a certain criteria has another weight factor?

The first criterion whose weight factor has been changed is implementation costs. The weight of this criterion has been changed to 0. The results of this can be found in Table O.7. The table shows that if implementation costs is not an important factor, the ranking of the alternatives will change. In this case 'Avoid' has the highest score.

Table O.7: Sensitivity of implementation costs

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| Implementation costs | 0 | 0 | 0 | 0 |
| Reliability | 0.82 | 1.32 | 0.99 | 1.15 |
| Capital value | 0.78 | 1.24 | 0.93 | 1.40 |
| Environmental impact | 0.22 | 0.18 | 0.35 | 0.18 |
| Economical value | 0.75 | 1.20 | 0.90 | 1.35 |
| Social Value | 1.01 | 1.62 | 1.62 | 1.42 |
| Implementation potential | 0.77 | 0.15 | 0.62 | 0.15 |
| Total score | 4.36 | 5.71 | 5.41 | 5.65 |

The second criterion whose weight factor has been changed is capital value. The weight of this criterion has been changed to 0. The results of this can be found in Table O.8. The table shows that if capital value is not an important factor, the ranking of the alternatives will change a little. In this case 'Mitigate' is still the best alternative.

Table O.8: Sensitivity of capital costs

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| Implementation costs | 0.64 | 0.13 | 0.51 | 0.26 |
| Reliability | 0.82 | 1.32 | 0.99 | 1.15 |
| Capital value | - | - | - | - |
| Environmental impact | 0.22 | 0.18 | 0.35 | 0.18 |
| Economical value | 0.75 | 1.20 | 0.90 | 1.35 |
| Social Value | 1.01 | 1.62 | 1.62 | 1.42 |
| Implementation potential | 0.77 | 0.15 | 0.62 | 0.15 |
| Total score | 4.22 | 4.60 | 4.99 | 4.51 |

In Table O.9 the comparison between the normal MCA results and the results of the sensitivity analyses are showed. The scores of the different alternatives are very close to each other.

Table O.9: Normal MCA results compared to sensitivity analyses

| | Accept | Avoid | Mitigate | Transfer |
|---|---|---|---|---|
| MCA normal | 5 | 5.84 | 5.93 | 5.91 |
| MCA without implementation costs | 4.36 | 5.71 | 5.41 | 5.65 |
| MCA without Capital value | 4.22 | 4.60 | 4.99 | 4.51 |