

# The design of an early warning system for floods in Dar Es Salaam, Tanzania

A case study for the local bus company

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# The design of an early warning system for floods in Dar Es Salaam, Tanzania

A case study for the local bus company

by

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# Foreword

After 7 years and a few months I conclude my student life with this Master Thesis. This report is performed as a Master Thesis as part of the MSc Track "Watermanagement" at the Faculty of Civil Engineering at the TU-Delft. This report is aimed at readers with an engineer background in general and specific for readers with a Civil Engineering background. Readers ideally have an interest in flood situations and problems in developing countries. More specifically, this report is aimed at readers that are interested in gaining knowledge on the design of warning systems that help prepare people/communities/organizations on a very short time scale to prevent financial damage to their assets.

I would like to thank my committee member for their extended time and effort. I would like to thank Hessel Winsemius for his guidance. In addition, I would like to thank the TU-Delft for the opportunity to obtain a degree in engineering in one of the best learning environments of the academic world.



# Acronyms

## List of Acronyms

EWS	Early Warning System
BRT	Bus Rapid Transport System
TAHMO	Trans-African Hydro Meteorological Observatory
DFID	United Kingdom Department for International Development
TURP	Tanzania Urban Resilience Program
UDART	Usafiri Dar es Salaam Rapid Transit
DART	Dar es Salaam Rapid Transit Agency
LAPF	Local Authority Pension Fund
NASA	National Aeronautics and Space Administration
SRTM	Shuttle Radar Topography Mission
TP	True Positive
FP	False Positive
TN	True Negative
FN	False Negative
ROC	Receiver Operating Characteristic
DEM	Digital Elevation Model
TPR	True Positive Rate
FPR	False Positive Rate
ITDP	Institute for Transportation and Development Policy
TMA	Tanzania Meteorological Agency
ROC	receiver operating characteristic





# Abstract

With climate change increasing its mark on all aspects of the hydrological cycle, societies all over the world living in flood-prone areas are increasingly exposed to flood hazards. In many parts of the world, especially in less developed areas, societies lack knowledge and data to predict future flood events. By predicting a future flood event, an organization creates a time frame in which it can implement a mitigating action that reduces the financial damage inflicted. In recent years, development in new measuring techniques has significantly lowered the cost of collecting data and information on different aspects of the hydrological cycle. These developments enable organizations in regions restrained of knowledge and data to establish methods to analyze aspects of the hydrological cycle and thereby predicting the probability of a flood hazard several hours or days in advance. This thesis explores various possibilities of designing and implementing an Early Warning System (EWS) for the Bus Rapid Transport System (BRT) in Dar es Salaam. The EWS design is based on the forecasting requirements, investigated with the BRT-system. Several operational forecasting methods are available. The EWS designed in this thesis makes use of rainfall data obtained from rainfall stations located in the Dar es Salaam region, installed and managed by the Trans-African Hydro Meteorological Observatory (TAHMO). This forecasting data is chosen because it provides the needed lead-time with the lowest margin of error. This forecasting data is processed and analyzed by the designed EWS and subsequently produces a probability level on a flood event. It thereby provides an advice on if the BRT-system should implement a mitigating action based on the principle of pursuing an optimal economic outcome. The designed EWS produces the flood probability in real-time, updated every hour with a lead time of one hour. This time frame enables the BRT-system to implement a mitigating action, thereby reducing the inflicted cost.

The probability level of a flood event is determined by training the EWS with historic flood and rainfall data. In addition, the implementation of both a hydrological and relational model in the EWS was tested. The results show that the hydrological model is the better option. The results also show that the implementation of an EWS ensures a decrease in financial damage endured by the BRT-system. The produced outcome of the EWS was validated by a 'leave one out' method. This validation was done by consecutively leaving one flood event out of the historical data frame and analyzing the variability of the resulting outcome. Finally, the designed EWS is best implemented in the BRT-system alongside the EWS-systems currently in place.



# Acknowledgement

First off all, I would like to thank Hessel Winsemius for his guidance and patience during the process of completing this thesis. You gave me the opportunity to perform an amazing study in a challenging environment. I am proud to say that I have grown a lot as a person during my time in Tanzania and after. I also want to thank all other members of my committee, Marie Claire Ten Veldhuis, Laurene Bouaziz and Winnie Daamen. You all were very helpful and inspired me to accomplish my thesis especially during difficult moments.

I would like to thank my family, my girlfriend, my friends and everybody else that supported me on an emotional level. Furthermore, I am very thankful for all people that helped me during my time in Tanzania, with special thanks to Ami.

Last but not least, I would like to thank my partner in crime Louise Petersson for the companionship during our stay in Tanzania.

Please enjoy reading this report and feel free to contact me any time if you have questions!





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# 1

## Introduction

Cities all over Africa are growing rapidly in size, both demographically and physically. By 2050, the amount of people living in African cities will triple from 410 million in 2010 to 1.23 billion in 2025. The city Dar Es Salaam, Tanzania is estimated to grow to 10 million inhabitants within the next decade (Kebede & Nicholls, 2012).

In recent years Dar es Salaam is dealing with increasing inundations related financial and humanitarian losses all through the rainy season. These floods result from degradation of the Msimbazi River system, the rapid and uncontrolled urban build-up, seawater level rise and increase of stormy weather (Congedo, Munafò, & Macchi, 2013; Kebede & Nicholls, 2011). Water is collected and transported by drainage systems, rivers and streams. Due to financial problems and inadequate budgeting, most of the systems and streams are clogged and poorly maintained (Secretariat et al., 2011). This and possibly other reasons cause an increase in flood problems resulting in loss of property and damage to infrastructures such as the BRT-System.

In order to mitigate the flood problems in Dar es Salaam the World Bank and the United Kingdom Department for International Development (DFID) have established a partnership named the Tanzania Urban Resilience Program (TURP). This is a partnership to support the Government of Tanzania in mitigating disaster risk and to increase resilience to climate change. The program activities are accommodated in three pillars; one - Risk Identification, two - Risk Reduction, three Disaster Preparedness and Emergency Management. Among other practices, a part of pillar three is the design and creation of EWS's usable for organizations and communities in Dar es Salaam. This study explores this further, by looking at possibilities of creating an EWS that helps mitigating flood problems endured by the BRT-system. This study is performed under the supervision of the TU Delft with the TURP partnership as client (Darragh Coward, 2018).

### 1.1. Research motivation

The managing team of the BRT-System has intentions to mitigate the financial losses caused by flood events and thereby to protect its assets. These financial losses are severe enough for the BRT-System to seek support from the TURP-program. This study explores the possibility of mitigating these financial problems by creating an EWS that, with its predicting power, benefits the current situation. A significant part of these financial losses occurs at the company's depot, where the buses are parked during idle time. The financial losses are caused because of loss in economic activity during or in the aftermath of a flood (Kost, 2018) because of an inundation at the mentioned BRT-depot. Therefore, this study will focus on creating an EWS that provides additional predicting power concerning future flood events at the location of this depot.

## 1.2. Problem Statement

The BRT-System is suffering significant financial losses because of floods, thereby giving rise to negative economic consequences.

Several knowledge gaps will need to be answered concerning the BRT-system and the hydrological cycle in which the depot is situated in. Important factors concerning the BRT-system are:

- Internal information distribution.
- Evacuation time of busses and personnel from the BRT-depot.
- Lead time requirements.
- Possible mitigating actions that can be implemented.
- Financial damage caused by the endured flood events.

Important factors concerning the hydrological cycle in which the BRT-depot is situated are:

- Maximum time of concentration of the catchment area.
- Average travel time of the catchment area.
- Flood types experienced at the depot location.
- Rainfall patterns experienced in the catchment area.

## 1.3. Research Objectives

Based on the problem statement and research motivation, the following objective for this study is:

- Objective: Design an Early Warning System (EWS) for the BRT-system, that can be used to timely and effectively take mitigating actions before a flood arrives; and investigate to what degree the design can already be established using presently available real-time data sources.

An EWS is a means by which people receive information prior to a disaster. This information has to be systematic and timely in order to implement an action that appearance or mitigate the consequences of this disaster. An EWS consists of a forecasting system, communication protocols and the implementation of a decision. For an EWS to be effective, there are three general components that need to function properly.

- Component 1: Data input
- Component 2: Data processing
- Component 3: Flood probability determination

In the next section in table 1.1 the research questions are stated. By answering these questions the design of these components is determined.

## 1.4. Research Questions

The following research questions are formulated to determine the design of the stated components of the EWS. In the next section the methods used to accomplish this are elaborated. By answering each research question the design of each of the components of the EWS are determined. In the next section the methods used to accomplish this, are elaborated.



Table 1.1: Research objective, research questions and corresponding components.

Objective: Design an Early Warning System (EWS) for the BRT-system, that can be used to timely and effectively take mitigative actions before a flood arrives; and investigate to what degree the design can already be established using presently available real-time data sources.		Component
<b>Research questions:</b>		
1	What is the required lead time by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?	Component 1: Data input
2	What are the travel time and the time of concentration within the Msimbazi catchment area during heavy rainfall periods?	
3	Which operational data is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?	
4	Which operational model is required by the EWS to process the operational data?	Component 2: Data processing
5	What output has the EWS to produce for the BRT-system to implement an action that mitigates the financial damage caused by a flood event?	Component 3: Flood probability determination
6	What gap in lead time or operational data remains and what data, information, models are needed to fill this?	

## 1.5. Research Approach

The research questions stated in the previous section will help the design of the EWS for the BRT-system. In this section the research approach used to answer these research questions are stated.

- Research question one: What is the required lead time by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

The BRT-System will be examined to answer this research question. Data will be collected by conducting interviews with BRT-System staff. By data collected with the held interviews, it can be determined how much time it takes for the BRT-system to execute the mitigating actions that are in place and what kind of mitigating actions can be implemented.

- Research question two: What are the travel time and the time of concentration of the Msimbazi catchment area during heavy rainfall periods?

This research question is answered with data collected by fieldwork performed in the Msimbazi catchment area. Data on the slope and the consistency of the soil of the catchment area is collected to determine the time of concentration over land. Data on the velocity and profile of the Msimbazi river is collected to determine the travel time of a waterbody. With these results the total travel time of the Msimbazi catchment area is determined.

- Research question three: Which operational data is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

This research question is answered by comparing the outcome of research question one and two. By comparing the required lead time of the BRT-system with the travel time and the time of concentration of the Msimbazi catchment area, a forecasting method can be selected as input source for the designed EWS. This forecasting method needs to produce data that allows the BRT-system to timely and effectively implement a mitigating action.

- Research question four: Which operational model is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

In this study, a relational and a hydrological model are tailored and tested to process the input data for the case at hand. Both models are tested and compared on their consistency and their predicting power. Based on these analyses, a decision is made on which model type is the best fit for the designed EWS.

- Research question 5: What output is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

In this study, an evaluation is made on how the processed data should be interpreted in order to determine if the BRT-system should implement a mitigating action. This is done by training the EWS,

and subsequently validating its output with historical data. Furthermore, several methods on how the data should be communicated are determined as well.

- Research question 6: what gap in lead time or forecasting data remains and what skill would be needed to fill this?

Based on the outcome of the results of the chosen model, forecasting method, required lead time and the designed EWS, an evaluation is made on the skill and knowledge obtained in this study. This research question is answered by determining what needs of the BRT-system are not fulfilled by this study. The answer is stated in the discussion section because it is, in a way, a reflection on this study.

## 1.6. Report outline

This report consists of eleven chapters each one focusing on a separate subject matter. All chapters are evaluated on their purpose and their relationship with the following chapter and with the report as a whole.

- Introduction

Introduces the knowledge gap, the research objectives and the research questions to cover the knowledge gap. It also states the motivation for initiating this study.

- Theoretical Framework

This chapter provides an overview of the existing literature about EWS's and how a new one can be designed for the case study at hand. It provides insight on how the stated components in section 1.3 are supported by literature.

- Case Study

This chapter describes the case study at hand. The important aspects are the BRT-system, the study area and the flood problems.

- Methodology design EWS

This chapter states the methodology and the framework used for the design of the EWS. A detailed description is provided on the framework of the components that make up the EWS and where it is implemented in the BRT-system. The method used to determine the economic value of the designed EWS is also stated in this section. The results consequential are stated in section 'The final design EWS' 9.

This section also provides an overview of the chapters that elaborate on how the design of the EWS is described in this rapport. This is visualized in a flowchart and described in a summary.

- Data

This chapter describes the used data sources. It also provides an overview on the data sets created in this study and how they are used in the design of the EWS.

- EWS component 1: Forecasting location and method

This chapter states the methods and results on which the design of component 1 of the EWS is based. The results are divided in the hydrological outlay of the Msimbazi catchment area, the required lead-time of the BRT-system and what type of forecasting location and method are determined optimal for the designed EWS.

- EWS component 2: Relational vs hydrological model

This chapter states the methods and results on which the design of component 2 of the EWS is based. In this chapter the relational and the hydrological model are evaluated on there predicting power and there consistency. Subsequently, a statement is produced on which model fits the designed EWS best to process the input data.

- EWS component 3: Flood probability determination

This chapter states the methods and results on which the design of component 3 of the EWS is based. This chapter states how the EWS is trained and a determination is made on the relationship between the processed data and the produced flood event probability. Subsequently, a statement is produced on how the output of the EWS is communicated to the BRT-system.

- Final EWS design

In this chapter the final design of the EWS is stated. The final design of the EWS consist of the design of the three components.

- Conclusion

This chapter states the answers on the research questions.

- Future research and discussion

In this chapter a retrospect on the designed EWS is provided. Furthermore, an analysis is stated on the credibility of the used data sets and sources. A recommendation on how an optimal implementation would look like in reality will be provided as well.



# 2

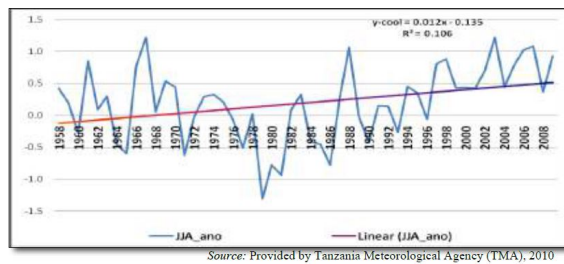
## Theoretical Framework

In this chapter, the needed background information is given to provide an improved understanding of the conducted research. This chapter is divided into several sections. The first section is Climate change and flood events 2.1 and gives background information on climate change and rapid urbanisation and how this leads to an increase in flood related problems in Dar es Salaam. The second section 2.2 gives background information about the use of an EWS. The fourth section is The BRT-system concept 2.3 and gives background information on BRT-systems around the world.

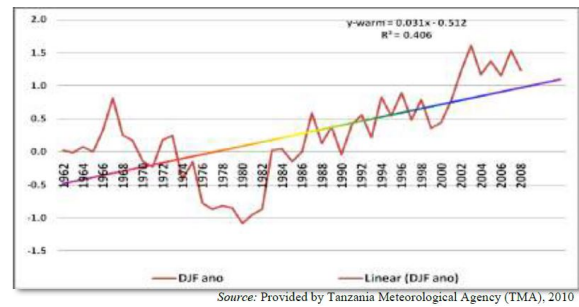
### 2.1. Climate change and flood events

The scientific consensus is that temperature rise has started in the 20<sup>th</sup> century and started to increase significantly during the 1970's. Scientific research has shown that the temperature rise is very likely to continue in the coming decades. An increase of the atmospheric temperature has consequences on hydrological cycles dictating the weather patterns all over the world. This relation is described by the Clausius Clapeyron theory, and stated in various scientific articles such as (Koutsoyiannis, 2012). At higher temperatures the atmosphere can contain a higher percentage of moisture. This increase in moisture percentage can cause an intensification of a hydrological cycle, thereby creating heavier rain showers, extended dry periods and increased overland- and river run-off (Berg, Moseley, & Haerter, 2013). Urban area's are, when subjected to these intensification's, exposed to increased flood risks due to increasing run-off peaks. These run-off peaks are aggravated in build-up area's because of decrease in infiltration capacity of the soil and the loss of buffer capacity.

Research indicates that the mentioned intensification of the hydrological cycle is already in progress in the Dar es Salaam region. Temperature levels are expected to increase in the coming years for Dar es Salaam and Tanzania as a whole. By 2100 the expected mean temperature level is project to increase with 1.7 degrees (Jury, Matari, & Matitu, 2009; Hunt & Watkiss, 2011). Figure 2.1a shows the historical rising trend of the mean annual temperature change up to 2008. Figure 2.1b shows the historical monthly maximum temperature up to 2008. Both figures suggest that the mean and average temperature values have increased last century. The pictures where provided by TMA.



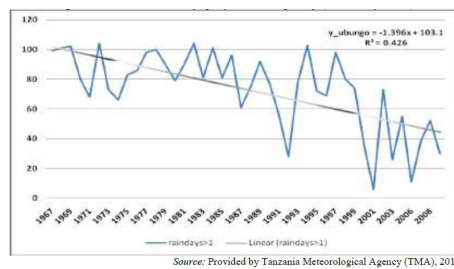
(a) historical rising trend of the mean annual temperature change up to 2008, (TMA, 2011)



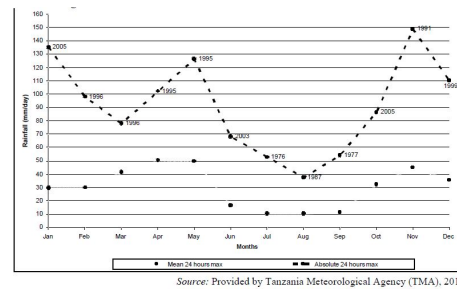
(b) historical monthly maximum temperature up to 2008, (TMA, 2011)

Figure 2.1: Both figures illustrating separate aspects of the climate change in Dar es Salaam

Figure 2.2a shows the historical increase in rainfall intensity in the last decades. Figure 2.2b shows the historical decrease in rainfall events over the last century. (Mtongori, Stordal, & Benestad, 2016), concluded in their research about Tanzania that the average rainfall on the coast line of Tanzania will increase during the long rainy period by up to 6 percent. If rainfall indeed increases in severity, and the total amount of rainy days stays the same or decreases, as depicted in 2.2, then the intensity will increase, which has a significant impact on flood risks in the future. With the decrease in rainfall events, there is also an expected increase in periods of drought, which contributes to the flood risk by decreasing the infiltration capacity of the soil (Jury et al., 2009; Hunt & Watkiss, 2011).



(a) Historical decrease in annual rainfall, (TMA, 2011)



(b) Rainfall event intensity increase in Dar es Salaam. The rainfall in mm/rainfall event is depicted in this Figure, (TMA, 2011)

Figure 2.2: Both figures illustrated two separate changes in rainfall patterns contributing to flooding problems in Dar es Salaam

The English dictionary defines a flood as 'water covering previously dry area: a very large amount of water that has overflowed from a source such as a river or a broken pipe onto a previously dry area'. Flood events can be divided into the following four types. After (Jonkman, 2005).

- Coastal floods

During a coastal flood the water flooding a region originates from the sea. A coastal flood can be caused by a windstorm and low atmospheric pressure or a dike breach.

- Flash floods

In region's with steep slopes, little water is retained in the soil after a rainfall event. After an intense rainfall event or sudden melting of snow, a large amount of water is released in a catchment area. This water is collected along the slopes of a river accumulates mass and speeds during its path downstream. The water level rises fast and floods a region in a short time. Flash floods are considered dangerous because it is difficult to observe them.

- Ponding (or pluvial flooding)

Local rainfall causes this type of flooding when it exceeds the conveyance capacity of the drainage system at the location. It occurs in relatively flat regions, especially in build-up areas with limited drainage capacity.

- River or fluvial floods

Caused by a rainfall event that extends over period of time. Water accumulates in the river of a catchment area, thereby increasing the water level. Downstream regions of catchment areas are vulnerable for this type of floods.

A water body causing river floods has a considerable travel time because it precipitated upstream from the flooded location. This provides the possibility for communities and organizations to act in recognition of such a flooding event (Arnell & Gosling, 2016).

## 2.2. Early Warning System Concept

An EWS provides agency's an advanced warning of probable floods, providing the possibility of implementing an action that mitigates or completely avoids potential damage. This advanced alarm is produced by collecting and analyzing forecasting data and by providing an output that can be used as an alarm. An alarm consist of information and means for disseminating this information among agency's in threatened regions (Cools et al., 2012).

An agency is interested in using an EWS if the advanced warning has a lead-time that surpasses the needed time of implementing a mitigating action. In this study, the EWS is designed for the implementation of one mitigating action by the BRT-system<sup>1</sup>. This mitigating action requires a certain amount of time that has to be surpassed by the lead-time of the EWS. When the required lead-time is established, the forecasting method and location can be determined to acquire forecasting data used as an alarm. This data has to be acquired somewhere in the hydrological cycle from the following sources.

- River discharge

Acquired by measuring the water level and velocity at several locations in a river system, thereby establishing the total discharge at a location downstream. This is generally used when the required lead-time is relatively short. It provides a relative accurate flooding prediction. Methods used to acquire this data are radars, pressure meters or staff gauges.

- Groundwater discharge

Acquired by measuring the groundwater level and velocity at several locations in a catchment area. An increase in groundwater level and velocity can result in seepage and an increase in river discharge that thereafter can result in a possible flood event. Measuring groundwater generally provides an extended lead-time compared to measuring river discharge. This data source is relatively little used because acquiring data is proven to be difficult.

- Rainfall

Acquired by rain-gauges distributed over a catchment area. Generally provides an extended lead-time compared to measuring ground or river discharge. Mostly used when an extended lead-time is required or if the time of concentration over land is a significant part of the hydrological cycle.

- Future rain prediction

Acquired by satellite stations or radar antennas. Generally used when no other measuring techniques are available in a catchment area or when the lead-time is such that it extends beyond the lag time of the catchment area.

When a proper forecasting method and location is chosen, then this forecasting data is processed by a model. The type of model used in an EWS depends on the data input and the required warning output. In general two types of models can be used to process the forecasting data which are relational and

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<sup>1</sup>The mitigating action is explained in chapter 3

physically based models such as a hydrological model. In this study both types of models are analyzed and compared for which type fits this case study best<sup>2</sup>.

Finally, a warning is communicated to an agent. A distinction is made between a probabilistic and a deterministic warning. A probabilistic EWS provides a probability on a flood event as warning output. The agent that uses this EWS can determine which mitigating action has to be implemented along the EWS provided probability output on a flooding event. A deterministic EWS provides a binary alarm only stating whether or not an agents have to implement a mitigating action. Several case studies, documented in (Theis, Hense, & Damrath, 2005), (Verkade & Werner, 2011) and (Pawlak, Wong, & Ziarko, 1988), state that a probabilistic EWS results in a higher economical value for the agent if it has the skills to interpret the communicated warning correctly. The agent in this study is the BRT-system which is determined skilled enough to interpret the probabilistic alarm correctly<sup>3</sup>.

### 2.3. The BRT-system concept

In the recent years, the term BRT-system has been applied widely to name bus services around the world. In 2012, the Institute for Transportation and Development Policy (ITDP) has published the BRT-standard thereby making it easier to standardize and compare bus services around the world. In the year 2019, a total of 166 cities have implemented a BRT-system. Typically, a BRT-system comprises of lanes dedicated to busses, and provides priority to the busses at intersections. The BRT-system is designed to ensure a save and fast commuting possibility in a busy and congested city, its goal is to combine the speed of a metro, with the low cost and flexibility of a simple bus-system.

The most heard criticism on BRT-systems is the air pollution caused by the gasoline powered engines of the busses. Especially, compared with a metro system that is powered by electricity, the BRT-system has significantly more impact on its environment. Furthermore, most BRT-systems suffer from overcrowdedness and poor service quality. The busses take a long time to arrive and the waiting time is much higher then anticipated in advantage (Levinson et al., 2003).

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<sup>2</sup>The exploration of both types of models is further discussed in the next section

<sup>3</sup>The BRT-system of Dar es Salaam is further discussed in chapter 3



# 3

## Case Study

This chapter describes the case study at hand and elaborates on the specific factors that influences this study. Section 3.1 describes the BRT-system in Dar es Salaam. Section 3.2 describes the flood problems that are experienced by the BRT-system. Section 3.3 describes the Study area. Section 3.4 elaborates on selecting an optimal predicting model.

### 3.1. The BRT-system in Dar es Salaam

Problems faced in urban societies are complex. Dar es Salaam is growing steadily, increasing traffic and transport problems in the process. To mitigate these traffic problems, the municipality of Dar es Salaam has introduced its very own BRT-system. It has proven to be an effective method to mitigate urban mobility challenges(Chengula & Kombe, 2017).

Construction of the BRT-System started in 2012 and is completed around 2035(Suzuki, 2008). The BRT-system embodies a three billion dollar investment in buses, bus stations and improved infrastructure to deal with the rapid urbanization of Dar es Salaam. In 2012, before the construction started, 5200 buses used for public transport where in operation in the city. Despite this big number of buses, other means of transportation such as motorcycles, tricycles(bajajeeh) and personal car use remain high(Ahferom & Svensson, 2009). These factors along with poor infrastructure, crowded roads, waiting time for daladala's and unclear bus stops have severe impact on the safety and crowdedness of the city's infrastructure, thereby causing accidents and severe traffic jams. (Ka'bange, Mfinanga, & Hema, 2014). The government of Tanzania decided to mitigate these problems by introducing a BRT-System in Dar es Salaam. This system consists of buses and bus lanes, enabling a safer transport of large amounts of commuters through the city.

The BRT-System in Dar es Salaam comprises six phases. The construction of phase one was completed in December 2015. The total cost was approximately 134 million which was funded by the African Development Bank, World Bank and Government of Tanzania. BRT-phase one began full operations in May 2016, covering 20.9 km of corridor, connecting the outskirts and the center of Dar es Salaam. The total corridor length for the whole project is 130 kilometers and it is expected to save 90% of commuting time, thereby reducing time lost in traffic jams.(Venant Rwenyeri, 2015).

Phase one of the BRT-System is operated by a company named Usafiri Dar es Salaam Rapid Transit (UDART) and is under the surveillance of the Dar es Salaam Rapid Transit Agency (DART)-organization which acts as a controlling agency that is responsible for the quality and safety standards of the BRT-System. The company that will be granted the public tender of each of the next five phases are yet to be determined (HEMA, 2019; Venant Rwenyeri, 2015).

Figure 3.1a gives an overview of the bus corridors of all phases and the location of the BRT-Depot. Table 3.1 gives the corridors and its length of each phase of the BRT-system when completed.

Table 3.1: BRT-System all phases and Road corridor lengths

DART Phases	DART Road Corridor	Length (Km)
Phase 1	Morogoro -Kawawa North- Msimbazi-Kivukoni	20.9
Phase 2	Kilwa-Kawawa South	19.3
Phase 3	Uhuru Street-Nyerere-Bibititi-Azikiwe Street	23.6
Phase 4	Bagamoyo-Sam Nujoma	16.1
Phase 5	Mandela Road	22.8
Phase 6	Bagamoyo Road	27.6

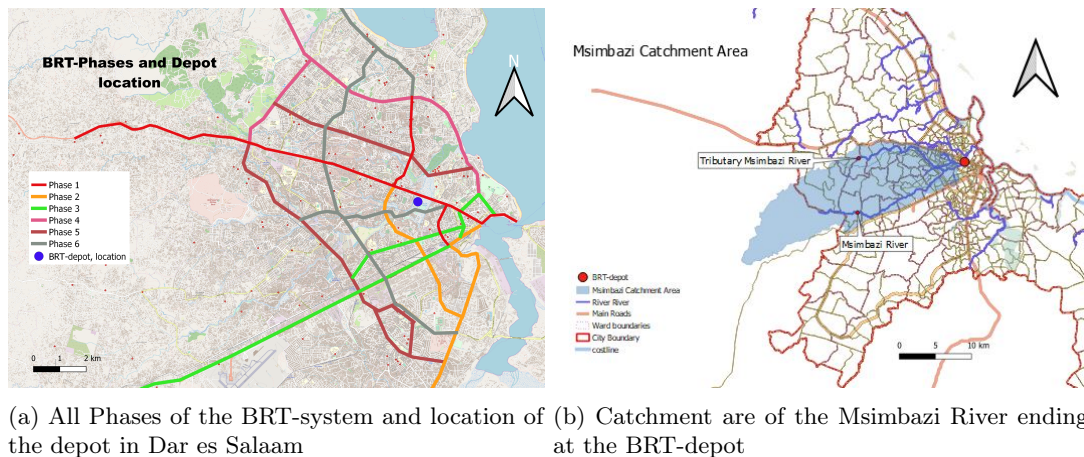


Figure 3.1: Figure a: location of all 6 BRT-phases in Dar es Salaam, Figure b: location of the Msimbazi catchment area in Dar es Salaam. (Open Street Map, howpublished = <http://https://www.openstreetmap.org/#map=8/52.154/5.295>, note = Accessed: 2019-09-30, n.d.)

### 3.1.1. UDART

The corridor operated by UDART is served by 140 buses, which are stationed at the BRT-Depot as depicted in figure 3.1a. The UDART assets consist of buses, spare parts and tools to maintain the buses. Transport services are provided from 05:00 am to 23:00 pm hrs daily. The phase 1 corridor consists of 21 km of bus corridor and 60 km of feeder roads. Furthermore, there are 5 main terminals and 27 bus stations. Figure 3.2 shows the road network which includes trunk and feeder roads, stations and terminals. UDART is a privately owned company and received the task to operate phase one of the BRT-system by a public tender. The main office of UDART is located inside the BRT-Depot since its construction in 2017 and is used to manage all daily operations (Suzuki, 2008),(Chengula & Kombe, 2017).



Figure 3.2: Detailed description of phase 1, ((Kost, 2018), p. 23)

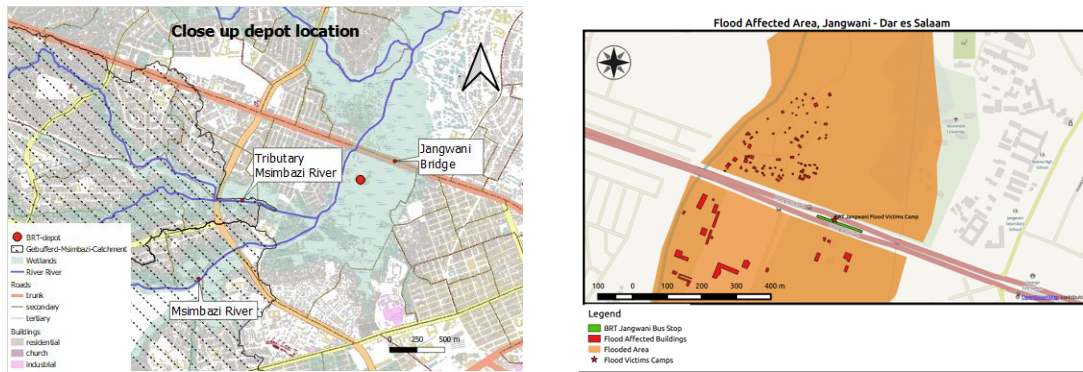
### 3.1.2. DART-Organization

The DART-organization is part of the local government and has educated personnel specialized in public transport, infrastructure and water management (HEMA, 2019). DART is also responsible for several assets which are, the BRT-Depot, the bus stations and the corridors. DART has its office inside one of the Local Authority Pension Fund (LAPF) Millennium Towers thereby creating a distance to UDART and the BRT-System. This is done intentionally with the future in mind because the DART-organization is also responsible for other companies which will operate the other five phases of the BRT-system (Kironde, 2016; HEMA, 2019). It was the DART-organization that, on behalf of the BRT-System together with the World-Bank, reached out for additional expertise on the currently encountered flooding problems.

The DART-organization acts as a controlling agency which ensures several quality and safety standards. DART personnel is hired by the government and selected by their expertise on infrastructure, safety and water management. Formally, DART is responsible for UDART meeting all quality and safety standards and has to provide expertise and information to UDART in order for them to meet these standards (Suzuki, 2008).

## 3.2. Flooding problems BRT-system

BRT-System is experiencing increasing flooding problems causing financial damage at its depot. The BRT-Depot is located in a low lying region that acts as a flood plain during the rainy season. During or after an increased rainfall event, the Msimbazi river emerges from its banks flooding the region where the depot is constructed. These flood events are increased in size and duration by the Jangwani bridge. The Jangwani bridge is a low bridge with an underpass height of 2 meters located a few meters downstream of the depot. This height is even lowered when sediment builds up in front of it after a large volume of water has passed it. In other words, this bridge acts like a dyke, retaining the water of the Msimbazi river inside the region of the depot. In Figure 3.3a an overview is presented of the location of the depot and the Jangwani bridge. In Figure 3.3b, a more detailed overview of the buildings prone to flooding in the Msimbazi wetland area are depicted. In Figure 3.4a a 3D picture is presented which provides a clear view on how the water is retained by the Jangwani bridge in the upstream region



(a) Overview of the wetland region where the BRT-depot is located (b) Detailed overview of the BRT-depot and the flood problems, (Ramani Huria, Dar Es Salaam, 2019)

Figure 3.3: Figure a: general overview of the wetland area, where the BRT-depot is situated Figure b: more detailed overview of the Msimbazi river and the buildings and locations prone to flooding.



(a) Overview picture of the Jangwani Bridge functioning as a dyke,(Ramani Huria, Dar Es Salaam, 2019)

(b) The Jangwani bridge clearly functions as a dike in this picture.

Figure 3.4: Figure a: Overview picture of the Jangwani Bridge functioning as a dyke,(Ramani Huria, Dar Es Salaam, 2019), Figure b: The Jangwani bridge clearly functions as a dike in this picture.

where the depot is located. In Figure 3.4b, a picture taken from the side of the Jangwani bridge, also depicts how the the Jangwani bridge acts like a dyke. Furthermore, increased build-up areas inside the floodbanks in upstream areas of the Msimbazi river decreases the retaining capacity of these flood banks thereby increasing the water flow velocity. This additional velocity translates into an increased simultaneously experienced water volume in downstream regions such as the region where the depot is located. Figure 3.7 provides a clear view on this process.

From the interviews held with BRT-staff the following properties of the flood events at the BRT-depot are determined. <sup>1</sup> These properties will help determining data sets on the flooding event stated in section 5.

- Firstly, the Msimbazi river rises from its banks. Secondly, the water level rises further and floods the floodplains in which the BRT-depot is located.
- The highest recorded water level during a flood is around two meters from the ground floor of the BRT-depot.
- It takes between 10 hours and 48 hours for the water level to go down and operation to be continued.

<sup>1</sup>information about the properties of the flood events at the BRT-depot is obtained from the interview held with the bus-driver and Mister Deus, full interview can be consulted in Appendix B



- The length of a flood is correlated with the water level at the BRT-depot. This means that a flooding event increases in length in a linear fashion with the maximum water level.

In section 2.1 four types of flooding causes are distinguished. The flooding problems faced by the BRT-system at their depot is clearly an example of fluvial river flooding. In this situation, rainfall accumulates in the Msimbazi river by a run-off process over land. The rainfall increases the water level in the Msimbazi river, thereby emerging from its banks and floods the surrounding region.

### 3.2.1. BRT-system and how it is currently dealing with flooding problems

In this subsection an overview is provided on how the BRT-system as an organization responds on a catastrophe such as a flooding event as it is now. By assessing how the BRT-system responds and what type of measures there are already in place a better understanding is created on what type of EWS has to be designed and how it has to be implemented. As mentioned in in section 1.5 data on the BRT-system is obtained by interviews with personnel of the BRT-system. The questionnaire can be consulted in appendix A, the transcripts of these interviews can be found in appendix B.

#### Emergency plan flooding BRT-depot

The following three emergency plans have been developed by DART during the year 2018. These emergency plans are developed to mitigate consequences to the BRT-depot caused by a flooding event. Each emergency plan is tailored for a distinguished situation. All emergency situations start with the following pre-conditions.<sup>2</sup>

1: the Head Transport Officer is in charge of preparing the drivers database showing their current residence, phone numbers and designated routes. 2: All staff members are aware of the emergency plans and are always on alert during the rainy season and should be reachable at all times.

- Scenario 1, situation: all buses are out operating and the depot is inaccessible due to water or other reasons.

In this scenario all buses will be parked in the terminals i.e. Kimara, Terminal, Gerzani Terminal, Kivukoni Terminal. The selected terminal is determined in order of their daily dispatches. Drivers and Transport officers are updated on the fuel states of each bus. Each terminal is equipped with a mobile fuel tanker available for refueling. Security is maximized at all terminals as the buses will have to stay there overnight. The police-force and UDART are consulted to enhance the security at these terminals.

- Scenario 2, situation: BRT-depot is inaccessible and the Jangwani road is closed.

In this case the Jangwani bridge and -road are flooded, the bus routes are split and an emergency route is introduced which is as followed.

1: on the Kimara side the following routes are determined: Mbezi to Kimara, Kimara to Morocco and Kmiara to Magomeni Mapipa.

2: on the CBD side the following routes are determined: Gerzani to Muhimbili, Gerazni to Kivukoni and Kivukoni to Muhimbili.

When the BRT-depot is inaccessible and the Jangwani road is closed, first this information is disseminated to all personnel especially cashiers and terminal supervisors so that all passengers are made aware of the situation. All corridor roads are cleaned as fast as possible. This is performed with hired machines for cleaning mud and pumps to clear out the water.

- Scenario 3, situation: All buses are inside the BRT-Depot and there is risk of a flooding event inside the depot.

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<sup>2</sup>All information about the emergency plan is obtained from the interview held with Mister Deus, full interview can be consulted in Appendix B

In this scenario the pre-condition is that all Transport Officers and Security Officers are on high alert and constantly monitoring the water level at the Jangwani Bridge. Furthermore, an adequate amount of bus drivers have to be present at all times at the BRT-Depot.

Action plan: All available drivers start driving the buses to nearby terminals while the depot is still accessible. 70% go to the Kimara side and 30% to the CBD side. All transport officers communicate to all drivers nearby to join the operation and assist in the relocation of the buses.

Make note, scenario three and the associated mitigating action is further used in this study and in the design of the EWS. This is due the fact that the first two scenarios reason from a flooding event that is already in process.

Several other issues also have to be taken care of concerning other problems not related to the buses such as:

- Electricity has to be shut off at the depot.
- The fuel availability needs to be checked at all terminals and complemented if necessary.
- Relocate all movable tools from the depot workshop to the Gerzani terminal.

### Communication matrix

There are two main information streams inside the BRT-system concerning flooding hazards. The first one is the weather forecasting information stream provided by Tanzania Meteorological Agency (TMA) to DART and UDART. In this information stream TMA provides a weather forecasting to DART. This forecasting is communicated via email or via mobile phone. Subsequently, DART interprets this weather forecast and forwards this to UDART in the form of an advice on how to respond. This advice can contain various actions and precautionary measures proposed to UDART. This advice is also communicated via email or mobile phone.

The second information stream is the internal information stream between staff members. In order to execute one of the three previously mentioned scenarios properly and safely the same communication matrix is used to make sure that the information is dispersed through the UDART organization as secure and fast as possible. All staff members are expected to be aware of this communication matrix. The communication matrix looks as follows and should take less than 5 minutes. 1. Transport Officers and Supervisors → 2. Operational managers, service delivery manager, finance manager and safety officers → 3. Chief of Operation and Compliance Manager → 4. MD/Director. Every profession previously mentioned is responsible for the dispersion of the provided information to the part of the BRT-organization for which he or she is responsible<sup>3</sup>.

### Current EWS's in place, high alert status

The BRT-system has already two EWS's in place that are used to provide knowledge on a possible flooding event. The first EWS is based on the weather forecasting prediction for the coming 7 days provided by TMA. This forecasting provides information on the probability on a rainfall event and is used by the BRT-system to determine their level of alertness. In principle there are two alert statuses.

- Alert status 1: no increased flooding risk

This alert status could be considered as 'normal' and is maintained outside the rainy season when the weather forecasting provided by TMA indicates that there is no significant change on a flooding event.

- Alert status 2: increased flooding risk

This alert status is implemented when there is an increased risk on a flooding event based on the weather forecasting provided by TMA. During this situation all UDART personnel should be on high alert and

<sup>3</sup>All information about the communication matrix is obtained from the interview held with Mister Fanuel, full interview can be consulted in Appendix B

ready to respond on a possible flooding. This means that enough bus drivers and other personnel should be available at the BRT-depot, ready to drive the buses to a safe location.

The second EWS in place is the water level determination by a staff member of UDART at the Jangwani bridge. This EWS is actually used to determine if a mitigating action is implemented. When the water level surpasses a certain threshold value UDART makes the decision of implementing a scenario based on a situation as previously described. <sup>4</sup>

### 3.3. Study Area

Dar es Salaam, located on the east coast of Tanzania border the Ocean to the east and the Pwani region to the other side. The total land area is 1.630 km<sup>2</sup> which is about 0.2% of the total Tanzania mainland (Saha et al., 2014).

Dar es Salaam and its greater region is part of the coastal catchment area of the Wami/Ruvu basin. Dar es Salaam can be divided into four major catchment areas belonging to four major coastal rivers: Msimbazi, Mzinga, Kizinga and Mpiji. The Msimbazi river rises from the Pugu forest and flows through Dar es Salaam into the Indian Ocean.

Of all river systems, the Msimbazi river has the largest hydrological impact in the Dar es Salaam region. The study area is fully mapped in terms of buildings, elevation height and drainage system by the Ramani Huria project. Phase one and the Depot of the BRT-system are both located inside the Msimbazi catchment area, therefore this region will be the main focus point of this study. Figure 3.1b illustrates a full overview of the Msimbazi river and the catchment area that drains to the depot. Figure 3.5 depicts all six BRT-phases and their location inside the Msimbazi catchment area.

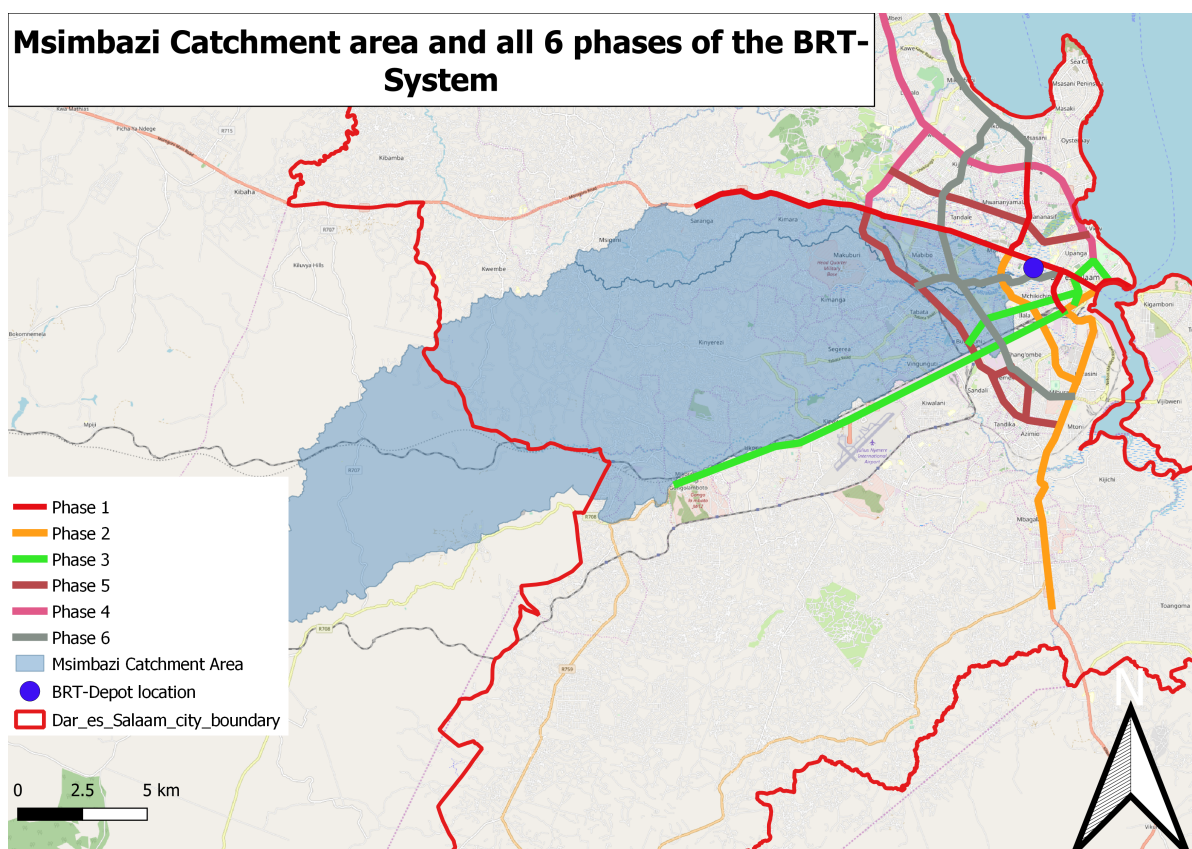
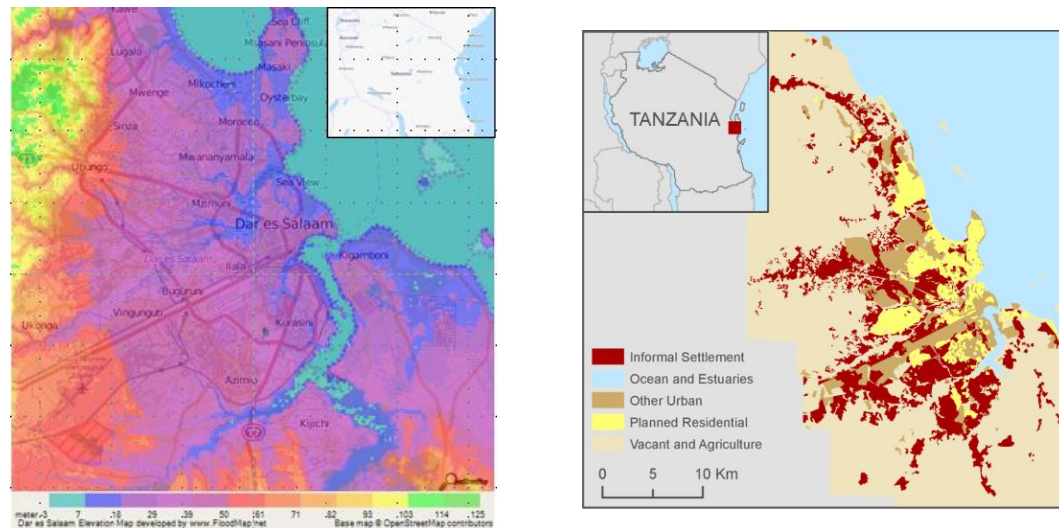


Figure 3.5: Location of the Msimbazi catchment area and the BRT-phases.

<sup>4</sup>All information about the EWS's in place and the high alert status are obtained from the interview held with Mister Ami, full interview can be consulted in Appendix B



(a) Altitude chart of Dar es Salaam, (NASA's SRTM, [uzas, 2016](#))  
 (b) Illustration of land use in Dar es Salaam (R.V. Sli-

Figure 3.6: Figure a: altitude chart, Dar es Salaam. Figure b: Land use in Dare es Salaam.

### 3.3.1. Topography

Figure 3.6a shows the elevation map of Dar es Salaam, it is generated using elevation data from the National Aeronautics and Space Administration (NASA) 90m resolution Shuttle Radar Topography Mission (SRTM) data. Dar es Salaam is clearly located in a low lying region with little altitude differentiation, this is because the city is located inside a delta region. The total length of the catchment area is approximately 35 kilometers, its main tributaries are Sinza, Ubungo, and Luhanga. Its catchment area is roughly 289 square kilometers. The Pugu forest is located 200 meters above sea level, the catchment area has therefore a slope of 0.04 m/m (Saha et al., 2014). It is clear that large parts of the Msimbazi catchment area are prone to flooding from both rivers and the ocean (Kebede & Nicholls, 2011). More than 80 percent of the people in Dar es Salaam resident in unplanned settlements with poor drainage and flooding protection infrastructure. Significant parts of these unplanned settlements are located in the flood banks of the rivers in Dar es Salaam, thereby making them prone to year round flooding and add to additional flooding problems in down stream regions.

### 3.3.2. Climate

Dar es Salaam is subjected to a binomial rainfall distribution and receives roughly 1100 mm/year per year. The first rainy season is from mid-March to the end of May and is referred to as the long rainy season. The second rainy season is from mid-October to late September and is referred to as the short rainy season. However, with Dar es Salaam being a coastal city, small rainfall events occur the whole year round. Dar es Salaam has a tropical climate, typified by little temperature changes (ranges from 20 to 30 Celsius) and humid conditions. Reason for this is the proximity of the equator and the warm Indian Ocean (Shemdoo, Rugai, & Fantini, 2016).

### 3.3.3. People and land use

Urban regions in Dar es Salaam are developing and growing fast, the population will grow to 10 million people the coming decade. This is most visible along the four main roads that connect the city with the rest of the land. With the increase of the population the total build-up area is also increasing, this changes the land from permeable soft soil to impermeable paved roads. These roads increases the



run-off ratio thereby contributing to the flooding problem. Expectations are that the increase in build up areas will contribute to the impacts of flooding both in numbers and in impact (Huvisa, 2012). In figure 3.6b an overview is presented of the land-use. Figure 3.7 shows a 3D overview of the Msimbazi River and the houses that are constructed on its flood banks. These unplanned "neighborhoods" are located on almost every flood bank on every river in Dar es Salaam. People tend to live here because of the proximity to the inner city where the economic activity is located and the housing cost is relatively low (Secretariat et al., 2011).



Figure 3.7: Build up sections of flood banks along the Jangwani Bridge. These build up regions can be found along the banks of all rivers in Dar es Salaam. (Ramani Huria, Dar Es Salaam, 2019)

### 3.3.4. Rainfall pattern in Dar es Salaam

For this study, the spatial correlation of the rainfall pattern in Dar es Salaam is checked. This is done to determine if forecasting data obtained from rain-gauges distributed over the Dar es Salaam region are dense enough in space to describe the spatio-temporal dynamics of rainfall. The correlation between data obtained from different rain-gauges is determined with a Pearson correlation method as described by formula 3.1. With the Pearson method the correlation between rain-gauges is determined, these correlation values are plotted by its corresponding  $\Delta x$  in meters distance between the rain-gauges in a scatter plot. Subsequently, a trend line is plotted in the same graph. Together, the scatter plot and trend line provide insight on the rainfall patterns and correlation over the distance in the Dar es Salaam region. Figure 3.8 illustrates the rainfall correlation over distance in Dar es Salaam. Various studies such as (Svoboda, Máca, Hanel, & Pech, 2015) validate that the correlation over distance, illustrated in Figure 3.8, is high enough to use as a data source for the EWS designed in this study. For example, the spatial correlation in Dar es Salaam is similar to the correlation in European regions such as the Netherlands. Figure 3.8 also depicts that even the hourly rainfall data shows significant correlation. This also indicates a significant correlation, and this is the scale of interest.

The evaluation of the rainfall pattern in Dar es Salaam is performed with data obtained from TAHMO-weather stations located in the Dar es Salaam region. These TAHMO-stations are also used as data source when determining several results. The TAHMO-stations are further discussed as data source in section 5.3.

$$p = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad (3.1)$$

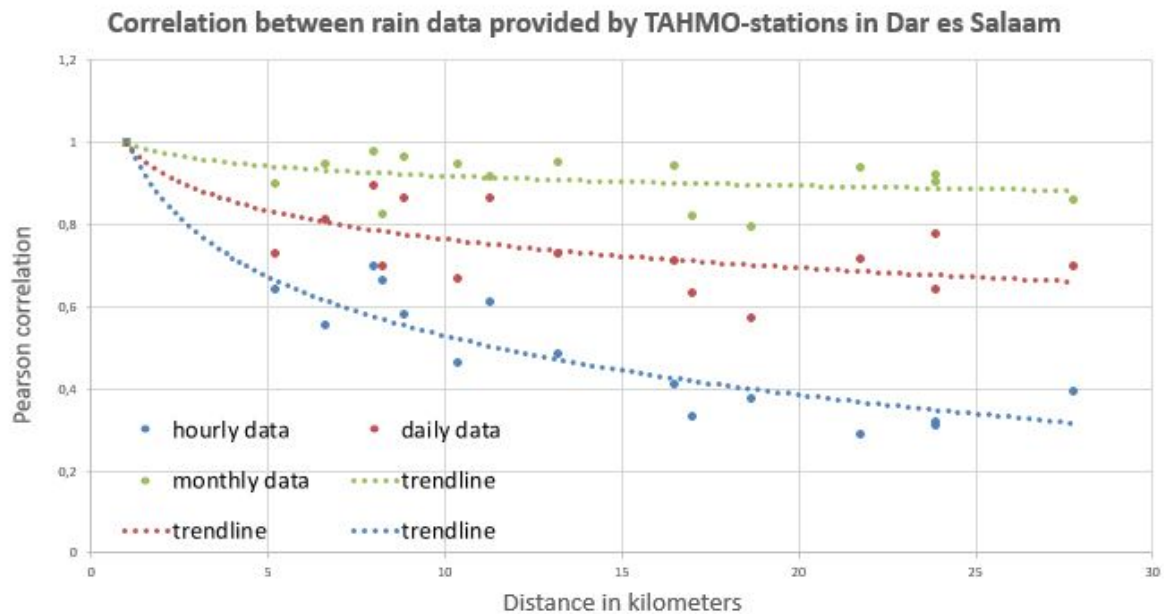


Figure 3.8: Pearson correlation graph. Illustrates the rainfall pattern of which the Dar es Salaam region is subjected to. The correlation over distance is illustrated for monthly, daily and hourly rainfall data.

### 3.4. Selecting an optical forecasting model

There are numerous types of forecasting models. In this study, a hydrological and a relational model are tailored and tested for component two of the designed EWS. One could argue that a relational model, models a system in a 'simplified' manner. It leaves out several significant factors that may influence the outcome, thereby increasing its margin of error and lowering its predicting power. The advantage of a relational model is, that it is efficient and relatively easy to implement. A hydrological model, on the contrary, does take into account the physics of a system. It thereby takes into account important factors that could influence the predicting power. It therefore has normally a lower margin of error and a high predicting power. However, a hydrological model is complicated and consist of many factors that have to be determined. Furthermore, hydrological models are, because of there complexity, more difficult to implement and operate.

Therefore, in this study, a comparison is made between a hydrological model and a relational model. The predicting power and the consistency of both models are tested and analyzed. Based on the distinction between the models an assumption is made on which model is the better fit for component two for the designed EWS.

A regression analysis is used to design the relational model. The 'Regression analysis' is a widely used method in statistical modeling. It provides insight and understanding on how the value of a dependent parameter changes when one of the independent parameters is changed. In this study, the relationship between forecasting data and flood events will be used to determine for which forecasting values a certain probability of a flood event is determined by the EWS.

In order to ensure that the EWS will use an optimal relationship between the forecasting and flood events a supervised training and validating method will be used. Historical forecasting and flood event data will be used as a training set. In order to determine the exact relationship between the two data

sets the forecasting data, used as input data, is compared for every value between an upper and a lower boundary condition with the flood event data set. Subsequently, a check is made if a forecasting data point induces a flooding event. The threshold value that provides the highest predicting power based on the training data set will be used further in this study.

When a rainfall event takes place in a hydrological cycle it causes the amount of water inside a hydrological system to increase and thereby increasing the run-off flow. In this case study, the increased flow causes the water level to rise which could lead to a flooding event. Several factors play a role in the likelihood of a rainfall causing a flooding event. Such factors are: groundwater level, saturation index, build-up areas, soil types etc. For this study an existing hydrological model named W-flow simulates these conditions and is calibrated for the case study at hand.

W-Flow has been developed by research institute Deltares and has practical uses for modelling several hydrological processes in a study area of interest. Deltares has designed and calibrated a W-Flow model specifically for the Dar es Salaam region. This model calculates flow and water levels on a relatively large scale with a tile resolution of 50 meters. A W-Flow model takes several factors into account that have an impact on the hydrological behaviour of a study area.

Figure 3.9 presents a schematic overview on how a W-Flow model functions and which variables have to be implemented

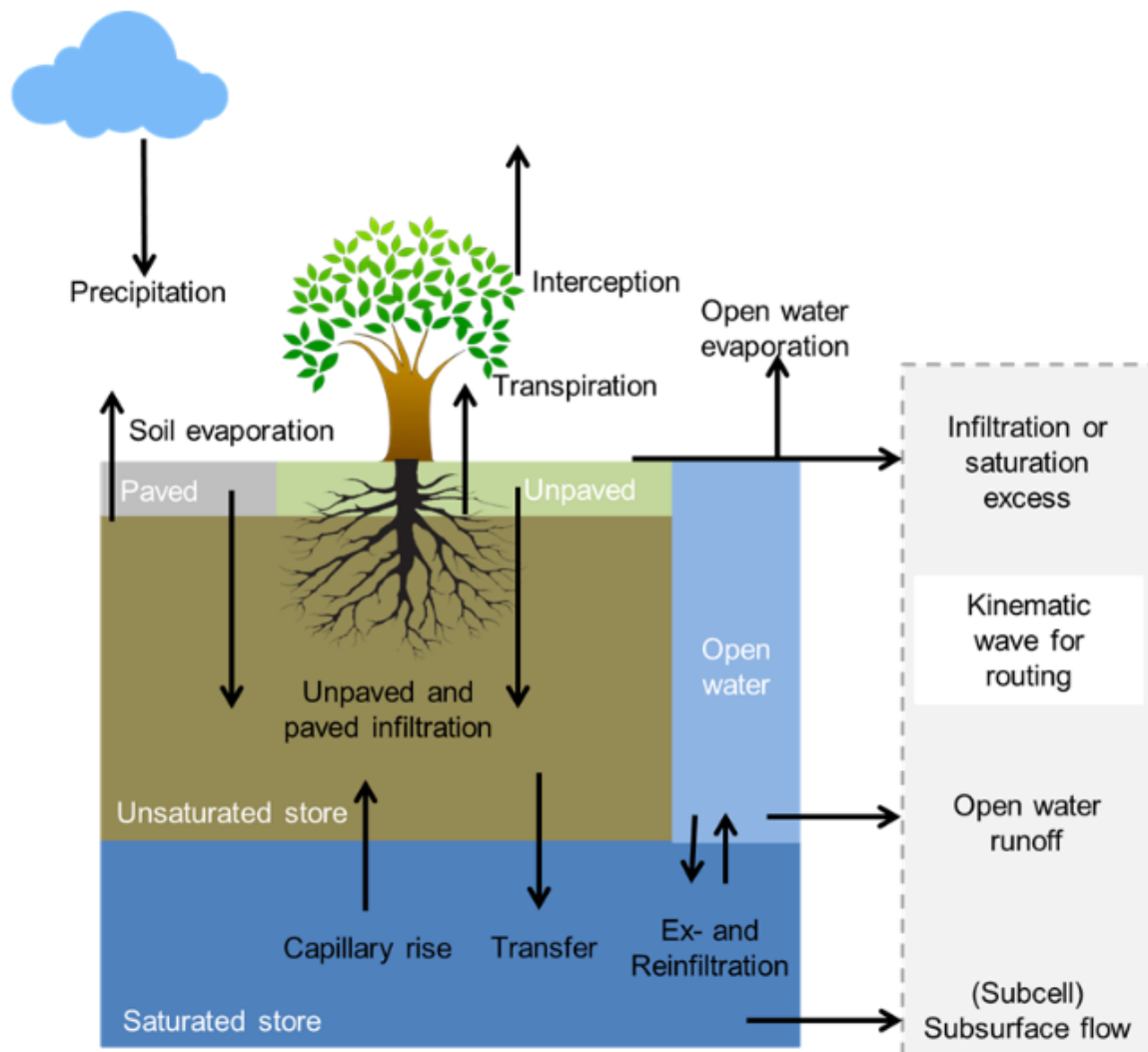


Figure 3.9: Schematic overview of all parameters inside the W-flow model, (W-flow model, 2019)



# 4

## Methodology design EWS

This chapter describes the used framework and the implementation of the EWS in the BRT-system. It also describes how the economic value of the designed EWS is determined. The results based on the methods stated in this chapter are stated in chapter 9, where the final EWS is presented.

In section 4.1 the implementation method and location of the EWS in the BRT-system is stated. In section 4.2 the framework of the designed EWS is stated. In section 4.3 the method to determine the economic value of the EWS is described.

### 4.1. Implementation method and location in the BRT-system of the designed EWS

The BRT-system has currently two functioning EWS's in place to provide an early warning for a risk on a flood event at their depot. The first EWS is based on the weather forecasting prediction for the coming 7 days provided by TMA. This EWS provides a low accuracy flood warning with an extended lead-time. The second EWS is the water level determination by a staff member of UDART at the Jangwani bridge. The second EWS has an high accuracy on flood warning with a short lead-time. The second EWS is executed if the prediction by the first EWS states that there is an elevated risk on a flood event. As one would expect, the second EWS does not always provide a lead-time sufficient enough to execute the action of removing all busses from the depot<sup>1</sup>.

The EWS designed in this study is implemented along side both existing EWS's thereby creating a maximum potential for responding on a flood risk. The designed EWS will have to provide a lead-time that enables the BRT-system to implement a mitigating action that is not possible with the current two implemented EWS's. Figure 4.1 provides an schematic overview of all three EWS's.

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<sup>1</sup>The statements on the two EWS's already in place are reproduced from section 3.2.1

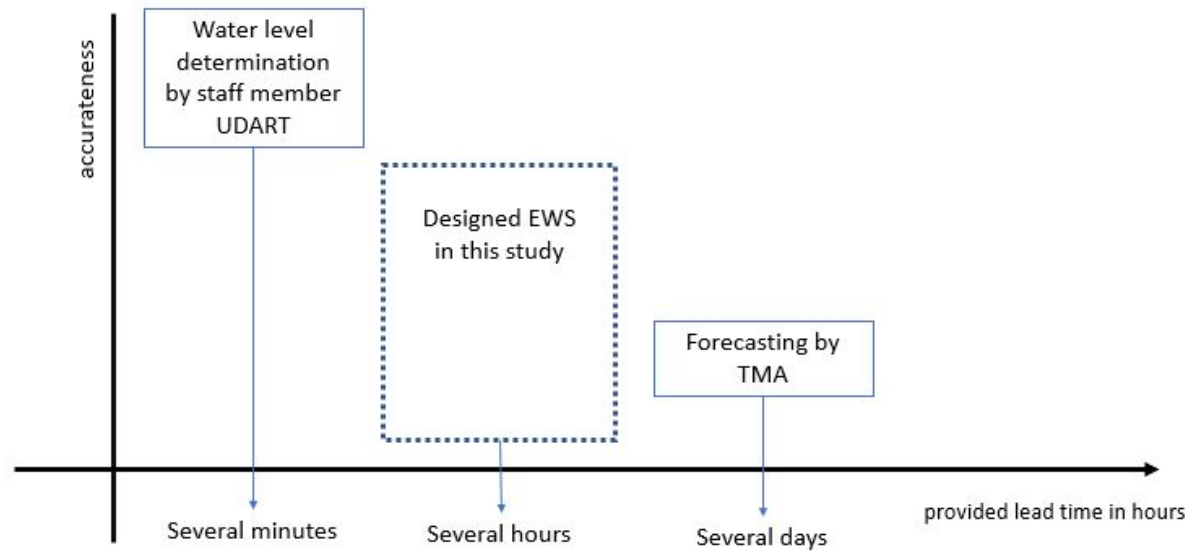


Figure 4.1: Schematic overview of all three EWS's. The y-axis presents the accurateness and the x-axis presents the provided lead-time for all three EWS's.

## 4.2. Framework of the designed EWS

In this subsection all components of the designed EWS are stated again in detail and suited, for the case study at hand. The design of the EWS for this study is based on the theoretical framework stated in section 2.2.

- Component one: forecasting data input

Real-time forecasting data input is the first component of the designed EWS. The forecasting method has to produce data that can predict a flood event, with a lead time in which the EWS can produce a warning and the BRT-system can implement its mitigating action. The determination on which forecasting location and method is used for this EWS is stated in section 6.

- Component two: data processing

The data output as described above is processed by a relational or a hydrological model. In section 7 both model types are analyzed and the optimal model for this case study is determined.

- Component three: Flood probability determination

The output data generated by the relational or hydrological model as stated above, is compared with pre-defined threshold values that, when exceeded, will issue a warning in the form of a probability on a flood event. The communication method of the output is based on the fact that it is used by professionals in a professional environment as described in section 2.2. Therefore, a probabilistic output is chosen over a deterministic one. Along with this flood event probability, an advice is communicated on how the BRT-system should act. This advice is based on the principle of optimal economic perspective. This means that the BRT-system will act in a matter that from an economic perspective is determined 'optimal'. In section 8 the method and the result on component three is stated.

## 4.3. The economic value of the designed EWS

In order to determine the economic value, a method is used described in 'Estimating the benefits of single value and probability forecasting for flood warning' described by (Verkade & Werner, 2011).



	Event Observed	Event Not Observed	<i>sum</i>
Warning issued	hits: $h(C + L_u)$	false alarms: $f(C)$	$w$
Warning NOT issued	missed events: $m(L_a + L_u)$	correct negatives: $q(-)$	$w'$
<i>sum</i>	$o$	$o'$	$N$

Table 4.1: Contingency table, This table indicates the four outcomes of an EWS. This type of contingency will be used for both determining the optimal EWS based on historical data and to validate the economical value of the EWS when in place, (Verkade & Werner, 2011)

In this method the model of Expected Annual Damage (EAD) is combined with the Theory of Relative Economic Value (REV), (Murphy, 1985) and (Zhu, Tóth, Wobus, Richardson, & Mylne, 2002)). In this study a probabilistic forecasting system will be used because the end user is a professional agency that works in a professional environment as previously described in 3.4. Moreover, a professional agent can make its own assumption on a probabilistic decision rule that is based on its personal cost-loss ratio, thereby optimizing its response on expected costs.

In order to determine the economic value of the designed EWS in this case study, the following financial cost need to be determined.

- The cost of implementing a mitigating actions. It is important that all factors are taken into account, such as the cost of the action itself and the lost revenue caused by loss in operation.
- The avoided cost when a mitigating action is implemented timely and effectively.
- The unavoidable cost that cannot be avoided by implementing a mitigating action.

Answers on these questions are obtained by interviewing the BRT-system personnel as stated in 5.

The true economical value  $V$  is determined with the contingency table as illustrated in table 4.1. The contingency table shows forecast/observations pairs for flood events. This is used to determine the cost when there is an imperfect EWS in place. These cost can be compared with the costs when there is no EWS in place and when there is a perfect EWS in place. By combining all three possibilities a true economical value which is in this case  $V$  can eventually be expressed. All stated formulas are obtained of (Verkade & Werner, 2011).

The situation where no EWS is in place is described by formula 4.1.

$$C_N = o(L_a + L_u) \quad (4.1)$$

Where

- $C_N$  = Endured cost when no EWS is in place,  $o$  = sum of events observed,  $L_a$  = avoidable cost,  $L_u$  = unavoidable cost.

The situation where there is an perfect EWS in place is described by formula 4.2. Both these formula's are expressed in the same units as used in the contingency table.

$$C_P = o(C + L_u) \quad (4.2)$$

Where

- $C_P$  = Endured cost when perfect EWS is in place,  $o$  = sum of events observed,  $C$  = cost mitigating action,  $L_u$  = unavoidable cost

The imperfect EWS can be described with formula 4.3 and is based on the contingency table.

$$\begin{aligned} C_I &= h(C + L_u) + fC + m(L_a + L_u), \\ &= oL_u + (h + f)C + mL_u \end{aligned} \quad (4.3)$$

Where

- $C_I$  = Cost endured when imperfect EWS is in place,  $h$  = hits,  $L_u$  = unavoidable cost,  $f$  = false alarms EWS,  $m$  = missed events,  $L_a$  = avoidable cost,  $o$  = sum observed events.

The True Economic Value (V) of an imperfect EWS is described with formula 4.4 which translates to formula 4.5 when implementing the units as described in the contingency table. Make note, that in the results section the final Relative economic value of an imperfect EWS is not stated. This is due the fact that this can only be established, after a substantial amount of time has passed in which the imperfect EWS is implemented.

$$V = \frac{C_N - C_I}{C_N - C_P} \quad (4.4)$$

Where

- $V$  = True economic value EWS,  $C_N$  = cost endured when no EWS is in place,  $C_I$  = cost endured when an imperfect EWS is in place,  $C_P$  = cost endured when a perfect EWS is in place.

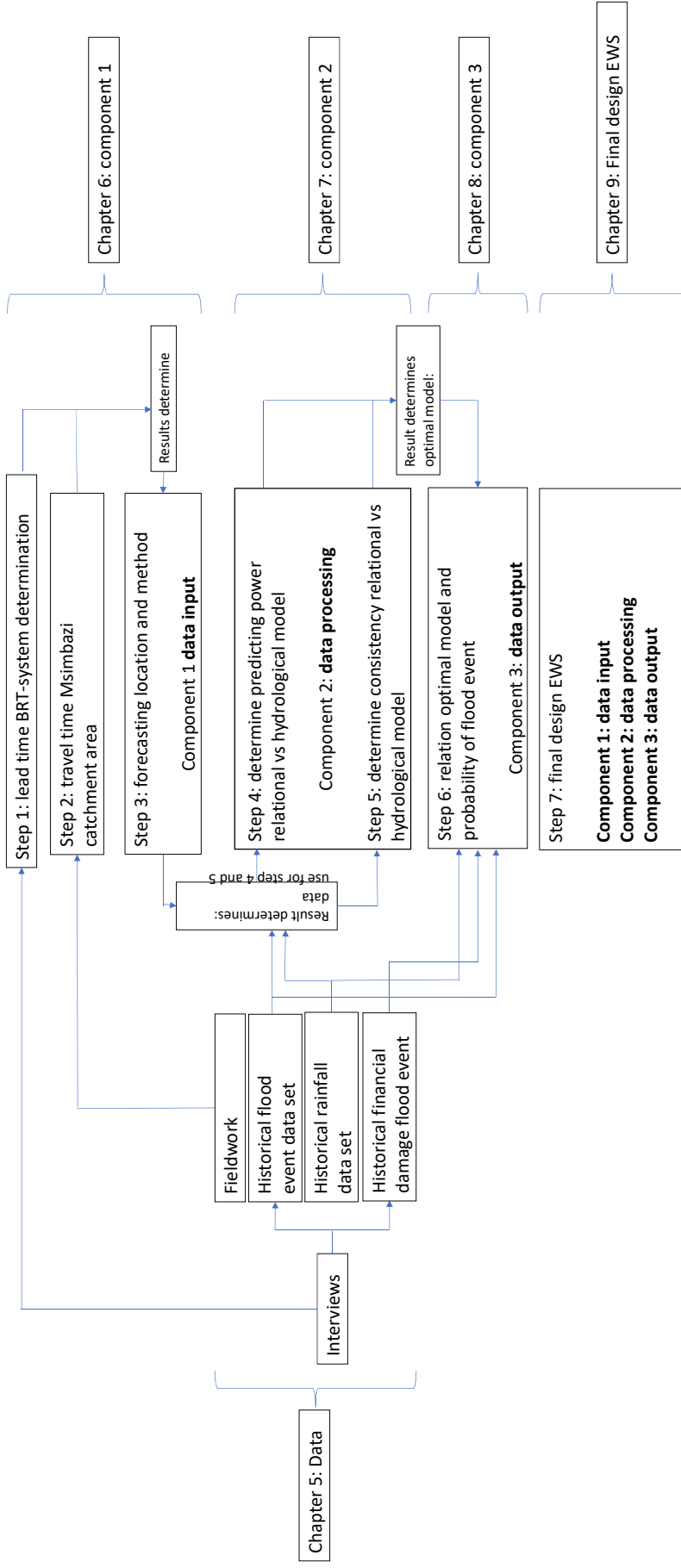
$$V = \frac{oL_a - (h + f)C - mL_a}{oL_a - oC} \quad (4.5)$$

Where

- $h$  = food events,  $C$  = cost mitigating action,  $L_u$  = unavoidable cost,  $f$  = false alarms EWS,  $m$  = missed events,  $L_a$  = avoidable cost,  $o$  = sum observed events,  $h$  = hits

On the next page, a workflow and a summary is presented that elaborates on how the following chapters are related to each other. In these chapters, the design of the components are described, the used data sources and data sets are stated and the final design of the EWS is determined.





## 4.4. Summary

In this section a summary is presented for the chapters 5 to 9. These chapters describe what methods are used to design the framework of the EWS. In this summary each of these chapters are described and how they are linked together. This summary is based on the previously presented workflow 4.3. The report set-up for this study is such, that the results of the designed framework of every component are stated in the same chapter. This is due the fact that the results of a certain component determines the method used to design the following component, this is indicated in the workflow with arrows. The used data sources and the created data sets used to obtain the resulting framework is stated in a separate chapter. This is due the fact that all data sets are used multiple times for different components. The workflow indicates with arrows which data sets are used for which component.

Furthermore, the research questions that relate to a certain chapter and thereby a certain component, are stated in the same chapter. Based on the design of every component, the final design of the complete EWS is stated in a separate chapter as indicated in the workflow.

Chapter 5 is called 'Data'. In this chapter all used data sources and the created data sets in this study are stated. In this study all data sets are used multiple times, and are therefore stated in a separate chapter. Furthermore, chapter 5 states the method used to ensure that in the future, flood events are monitored and registered to enhance the knowledge on the flood problems at the BRT-depot.

Chapter 6 states the methods used to design the framework of component 1 and the following results. In component 1 the data input used for the EWS is selected. This selection is based on the principle that the required lead-time by the BRT-system has to extend the time needed to implement a mitigating action. Therefore, this required lead time is determined. Subsequently, the travel time and the maximum time of concentration of the Msimbazi catchment area is determined. Based on this knowledge, the optimal forecasting method and location is determined to produce the needed input data. With this data a forecasting has to be produced that can predict the probability of a flood event for the required lead time. In addition, this forecasting needs to be as accurate as possible. Based on the lead-time condition and the accuracy preference, an optimal location and method is selected to produce forecasting data. The forecasting data is derived from a process in the hydrological cycle of the Msimbazi catchment area. Therefore the discharge levels of the Msimbazi river, rainfall levels at several locations in the catchment area or satellite imagery will be used as forecasting data.

- By designing the framework of component 1 research question 1, 2 and 3 are answered.

Chapter 7 states the methods used to design the framework of component 2 and the results that follow. In component 2 of the EWS the input data is processed by a model. In order to determine the optimal model, a relational and a hydrological model are compared on their predicting power and their consistency. The predicting power of both models is determined by forcing them with a historic forecasting data set and let both models determine the probability of a flood event as outcome. Subsequently, this outcome is validated with a historical flood event data set. This validation is made by determining how many times the outcome of both models matches with the historical flood event data set, and how many times there is a mismatch. Based on this information, a ROC-curve is produced for both models. Based on these ROC-curves a determination is made on the model with the highest predicting power by determining the surface area beneath these ROC-curves. The ROC-curve with the largest surface area beneath it represents the model with the highest predicting power.

Furthermore, a consistency check is made for both models with a 'leave one out' method. With this method, one data point of the flood event data set is taken out and a new ROC-curve is made by the same method as described in the previous paragraph. This process is repeated for every data point in the flood event data set. For the difference in the surface area's beneath the ROC-curves a standard deviation is determined and a normal distribution is produced. Based on these two analyses an optimal model is determined based on its consistency.

With the results of the consistency check and the predicting power check of both models, the optimal model is selected.

- By designing the framework of component 2 research question 4 is answered

Chapter 8 states the methods used to design the framework of component 3 and the results that follow. The output of component 3 is a probability of a flood event and an advice on if a mitigating action should be implemented by the BRT-system. The probability of a flood event is based on the output data of component two. In order to determine what probability level is associated with a certain output level, the EWS is trained. This training is performed by a supervised training method where a historical forecasting data set is forced through the model and validated with the historical flood event data set. Based on this comparison a determination is made on what probability of a flood event is associated with a certain processed data level.

With the help of a method called 'determining the optimal economic value', the advice associated with a certain probability of a flood event is determined which is communicated to the BRT-system. This advice is based on the idea that a mitigating action should be implemented in case the chance on a flood event multiplied with the cost caused by that event, surpasses the cost of implementing a mitigating action, when integrated over longer time and thus multiple events. This will provide an optimal economic outcome for an agent.

- By designing the framework of component 3 research question 5 is answered.

Chapter 9 states the final framework of the complete EWS. All components are stated together with the chosen forecasting method, the chosen model and the trained output. Furthermore, in this chapter, the True Economic Value of the designed EWS is stated as well.



# 5

## Data

In this study, three data sources are used to answer the stated research questions and to achieve the thesis research objective. All sources are elaborated in this chapter. Furthermore, all data sets created from the used data sources are stated in this chapter as well. The components of the EWS that are designed with the help of a certain data set are stated as well in this chapter.

### 5.1. Interviews with staff of the BRT-System

Interviews held with personnel working inside the BRT-system are the first source. The interviewed personnel all have different backgrounds and tasks in different sections and organizations inside the BRT-System. The interviews are held in an informal setting with several pre-determined questions. The reason for this is the fact that all interviewees are experts in their own line of duties. It is therefore important that the interviewees have enough opportunity in the conversation to tell their own story, and tell the facts from their point of view. Therefore personnel from all organizations inside the BRT-system have been interviewed as well as from all management levels. The transcripts of the questionnaire can be consulted in Appendix A. The transcript of the interviews held with the BRT-staff can be consulted in Appendix B. With data collected from the interviews the following data sets are created

- A timeline with all flood events occurred at the BRT-depot since its construction in 2017. This data set is used to determine the predicting power and the consistency of the relational and the hydrological model, this is described in chapter 7. This data set is also used to determine the relation of the data output and probability of a flood event, this is described in chapter 8.
- A timeline with all flood events occurred at the BRT-depot only this timeline holds the financial damage caused by every flood event as well. The financial damage is caused by damage to assets and materials and also loss in revenue. From the interviews it becomes clear that the only avoidable cost are the cost endured by the degradation of the busses. The effected busses have to be repaired or replaced. All other cost cannot be avoided and are therefore unavoidable. This data set is used to determine the economic value of the EWS and the optimal economic warning probability on which the BRT-system has to implement its mitigating action. Both parts of the EWS design are stated in chapter 8.

Figure 5.1 depicts the timeline of all recorded flood events. Table 5.1 presents the financial information of these flood events.

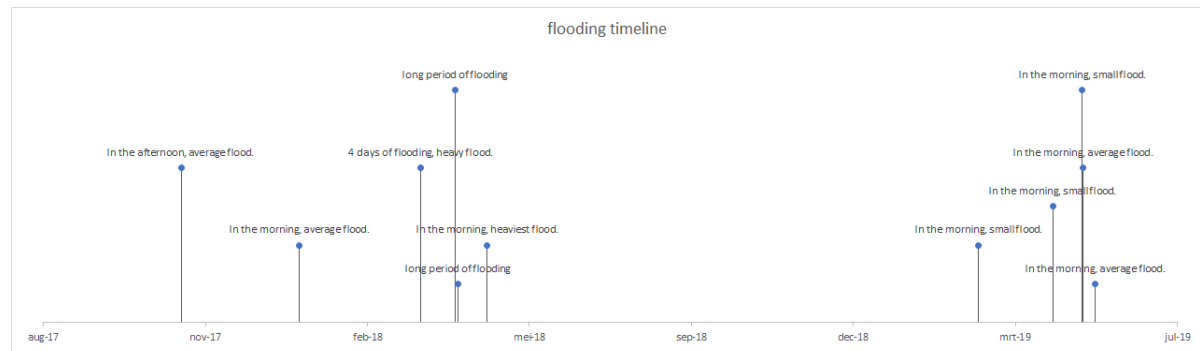


Figure 5.1: Dates flood events

Table 5.1: Financial damage flood events

Flooding	Date	Flooding type	Avoidable Cost in U.S dollars	Unavoidable Cost in U.S dollars	Flooding	Date	Flooding type	Avoidable Cost in U.S dollars	Unavoidable Cost in U.S dollars
1	27-10-2017	Average flooding	20.000	10.000	7	03-03-2019	Small flooding	5.000	10.000
2	08-01-2018	Average flooding	15.000	10.000	8	18-04-2019	Small flooding	5.000	10.000
3	24-03-2018	4 days of heavy flooding	50.000	100.000	9	06-05-2019	Small flooding	5.000	10.000
4	14-04-2018	Long period of flooding	30.000	20.000	10	07-05-2019	Average flooding	10.000	10.000
5	16-04-2018	Long period of flooding	20.000	20.000	11	14-05-2019	Average flooding	10.000	10.000
6	04-05-2018	Long period of flooding	100.000	100.000					

## 5.2. Fieldwork

The second source is a local inspection performed at five locations along the Msimbazi river in Dar es Salaam. All five locations are illustrated in Figure 5.2. The reason for choosing these locations is because during the inspection these locations were determined representative for their surrounding area. For the five visited locations, the river profile and the river flow during dry conditions were measured.

The data obtained by the fieldwork inspection is used to determine the travel time and the maximum time of concentration of the Msimbazi catchment area, this is described in chapter 6.

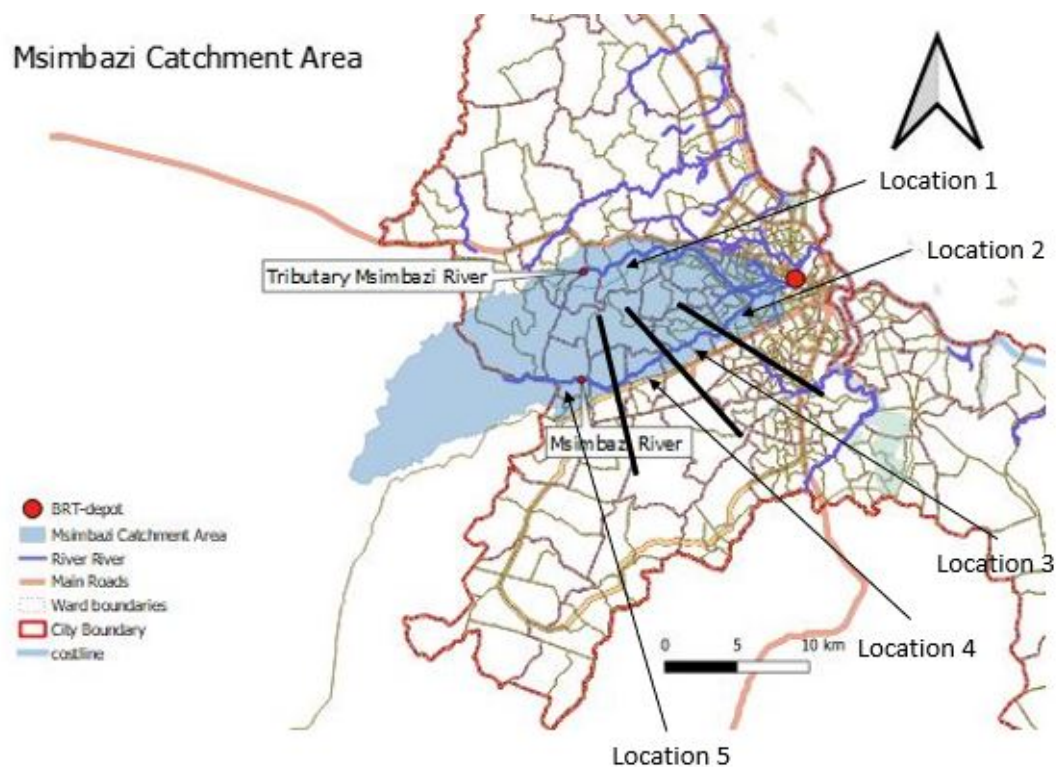


Figure 5.2: Schematic overview of locations where flow speed has been measured of the Msimbazi river. The black arrows indicate the areas of the Msimbazi river assigned to that measuring location. The black lines indicate the boundaries of these areas.

### 5.3. TAHMO-stations

TAHMO established eleven hydro-meteorological stations in the Dar es Salaam region of which eight measure rainfall on an hourly basis in mm. The TAHMO-stations are owned by the Ministry of Water and Infrastructure of Tanzania. The data provided by the TAHMO-stations is uploaded real-time in the form of a data point and stored on the server that can be accessed. The rainfall data is used in this study to provide historical and real-time data sets. The locations of the TAHMO-stations are depicted in Figure 5.3. All eight TAHMO-stations have been operating since 01-01-2018. However, several TAHMO-stations have not been recording or have not been producing usable data during this period. Therefore, before the TAHMO-stations are further used in this study, all TAHMO-stations are subjected to two analyses.

First, a check is made on if any data points are missing. The TAHMO-stations are required to create one data point every hour. With the help of a python script the amount of data points can be counted and compared with the amount of data points required between 01-01-2018 and 01-05-2019, which is equal to the amount of hours in this period. Second, a double mass analysis will be performed to check the consistency of every TAHMO-station, thereby determining which TAHMO-stations have a significant off-set towards the others. It is important to have a clear overview of possible missing data and possible off-set in between the data sets because it determines the robustness of the data supply.

Table 5.2 shows the results of the first analyses on all TAHMO-stations and Figure 5.4 provides an illustration on the double mass analysis performed on TA00272: Kinyereri primary school, TA00269: Ardhi University and TA00273: BRT. This illustration clearly shows that the rainfall in mm/hour produced by TA00272: Kinyereri primary school is significantly higher than the other stations. The double mass analyses of all 8 TAHMO-stations can be consulted in appendix D. The results of both analyses determine that the data of the TAHMO-stations stated under are not used for this study (the TA00272 Pugu station and the TA00270 Kinyereri primary school).



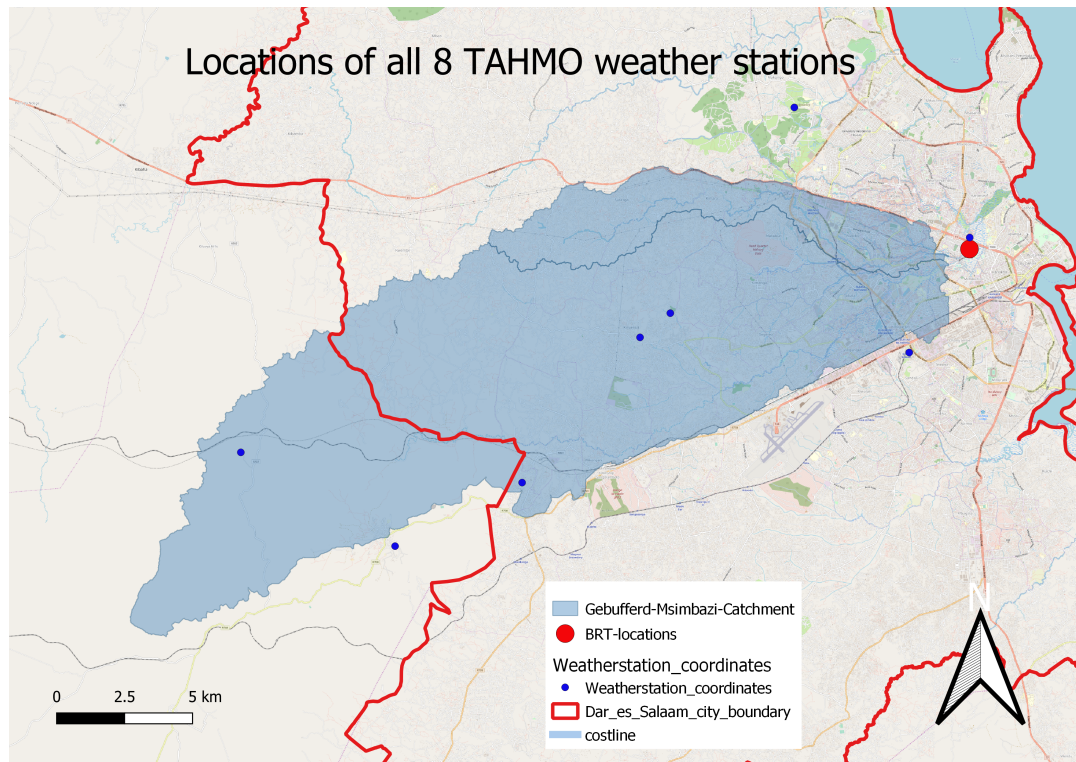


Figure 5.3: Locations TAHMO-weather stations

Table 5.2: All missing data points of every TAHMO-station for the data frame between 01-01-2018 and 01-05-2019. The TAHMO-stations produce one data point every hour.

TAHMO-Total station	Missing data points
TA00269 Ardhi University	0
TA00270 Kinyereri primary school	0
TA00271 Visegese	0
TA00272 Pugu station secondary school	1575 of 11 622 hours
TA00273 BRT	0
TA00493 Kisarawe Boma	0
TA00494 Macedonia Nursery and Primary School	0
TA00495 Tazara	4550 of 11 622 hours

- The data continuity test shows that: TA00272 Pugu station secondary school and TA00495 Tazara are missing data points between 01-01-2018 and 01-05-2019.
- The double mass analysis shows that TA00270: Kinyereri primary school produces a significant higher amount of rainfall data then the other TAHMO-stations.

A timeline with rainfall data in mm/hour measured by the five TAHMO-stations between 01-01-2018 and 01-05-2019 is determined reliable. This data source is used to create a data set. In order to create this data set, several alterations have to be made.

First, the different travel times between the TAHMO-stations and the BRT-depot cause the rainfall data measured at the same time but at a different location to 'hit' the BRT-depot at a different moment. For example, if the travel time between TAHMO-station (A) and the BRT-depot is 4 hours then the rainfall measured at the TAHMO-station will arrive 4 hours later at the BRT-depot. This arrival moment differs for all TAHMO-stations and have to be accounted for. This is done by 'moving' the rainfall data forward in time. Figure 5.5 provides an illustration of the described method. The actual travel time is determined in chapter 6.



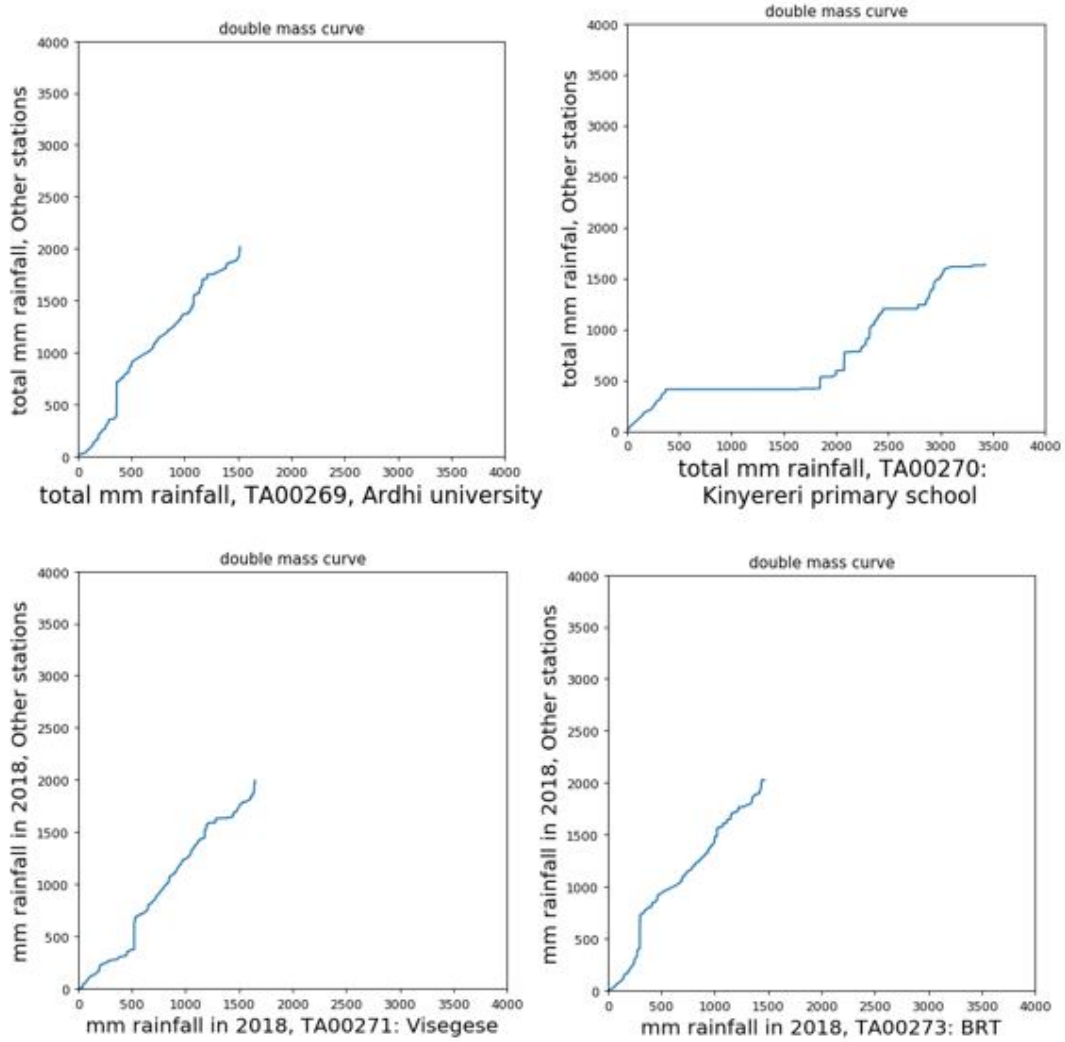


Figure 5.4: Double mass analysis of TA00269 Ardhi University, TA00270 Kinyereri primary school, TA00271 Visegese, TA00273 BRT.

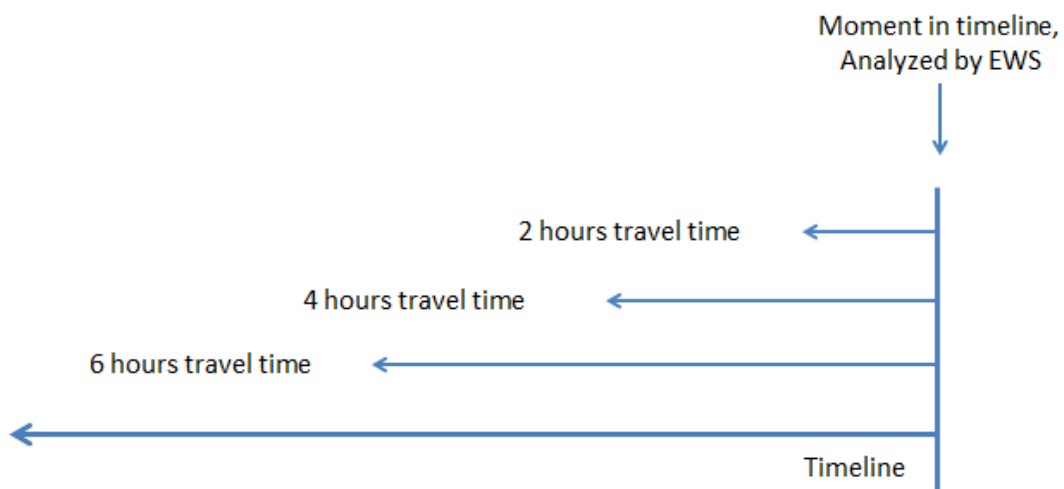


Figure 5.5: The arrows with corresponding travel time's depict how many hours the rainfall data is delayed before it is analyzed by the relational model. The 'delaying' time is equal to the travel time of a certain TAHMO-station to the BRT-depot. This action ensures that the rainfall that simultaneously arrives at the BRT-location is analyzed by the relational at the same moment.

Second, the rainfall measured by the different TAHMO-stations is summed and multiplied with the assigned surface area based on the Thiessen Polygon principle as visualized in figure 5.6 and presented in table 5.3. Make note, Figure 5.6 shows that only four TAHMO-stations are used. This due the fact that the travel time from the TA00272: BRT to the BRT depot is larger than the needed lead-time. The exact travel time from each TAHMO-station to the BRT-depot stated in table 5.3 is based on the results stated in section 6.2.2.

Table 5.3: The assigned region and travel time stated for the five used TAHMO-stations.

TAHMO-stations	THAMO-stations names and number	Assigned surface area:	Travel time to the BRT-depot:
TAHMO-station 1:	TA00271: Visegese	24 %	6 hrs
TAHMO-station 2:	TA00493: Kisarawe Boma	20 %	5 hrs
TAHMO-station 3:	TA00494: Macedonia Nursery and Primary School	40 %	3 hrs
TAHMO-station 4:	TA00269: Ardhi university	11,2 %	2 hrs

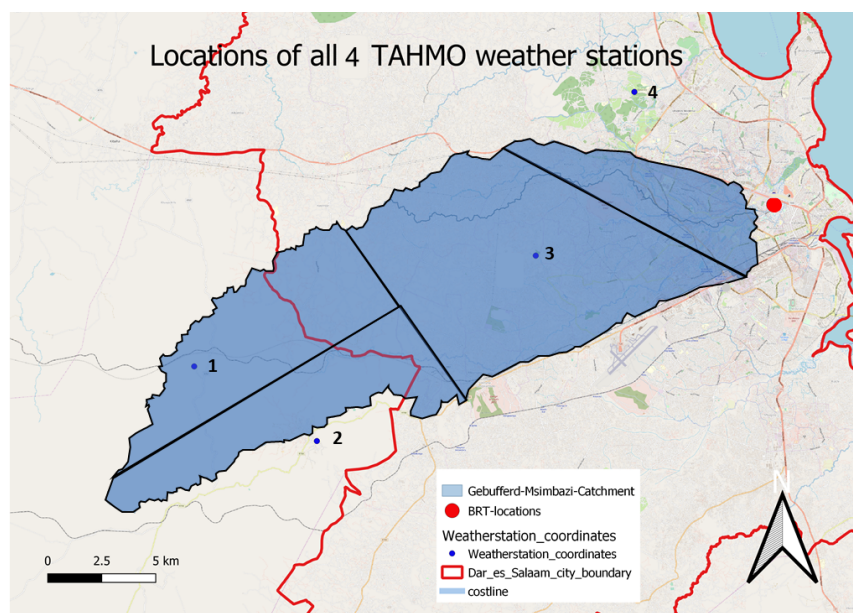


Figure 5.6: Schematic overview of the TAHMO-stations used in this study and their assigned regions based on the Thiessen polygon principle.

Figure 5.7 provides a time series the created data set. This data set is used to determine the predicting power and the consistency of the relational model, stated in chapter 7. This data set is also used to determine the relation between the data output of the optimal model and the probability of flood event, described in chapter 8.

Figure 5.7: Time line of the recorded rainfall in mm/hrs between 01-01-2018 and 01-05-2019

### 5.3.1. Hydrological model

A timeline with discharge data measured by all TAHMO-stations between 01-01-2018 and 01-05-2019 is also a created data set. This discharge data is produced by the W-flow model that uses the TAHMO-stations as input source. In essence, this data set is created from the same source, only this time adjusted by the W-flow model. This data set is used to determine the predicting power and the consistency of the W-flow model, stated in chapter 8. Figure 5.8 provides a schematic overview of the created data set.

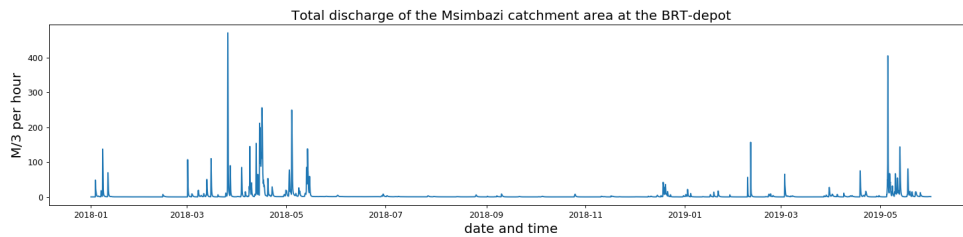


Figure 5.8: Time line of the discharge in m<sup>3</sup>/hrs at the BRT-depot between 01-01-2018 and 01-05-2019

### 5.3.2. Flooding update

This case study is the first step in creating an EWS for a local agency in Dar es Salaam. Several data sources are exploited and several methods are used to obtain the best possible product for, in this case, the BRT-system. However, the BRT-system came in to existence only two years ago. Therefore, the flood problems experienced by the BRT-depot only exist for a couple years as well. This means that the available historical data also only exist for a couple of years. To ensure the continuity of updating and improving the designed EWS a communication line between Deltares / TU-Delft and the BRT-system will be set-up to ensure a steady flow of information concerning new flood events. These flood events can be used as additional historical or validating data. This increases the accuracy of the EWS thereby providing an increased economical value for the BRT-system. A WhatsApp group will be used as communication method. This creates a fast and reliable way for the BRT-system to provide information for Deltares/TU-Delft of newly experienced flood events.



# 6

## EWS component 1: forecasting location and method

In this chapter the methods used to design the framework of component 1 and the following results are stated. In section 6.1, the methods used are stated. In section 6.2, the resulting optimal forecasting method and location are stated.

### 6.1. Method

In subsection 6.1.1 the method used to determine the lead time required by the BRT-system is stated. In subsection 6.1.2 the method used to determine the travel time and the maximum time of concentration of the Msimbazi catchment area is stated. In subsection 6.1.3 the method used to determine the optimal forecasting location and method is stated.

#### 6.1.1. Determination lead time, Werner's method

For the design of an EWS the needed lead time of the BRT-system needs to be established. The lead time is the period of time needed by an agent to prepare and execute a decision. In this case study the decision consist of implementing an action that mitigates or completely avoids financial damage caused by a flood event. In this case study, the implemented mitigating action is the evacuation of the busses from the BRT-depot. The maximum potential lead time is the time between establishing a threat and a threshold exceedance that determines the start of a flood event. In practice, the maximum potential lead time is difficult to utilize because several steps have to be taken, such as data collection and threat evaluation. These steps have to be taken first before the decision to implement a mitigating action can be taken.

In this study the method for determining the required lead time is obtained from (Werner, 2018). This method includes a framework to define the requirements for a flow forecasting system. In this case study this flow forecasting system will be used as a starting point for the proposed EWS.

With this framework a determination will be made on what the lead time requirements need to be and what type of forecasting is needed to provide a reliable warning. Every sub-component as described in Figure 6.1 will take a certain amount of time. The total amount of time to complete all sub-components is the total lead time. This schematic overview will also be used to describe the final lead time in the results section. The method illustrated in Figure 6.1 makes a distinction between the 'lead time' and the 'maximum lead time'. This distinction is made based on the fact that in most practical situations the two first components: Monitoring and Evaluation & Forecasting take a very short time and is thereby

insignificant in duration as compared to the other components.

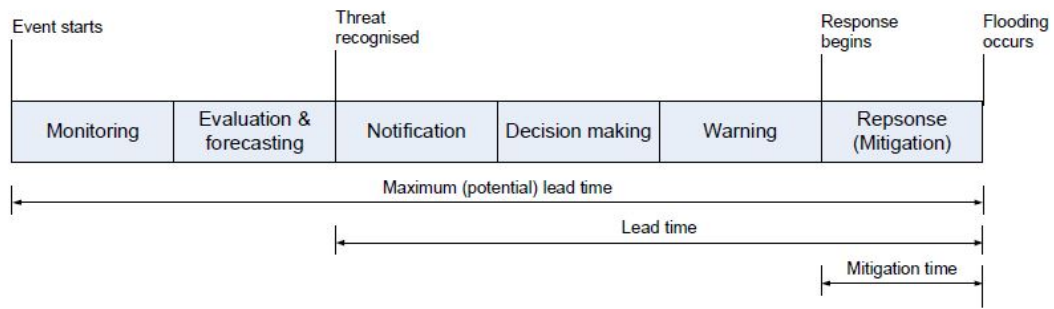


Figure 6.1: Forecasting and warning decision time line (Carsell 2004)

Figure 6.1 will be repeated in the results section of this chapter with the required time stated for each component. The required time of every sub-component will be determined with interviews with personnel of the BRT-system as described in section 5.1.

### 6.1.2. Determination of the maximum time of concentration and travel time, Msimbazi catchment area

The travel time of the Msimbazi catchment area indicates the time it takes for a water body to travel from the location where it hits the ground as rain to the end of the catchment area. The BRT-depot is located at the end of the catchment area as depicted in Figure 3.5.

The travel time of a waterbody in the Msimbazi catchment area can be divided into two section. First, the time of concentration over land, and second the travel time in the Msimbazi river. To determine the total travel time of the Msimbazi catchment area both time periods have to determined.

The time of concentration over land is based on a empirical study as described by (Li & Chibber, 2008). In this study an empirical formula 6.1 is described to formulate the 'Overland Flow Time of Concentration on Very Flat Terrains'. Of all literature consulted, this method is chosen because the case study used in this study shows most similarities with the case study at hand. The study area used in this study has a very flat slope and a mix of different soil types. Dar es Salaam is situated inside a river delta in an urban environment and has therefore similar characteristics.

$$T_c = 0.553 * L^{0.5} * n^{0.32} * \epsilon^{-0.277} * S^{0.127} * i^{-0.646} \quad (6.1)$$

Where

$L$  = Length of the watershed [m],  $n$  = Surface roughness (dimensionless factor),  $S$  = Slope of the watershed [m/m],  $i$  = Rainfall intensity [mm/min],  $T_c$  = time of concentration [min],  $\epsilon$  = Soil moisture [% ], (Li & Chibber, 2008)

The Surface roughness and the length of the watershed used in formula 6.1 are obtained from literature such as (Egmann, 1986) and (Li & Chibber, 2008). The slope of the watershed is determined with a Digital Elevation Model (DEM) delivered by the consultancy firm COWI, with approval of the World Bank. Access to this DEM was acquired from Deltares research institute. The slope of the Msimbazi catchment area extracted from the DEM is similar to the slope stated in consulted literature and stated in the case description.

To determine the travel time of a waterbody in the Msimbazi river the Manning formula is used. With this formula the velocity of a waterbody in the river during 'high' water is derived from the river profile and flow during 'low' water. The data set obtained by the performed fieldwork in Dar es Salaam as described in section 5.2 is used to establish this. Together with the slope of the hydraulic grade line

of the river and the GaucklerManning coefficient, the velocity during a wet period can be determined. The Manning equation is stated in formula 6.2.

$$V = R_h^{2/3} S^{1/2} \quad (6.2)$$

Where

$V$  = velocity [m/s],  $n$  = Manning roughness coefficient  $sm^{-1/3}$ ,  $R_h$  = Hydraulic radius [m],  $S$  = Hydraulic head loss [L/L]

By combining both methods the average travel time of the Msimbazi catchment area and the maximum time of concentration are determined.

### 6.1.3. Determination forecasting location and method

When the needed lead time of the BRT-system is determined, the forecasting time can be established. The forecasting time is the time available between the detection of a threat and the threshold exceedance that determines the start of a flood event. Based on the hydrological aspects of the Msimbazi catchment area a decision is made on where the flood forecast has to be situated. The principle behind the forecasting location is that the travel time of a waterbody from the forecasting location to the flood event location has to be longer than the lead time needed by, in this case, the BRT-System. A longer travel time from the forecasting location means that the EWS is able to predict a possible flood event further into the future. However, this also means that the accuracy of the EWS also decreases.

It could be possible that, when determining the forecast location, a trade-off has to be made between utilizing the potential maximum lead time, and thereby creating a possibility for the BRT-system to implement even more mitigating actions, and the maximum accuracy of the used forecasting location and method.

With this analysis the following four possible forecast locations inside a catchment area can be determined based on the concepts of (Liang, P. Lettenmaier, Wood, & Burges, 1994). A schematic overview of these locations is depicted in Figure 6.2. The four forecasting locations are determined by comparing the desired lead time ( $T_d$ ) with the hydrological response time ( $T_p$ ), which can be further sub-divided in the travel time of the water in the river ( $T_c$ ) and the time of concentration over land ( $T_r$ ).

The four forecasting locations are as followed (Liang et al., 1994).

- location 1:  $T_d < T_p$  and  $T_r \gg T_c$

In this situation the forecasting location is based on the time of concentration over land ( $T_r$ ). An accurate forecast mainly depends on rain gauges. Location 1 in Figure 6.2 could be an example of this situation.

- location 2:  $T_d < T_p$  and  $T_c = T_r$

In this situation the forecasting location is based on the travel time of the water in the river ( $T_c$ ) and the time of concentration over land ( $T_r$ ). An accurate forecast needs flow gauges inside the main river and rain gauges that measures the current rainfall. Location 2 in Figure 6.2 could be an example of this situation.

- location 3:  $T_d < T_p$  and  $T_r \ll T_c$

In this situation the forecasting location is primarily based on the water located in the river. The run-of time over land is insignificant. In this situation, flow gauges are primarily needed to forecast. Location 3 in Figure 6.2 could be an example of this situation.

- location 4:  $T_d > T_p$

In this situation the desired lead time surpasses the hydrological response time of the catchment area and the forecasting is based on information of future rain and satellite imagery.

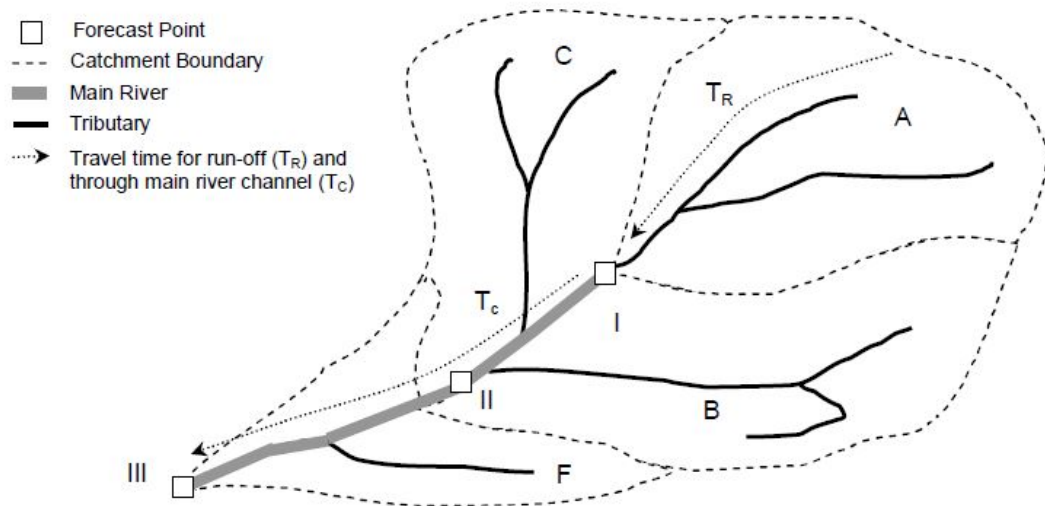


Figure 6.2: Schematic overview forecast locations in a catchment area, (Werner, 2018)

Based on the travel time of the Msimbazi river and the needed lead time required by the BRT-system a forecasting location and method can be determined. This location will have to comply with the condition that the travel time as described in section 6.1.2 of the waterbody is larger than the lead time required of the BRT-system as described in section 6.1.1. Based on this condition, one of the four different forecasting locations and corresponding forecasting methods is selected.

## 6.2. Results

In this section, the optimal forecasting method and location is stated. This is based on the required lead-time by the BRT-system and the maximum time of concentration and the average travel time of the Msimbazi catchment area. The required lead-time is stated in subsection 6.2.1. The maximum time of concentration and the average travel time of the Msimbazi catchment area is stated in subsection 6.2.2. The resulting forecasting method and location is stated in 6.2.3.

### 6.2.1. Required lead-time

In this subsection the BRT-system required lead-time is stated. This total lead-time is the exact time needed by the BRT-system to execute and finish the needed mitigating actions. In this section the time needed to execute every component will be stated. Subsequently, the total sum of these components corresponds to the total lead time. This can be consulted in figure 6.3.



Figure 6.3: Lead time required by the BRT-system



It is important to recognize the fact that the needed lead time by the BRT-system can vary, caused by different factors.

The most significant variation of the maximum lead time is determined on the alertness level of the BRT-system. The alertness level depends on the weather forecasting provided by TMA and the analysis of the weather patterns by personnel of the BRT-system itself. During a high alert situation it is ensured that all personnel is aware of the possible hazard and that sufficient bus drivers are present. In this situation the lead time of the BRT-System is between 1 hour and 45 minutes to 2 hours maximum. If the BRT-system is not on high alert then the mitigation time is between 2 and 3 hours and varies significantly. In this study, the lead time requirements of the BRT-system is determined for the situation when the BRT-system is on high alert.

- Monitoring (rainfall data), required time < 1 hour.

The first sub-component is monitoring the rainfall data measured by the TAHMO-stations. The rainfall data is monitored on a hourly basis. This means that at the end of an hour, all measured rainfall is assimilated in one data point which exported to the server at the end of this hour. Therefore, it takes one hour before the measured rainfall data can be extracted from the sever. The time needed to import this data point to the agent that requires this, depends on the internet speed but should be less than a minute.

- Evaluation & forecasting, required time < 1 minute.

The second sub-component is the evaluation of the rainfall data and subsequently producing a forecasting on the probability on a flood event. This will be performed with the described regression model. Processing the real time rainfall data by the regression model takes several seconds. If the process of feeding the rainfall data is automated than the total evaluation and forecasting time is below one minute.

- Notification, required time < 1 minute.

The third sub-component is the notification of the people and organization that is responsible for taking a possible action. This notification will take place in the form of a probability level and an associated action description. Both notifications can be communicated in an automated manner. This notification time is thereby below one minute.

- Decision making, required time < 1 minute.<sup>1</sup>

The fourth sub-component is the decision making process of the managing team of UDART. In theory the decision making process can be relatively fast and below one minute. However, in reality the decision is based on several EWS's functioning along side each other thereby increasing the time needed to make a decision on executing a mitigating action.

- Warning, differentiates determined on the alertness level of the BRT-System. If the BRT-System is on high alert, the warning time is under 10 minute. If the BRT-System is not on high alert the warning time can be up to 3 hours.<sup>1</sup>

The fifth sub-component is warning all organizations and people involved in executing a mitigating action. In practice this will be performed by the managing staff on duty. This person will use a mobile phone to communicate that a mitigating action will take place. During a high alert situation the warning time has a maximum of 10 minutes. If the BRT-System is not on high alert the warning time is between 1 and 3 hours. The alert level is based on the forecasting provided by TMA.

- Response (mitigation) time: 50 minutes.<sup>1</sup>

The sixth and final sub-component is the mitigating action executed by UDART and consist of driving the buses away from the depot to several terminals located on a elevated surface level.

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<sup>1</sup>All information about the lead time is obtained from the interview held with Mister Deus and the bus driver, full interview can be consulted in Appendix B

### 6.2.2. The maximum time of concentration and average travel time of the Msimbazi catchment area

The maximum time of concentration of the Msimbazi catchment area is the sum of the maximum travel time and the time of concentration over land from the furthest point of the catchment area to the source of the Msimbazi river. The maximum travel time of the Msimbazi river is calculated as stated under.

Table 6.1 shows all measurements taken along the Msimbazi river during dry conditions. With this data the surface roughness is calculated with the Manning equation. Equation 6.3 shows how these calculations are performed on location five. The calculated surface roughness is stated in table 6.1 as well. With this surface roughness the water velocity during a wet situation is calculated. Equation 6.4 show how these calculations are performed for location five. The velocity during a wet situation is stated in table 6.2. The wetted perimeter, hydraulic radius and the surface area of the Msimbazi river during a wet situation are determined with debris such as branches and plastics that were left by the river after such a wet situation. The height of the pile of this debris indicates how high the water would come. After calculating the water velocity during a wet situation at the visited locations, this data was extrapolated for its assigned region. The maximum time of concentration is therefore 5 hours and 15 minutes.

Table 6.1: Msimbazi river hydrological aspects during a wet situation. The locations correspond to the locations depicted in Figure 5.2.

Dry situation:					
Locations:	location 5	location 4	location 3	location 2	location 1
Velocity water body in m/s: (V)	1.2	0.9	0.7	0.4	1.2
Assigned river length in meters:	15500	6888	6888	6888	8857
Travel time in seconds:	12917	7653	9840	17220	7381
Travel time in hrs:	3.6	2.1	2.7	4.8	2.1
Surface area in m <sup>2</sup>	1.5	2	2.2	2	1.5
Wetted perimeter in meters:	5	6	8	12	5
Hydraulic radius: (Rh)	0.3	0.33	0.28	0.17	0.3
Slope in m/m: (S)	0.008	0.005	0.004	0.004	0.004
n:	0.033	0.038	0.038	0.048	0.024

$$n = \frac{R_h^{2/3} S^{1/2}}{V} \quad (6.3)$$

Where

$$V = 1.2, R_h = 0.3, \text{Slope} = 0.004 \text{ (L/L)}, k = 1, n = 0.033$$

$$V = \frac{k}{n} R_h^{2/3} S^{1/2} \quad (6.4)$$

Where

$$n = 0.033, R_h = 1, S = 0.004, k = 1, V = 2.68 \text{ m/s}$$

The time of concentration over land is determined 50 min. The calculations used to determine the time of concentration with equation 6.5 over land is stated under.

$$T_c = 0.553L^{0.5}n^{0.32}\epsilon^{-0.277}S^{0.127}i^{-0.646} \quad (6.5)$$

Table 6.2: Msimbazi river hydrological aspects during a wet situation.

Wet situation:					
Locations:	location 5	location 4	location 3	location 2	location 1
Velocity water body in m/s: (V)	2,68	2,17	1,66	1,32	1,2
assigned river lenght in meters:	15500	6888	6888	6888	8857
Travel time in seconds:	5788	3171	4161	5228	7381
Travel time in hrs:	1,6	0,9	1,2	1,5	2,1
Surface area in m2	15	25	25	30	1,5
Wetted perimeter in meters:	15	20	25	30	5
Hyrdraulic radius: (Rh)	1	1,25	1,00	1,00	0,3
Slope in m/m: (S)	0,008	0,005	0,004	0,004	0,004
n:	0,033	0,038	0,038	0,048	0,024

Where

$T_c = 50$  min,  $L = 10000$  m,  $n = 0.5$  roughness coefficient,  $\epsilon = 0.1$  %  $S = 0.004$  m/m,  $i = 10$  mm/h

The values used in formula 6.5 are collected from literature and have been previously stated in chapter 3.

In this case study the hydrological response time of the Msimbazi catchment area is relatively fast compared to other catchment areas. This is due to the fact that the catchment area has a size of 300km<sup>2</sup>, which is relatively small. This statement is even more true when there is an excessive amount of water in the basin as such during a flood event(Ngana, 2010).

The maximum travel time of the whole Msimbazi river is roughly 5 hours. Together with the time of concentration over land, a total time of concentration of roughly 6 hrs is determined for the furthest point of the Msimbazi catchment area measured to the BRT-depot during a wet situation. This means that on average the travel time of a waterbody in the Msimbazi catchment area is roughly 3 hours during a wet situation.

The results presented in this section are in line with data collected during the interviews with BRT-staff. Make note that the calculated maximum time of concentration and the average travel time have a significant margin of error due to the fact that only five locations have been visited to obtain data.

### 6.2.3. Forecasting method and location

Based on the travel time of the Msimbazi catchment area and the needed lead time of the BRT-system, the optimal resulting forecasting method and location can be discussed.

Based on these two factors, location one as mentioned in section 6.1.3 is most suited as forecasting location. This location is illustrated in Figure 6.2. For this location the optimal method to obtain the forecasting data are the rain-gauges of the TAHMO-stations. In reality, the TAHMO-stations are not located at location one but distributed over the whole catchment area. This difference in location and associated travel time to the BRT-depot has to be accounted for. It might be the case that several TAHMO-stations have a travel time that is too short and are thereby not useful in this case study.

The decision on using this location and method is based on two factors. The first one is that the travel time of the Msimbazi catchment area depends on both the travel time in the Msimbazi river and the run-off process over land. The second factor is to ensure that the forecasting time exceeds the needed lead time for the maximum part of the Msimbazi catchment area, without increasing the uncertainty of the forecasting data more than needed.

The forecasting time provided by this method is on average 3 hours, several regions within the Msimbazi catchment area have a shorter travel time than the needed lead time, but most parts of the Msimbazi catchment area and its run-off time are well above the needed lead time. The fact that rain-gauges

provided significantly more accurate forecasting data compared to satellite imagery makes the fact that a relative small part of the Msimbazi catchment cannot be used in this forecasting method because of the short travel time subordinate.

Taking these two factors into account, using rain gauges all across the Msimbazi catchment area to supply the forecasting data is considered the optimal method.

# 7

## EWS component 2: Relational vs Hydrological model

In this chapter the relational and the hydrological model are evaluated on their predicting power and their consistency. Subsequently, a statement is produced on which model fits the EWS best to process the input data. In section 7.1 the method used is stated. In section 7.2 the results are stated.

### 7.1. Methods

The forecasting data source as described in the previous chapter is used as input source for component two of the designed EWS. In this study, a relational and a hydrological model are tailored and tested for the case at hand.

Both models are forced with the same input data obtained from the TAHMO-stations in the Dar es Salaam region. However, a hydrological model takes into account real physical components of a case for which it is designed. It thereby consists of multiple sub-components that take skill to design and implement. This is in contrast with a relational model. This type of model describes the relation between one or more factors that are influenced by each other. It thereby leaves out all types physical processes that influences the relation between parameters. One could argue that a hydrological model is significantly more accurate compared to a relational model as predicting tool in any case study. However, in this study, the designed relational model is trained in order to determine the optimal rainfall accumulation time frame. When the optimal rainfall accumulation time frame is determined, both models are compared with each other, in order to determine which model is optimal for this case study at hand.

The optimal time frame and subsequently the optimal model, are determined with an receiver operating characteristic (ROC)-curve analyses. The ROC-curve analysis provides a visual interpretation of the performance of a created model with a pre-determined qualifier (Fawcett, 2006). The objective of an ROC-curve is to relate the performance of a chosen qualifier with a validation data set. The ROC-curve with the largest surface area below it represents the optimal qualifier.

The ROC-curve is created by classifying every data point of the rainfall data set in one of four classifiers. The classifiers are visualized in table 7.1 and are determined as followed. A correct classification is when the relational model predicts a flood event correctly, this is called a Hit, True Positive (TP). When the absence of a flood event is predicted correctly it is called a correct rejection, True Negative (TN) When the occurrence of a flood event is predicted falsely it is called a false alarm, False Positive (FP). When the absence of a flood event is predicted falsely it is called a missed event, False Negative (FN). These four situations can be converted into two rates that can be visualized in a graph. The two rates are

the True Positive Rate (TPR) and the False Positive Rate (FPR). The two rates are calculated with equations 7.1 and 7.2.

$$TPR = \frac{\sum TP}{\sum TP + \sum FN} \quad (7.1)$$

$$FPR = \frac{\sum FP}{\sum FP + \sum TN} \quad (7.2)$$

		Predicted	
		Positive	Negative
occurring	Postive	True Positive (TP)	False Negative (FN)
	Negative	False Positive (FP)	True Negative (TN)

Table 7.1: Contingency Table

In this study, this method is used to analyse the predicting power and the consistency of the relational model with various time frames, for which the rainfall is accumulated. With the ROC-curve analysis, the optimal time frame of the relational model is determined and the consistency is checked, both with the accumulated rainfall as qualifier.

This method is also used to analyse the predicting power and the consistency of the hydrological model. In order to determine this the qualifier is the produced discharge at the location of the BRT-depot.

In both cases the flood event data set is used as validation method. All data sets announced have already been mentioned in chapter 5.

### 7.1.1. Method used to determine the predicting power of the relational model for several time frames

In this section the method used to determine the optimal time frame to accumulate rainfall for the relational model is stated. The method used is based on a supervised training theory. The goal of this method is to create an ROC-curve for every rainfall accumulation time frame.

The process of determining the optimal rainfall accumulation time frame of the relational model is performed with the help of a historical rainfall data sets obtained from the TAHMO-stations and with the help of a historical flood events data set obtained from the interviews performed with the BRT-personnel. Both data sets have been discussed in section 5 and run from 01-01-2018 to 23-05-2019. The historical rainfall data set obtained from the TAHMO-stations is overlaid with the historical flood event data set, as depicted in Figure 7.1.

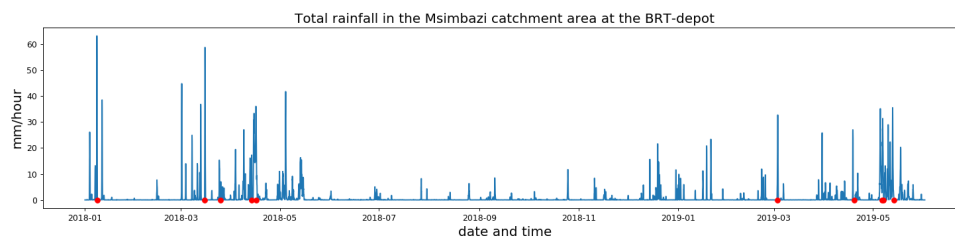


Figure 7.1: Time line of the recorded rainfall in mm/hrs at the BRT-depot with the flood events overlaid between 01-01-2018 and 01-05-2019. This figure depicts the relational model with the rainfall accumulation of six hours.

From this new 'overlying' data set eight new data sets are created by accumulating the rainfall in a time frame from 1 to 8 hours for every hour. The first reason for selecting the time frames from

1 to 8 hours is based on the hydrological response time of the Msimbazi catchment area. In section 6.2.2 a total hydrological response time of 6 hours was determined. Based on the fact that this results has a high margin of error the decision is made to extend the analyzed amount of time frames to 8 hours. The second reason for accumulating the rainfall data over a certain time frame is because the TAHMO-stations only measure rainfall for every hour. This causes the input data to vary significantly. By accumulating the data over a time frame a more homogeneous data set with less outliers both down and upwards is obtained.

Data accumulation over time frame is a method which is used as followed in this study. One takes a window size of  $k$  at time  $x$ . This window is a time frame that starts at moment  $(x - k)$  and ends at  $x$ . With this method the total rainfall measured inside the described time frame is accumulated and assigned to moment  $x$ . This action is performed not only for moment  $x$  but for every moment in the data set. This results in a new data set where for every moment the accumulated rainfall amount of window  $k$  is calculated for the whole data set. This method is repeated 8 times, thereby creating 8 new data sets.

All 8 newly created data sets consist of 12192 data points each indicating the amount of rainfall accumulated up to a certain hour between the dates 01-01-2018 and 23-05-2019. In each data set, every data point is subjected to a condition, in the form of a string of threshold values. The upper and lower threshold of the condition is equal to the highest and lowest data point in the data set. If the data point satisfies the condition a True statement is produced. If the data point does not satisfy this condition a False statement is produced. This produces a statement for every data point compared with every threshold value between the upper and lower threshold .

For example, for the rainfall data set depicted in Figure 7.1 the upper and lower threshold condition would be 0 and 63. This would create a threshold string of 63 points. Every data point is subjected to every threshold value thereby creating in total  $12407 \times 63 = 781641$  of True and/or False statements.

Subsequently, both the statements are validated to the historical flood event data set. If a True Statement corresponds with the historical data set of flood events a True Positive (TP) statement is generated. If a True Statement does not correspond with the historical data set a False Positive (FP) statement is generated. The same thing happens to a False Statement and will thereby generated a True Negative (TN) statement or a False Negative (FN) statement. In total four statements (TP, FP, FN, TN) are hereby determined.

Figure 7.2 provides a schematic overview of the validating process stated above. In this example the threshold value is determined for this particular case on 8mm. The relational model is designed to group every rainfall event occurring on its time line. There are two conditions which define the start of a rainfall event. 1: the rainfall amount is larger than 0 mm/hour, 2: the increase of rainfall  $\Delta R$  over 1 hour is greater than 2 mm/hour. The end of a rainfall event is determined by the rainfall amount being lower than 1 mm/hour. Condition 2 is also described in Equation 7.3. When the threshold value is surpassed by the rainfall quantity, the relational model groups the whole rainfall event and checks if there is an overlap with the lead time of a flood event on the time line. If this is true, a true positive (TP) statement is generated, if this is false, a false positive is generated (FP). The same validation for every data point will be made when the threshold value is not surpassed by the rainfall amount. If the data point overlaps with the lead time of a flood event a false negative (FN) is generated. If the data point does not overlap with a lead time a true negative (TN) is generated. If a true positive (TP) or a false positive (FP) statement is generated, all data points that come after this point until the rainfall event ends will not be evaluated. This is because multiple evaluations on one flood event is undesired. Furthermore, when a flood event is occurring, the data points of the rainfall data set during this flood event will also not be evaluated because it is clear that the threat for which the EWS is designed has already occurred.

$$\Delta R = \frac{R_{t_2} - R_{t_1}}{t_2 - t_1}, R = \text{rainfall in mm, } t = \text{time in hours.} \quad (7.3)$$

Figure 7.3 provides an schematic overview on how this validation process would look like on the total timeline of the accumulated data set of 4 hours. In this situation the threshold value is set on 35



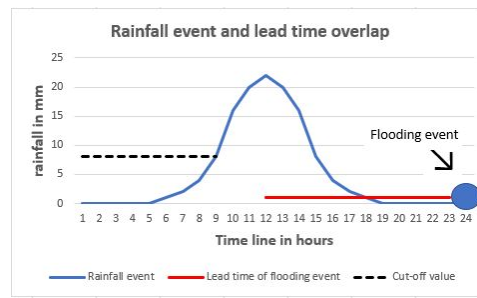


Figure 7.2: Schematic overview of the predicting method of a flood event of the relational model

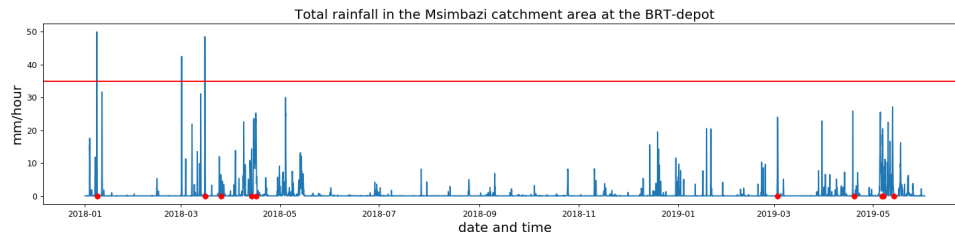


Figure 7.3: Timeline of the output of the relational model with the rainfall accumulation time frame of 4 hours. This figure depicts the threshold value of 35 mm/hour. It is clear that in this situation, three data points surpasses this threshold value.

mm. This results in the following determination of data points; 2 TP, 8 FN, 1 FP and 12396 TN. The number of TN is relatively high because for most data points the threshold value is not exceeded and no flood event takes places, therefore resulting in this large amount of TN statements. In Appendix J, the timelines with the accumulated rainfall amount for the other time frames are depicted.

The last step is the creation of an ROC-curve for every data set. This is done by determining the True Positive Rate and the False Positive Rate with formula 7.1 and 7.2 by varying the threshold value between the determined upper and lower boundary. The ROC-curves are created by plotting these 'rates' on a graph for every data set. By calculating the surface area beneath every ROC-curve the optimal qualifier and thereby the optimal rainfall accumulation time frame can be determined.

All steps stated above are illustrated in a schematic manner in Figure 7.4.

### 7.1.2. Determine predicting power of the hydrological model

In this subsection the method used to determine the predicting power of the hydrological model is briefly described. This method is almost similar to the method to determine the predicting power of the relational model as described in the previous section. The hydrological model used in this study is the W-flow model designed by Deltares as stated in section 3.4. The W-flow model is forced with the data set as described in chapter 5, which is the same data set used to force the relational model. This means that the same hourly rainfall data obtained from the TAHMO-stations is used from 01-01-2018 to 23-05-2019. The W-flow model produces a discharge in m<sup>3</sup>/h at the BRT-depot. This output data is used subjected to a condition, in the form of a string of threshold values. The upper and lower threshold is again equal to the highest and lowest data point of the data set. Figure 7.5 provides a schematic overview of the discharge at the BRT-depot from 01-01-2018 to 23-05-2019 modelled by the W-flow model overlaid with the flood event data set.

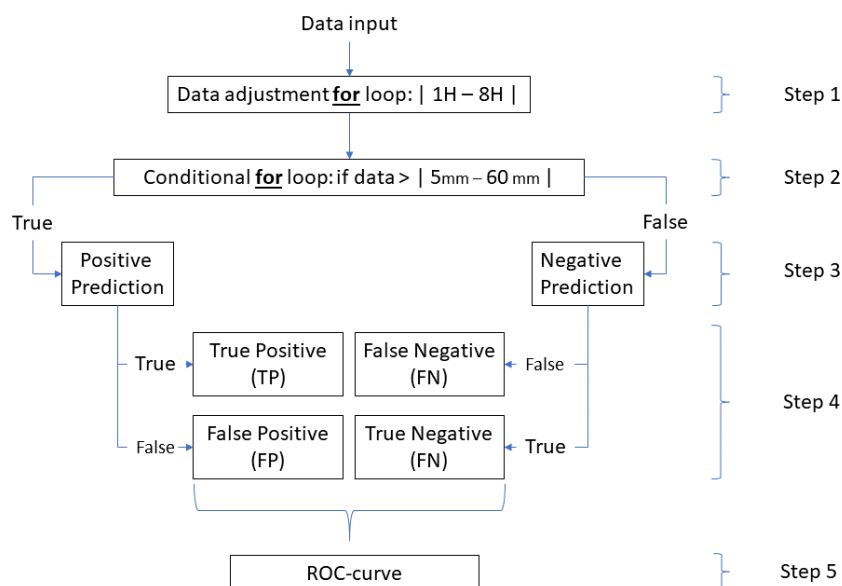
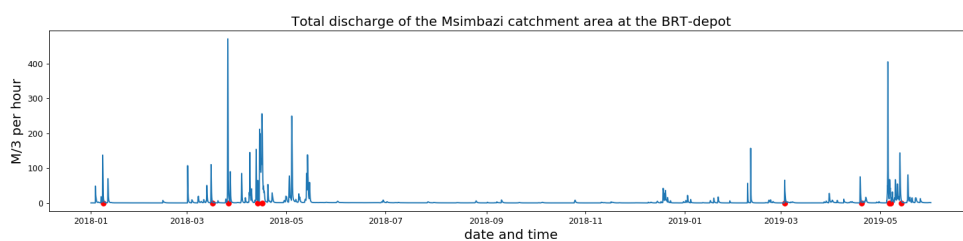


Figure 7.4: Flowchart of the taken steps

Figure 7.5: Time line of the recorded discharge of the W-flow model in m<sup>3</sup>/hrs at the BRT-depot with the flood events overlaid between 01-01-2018 and 01-05-2019.

The ROC-curve for the data set of the hydrological model is created in the same way as for the data sets of relational model only this time only one data set is tested. This is due the fact that accumulating the discharge data over a period of time makes no sense. This is due the fact that the W-flow model has already done this by the incorporate sub-components that model the hydrological processes in the Msimbazi catchment area. The ROC-curve for the data set for the hydrological model is compared with the ROC-curves created for the relational model and the ROC-curve with the largest surface area beneath it is considered representing the model with the highest predicting power.

### 7.1.3. Method to determine the consistency of the relational and the hydrological model

In order to determine the consistency of both models the ROC-curve method is used again. The relational model with the selected optimal time frame and the hydrological model area subjected to a sensitivity analysis performed by a 'Leave One Out' method. In this analysis the flood event data frame is resampled by leaving one flood event out of the data frame. This action is performed for every flood event, thereby creating 10 different data strings. This is due the fact that 10 flood events have been recorded. For every data set, an ROC-analysis is performed thereby creating 10 ROC-curves. For every ROC-analysis the area below the ROC-curve is calculated. Subsequently, the standard deviation of these 10 surface area's is calculated and the normal distribution is determined. The distribution of

the resulting surface area's in every section is analyzed. Based on the results of the sensitivity analyses of both the relational model and the hydrological model, a statement is produced on which model is more stable.

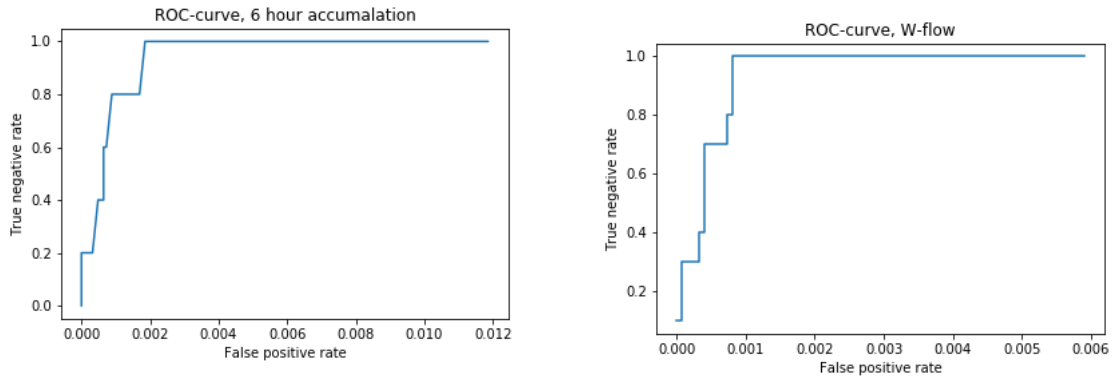
## 7.2. Results: predicting power and consistency check of both models

In this section the predicting power and the consistency check of the relational models and the hydrological model is stated.

Table 7.2 states the surface area calculated beneath the created ROC-curves. These surface area's indicates that the six hour accumulation provides the best predicting power for the relational model and that the hydrological model provides overall the best predicting power. The difference in surface area beneath the different ROC-curves are relatively small. The difference between the ROC-curve with the largest surface area and the ROC-curve with the smallest one is only 0.2 % as calculated with formula 7.4. This difference might look insignificant but in reality it is not. The small difference between the surface area's beneath the ROC-curves is due the fact that the ROC-curves have been extended to the x and y coordinate of 1. This is due the fact that only this way a fair comparison can be made between the ROC-curves. Figure 7.6 illustrates the ROC-curves of the relational model with a 6 hour time frame and the hydrological model and can be used as an example. In sub-figure a and b of figure 7.6 the ROC-curves are depicted when not extended to the x and y coordinate of 1. It is clear that the y coordinate runs to 0.006 for the W-flow model and 0.012 for the relational model. If one would calculate the surface area beneath both ROC-curves then the ROC-curve representing the relational model would have an unfair advantage of extending further along the y-axis. Therefore, both ROC-curves have been extended to the x and y coordinate of 1 for calculating the surface area, thereby creating a fair comparison method. Because of this extension, the difference between the surface area between the two ROC-curves have become relatively small. The reason for the fact that the ROC-curves do not run all the way to the x and y coordinate of 1, has to do with the fact that the amount of TN's is relatively high. This phenomenon has already been explained chapter 7.1.1. Figure 7.7 provides an overview of the ROC-curves of both models in one illustration for better comparison.

$$\Delta x = \left(1 - \frac{ROC \text{ curve score } W\text{-flow model}}{ROC/curve \text{ score relational model 1 hour accumulation}}\right) * 100 \quad (7.4)$$

Figure 7.6 depicts the ROC-curves for the hydrological model and the relational model with a rainfall accumulation time frame of 6 hours. This is due the fact that these two models provide the optimal predicting power. All other ROC-curves can be consulted in G.



(a) ROC-curve relational model with six hour rainfall accumulation (b) ROC-curve W-flow model

Figure 7.6: Figure a: ROC-curve relational model with six hour rainfall accumulation, Figure b: ROC-curve W-flow model

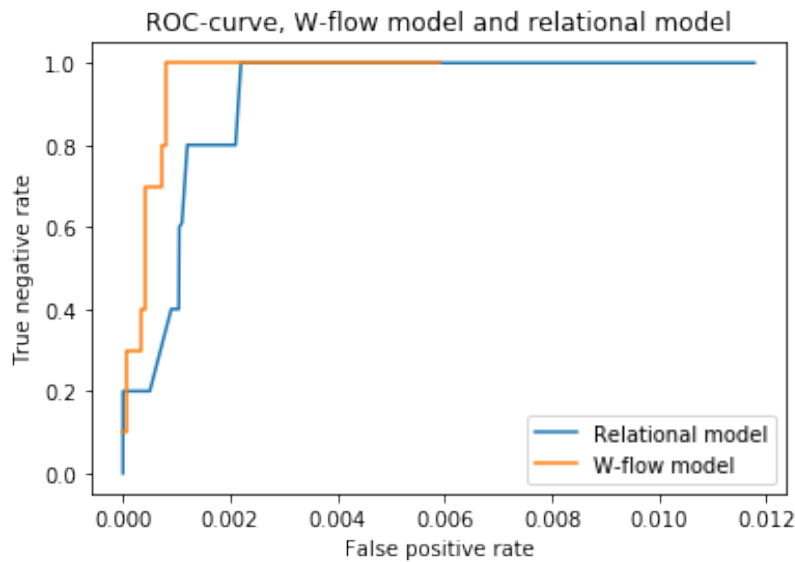


Figure 7.7: The ROC-curves of the W-flow and the relational model overlaid in one graph

The results of the consistency check are stated in table 7.3. Make note that the consistency check is only performed for the hydrological model and the relational model with the rainfall accumulation time of six hours. Table 7.3 depicts the standard deviation, the mean and the amount of flood events in a certain section of the normal distribution. Figure 7.8 illustrates the normal distribution based on the standard deviation and the mean for both the relational and the hydrological model. This figure also illustrates the normal distribution of both models in the same graph.

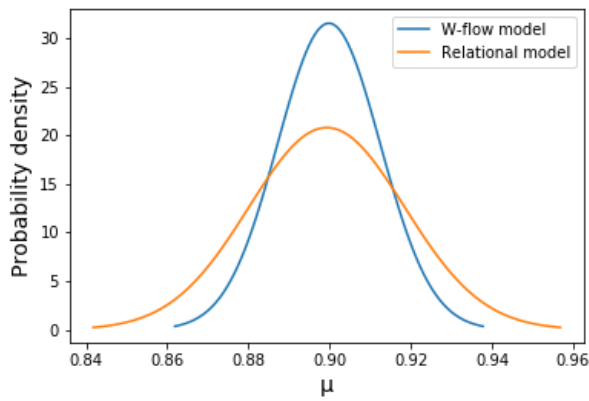
In appendix H the script written to train the relational models and the hydrological model is stated.

Table 7.2: In this table the surface area's beneath the ROC-curves composed for the relational models and the W-flow model are stated.

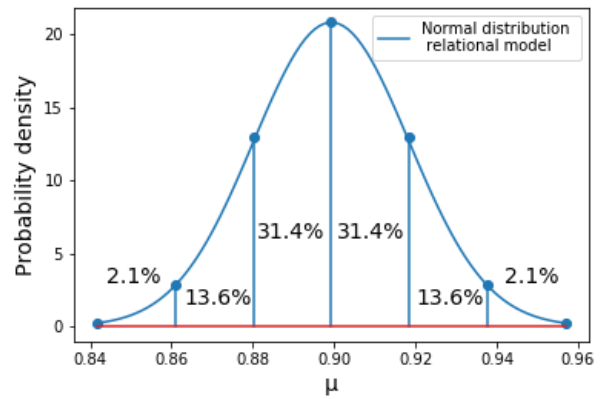
Time frame accumulation	Surface area below ROC-curve	Time frame accumulation	Surface area below ROC-curve
1 hrs:	0,897906751	5 hrs:	0,899193353
2 hrs:	0,898830362	6 hrs:	0,899314350
3 hrs:	0,898911027	7 hrs:	0,899286118
4 hrs:	0,899096556	8 hrs:	0,899214350
W-flow model:	0,899833453		

Table 7.3: In this table the mean, average of the normal distribution are stated. The distribution of the resulting surface area of the ROC-curves in the different sections composed with the standard deviation are also stated.

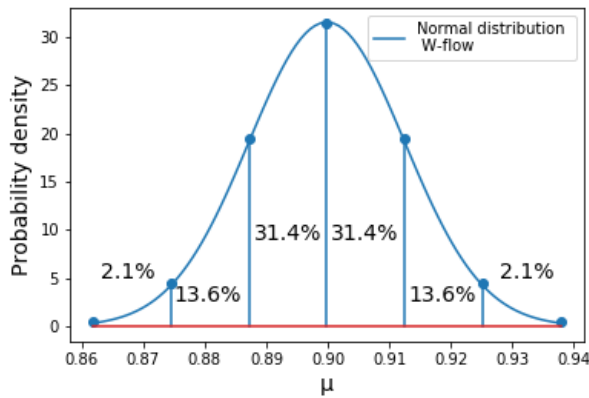
	mean	standard deviation	number of flood events in the 31,4 % sections	number of flood events in the 13,6 % section
Normal distribution relational model	0,899314350	0.000367951	8	2
Normal distribution hydrological model	0,899833453	0.000159979	9	1



(a) The normal distribution of both models overlaid in one graph



(b) Normal distribution of the relational model



(c) Normal distribution of the hydrological model

Figure 7.8: Figure a: The normal distribution of both models overlaid in one graph, Figure b: Normal distribution of the relational model with six hour rainfall accumulation, Figure c: Normal distribution of the hydrological model.

# 8

## EWS component 3: Flood probability determination

In this chapter, the design of component three, the probability on a flood, is stated. The flood probability determination component of the designed EWS consist of a flood event probability and an advice. Make note, in this chapter, only the output of relational model with a rainfall accumulation time frame of 6 hrs and the hydrological model are determined. This is due the fact that these models are determined 'optimal'. In section 8.1, the method used to determine the flood event probability is stated. In section 8.2 the method to determine the associated advice is stated. In section 8.3 the results on the design of component three is stated. Furthermore, the economic value of the final EWS is stated in section 8.4.

### 8.1. Method: model training to determine the relationship between the processed data of component two and the produced flood event probability

The determination of the flood event probability is determined in a similar fashion as the predicting power and the consistency of both models as stated in chapter 7. Only this time, not a ROC-curve is created but the flood event probability is determined. For the relational model, this flood event probability is based on the rainfall in mm/hrs and for the hydrological model this flood event probability is based on the produced discharged in m<sup>3</sup>/h.

To determine the flood event probability first both data sets are subjected to a condition in the form of a string of threshold values. the upper and lower boundary are equal to the highest and lowest data point in the data set. If a data point satisfies a condition a True statement is produced. If a data point does not satisfy a condition a False statement is produced. This procedure is repeated for all data points in the data set. Subsequently, both statements are validated to the historical flood event data set. If a True Statement corresponds with the historical data set of flood events a (TP) statement is generated. If a True Statement does not correspond with the historical data set a (FP) statement is generated. The same process is implemented for a False Statement, thereby generating a (TN) statement or a (FN) statement. In total four statements (TP, FP, FN, TN) are thereby determined for every data point. So far, this procedure is equal to the procedure of determining the predicting power and the consistency of both the relational model and the hydrological model as described in chapter 7. This is also the reason why a consistency check is not necessary. This is due the fact that the data set is used but this time for a different result.

In order to determine the probability of a flood event in this situation, instead of creating a ROC-curve for every data set, the probability on a flood event is determined for every threshold value between the upper and lower boundary of the threshold value string. This is done with formula 8.1 Figure 8.1

provides an example for the relational model with the six hours rainfall accumulation with a threshold value of 30 mm/hour. For this example the lower boundary is 0 mm/hrs and the upper boundary is 63. For this threshold value 6 TP and 4 FP are determined. This makes the probability level of a flood event therefore  $6 / (6 + 4) * 100 = 60\%$

$$\text{Probability Flooding} = \frac{\text{True Positives (TP)}}{\text{True Positives (TP)} + \text{False Positives (FP)}} * 100 \quad (8.1)$$

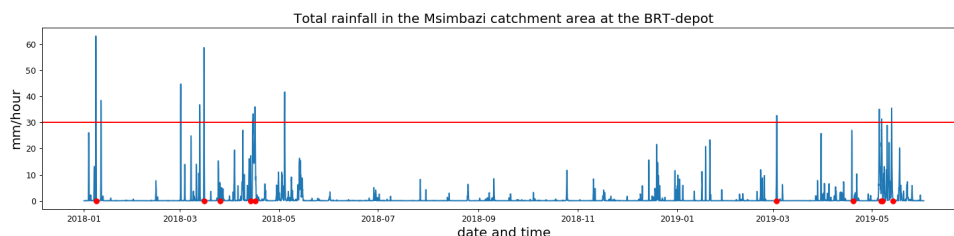


Figure 8.1: Timeline of the output of the relational model with the rainfall accumulation time frame of 4 hours. This figure depicts the threshold value of 35 mm/hour. It is clear that in this situation that three data points are surpassing this threshold value.

## 8.2. Method: associated advice determination

In order to determine the advice associated with a probability on a flood event a method is used described in 'Estimating the benefits of single value and probability forecasting for flood warning' described by (Verkade & Werner, 2011).

In this method, the model of Expected Annual Damage (EAD) is combined with the Theory of Relative Economic Value (REV), (Murphy, 1985) and (Zhu et al., 2002)). In this study a probabilistic forecasting system will be used because the end user is a professional agency that works in a professional environment. Moreover, a professional agent can make its own assumption on a probabilistic decision rule that is befitting of its cost-loss ratio, thus optimizing their response on expected cost and benefits.

In this section the 'Optimal Warning Probability'  $\rightarrow C$  is determined. In this determination the BRT-system is considered to be on high alert status and the other EWS's used by the BRT-system are in place as described in section 3.2. The avoidable cost  $L_a$  and the unavoidable cost  $L_u$  caused by a flooding event are based on a combination of the last four occurred flood events as described by the data set 'financial damage flood events' in chapter 5. This is due the fact that the BRT-system has implemented several mitigating measures over the years to ensure minimisation of the endured financial damage. The last 4 events have been determined representative for the future financial damage caused by flood events, because these mitigating measures were implemented by that time.

When the relational model produces a probability on a possible flooding event, then these results will have to be communicated to the BRT-system. In this study a direct method will be chosen on delivering the probability of a possible flooding event. This means that the real time probability of a flooding event will be communicated directly to the BRT-system. This probability will be communicated in a percentage value between 0 and 100 % chance on flooding. Furthermore, a textual advice will be provided that goes along with the flooding probability as stated. This textual advice is determined on the financial impact of a rainfall event based on historical data.

The warning probability containing an advice to start a mitigating action will be issued when the probability on a flooding event  $P$ , is greater than  $C/L_a$  as stated by formula 8.2. This will be the optimal warning probability which indicates the moment that performing a mitigating action imposes a greater economical value than performing no action. The value of the parameters described in this formula are derived from table 4.1. With this table, the advice on implementing a mitigating action is derived.



$$\begin{aligned}
 C + PL_u &< P(L_a + L_u), \\
 P &> \frac{C}{L_a}
 \end{aligned}
 \tag{8.2}$$

### 8.3. Results

In this section, the probability on a flood event associated with the output of both the relational and the hydrological model is stated. In the case of the relational model, with a rainfall accumulation of 6 hours, the probability on a flood event is associated with the rainfall output from the Msimbazi catchment area at the BRT-depot accumulated over 6 hours. This can be consulted in table 8.1. In the case of the hydrological model, the probability on a flood event is associated with the discharge output at the BRT-depot in m<sup>3</sup>/s, and can be consulted in table 8.2.

Furthermore, the warning probability containing an advice to start a mitigating action, will be issued when the probability on a flooding event P, is greater than  $C/L_a$  as stated by formula 8.3. As mentioned before, implementing the mitigating action at this level of chance on a flood event provides an optimal economic outcome.

$$\begin{aligned}
 C &= \text{€ } 3.000, L_a = \text{€ } 7.500, \\
 P &> \frac{C}{L_a}, \\
 P &> 40\%
 \end{aligned}
 \tag{8.3}$$

Table 8.1: Probability on a flooding event based on a 4 hour rainfall accumulation in mm.

Accumulated rainfall in mm in the 6 hour time frame:	Chance on a flooding event in %
5 mm	10 %
10 mm	15 %
15 mm	20 %
20 mm	30 %
25 mm	45%
30 mm	60 %
35 mm	70 +

Table 8.2: Probability on a flooding event based on the W-flow extended regression model In this table the probability on a flooding event is correlated with the discharge of the Msimbazi river in m<sup>3</sup>/s.

Discharge in m <sup>3</sup> /s	Chance on a flooding event in %
15	15 %
45	30 %
60	40 %
90	50 %
105	60 %
120	70 +

### 8.4. Economic value final EWS

The economic value of the designed EWS is based on the cost ratio between a perfect warning and

an imperfect warning as described in section 4.3. With formula 4.4; the 'True economic value'  $\rightarrow V$  is determined. In this determination the BRT-system is considered to be on high alert status and the other EWS's used by the BRT-system are in place as described in section 3.2.1.3. The avoidable cost  $L_a$  and the unavoidable cost  $L_u$  caused by a flooding event are based on a combination of the last 4 occurred events. This is due the fact that the BRT-system has implemented several mitigating measures over the years to ensure minimisation of the endured financial damage. The last 4 events have been determined representative for the future financial damage caused by flooding events. This is due the fact that during the year 2019 several mitigating measures where implemented. The implementation of these mitigating measures where possible due the fact that the BRT-system increased their knowledge on floods and how to deal with them. The financial damage caused by a flood stabilized in 2019 as stated in table 5.1 and are therefore determined representative for the future.

The financial cost endured when no EWS is in place is described in formula 8.4.

$$C_N = o(L_a + L_u) \quad (8.4)$$

Where

$$o = 11, L_a = 7.500, L_u = 10.000, C_N = 190.000,$$

The financial cost endured when a perfect EWS is in place is described in formula 8.5.

$$C_p = o(C + L_u) \quad (8.5)$$

Where

$$C_p, o = 11, C = 3.000, L_u = 10.000,$$

The financial cost endured when an imperfect EWS is in place is described in formula 8.6. However, in order to get a full picture of all cost endured by the BRT-system when the EWS is in place it is necessary to wait a substantial amount of time to ensure that enough flooding events have occurred and that all financial cost caused by these flood events are accountant for.

$$\begin{aligned} C_I &= h(C + L_u) + fC + m(L_a + L_u), \\ &= oI_U + (h + f)C + mL_u \end{aligned} \quad (8.6)$$

Where

$$C_I = \text{Cost endured when imperfect EWS is in place, } h = \text{hits, } L_u = \text{unavoidable cost, } f = \text{false alarms EWS, } m = \text{missed events, } L_a = \text{avoidable cost, } o = \text{sum observed events.}$$

# 9

## Results design EWS

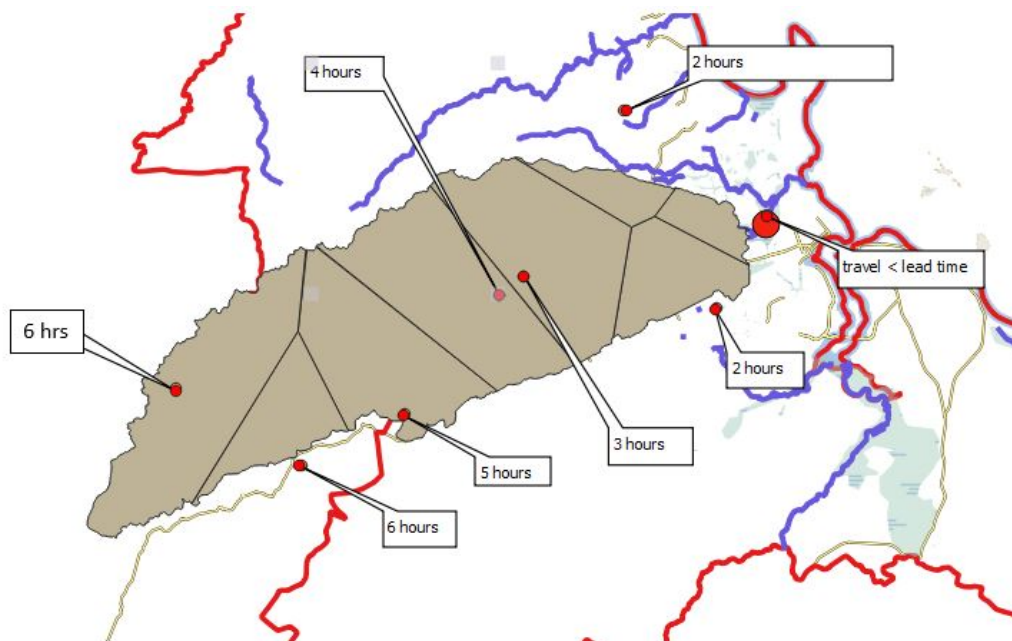
In this chapter the results on the design of the framework for the EWS, based on the three components as described in previous chapters 6, 7 and 8 is stated. These results are based on the methods stated in section 4.

### 9.1. Final EWS

In this section all three components of the final EWS are stated.

- Forecasting method

Rainfall data acquired by the 7 TAHMO-stations located in the Dar es Salaam region are used as forecasting method. All TAHMO-stations and their assigned region and lead time are depicted in Figure 9.1.



Equation: 9.1: All TAHMO-stations and there assigned region and lead time are depicted in this Figure.

- Hydrological model

For the designed EWS in this study, the hydrological model is chosen over the relational model. The hydrological model processes the forced data and produces a discharge amount in m<sup>3</sup>/s of the Msimbazi river at the location of the BRT-depot. The hydrological model provides a significantly better distinction in events than a simple relational model.

- Flood probability determination

The resulting discharge is compared with pre-defined threshold values which comply with a probability on a flooding event. The probability level complying with a discharge amount in m<sup>3</sup>/s can be consulted in table 9.1.

Table 9.1: Probability on a flooding event based on the W-flow extended regression model In this table the probability on a flooding event is correlated with the discharge of the Msimbazi river in m<sup>3</sup>/s.

Discharge in m <sup>3</sup> /s	Chance on a flooding event in %
15 m/s	15 %
45 m/s	30 %
60 m/s	40 %
90 m/s	50 %
105 m/s	60 %
120 m/s	70 +

The change on a flooding event is directly communicated to the BRT-system. This change on a flooding event is accompanied with an associated advice on implementing a mitigating action. This advice is based on the optimal economic value principle and is stated under.

- Flooding probability is low, no action needed.

This advice is communicated to the BRT-system if the modelled discharge is below 45 m/s. The probability on a flooding event is considered low and therefore no action is needed.

- Flooding probability is moderate, maintain high alert.

This advice is communicated to the BRT-system if the modelled discharge is between 45 m/s and 60 m/s. No action is needed at this moment but the modelled discharge could increase to a dangerous level.

- Flooding probability is high, mitigating actions are advised.

This advice is communicated to the BRT-system if the modelled discharge is above 60 m/s. Above this discharge level the probability on a flooding event is high and therefore mitigating actions are advised.

# 10

## Discussion

In this chapter all results are elaborated on consistency and accuracy and research question 6 is answered. In section 10.1 the results and associated data sources used on the study for the BRT-system are evaluated. In section 10.2 the results and associated data sources used on the study for the flood hazard are evaluated. In section 10.3 the results on the design of the EWS are evaluated. Finally, possible future research subjects are described.

- Research question 6: what gap in lead time or forecasting data remains and what data, information, models would be needed to fill this?

It can be concluded that the desired lead time by the BRT-system is determined and is usable for this study. When it comes to the forecasting data, two main data gaps will have to be filled in order to ensure that the margin of error of the designed EWS can be adequately determined and is as low as possible. First, the historical flooding event data set will need to be extended with a validation set. For now, a 'leave one out method' is used to determine the dependency of the resulting relation between a flooding probability and the corresponding rainfall amount on all individual historical flood events. This method provides a certain degree of validation, but to ensure that the designed EWS is truly validated it will have to be tested by forcing a validation flooding event data set through it.

### 10.1. Study on the BRT-system

In this section all results and associated data sources used on the study of the BRT-system are evaluated on consistency and accurateness. The results on the BRT-system are based on the interviews held with the BRT-system staff. The results were obtained from interviews held with different staff members working in different sections of the BRT-system.

#### Status quo determination BRT-system

Concerning the status quo determination, the results obtained from different BRT-system staff members show significant correlation. The answers of different interviewees concerning a specific topic were mostly in line with each other. Therefore, it can be stated that for this study a clear overview and an objective understanding is created concerning the status quo determination for the BRT-system.

#### Lead time requirements

The lead time requirements of the BRT-system are mostly obtained from the interview with staff of

UDART. The answers of different interviewees show good correlation with each other. The required lead time is therefore likely correct with a low margin of error.

Remarkable is the fact that there is a clear discrepancy on how a mitigating action should be implemented in theory and how this is actually done in reality. DART has set up several standards and protocols on how to act during a flood hazard. These standards are not always implemented by UDART. The main difference is that UDART is willing to take far more risk during a flood hazard.

A finding in this study is that DART has problems with determining the likelihood on a flood event because of the lack of data and knowledge. With this study additional information of flood risks for the BRT-system is gathered. With this additional data, DART is able to enhance their advice on flood risks.

This has as an additional positive side effect that, when predictions by DART are more reliable, UDART will be more interested in the advises communicated by DART.

## 10.2. Study on the flood hazard

The study on the flood hazard results are based on the interviews held with the BRT-system staff, fieldwork performed in Dar es Salaam and acquired from the TAHMO-stations in Dar es Salaam.

### Detailed descriptions of historical flood events

The results on the definition of a flood event are mostly based on interviews held with UDART personnel. The water level indicating the start and end of a flood event is based on the practicability of the mitigating action at hand. The determination of this water level is therefore very straightforward for UDART personnel stationed at the BRT-depot, and therefore determined accurately.

The results used to determine the number of flood events and the financial impact experienced by the BRT-system since 2017 are again mostly based on the interview with UDART personnel. After cross-referring all answers on this topic it can be determined that the date and duration of the last 8 flood events are determined with a high accuracy. The date and duration of the first three flood events are significantly less precise.

The financial impact of every individual flood event has been determined with data obtained from the interview held with personnel of UDART and DART. The financial information of the last 4 flood events retrieved can be considered accurate. This is due to the fact that the total cost endured by these flood events have been administrated. The total cost endured by the previous flood events where determined by memory, which has proven to be much less reliable.

### Economic value EWS

The data used to determine the possible economic value of the designed EWS is obtained by interviews held with BRT-staff as elaborated in the previous section. To determine the actual economic value of the EWS the financial cost caused by flood events in the future have to be determined as well. This is elaborated in detail in the next section 10.4. The economic value of the EWS is based on only the last four flood events. This is due to the fact that these cost represent the financial impact in the future without an EWS most accurate.

### TAHMO-stations, Sensitivity analyses

The sensitivity analyses performed on the TAHMO-stations determine if a TAHMO-station has been producing the right amount of data points over an extended period and if these data points could be considered correct.

The analysis on the TAHMO-stations that have been producing the right amount of data points, is highly accurate because the validation method is simplistic. If the number of data points deviate from the amount of number of data points that should have been produced during this period then this means this TAHMO-station has been unreliable. Furthermore, it is very straightforward to determine for which period a certain TAHMO-stations has not been producing the right number of data points. In all cases, if a TAHMO-station was not producing any data, then this was caused by the fact that this TAHMO-station was not reporting.

The validation method used to validate if the produced data points are correctly measured, is more complicated. In theory, two types of errors can be distinguished for this study; systematic errors and random errors. Systematic errors can be distinguished by comparing the recorded rainfall data of all THAMO-stations with each other. Any significant off-sets between TAHMO-stations were correctly distinguished and the TAHMO-stations in question excluded in this study. However, the random errors are much more difficult to distinguish. If the data points of a specific TAHMO-station have a significantly larger spread then it is difficult to determine the accuracy, by just evaluating the produced data points. The best way to determine this type of off-set is to examine the TAHMO-stations on location and see if they function correctly.

## Hydrological aspects of the flood events

The hydrological aspects of the endured flood events are largely based on data collected by interviews with BRT-system staff and validated by fieldwork examination. The validating in this situation is done by establishing if a statement made in an interview is considered probable with the hydrological properties of the Msimbazi catchment area and with the local surrounding of the BRT-depot. The local hydrological properties determined in the result section are considered accurate. This is based on the fact that the endured flood events all hit the BRT-depot in a similar manner and only differ in severity. This is determined by the fact that all interviewed BRT-staff gave consistent answers on how the individual flood events played out.

## The maximum time of concentration and average travel time of the Msimbazi catchment area

The maximum time of concentration and average travel time are determined, by determining the river profile and the water velocity during a dry period. The measuring techniques that were used are relatively simplistic and have various shortcomings that increases the uncertainty of the data obtained. The composed maximum time of concentration and average travel time in this study have been validated by questioning the interviewees, with knowledge on this matter. The interviewees concluded that the results are in line with what could be expected. This gives a fair indication on the usability of the obtained results. Below, the various uncertainties of the collected data are summed up.

- Uncertainty one: river profile and water velocity. With the used measuring technique a significant off-set in river profile and water velocity is expected at the inspected sites. This is due to the difficult terrain and simplistic gear used.
- Uncertainty two: The fact that the river profile was measured only one time. The variety of the river profile during dry period is relatively low compared to other catchment areas. This is due to the relative small size, this results in a relative short time of maximum concentration which causes the river to originate after a rainfall event to its base flow. However, small changes can have a significant impact on the results.
- Uncertainty three: in total five sites where inspected. These sites were chosen because they were determined representative for the total river profile and velocity for its assigned region. In reality it is likely that the river profile and water velocity differentiate over the course of the river.
- Uncertainty four: no data was collected to determine the time of concentration over land in the Msimbazi catchment area. The time of concentration was based on a case study with a study area



that has a lot of similarities with the study area in this study.

- Uncertainty five: the methods used to determine the maximum time of concentration and the average travel time are generalized formula's that are designed to be implementable in a variety of situations. A significant off-set towards reality should be expected for the implementation of these methods.

## Forecasting method and location

Any significant errors in the determination of the forecasting method and location is caused by the results of the maximum time of concentration, average travel time and the required lead-time. The ratio between these results determine the optimal forecasting method and location. Despite these uncertainties, they probably do not affect any conclusions. This is due to the significant difference between the needed lead-time of 2 hours and the travel time of 6 hours. Therefore, rainfall measurement is still the forecasting method that has the highest probability on delivering the optimal output.

In this study, the forecasting locations are partly based on what in theory are the optimal locations and partly based on where in this study the TAHMO-stations are located in the Dar es Salaam region. This is due to the fact that if the designed EWS is implemented by the BRT-system it is most beneficial to use existing infrastructure.

### 10.3. Designs of the EWS

In this section all results and associated methods used on the design of the EWS are evaluated on consistency and accurateness.

#### Relational model, optimal time frame, rainfall and flood event relationship

All results stated in sections 10.1 and 10.2 have been used in the design choices for the relational model. The training of the relational model was performed with the help of a rainfall data set and a flood event data set. Of both data sets the flood event data set has potentially the highest inaccuracy. This is due to the fact that the flood event date was produced by memory. Especially the exact date of the first couple of flood events endured by the BRT-system in 2017 have been difficult to remember by Alex as referred to in section 10.2.

#### Hydrological model, rainfall and flood event relationship

All results stated in sections 10.1 and 10.2 have been used in the design choices for the hydrological model as well. The most likely reason for inaccurate results is the flood event data set which is similar as for the relational model mentioned in the previous section. In the next section the method used to determine the accurateness of both the relational model and the hydrological model is discussed.

#### 'Leave one out' method

To assess the optimal value of the relational model and the hydrological model, a statistical analysis was performed on both models. The surface areas below the created ROC-curves are determined and the spread in a normal distribution and the standard deviation is determined subsequently. This spread and standard deviation clearly illustrates that the hydrological model is the better choice. The hydrological model, which is in this study the W-flow model created and maintained by Deltares, needs additional efforts and skills to implement and to operate. Further research needs to be conducted on how feasible an implementation is in an organization such as UDART.

## Communication method

The BRT-system will receive the probability level on a flood event with an associated advice in real-time. The EWS is, as mentioned in section 10.3, validated, but inaccuracy of the produced results cannot be excluded. It is therefore that the associated advice is truly an advice. The BRT-system is free to interpret the probability on a flood event and to adjust their response according to the situation at hand. The BRT-system has several other EWSs in place and this one will be complementary to the current status quo.

## 10.4. Future research

This thesis is finalized by stating several ideas which could improve the quality of the designed EWS and how it could be implemented in other situations both in Dar es Salaam and other locations.

### Recommendations for future improvements of the designed EWS

Many improvements can be made on the designed EWS. Some of these ideas relate to improving the acquired results, thereby improving the predicting power of the designed EWS. Others relate to new ideas on how the designed EWS could be improved or extended in the future.

- The validating of both models could be improved by forcing a validation data set through both. In this study the choice was made to use a 'leave one out' method, due to the low amount of recorded flood events. With the help of additional validating methods the differences in produced data of both models can be further examined.
- The implementation of a method that ensures the registration of new flood events endured by the BRT-system. These flood events can be used to validate the designed EWS and to acquire additional knowledge on how the flood problems evolve over time. For now, the registration of new flood events is done by posting a picture and several properties of a new flood event on in a Whats-App group.
- Determine under what circumstances the W-flow model can be used by the BRT-system as a hydrological model in the designed EWS. The W-flow model is currently owned and exploited by the World Bank.
- Data collection on the hydrological properties of the Msimbazi river can be performed on more locations.
- In this study no data is collected on the time of concentration on land in the Msimbazi catchment area. This could be done in the future.
- The cost endured in the future by will have to be registered. This allows the BRT-system to determine the added financial value of the implementation of the designed EWS.

### Recommendations for future research

The following research topics can continue the study of designing and implementing EWS's. Several of those are proposed here.

- The method used in this study can be implemented for more agents in Dar es Salaam. The EWS is in essence designed based on the same principles but subjected to different boundary conditions.
- The methods used in this study can be used in different places all over the world if sufficient data sources are at hand.

- Several additional data sources such as rainfall data and water level data can be used together as data sources.
- Extend the lead-time of the EWS for other use cases.

# 11

## Conclusion

The study carried out in this thesis has been guided by six research questions. Five of these are answered in this chapter. The sixth and last research question provides a reflection on the study carried out and is therefore answered in the discussion section. In addition, based on the answers on the research questions, an answer is formulated on to what degree the objectives of this study are achieved.

- Research question one: What is the required lead time by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

The implementation time of the mitigating actions in place is subjected to the alertness level of the BRT-system. If the BRT-system is expecting a flooding event in the nearby future and is therefore on high alert, the mitigating time is roughly one hour. If the BRT-system is not expecting a flooding event in the nearby future and is therefore not on high alert, the mitigating time is between 2 and 3 hours.

- Research question two: What are the travel time and the time of concentration of the Msimbazi catchment area during heavy rainfall periods?

It can be concluded that a typical travel time from upstream to downstream within the Msimbazi catchment area during heavy rainfall period is around 6 hours. The average travel time is around 3 hours and the maximum time of concentration is 6 hours. However, this is subjected to considerable uncertainty, because the response time of the catchment area is significantly larger than the required lead time. This means that observed rainfall should provide enough lead time and no meteorological forecasts are required for this specific use case.

- Research question three: Which operational data is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

In order for the BRT-system to implement the identified effective mitigation actions it is best to use rainfall data of the Dar es Salaam region.

Based on the hydrological properties of the Msimbazi catchment area this forecasting data is best produced by the forecasting method of measuring rainfall data by TAHMO-stations. This rainfall data is measured throughout the whole Msimbazi catchment area. This data produces forecasting data that complies with the desired lead time and has the lowest uncertainty for this case study.

- Research question four: Which operational model is required by the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

In order to produce a forecasting output by the EWS, this data is best processed by a the hydrological model such as the W-flow model to determine the real-time probability on a flood event. With the W-flow model, the highest skill is achieved. This is likely because the W-flow model takes into account several sub-components of the catchment area.

- Research question 5: What output has the EWS to produce for the BRT-system to implement an action that mitigates the financial damage caused by a flood event?

Based on the required lead time needed by the BRT-system the designed EWS will have to produce forecasting data with a lead time of at least one hour based on the situation where the BRT-system is on high alert. Subsequently, this probability on a flooding event is accompanied with a corresponding advice on an action that can be implemented by the BRT-system. This advice is determined for the design of an EWS that has an optimal economic value. Finally, the probability on a flooding event and the corresponding advice are communicated to the BRT-system. The BRT-system has to implement a mitigating action when the probability on a flood event is 40 %. This happens when the W-flow model predicts a discharge amount of 60 m<sup>3</sup>/s.



# Appendix A : Questionnaire

## Operational staff

bus drivers, cashiers, employees working on depot.

- What kind of flooding have you experienced during your work?
- What was the impact of the flooding on your work and your working environment
- What kind of action are you ordered to take towards an expecting flood?
  - How do they differ during day time, night time and the weekend?.
- What kind of action are you ordered to take towards an occurring flood?
  - How do they differ during day time, night time and the weekend?.
- How do you receive the information of the mitigating actions ordered to you?
- Out of which components do the mitigating actions exist and how much time does every component cost?
- What kind of changes could be made to the mitigating actions in place towards the future?
- What kind of different mitigating actions could be added to, or replace the current mitigating actions?
- Are the communicated actions always carried out as expected? If not what is going wrong?

## Transport Officers and Supervisors

- What kind of flooding is experienced by the BRT-system in terms of impact and duration on your location?
- What is the exact time and date of these flooding on your location?
- What was the impact of the flooding on the BRT operations and on its assets, does it increase over the past years on your location?
- How and what kind of flooding information do you receive?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an expecting flood are in place at your location?
  - How do they differ during day time, night time and the weekend?.

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- What responding mitigating actions towards an occurring flood are in place at your location?
  - How do they differ during day time, night time and the weekend?.
- How are the proposed mitigating actions communicated to you at your location?
- How does it differ during day time, night time and the weekend?
- Out of which sub-components do the mitigating actions exist that you are responsible for? Also, how much time does every component cost?
- What kind of changes could be made to the mitigating actions in place towards the future?
- What kind of different mitigating actions could be added to, or replace the current mitigating actions?
- Are the communicated actions always carried out as expected? If not what is going wrong?

## Operational managers

- What kind of flooding is experienced by the BRT-system, what is the impact on the service and does it increase over the years?
- How and what kind of flooding information do you receive?
  - How do they differ during day time, night time and the weekend?.
- What responding actions towards an expecting flood are in place concerning the service level impact?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an occurring flood are in place concerning the service level impact?
  - How do they differ during day time, night time and the weekend?.
- How are the proposed mitigating actions communicated to you?
- Out of which sub-components do the mitigating actions exist that you are responsible for? Also, how much time does every component cost?
- Are the communicated actions always carried out as expected? If not what is going wrong?
- What kind of changes could be made to the mitigating actions in place, towards the future?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?

## Service delivery manager

- What kind of flooding is experienced by the BRT-system, what is the impact on the service and does it increase over the years?
- How and what kind of flooding information do you receive?
  - How do they differ during day time, night time and the weekend?.
- What responding actions towards an expecting flood are in place concerning the service level impact?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an occurring flood are in place concerning the service level impact?
  - How do they differ during day time, night time and the weekend?.



- How are the proposed mitigating actions communicated to you?
- Out of which sub-components do the mitigating actions exist that you are responsible for? Also, how much time does every component cost?
- Are the communicated actions always carried out as expected? If not what is going wrong?
- What kind of changes could be made to the mitigating actions in place, towards the future?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?

## Finance manager

- What kind of flooding is experienced by the BRT-system, what is the financial impact and does it increase over the years?
- How and what kind of flooding information do you receive?
  - How do they differ during day time, night time and the weekend?.
- What responding actions towards an expecting flood are in place concerning the financial impact?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an occurring flood are in place concerning the financial impact?
  - How do they differ during day time, night time and the weekend?.
- How are the proposed mitigating actions communicated to you?
- Out of which sub-components do the mitigating actions exist that you are responsible for? Also, how much time does every component cost?
- Are the communicated actions always carried out as expected? If not what is going wrong?
- What kind of changes could be made to the mitigating actions in place, towards the future?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?

## Safety officers

- What kind of flooding is experienced by the BRT-system and what is the impact on the safety of the staff?
- What responding mitigating actions towards an expecting flood are in place concerning safety of the staff?
  - How do they differ during day time, night time and the weekend?
- What responding mitigating actions towards an occurring flood are in place concerning safety of the staff?
  - How do they differ during day time, night time and the weekend?.
- How are the proposed mitigating actions communicated to you?
- Out of which sub-components do the mitigating actions exist that you are responsible for? Also, how much time does every component cost?
- What kind of changes could be made to the mitigating actions in place, towards the future?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?

## Chief of Operation and Compliance Manager

- What kind of flooding is experienced by the BRT-system in terms of location, impact and duration?
- What is the exact time and date of these flooding?
- What was the impact of the flooding on the BRT operations and on its assets, does it increase over the past years?
- How and what kind of flooding information enters the BRT-system?
  - How do they differ during day time, night time and the weekend?
- What responding mitigating actions towards an expecting flood are in place?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an occurring flood are in place?
  - How do they differ during day time, night time and the weekend?.
- How does the information matrix looks like in the BRT-system?
- Out of which sub-components do the mitigating actions exist and how much time does every component cost?
- What kind of different mitigating actions could be added to, or replace the current mitigating actions?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?
- Are the communicated actions always carried out as expected? If not what is going wrong?

## MD/engineering staff

- What kind of flooding is experienced by the BRT-system in terms of location, impact and duration?
- What is the exact time and date of these flooding?
- What was the impact of the flooding on the BRT operations and on its assets, does it increase over the past years?
- How and what kind of flooding information enters the BRT-system?
  - How does it differ during day time, night time and the weekend?
- What responding mitigating actions towards an expecting flood are in place?
  - How do they differ during day time, night time and the weekend?.
- What responding mitigating actions towards an occurring flood are in place?
  - How do they differ during day time, night time and the weekend?.
- How does the information matrix looks like in the BRT-system?
- Out of which sub-components do the mitigating actions exist and how much time does every component cost?
- What kind of different mitigating actions could be added to, or replace the current mitigating actions?
- What kind of mitigating actions could be added to, or replace the current mitigating actions?
- Are the communicated actions always carried out as expected? If not what is going wrong?

# B

## Appendix B : Interviews

### interview, Staff UDART, person 1

Question - What kind of flooding is experienced - location, impact and duration?

Depot is located at the bank of the river. If the river floods, the depot floods as well. There are two main cases that can occur next to the flooding of the depot when it come to flooding that effect the bus scheduling:

1: The Jangwani bridge is flooded: the routes are split up and emergency routes are introduced. The bus routes will consist out of two both separately operating routes, Kamari terminal to Marrocco terminal(30% of the buses) and Kariakoo to Kivukoni terminal(70% of the buses).

2: The Kawawa Road is flooded: the routes are split up and emergency routes are introduced. The bus routes will consist out of two both separately operating routes, Kamari terminal to Kivukoni terminal(70% of the buses) and Kanisani to Marrocco terminal(30% of the buses).

When you focus on the depot flooding there are 3 situations under which a flooding can occur. In all of these situations the Jangwani Bridge will flood first, only after that the depot will flood as well. When the Jagnwani Bridge is truly flooded the buses cannot be evacuated from the depot.

- The first scenario: during the night, all buses are parked inside the depot. At the depot, there are bus drivers on duty, they are taking the buses back and forward between the workshop and depot. During a flooding hazard we are on high alert and we make sure that we have enough bus drivers on stand-by next to the bus drivers that are on duty. They are ready on any given moment to take the buses out the depot before the water comes. This is done in the following way, 70% of the buses are taken to the Kimara site and parked at local terminals along this route. The rest of the buses will be taken to the Marrocco site of the busline.

So, how do we know that it is time to take out the buses? We have local means of measuring the water level at the Jangwani bridge. We have been measuring the water level at the bridge for the last 2 years. If we have an alert of TMA that the rainy season has begun and a lot of rain is expected. We make sure that we have a person that is measuring the water level at the Jangwani bridge. If the water level reaches a certain level, we know, this in an alarming level and it is time to take action and to evacuate the buses. By the time the water floods the bridge the buses all need to be outside the depot. This is done by driving the buses out to the nearest possible stations with more than 2 lanes. We make sure that we do not drive them to stations that are further away. The buses are again divided with an ratio of 70/30% to both the lane leading to Morrocco terminal and the lane leading to Kimara terminal. We used to also take them to the Ubungo station, but this station is under construction so this is not possible.

- Second scenario: during day time, the buses will be in operation and they are not located inside the depot. We will keep measuring the water level the same way against the bridge as in the first scenario.

If the water level is alarming, we tell our people to stop selling the tickets first and then we warn the local police. In a dangerous situation, it is being assured that all personnel is in place to act. A member of the staff at the depot checks when the Jangwani bridge becomes to flooded, therefore stopping bus operations when this happens. The police decides when the bus line cannot continue operating along the Janwani Bridge, at that point we close down operation.

- third scenario: this scenario can happen either during the day or at night. kanisani to Morrocco line, also flooding can happen. in this situation they stop operating towards Morrocco. They will hire Dalada's so that they will take over operations. In every situation when a certain part of the BRT line is shut off. Dalada's can be licensed to operate at these locations.

The flooding can come up to chest height. last may 2018: hit by a flood that lasted 2 day. It took months to clean up and to get back to operation, a lot of activity. The depot location has always been prone to flooding. Last year they had floods in October, November and January, march April and May. From January to may last year. In 5 months from January to June there where 4 floods through out.

8 January afternoon during operation, 26 march night, 14 April - during the night, 4 may - during the evening. flooding moments all during 2018.

Does the flooding problems and damage increase? Heavy rain starts earlier every year

The flooding information comes from TMA trough DART to you? We receive general weather forecast from TMA, so like the rainy season will start from the first of March and will continue for a couple of weeks. When we receive this kind of information we will be on high alert and bring in our reserve drivers/managers to spent the night at the depot. A significant part of the information provided by TMA is not specific. The last flood happened when I was at the depot, therefore I made the decision on when we had to start evacuate the buses from the depot. Last time, we took out the buses because of flood risk, eventually there was no flooding because the rain did not continue during the night. As a precaution we did keep the buses outside the depot at other locations.

When there is a flood occurring and you are to late with getting the buses out, what can you do? It takes a minimum of two weeks to return back to the depot after flooding situation.

How does the information matrix looks like when there a flooding hazard? The information matrix starts at the 'Bridge spotter'. He provides the information on a possible flood. The bridge spotter notifies me, if he cannot find me (head of operations) he will go to the CEO and notifies him. There is always somebody here from management, he will be informed if me or the CEO are not available. When I am notified by the 'Bridge Spotter' I will directly communicate to DART that they will start evacuating the depot. Dart at their turn communicates this information to the Police, Fire Department, local communities and the local government.

For example: Last November flood during the day there was a boardroom meeting, the bridge spotter came and informed me that the water level is now on the alarming level. All the buses that where in maintenance where taken out.

- During operation: I will call the security at the gate of the depot, they will stop any bus that tries to get inside. I myself I just go outside to the workshop and tell everybody that they need to start evacuating and notify everybody in the depot to help along. During the day it is easy because we are all here to see when a flooding is happening. A lot of possible communication methods are not working because the power is shut of when a flood is about to happen. Also, there is no willingness to invest in new ways to communicate because there is a strong feeling that this depot should not be here and that it will be relocated in the near future. But this is for DART to decide and not the U-DART because it is there property.

During the day it takes 5 minutes after the alarm to have the first bus outside the depot and into safety. Because there are not much buses at the depot the last bus is relocated to safety after 10 minutes after the warning has been sound.

During the night it takes 90 minutes to get all the buses to safety. Example, 4 may during the night: 20 drivers took 90 minutes to get all the buses to safety. The 20 bus drivers where relocated to the depot beforehand. there are 140 buses to relocate. every bus takes around 5 minutes to relocate.

Cost: We have to pay overtime for the bus drivers, maintenance problems, reduced capacity. example: 130 buses flooded, which costed 1 billion Tanzanian Shillings.

How much does a falls alarm and response cost? ask finance guy.

We also have a database of all of the drivers that live nearby the depot. If necessary they will be contacted to help evacuate the buses, we will make sure that we put these drivers on high alert by notifying them beforehand. This communication goes through WhatsApp, Calling or ringing there doorbell.

Even when the Jangwani Bridge is flooded we still evacuate the buses towards the city center at CBC. When there are not enough bus drivers around it is possible for them to take out more buses per persons by driving back to the terminal.

What could be done better in the future? the depot needs to be relocated, the river needs to left to be river. The water needs to receive more space and needs be allowed to flow freely. The water does not forget its way. The Msimbazi needs to be protected better. The Jangwani bridge acts like a dike because sediment build up at the river floor. Therefore, the space below the bridge reduces from 4 meters to 0.5 meters thereby not letting the water pas below it.

What also could be done is provide personnel better means of communications. Thereby it is easier to alarm everybody inside the company and to tell them what they have to do. There should be better and clearer communications line between all involved parties such as U-Dart, DART, TMA and the Police. Everybody should be kept into the 'loop' so that every body knows what is going on. Especially U-DART where I work for is left out of this communication matrix. The U-Dart has to do everything from evacuating the buses to cleaning the road and the depot after a flooding. A deviation of responsibilities to other parties might help.

Last flood at the March 3th 2019, we started to evacuate the buses by keeping notice of the weather. The rainfall was increasing and there was no sign of it slowing down. Even so there was no flooding yes, we still decided to evacuate the buses from the depot. This was a very good decision because the actual flooding started 50 minutes later.

## interview, Staff UDART, person 2

Question: How would you describe the flooding that you experienced when you where working at the depot?

Answer: Operation at this location started at 2016 April, at first operations started slowly. At 2016 May, the operation was completely and fully running. 24 October 2017, there was heavy rain for 3 days, the fourth day during the night around at 4am heavy rain started again after it laid down for a while. Around 8am on the fourth day the rain slowed down. At this point the river was full of water and the water was flowing through most of the open places. The flooding started at 28 October at 9am.

The ocean was not receiving water that day causes by blockages, thereby the water was flowing towards open places such as roads, houses and this depot. This compound has a pipe system that helps the water flow out of the system. This system was full of water and overwhelmed. Thereby it could not drain sufficient amount of water. The water started to come up from the peat and clay layers at this point. This is how the flooding starts at 9am on the fourth day (14 October 2017). When a flood starts, first the bridge floods and the all of the open spaces flood. The water comes in via all of the gates from every direction.

The flood comes up to waist height at the inventory office. Person 2 experienced 4 floods in total. The last and biggest flood was experienced at 14 may 2018 around 8am. The other dates he cannot remember anymore. After 2 hours of rain the flood starts at 10 pm.

Question: what was the impact of the flooding?

Answer: when the flooding comes in the depot the workshop needs to be moved to Terizani. This happens after the flood, the workshop is moved as well as the buses. In the depot there is a lot of mud and rubbish, cleaning takes about 2 months.

When there is a flood the inventory manager stays at the depot to manage and watch over the inventory. The inventory manager helps and looks over the cleaning process after a flood. The input of the inventory manager

Question: what do you think that can be done to improve the situation.

Answer: we should dig-out the river at the bottom in order to make sure that more water can pass through. This is especially important at the all of the bridges. The Jangwani bridges used to have a pass trough height for water of 4 meters, at this moment it is only 0.5 meters. We should remove all the mud and clean the river from all its rubbish all the way to the ocean. The pass trough height of the water at Salenda bridge should dramatically be increased. The trees at this bridge should also be removed in order for the water to pass through. However, this is prohibit by the government which is a bad decision.

At this moment, when there is a flood we driver the buses away. When there are signs of flooding the bus drivers are stationed at the depot. To drive away all of the buses it takes about 1 hour. This could be improved by finding an open place, but mostly by digging and creating more space for the rivers. Also, we need to make culverts inside and around the depot so that the depot for the mud to run through. This has done before and works really well.

### interview, Staff UDART, person 3

Question: How would you describe the flooding that you experienced when you where working at the depot?

It has a negative impact on our financial situation and on our transporting capabilities. We suffered a lot, 500 million shilling was the cost of the flooding when it comes to repairing the buses and cleaning and repairing the depot. This loss of 500 million was experienced after the first flood that hit the depot in 2017. After this the loss has decreased significantly because we are better prepared these days.

We lost a lot of revenue as well, also our customer relationship is damaged when we cannot perform our duty as a public bus operating company. For every flood we lose about 60 million Tanzanian dollars per day on revenue caused by the floods. This revenue loss extends sometimes for multiple weeks because that is how long it takes to get back to full operation.

The flooding comes really high, about waste height. We receive our flooding information from TMA. This information is not precise but we use it to determine if we need to prepare and take measurements.

Question: what kind of financial preparations are taken when there is a flood risk.

Answer: first, we suffered a lot during the first flood. But after we learned and we became better at responding towards a flood. The biggest improvement is the reaction time of our organization. This reaction time has influence on several processes in our company, but the most important one is the time it takes to remove the buses, which has gone down significantly.

The communication in the company is mostly done by meetings. During these meetings the risk on potential flooding is discussed and proportional measures are taken. The community is also informed when there is a flood risk. This is done by public awareness, we tell the people that there is a high change that we cannot perform our duties in the coming period.

Question: what kind of improvement can be made?

Answer: I do not believe in an improvement when the depot remains at this location. We need to move our depot to a safe location where flooding is not an issue. During the aftermath of a flood, U-DART experience 80 million Tanzanian shillings of damage the first day. After that, we slowly get back to our normal operating level which takes about 7 days.

Question: what are the cost of a mitigating action?

Answer: the cost of the actual action is close to zero. This is because the cost of the bus drivers that have to perform the evacuating action is close to zero. This is because the bus drivers are in permanent service and do not receive additional payment when an evacuating action needs to take place. The

largest cost is the loss in operation after an evacuating action. This is because all the buses are placed at different locations along the Morogoro road. However, this year we have become more experienced in making sure that U-DART operations can continue even when the busses are scattered across the Morogoro road.

In my opinion, The total cost of a mitigating action is around 12 million Tanzanian shillings. These costs mostly consist of lost operations the days after.

## interview, Staff UDART, person 4

Last flood started at 6 in the morning and lasted more than 2 days before the water retreated back to the river. My manager (head of transport officers, he manages the transport officers) called me that morning and asked me to come to the depot. The transport officers are normally in charge of the evacuation progress during a flood event. He specifically called me to come because I live close by. The road that leads to the depot was flooded when I came out my house. I called my supervisor and asked him if it was possible for me to get to the depot and how I would manage to get there. My supervisor told me to use the back road that leads to the gate at the back of the depot. The back road was indeed free of water, I used this road and got to the depot. I picked up a bus and drove it to another bus station.

The interesting thing was that it was not raining at the depot, the flooding was caused by a rainfall event upstream in the catchment area. If the transport officer needs me to come to the depot in case of an emergency it is communicated through a call, text or WhatsApp. The management decides based on the current and forecasted weather if there is a significant risk on flooding. If this is the case during the night, we are ordered to stay and sleep at the depot. We are woken up by the transport officers on duty and ordered to drive the buses to safety when the flood actually starts. This safety measure is not yet performed in reality but it will during the next flood risk during the night according to my manager.

Currently there is a WhatsApp group that we use to warn everybody when there is a risk on flooding or any other potential calamity. This group app is used regularly and to my understanding it works well. Of course, during the night the usability of the group WhatsApp is far less because most people are asleep.

In this depot there are 140 buses stationed during the night. If there is a risk on flooding it is my believe that a significant part of these buses should be stationed at other locations that are not prone to flooding.

There is no official communication method between bus drivers and transport officers. We mostly communicate the way that fits best for that moment.

For future improvement, the plan to let drivers stay at the depot at night should be become reality and not just be forgotten. If it is not possible to let bus drivers sleep at the depot or a flood is very sudden, there should be better communication methods with drivers that live close by the depot in order to ensure there fast arrival. They should contact the drivers in such a manner for them to react fast, also the communication method should be reliable and reach the bus drivers at all times. I believe that calling is the best communication method at night.

Furthermore, the bus drivers are well trained and the evacuation progress is efficient and mistakes rarely happen.

## Interview, Staff DART, person 1

I still remember the date of 2 heavy flash floods. One was in 2017, one was at 14 to 16 April 2018, this caused very heavy damage to the depot and services. There was a lot of heavy damage to the buses, buildings and other materials. The depot was fully submerged, the water came up to 1 meter.

During the April flood it took more than 2 weeks to clean the depot and get back to full operation. After the first major flood at the depot we developed a emergency plan which contains all actions,



the communication matrix and progresses than need to be followed and for filled. The communication matrix for any flooding possibility is as followed. First the DART organization receives information on long(3 months), middle(1 month) and short weather(5 days) forecasting from TMA. Based on this information we decide what the flood risk is for the BRT-system and the depot in particular. The flood risk is determined on short term for the next days and on long term for the coming weeks. Based on this risk analyses we communicate a message to U-Dart which again contains a short term action plan and long term preparedness level.

There are two possible short term advises from us to the U-Dart organization. The first one is to evacuate the depot and put all mitigating actions into place to deal with a possible flooding. This advice is given when there is a very high risk on flooding in the coming hours or day. The second short term advice is to proceed with operations as normal or as described in the long term advice. This advice is given when there is no immediate high risk on flooding in the coming hours or days.

Just as the short term advice there are also two possible long term advises that we give to the U-Dart organization. This advises contains a preparedness level that DART believes U-Dart should maintain. The first one is to carry on with operations as usual, this advice is given when there is no flood risk in the coming weeks or months. The second long term advice is to be on high alert because there is a elevated chance on flooding in the coming days or weeks. This advice is given when we believe that there is a high chance on flooding based on the information and weather forecast received from TMA. We present our advice to U-Dart by email, calling or personal interaction.

When a flood is actually happening several other progresses are also set in motion as described in our emergency plan. First, all 14 stakeholders are informed that there is a flood occurring, these stakeholders range from the police, fire department, local community, local government, etc. All these stakeholders have their own tasks and responsibilities which they will perform as agreed.

In total, three evacuation alerts where given by DART to U-Dart in 2018. The U-Dart responded positive to these alerts and took mitigating actions as required. Only during the flash flood in April/March there was severe damage encountered by U-Dart. The fact that TMA and DART where not able to predict these flooding because of the nature of them made the U-Dart encounter sever financial losses. The flash flood in March was not responded well to. The floods in January and April came in gradually and took a few hours to completely submerged the depot, the response and mitigating actions to these floods where adequate.

We would very much benefit from additional rainfall data and hydrological data in general from the upstream region of the catchment area. With this information we could even better determine how significant the flooding risk is for the BRT-system. To sum up the communication matrix one more time, we get a probabilistic flooding risk from TMA, this information is send forward to U-Dart in a deterministic manner. We decide if the U-Dart has to perform mitigating actions or not. of course, sometimes there are communication problems, this means that the U-Dart does not act upon our advice as agreed. This creates problems and increases the chances on sever financial costs for all of us.

For your information, if you want to create an early warning system you have to contact TMA and ask them to implement your system inside their organization. This is because TMA is very protective on their position and there expertise, if you want this to be done than you need to include them in your project.

## Interview, Staff DART, person 2

We receive three types of forecasting periods from TMA, seasonal(3 months), monthly and daily. We also receive flooding information from the TV and radio. We developed an emergency operation plan that U-Dart needs to follow. In this plan all of the mitigating activities are explained and detailed. This emergency plan is based on the forecasting time of 5 days. In this emergency plan we have defined all the activities that U-Dart needs to take.

So far, mitigating actions are based the real time water height of the Msimbazi River. In the future we hope to move to a more pro-active style where we react to information that predict the hydrological situation in the coming 4 or 6 days of the Msimbazi River. With this information we can better react to

flooding risks and mitigate our financial losses even better. At this point DART already communicates to U-Dart to place their buses at different locations when there is a flood risk. Of course sometimes this information is misinterpreted or not received in time. This means that the U-Dart cannot implement mitigating measurements on time thereby increasing their financial losses.

Currently we are dealing with the following situation. U-Dart does not always follow our advice, they have decided to place a spotter on the Jangwani bridge to check the real time water level and create a warning system for them self. The advice that we give is thereby not always met with actions accordingly. A lot of times they only use our advice as a indication method to determine if there is a high risk on flooding, with the help of the bridge spotter the actual decision on to act on a flooding risk is taken. U-Dart does this because our advice is not always accurate and sometimes we advice to implement mitigating actions while the actual flooding is not occurring. The mitigating actions taken caused by an 'false' alarm cost money for the U-Dart therefore they rather try and find their own way on predicting a possible flooding event.

A serious problem is the communication line between DART and U-Dart. The communication line is not clear therefore a lot of misinterpretation and other problems are created. The biggest problem of the emergency plan is that it is unclear how plan is activated. It is not clear when U-Dart should start moving the buses out and start with getting everybody into safety. It is also not clear what observatory is used to determine if there is a flood coming. We should create a clear and understandable operating procedure and operation levels that indicated how and when mitigating actions should be put into place. I believe that we need a clear signal/warning that indicates the start of a mitigating action when there is a flood risk. The 'spotter' method used right now is not always trustworthy. Especially in a flash flood situation a spotter is able to signal a warning when a flood is occurring. I believe that we need some type of information from the upstream area of the Msimbazi catchment area that indicates if there is a chance on flooding. This information should trigger a warning when certain threshold values exceeds certain values. This warning should contain information on the severity of the flood and the response time of U-Dart.

The response time of the Msimbazi river is 3 hours, of course this is a generalized time frame. In reality this time frame differs for particular situations. Several factors have to be taken into account when one wants to determine the response time of the Msimbazi river. These factors are solid waste, wetness of the soil, build areas and current water levels. Of course several parameters are very difficult to determine but it is important to at least know that they are there and have an impact.

I believe that the emergency plan is a good document. However, I believe that it is unclear how the actual implementation those mitigating actions. I believe we can gain a lot when it comes to that. If you ask to different people how mitigating actions are taken then they all will respond differently. This clearly indicates that the response plan is not completely clear and different people have a different understanding on what should be done in an emergency situation.

what also can be improved, is how we can insure that our services are maintained after or during a flooding situation. It is important that we do everything we can to get the people of Dar es Salaam to their destination.

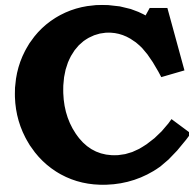
The command chain for different kind of processes in a emergency situation are also not clear. For example, when the BRT buses cannot be used for operation Daladala buses need to be used to ensure the continuation of operations. Everybody knows that this needs to be done but the responsibilities for different aspects of this procedure are unclear in reality and therefore not executed as needed.

To end this interview I would like to stress that the communication methods and procedures during an emergency situation are unclear and need to be improved. This starts when the warning is issued and ends when all the mitigating actions are finished. All the communication lines, command chain and procedures should be clear and everybody should know their responsibilities. This is vital to ensure a safe, fast and adequate response to any kind of emergency.

Question: what are the cost of an mitigating action?

The mitigating action itself cost almost no money, this is because the bus drivers that perform these actions are on the payroll of U-DART. The cost of missed operations in the days after are somewhere around 14 million shillings.





## Appendix C : Flooding events

In this appendix the results of the hydrological aspects, financial aspects and quantity of the flooding events are stated in table . The results are collected from the interview data.

In this appendix the avoidable and unavoidable cost based on historical flooding events are also stated elaborated. The cost have been determined by consulting several staff members working for the UDART organisation and are stated in table C.1.

### Detailed hydrological description of the flooding events

- 27-10-2017, average flooding event in the afternoon.

First flooding event recorded by the BRT-system. The exact time of the flooding was around the afternoon. The flooding event duration was approximately one day. The approximately total avoidable cost  $L_a$  was 20.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 08-01-2018, average flooding event in the morning.

The exact time of the flooding was around the morning. The flooding duration was approximately one day. The flooding event duration was approximately one day. The approximately total avoidable cost  $L_a$  was 15.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 24-03-2018, 4 days of heavy flooding.

This flooding event extended over four days. The flooding event started at the 24th of march and ended on the 28th of March. The approximately total avoidable cost  $L_a$  was 50.000 \$ and the total unavoidable cost was  $L_u$  100.000 \$.

- 14-04-2018, long period of flooding.

This flooding event extended over 2 days. The flooding event started at the 14th of April in the afternoon and ended on the 16th of April in the morning. The approximately total avoidable cost  $L_a$  was 30.000 \$ and the total unavoidable cost was  $L_u$  20.000 \$.

- 16-04-2018, long period of flooding.

This flooding event extended over 1.5 days. The flooding event started at the 16th of April in the night and ended at the 17th of April in the afternoon. The approximately total avoidable cost  $L_a$  was 20.000 \$ and the total unavoidable cost was  $L_u$  20.000 \$.

- 04-05-2018, long period of flooding.

This flooding event extended over 2 days. The flooding event started at the 4th of May in the afternoon and ended at the 6th of April in the afternoon. The approximately total avoidable cost  $L_a$  was 50.000 \$ and the total unavoidable cost was  $L_u$  50.000 \$. This flooding event can be described as a flash flood.

The BRT-system was unaware of the incoming water body and therefore unprepared. The total cost is therefore high.

- 03-03-2019, small flooding.

This flooding event extended over 12 hours. The flooding event started at the 3th of March in the morning and ended in the evening. The approximately total avoidable cost  $L_a$  was 5.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 18-04-2019, small flooding.

This flooding event extend over 12 hours. The flooding event started at the 18th of April in the morning and ended in the evening. The approximately total avoidable cost  $L_a$  was 5.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 06-05-2019, small flooding.

This flooding event extend over 12 hours. The flooding event started at the 6th of May in the morning and ended in the evening. The approximately total avoidable cost  $L_a$  was 5.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 07-05-2019, average flooding.

This flooding event extend over one day. The flooding event started at the 7th of May in the morning and ended the 8th of May in the morning. The approximately total avoidable cost  $L_a$  was 10.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

- 14-05-2019, average flooding.

This flooding event extend over 1 day. The flooding event started at the 14th of May in the morning and ended at the 14th of May in the morning. The approximately total avoidable cost  $L_a$  was 10.000 \$ and the total unavoidable cost was  $L_u$  10.000 \$.

Table C.1: The avoidable cost and unavoidable cost are stated in this table. The weighed avoidable and unavoidable cost are also stated.

	flood 1	flood 2	flood 3	flood 4	flood 5	flood 6	flood 7	flood 8	flood 9	flood 10	flood 11		
avoidable cost in :	20.000	15.000	50.000	30.000	20.000	50.000	5.000	5.000	5.000	10.000	10.000	average avoidable cost in :	20.000
unavoidable cost in :	10000	10.000	100.000	20.000	20.000	100.000	10.000	10.000	10.000	10.000	10.000	average unavoidable cost in :	28182
weight factor:	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5		
weighthed avoidable cost in :	10000	9000	35000	24000	18000	50000	5500	6000	6500	14000	15000	weighted average avoidable cost in :	17545
weighted unavoidable cost in :	5000	6000	70000	16000	18000	100000	11000	12000	13000	14000	15000	weighted average unavoidable cost in :	25455

# D

## Appendix D : Analyses of all TAHMO-stations

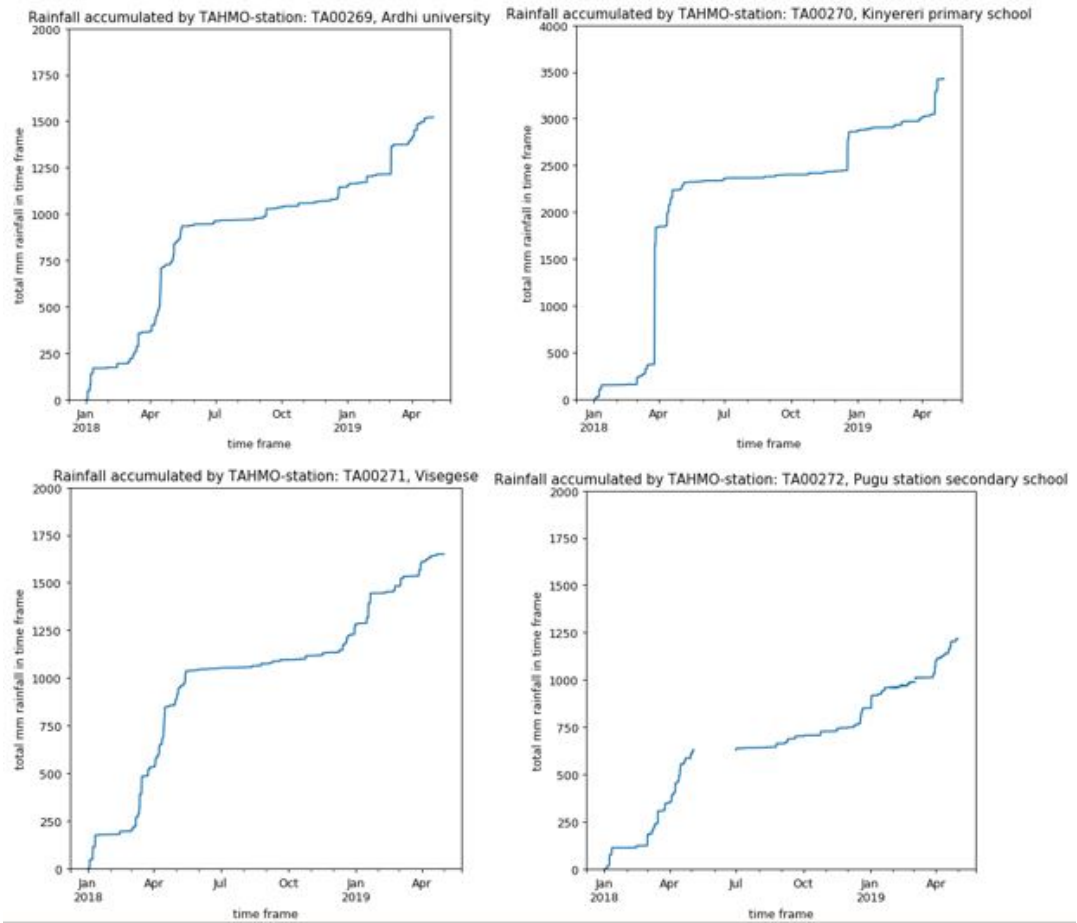
### Double mass analysis and data continuity analysis of the TAHMO-stations between 2018-01-01 and 2019-05-01.

In this section the graphs of all double mass analyses of all TAHMO-stations are stated and the analysis of the data continuity between 2018-01-01 and 2019-05-01.

The following two figures contain the double mass analysis performed on the six TAHMO-stations that do not miss any data points. The time frame used to perform these analysis is the same.

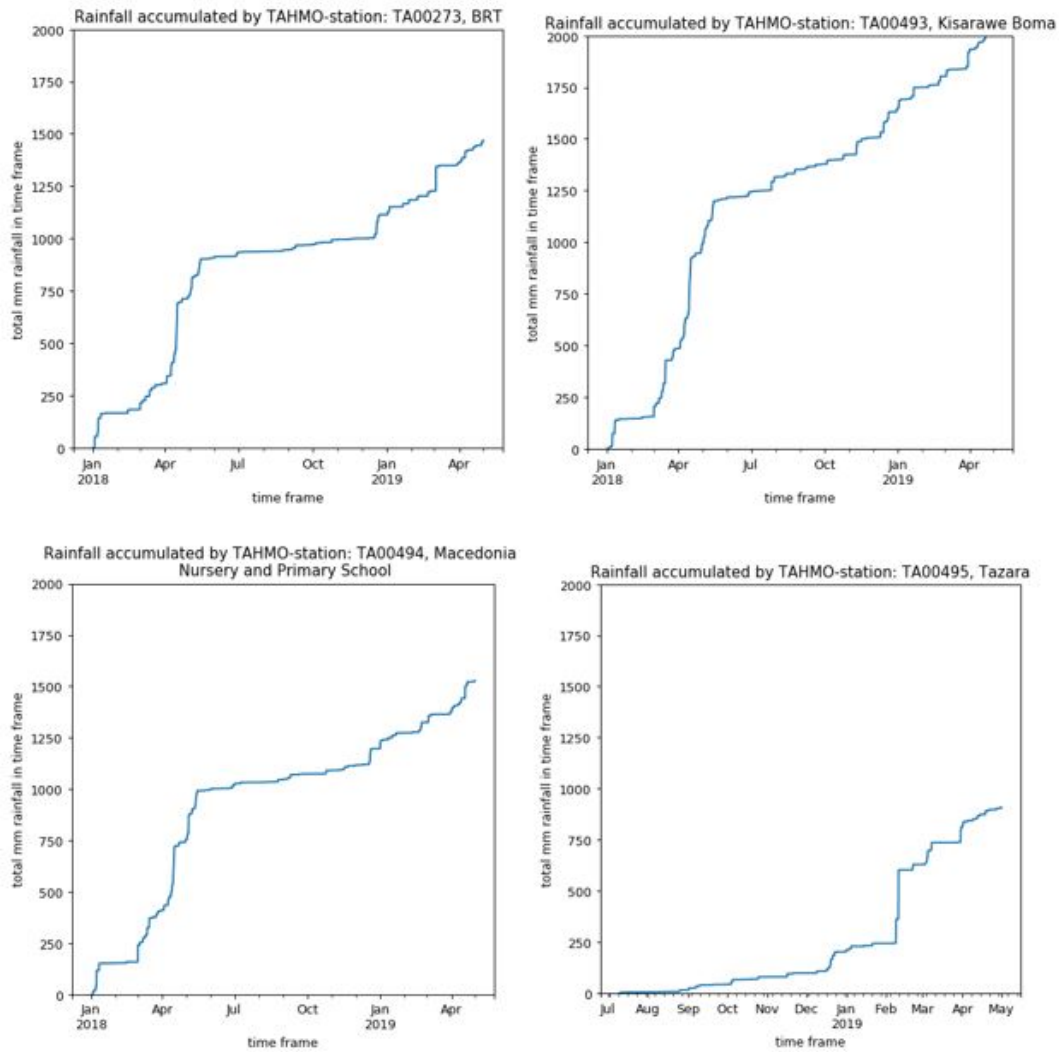
Table D.1: All missing data points of every TAHMO-station for the data frame between 01-01-2018 and 01-05-2019.

TAHMO-Total station	Missing data points
TA00269 Ardhi University	0
TA00270 Kinyereri primary school	0
TA00271 Visegese	0
TA00272 Pugu station secondary school	1575
TA00273 BRT	0
TA00493 Kisarawe Boma	0
TA00494 Macedonia Nursery and Primary School	0
TA00495 Tazara	4550

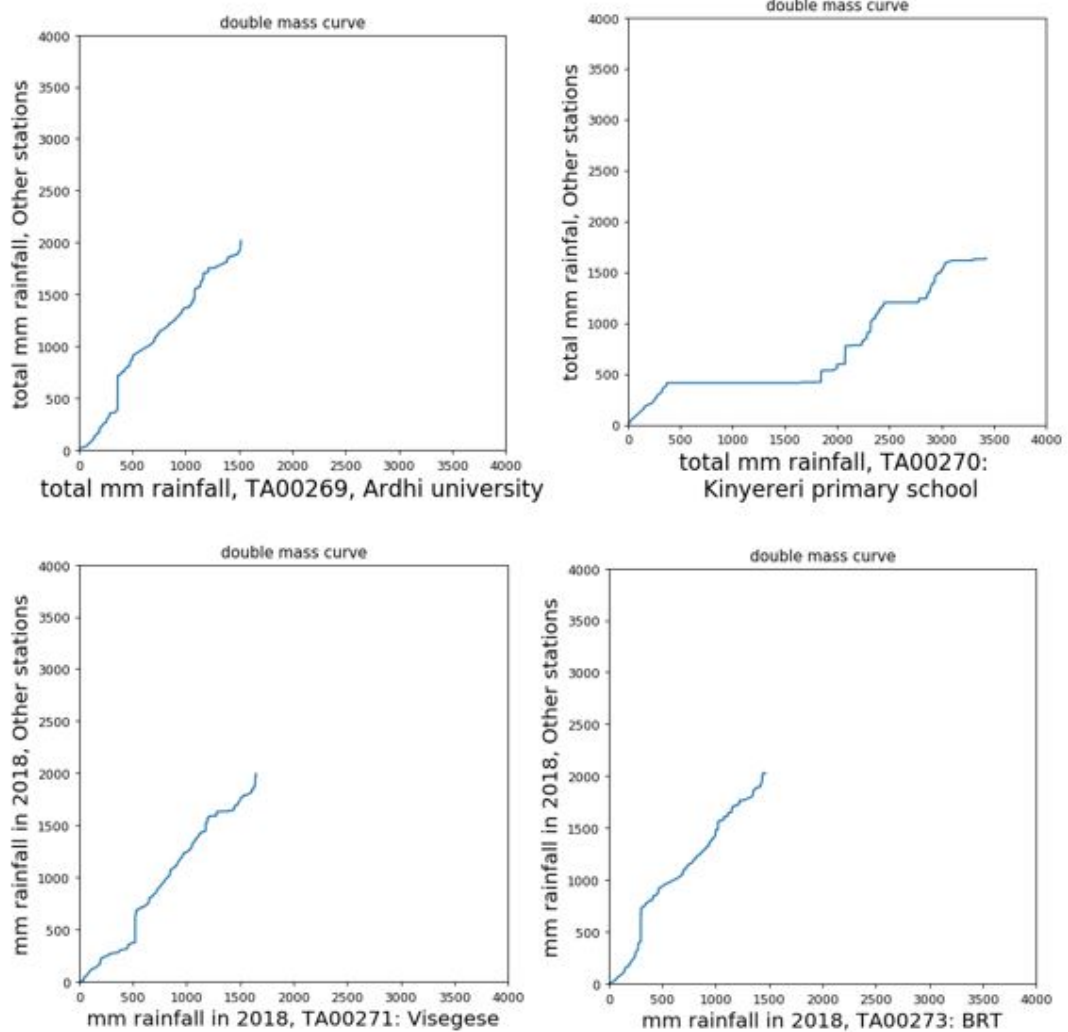


Equation: D.1: Accumulated rainfall of TA00269 Ardhi University, TA00270 Kinyereri primary school, TA00271 Visegese, TA00272 Pugu station secondary school

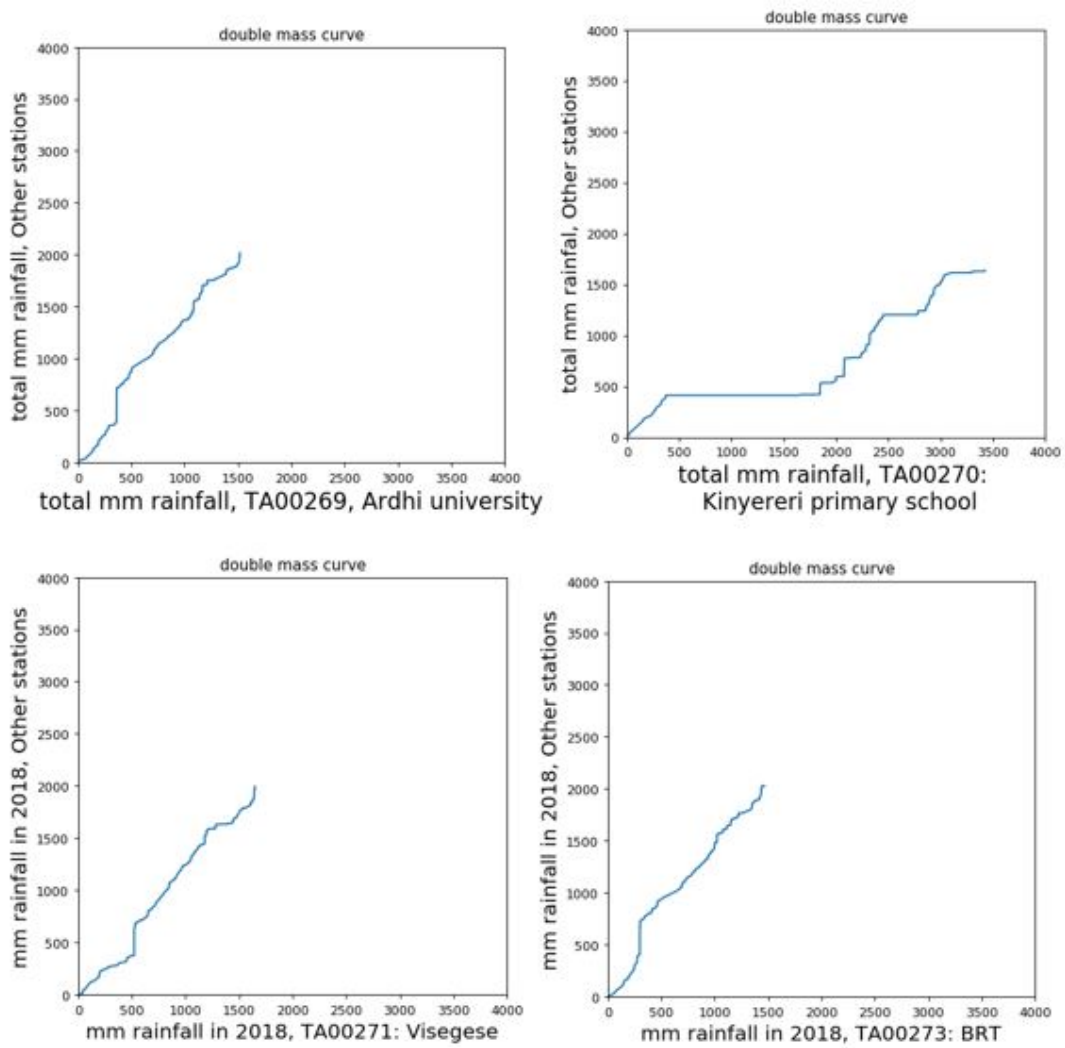




Equation: D.2: Accumulated rainfall of TA00273 BRT, TA00493 Kisarawe Boma, TA00494 Macedonia Nursery and Primary School, TA00495 Tazara

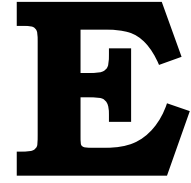


Equation: D.3: Double mass analysis of TA00269 Ardhi University, TA00270 Kinyereri primary school, TA00271 Visegese, TA00273 BRT.



Equation: D.4: Double mass analysis of TA00493 Kisarawe Boma and TA00494 Macedonia Nursery.





## Appendix E : Concentration and travel time Msimbazi catchment area

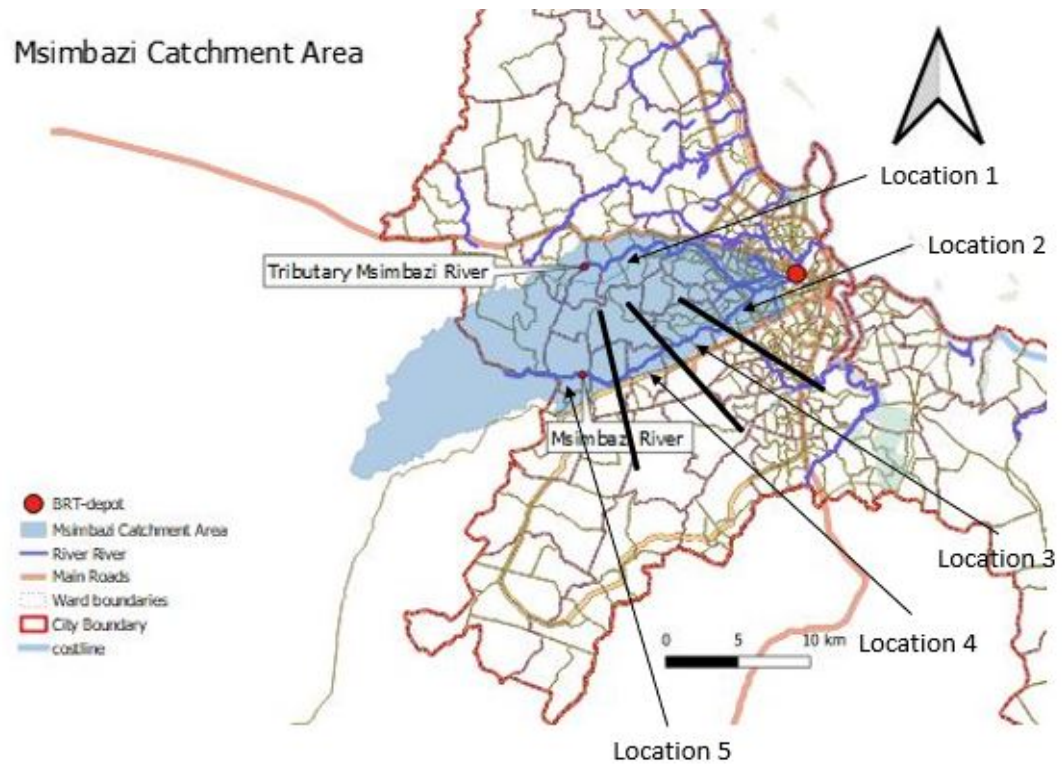
In this section the calculations performed to determine the maximum time of concentration and the average travel time of the Msimbazi catchment area are stated.

Figure E.1 shows the locations where data of the Msimbazi river is collected. Figure E.1 also shows the regions that by extrapolating this data have been assigned the same properties. Table E.1 shows all the data collected at the locations for a dry situation as illustrated in figure E.1. With the help of the Manning formula the GaucklerManning coefficient of the Msimbazi river is determined. With the help the GaucklerManning coefficient the Msimbazi river properties during a wet period is determined. Table E.2 shows the Msimbazi river properties during wet situations. With formula E.1 the calculation of the GaucklerManning coefficient is shown. With formula E.2 the calculation of the velocity during a wet situation is shown. For both examples location 5 is used. To determine the run-off time over land the

With the collected data the maximum time of concentration and the average travel time of the Msimbazi catchment area can be determined. Formula E.1 shows the calculations performed to determine these.

$$\begin{aligned}n &= \frac{R_h^{2/3} a^{1/2}}{V} \\V &= 1, 2 \\R_h &= 0, 3 \\Slope &= 0.004(L/L) \\k &= 1 \\n &= 0, 033\end{aligned}\tag{E.1}$$

$$\begin{aligned}V &= \frac{k}{n} R_h^{2/3} a^{1/2} \\n &= 0, 033 \\R_h &= 1 \\S &= 0, 44 \\k &= 1 \\V &= 2, 68m/s\end{aligned}\tag{E.2}$$



Equation: E.1: Schematic overview of locations where flow speed has been measured of the Msimbazi river. The black lines indicate the areas of the Msimbazi river assigned to that measuring location.

$$T_c = k * L^a * n^b * S^y * i^z$$

$L = \text{length of the watershed,}$   
 $n = \text{Surface roughness,}$   
 $S = \text{Slope of the watershed,}$   
 $i = \text{Rainfall intensity,}$   
 $T_c = \text{time of concentration,}$   
 $k = \text{constant,}$   
 $a, b, y, \text{ and } z = \text{exponents}$

(E.3)

Table E.1

Dry situation:					
Locations:	location 5	location 4	location 3	location 2	location 1
Velocity water body in m/s:	1,2	0,9	0,7	0,4	1,2
assigned river lenght in meters:	15500	6888	6888	6888	8857
Travel time in seconds:	12917	7653	9840	17220	7381
Travel time in hrs:	3,6	2,1	2,7	4,8	2,1
Surface area in m2	1,5	2	2,2	2	1,5
Wetted perimeter in meters:	5	6	8	12	5
Hyrdaulic radius:	0,3	0,33	0,28	0,17	0,3
Slope in m/m:	0,008	0,005	0,004	0,004	0,004
n:	0,033	0,038	0,038	0,048	0,024

Table E.2

Wet situation:					
Locations:	location 5	location 4	location 3	location 2	location 1
Velocity water body in m/s:	2,68	2,17	1,66	1,32	1,2
assigned river lenght in meters:	15500	6888	6888	6888	8857
Travel time in seconds:	5788	3171	4161	5228	7381
Travel time in hrs:	1,6	0,9	1,2	1,5	2,1
Surface area in m2	15	25	25	30	1,5
Wetted perimeter in meters:	15	20	25	30	5
Hyrdaulic radius:	1	1,25	1,00	1,00	0,3
Slope in m/m:	0,008	0,005	0,004	0,004	0,004
n:	0,033	0,038	0,038	0,048	0,024





# F

## Appendix F : Data obtained from the interviews

In this section all data obtained from the interviews are structured. This is done by answering some general question which are similar to the questions stated . The interviews all where performed with personnel that work for the the DART or the U-Dart organization. The main idea behind the performed interviews was to get as much information as possible from as many angles as possible. Therefore, interviews were performed with people, all with different professional backgrounds active in different parts of the BRT-organization. By cross-referencing the interviews with the reports and the published articles a complete and honest picture of the BRT-system and all its assets is created. The analyses performed on this data was done with the intention of getting a clear understanding on how the BRT-system functions as an organization, what progresses, operations and communication methods are used and what assets are maintained and held by the BRT-system. With this information first a lead time requirement will be determined in which the BRT-system is able to respond on an emergency warning. Second, the response and failure cost caused by a flooding will be determined. This will help determine how a warning needs to be interpreted if there is a significant the uncertainty. A questionnaire has been set up with the intention of being answered with the reactions received in the interviews. The set up of the interviews was intentionally as non restrictive as possible. This was done by asking a few short question to provide room for the interviewed person to react as free as possible. Below the questions and their answers are stated, the transcript of the interviews can be consulted in appendix A.

- What kind of flooding is experienced by the BRT-system in terms of location, impact and duration?

The construction of the depot started in January 2017 and ended in June 2017. The current location of the depot was originally meant to house the depot temporarily until a more suitable location was found. So far, the DART-organization and the local government where not able to do so. The current location of the depot is inside a low lying wetland area just upstream of the Jangwani bridge. The flooding of depot happens as followed. during or after a intense rainfall event the gate way underneath the Jangwani bridge is not able process all of the discharging water from the upstream areas of the basin. This causes the bridge to act like a dike thereby backing up the water upstream causing a flood inside the depot. So far there where 10 flooding events registered by U-DART personnel. These flooding events can be divided by water level inside the depot into three groups; small(two floods), average(8 floods) and heavy flooding(1 flood). The speed of the rising water level variate between a few centimeters per hour during a small flood and 30 to 60 centimeters meters per hour during a heavy flood. The water level height for a small flood is at its peak about 30 centimeters, for a average flood about 1 meter and for a heavy flood 2 meters. The retreating process of the water takes 1 day for a small flood, 3 to 5 days for an average flood an a maximum of 2 weeks for a heavy flood. In all flooding cases solid waste, mud and other unwanted materials where left behind. These unwanted materials have a negative impact on the operational quality of the BRT-system. Driving in and driving out of the buses, maintenance work and other activities in the depot are hindered by shambles left behind by a flooding event. Furthermore,

the bus route following the Morogoro road will be split into two during an average or heavy rainfall. In this situation the buses will keep operating on one of the two newly formed bus routes depending on where they are located on the moment of flooding. Next to the flooding of the depot there is one more location that is prone to flooding which is the bridge section of the Kawana Road. Every time the depot floods this location has also flooded until now, therefore there were 10 flooding events at the Kawana Road just as at the depot. When the bridge section of the Kawana Road floods the bus route is cut into two pieces just as the Morogoro Road bus route. The two newly created bus routes keep on operating independently from each other. The buses keep on driving on one of the two new bus routes depending on where they are located at the moment of flooding. Furthermore, a distinction can be made for flash floods where there is no rainfall event occurring at the depot. One registered flooding event belongs in this category, all the other flooding events had a rainfall event occurring or preceding it. During all of those 10 events a flood starts with the incoming water backing up at the Jangwani bridge, subsequently the water starts to flow into the depot mostly through the east gate.

- What is the exact time and date of these flooding?

In total there were 9 recorded flooding events since the start of the BRT-system and the construction of the depot. The exact data and time can be determined of 7 of those, the other 3 have a significant uncertainty when it comes to determining when the flooding event started. This is caused by the fact that these flooding events occurred during the rainy season in 2018. During this period there was an extensive period of continuous flooding. Interviewed personnel had trouble to determine when one flooding event would end and the next one would start. After cross-referencing all of the data sources 5 different flooding events have been distinguished in April. As mentioned before the certainty of the exact date and time of these flooding events is low. table.. shows all flooding events and figure ... shows all flooding events structured in a time line.

- What was the impact of the flooding on the BRT-system operations and on its assets, does it increase over the past years?

Impact of a flooding event can be divided in operational losses and damage to its assets. Operational losses can be divided in the BRT-system not being able to provide its services for a certain amount of time and the loss in confidence by the customers who thereby increasingly choose other means of transport. When the BRT-system is not able to provide their full services caused by a flooding it cost about 60 million shillings a day. It takes about 3 weeks for people to fully retain their confidence in the BRT-system this accounts for a loss of 10 to 20 million shillings a day.

The losses caused by asset damage can be divided into water damage to the buses and cleaning cost of the depot. Repair cost of per bus is roughly 5 million shillings. During the flood on the 4th of May more than 100 buses were damaged, repair cost was therefore 5 million x 100 = 500 million shillings. The amount of buses that suffer damage depends on the moment of flooding in the day and the response time at that moment. These factors determine the amount of buses that are vulnerable for flooding and sustain damage. Furthermore, water level inside the depot needs to reach a certain height before key parts of a bus sustain damage. This water level height is about 50 centimeters, only when this threshold value is exceeded during a flood significant damage is sustained to the engine or transmission of the buses.

- What kind of flooding information enters the BRT-system?

There are three different weather forecasting periods communicated by TMA to DART. - short period -> up to 5 days - middle period -> 1 month - long period -> 3 months (seasonal) These forecasts provide information on how much rainfall will be experienced in Dar es Salaam for the pre-determined period. Based on this information a flood risk is determined on short term (next days) and on long term (coming weeks). DART communicates a message to U-Dart based on this information which contains a short term command and a long term preparedness level. There are two short term commands, the first one is to proceed operations as normal. This command is issued when the short term flood risk is not critical. The second short term command is to start evacuate the depot immediately and to put all mitigating actions into place. This command is issued when the chance on flooding is critical. There are also two long term preparedness levels that are communicated by DART to U-Dart. The first preparedness level is to proceed as normal, this is issued when the chance on flooding is low. The second preparedness level

is to be on high alert, this means that U-Dart is able to react immediately on a possible flooding event on short term bases. ... presents a schematic overview of the information matrix inside the BRT-system.

- How does it differ during day time, night time and the weekend?

Weather forecast provided by TMA is only issued a couple of times a week during the day. long term preparedness level by DART is also only issued during the day and not by night. The information within the short term command by DART to U-DART is always the same, only the communication method differs during day time, night time and the weekend.

- How does the flooding information enters the BRT-system?

TMA communicates its forecasting periods trough email, radio and social media. DART communicates its short term command and long term preparedness level to U-DART by telephone, email or by physically speaking to personnel. The method of communication differs and it does not posses a clear structure. The communication method is mostly chosen depending on what the person that needs to communicate prefers at that moment.

- How does it differ during day time, night time and the weekend?

TMA only communicates its forecasting periods on Tuesday and Thursday during the day. DART communicates the long term preparedness level a couple of times a week during the day. When immediate mitigating actions are in need the short term command is communicated through a method that the sender believes will have the highest chance of reaching the receiver on time at that moment. During the night or weekend the telephone is thereby more likely to be used, during day time Whats App and email are more likely to be used.

- What responding mitigating actions towards an expecting flood are in place?

When TMA issues a weather forecast that states a significant chance on flooding in the coming weeks U-DART will make sure that they are on 'high' alert. During a high alert situation U-DART will make sure that they have enough bus drivers located at the depot to evacuate all buses from sight. U-DART also places a bridge spotter at the Jangwani bridge to analyze the water level of the Msimbazi river. When this bridge spotter determines that the water level of the Msimbazi river has reached a critical level a warning is issued to all managing staff on sight. Also, during a high alert situation the inventory manager takes several necessary precautions to mitigate several problems caused by a flooding. These precautions are, relocating expensive tools and part of the buses and relocating fuel tanks to other bus depots that are not prone to flooding.

- How do they differ during day time, night time and the weekend?

It is important to U-DART that there is enough personnel located at the depot at all times to relocate the buses to a safe place. During the day or in the weekend this is not a problem because most buses are outside the depot driving along the bus route and enough bus drivers are on sight to act and drive out the remaining buses. During the night however all buses are inside the depot, this means that more than 40 bus drivers will have to stay at the depot at night to relocate the buses if necessary. However, this plan is newly formulated and has not yet been used in practise.

- What responding mitigating actions towards an occurring flood are in place?

When the decision by U-DART is made to act on an opposing threat such as a flooding event the following processes take place. First, management makes sure that all personnel is in safety and that personnel that do not have a roll in the mitigation plan are evacuated. After this the inventory manager makes sure all tools and bus parts are locked away. At the same time, the head of operations will mobilize all bus drivers on sight to start evacuate all buses inside the depot. The head of operations will also call the security at the gate of the depot, they will stop any bus that tries to get inside.

When a bus route has been flooded at a certain location, this bus route will be split into two independently operating systems. The buses will keep on driving and providing services on the system where it was located before the flooding event has started.

DART is responsible to inform all stakeholders in the city during a flood. Stakeholders are the local government, fire department, police department, local community and TMA. DART has also set up a

rapport with all progresses are explained that need to be executed concerning floods.

- How does the information matrix looks like in the BRT-system?

There are two main information streams inside the BRT-system concerning flooding hazards. The first one is the weather forecasting information stream provided by TMA to DART and U-DART. The second information stream consist out of the short term command and the long term preparedness level communicated from DART to U-DART. Figure ... gives an overview of these information streams. Communication methods are calling, Whats App, SMS, radio and email. All these communication methods are used without a clear structure.

During a flooding situation the electricity is shut down for safety reasons. This power cut creates several communication problems such as down time of the telephone lines.

- How do they differ during day time, night time and the weekend?

During day time and in the weekend Whats App, email and SMS are the most used form of communication. during the night calling is preferred because the chance of response increases with this form of communication.

- Out of which sub-components do the mitigating actions exist?

There are two clear mitigating actions that U-DART implements when a flood event occurs, evacuating the buses from the depot and splitting the bus route into two independently working systems. The bus evacuation composes out of three main sub components. First, the bridge spotter warns the managing staff, second, the managing staff orders the personnel to evacuate them self and orders the bus drivers to evacuate the buses, third, the buses are evacuated by the bus drivers to nearby safe locations. Furthermore, the inventory manager makes sure that all the posses are locked away and secure.

The 'splitting' of the bus routes is basically on process where the bus drivers decide to keep on operating on one of the independent systems where he is driving when a flooding event is occurring.

- How much time does every component cost?

The time needed for the warning to travel from the bridge spotter to the bus drivers via the management team is 10 minutes. The time to take out the buses is roughly 60 minutes. The bus rout splitting process takes virtually no time because it instantly happens when a section of the bus route is unavailable due to flooding.

- What kind of improvements could be made to the mitigating actions in place towards the future?

the depot needs to be relocated, the river needs to left to be river. The Msimbazi needs to be protected better. The Jangwani bridge and the surrounding area should be cleaned and maintained properly, if not it will keep acting like a dike because sediment build up at the river floor.

There should be better and clearer communications line between all involved parties such as U-Dart, DART, TMA and the Police. Everybody should be kept into the loop so that every body knows what is going on. Especially U-DART is left out of this communication matrix.

The U-Dart is responsible for every process from evacuating the buses to cleaning the road and the depot after a flooding. A deviation of responsibilities to other parties might help. There is no official communication method between bus drivers and transport officers, this could be standardized or at least better structured. People involved in processes surrounding flooding event will thereby know better wat to do and what to expect.

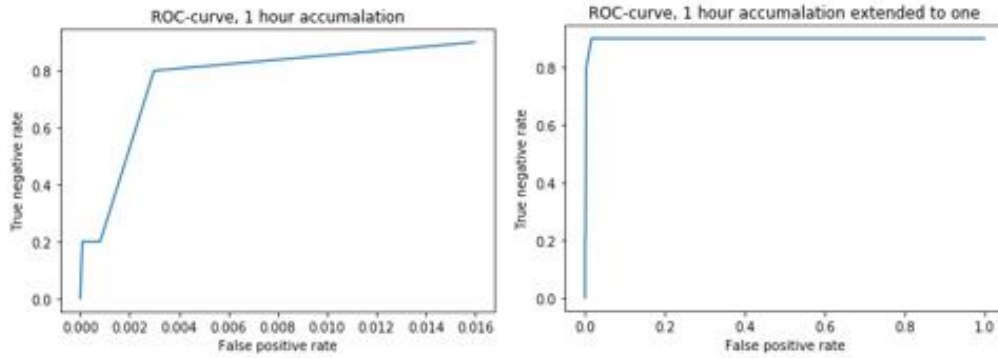
It is unclear how the actual implementation of the mitigating actions take place for most people. It is not completely clear and different people have a different understanding on what should be done in an emergency situation, this should be improved.

The command chain for different kind of processes in a emergency situation are also not clear. For example, when the BRT buses cannot be used for operation Daladala buses need to be used to ensure the continuation of operations. Everybody knows that this needs to be done but the responsibilities for different aspects of this procedure are unclear in reality and therefore not executed as needed.

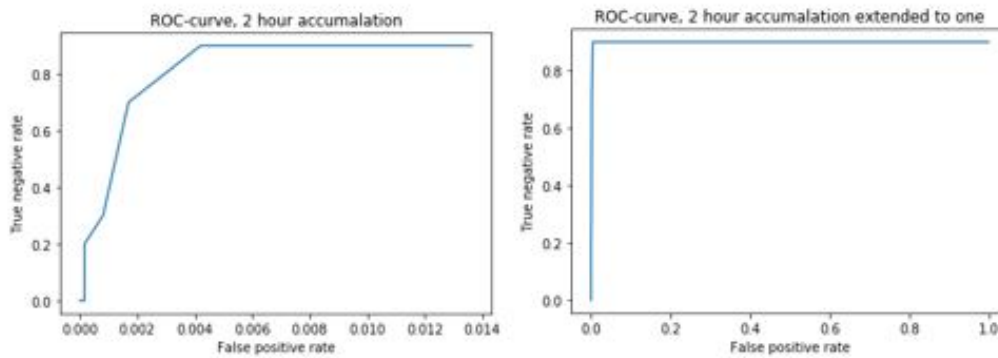
# G

## Appendix G : ROC curves relational and hydrological model

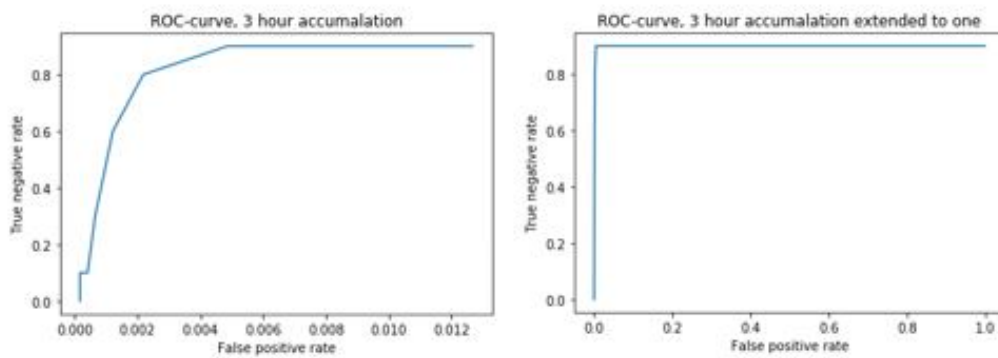
In this section all ROC-curves produced by the regression model analysis are stated. The ROC-curve produced by the W-flow model is stated as well. The ROC-curves produced in this analyses have a very low false positive rate. This is due the fact that the quantity of true negatives is much higher than the other outcomes. In order to determine the surface area under the ROC-curves, each ROC-curve will be extended to the X and Y point of 0,9. This creates an equal surface area determination, thereby ensuring that the optimal model is chosen. All ROC-curves produced by the regression model are illustrated in figures [G.1](#), [G.2](#) and [G.3](#). The regression model that produced by the W-flow model is illustrated in figure [G.4](#).



Surface area below curve, 1 hour accumulation: 0.8979067516334597

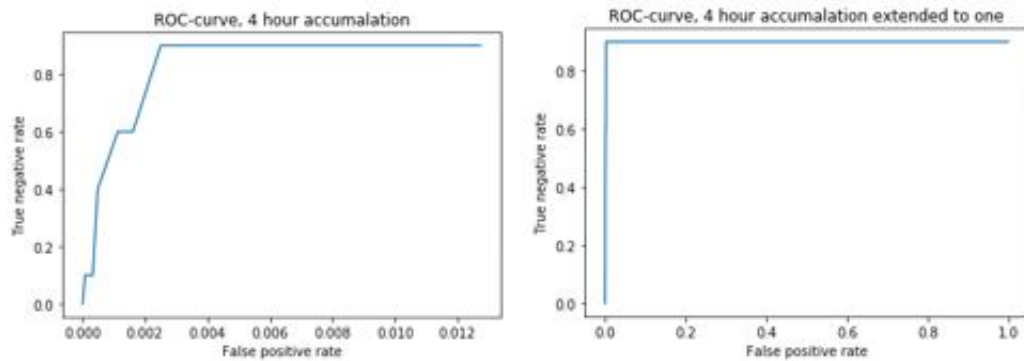


Surface area below curve, 2 hour accumulation: 0.8988303621843994

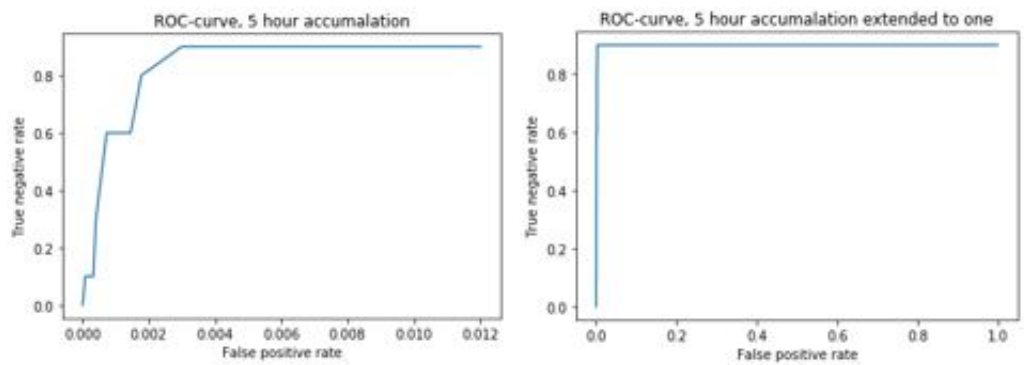


Surface area below curve, 3 hour accumulation: 0.8989110268613374

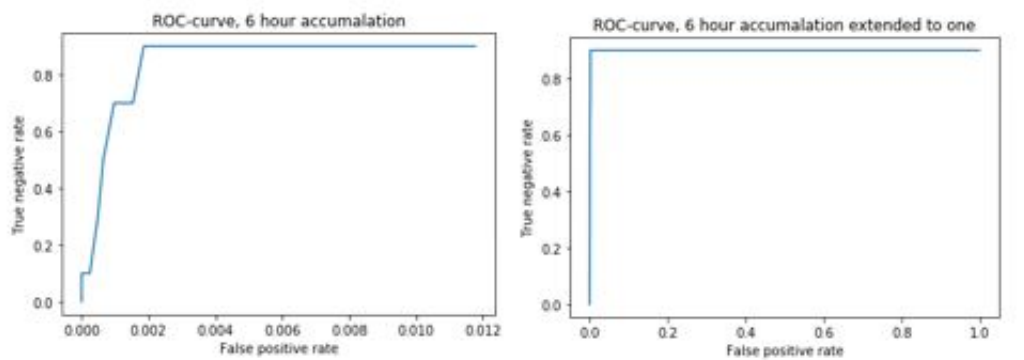
Equation: G.1: Illustration of the ROC-curves of the 1,2 and 3 hours rainfall accumulation.



Surface area below curve, 4 hour accumulation: 0.8990965556182948



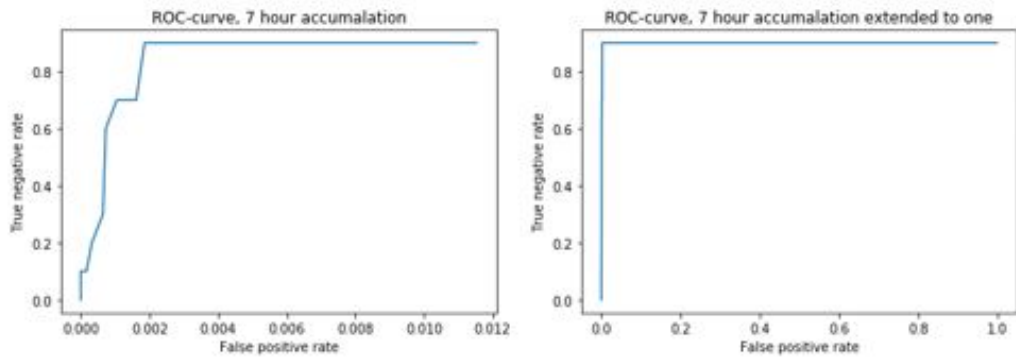
Surface area below curve, 5 hour accumulation: 0.8991933532306203



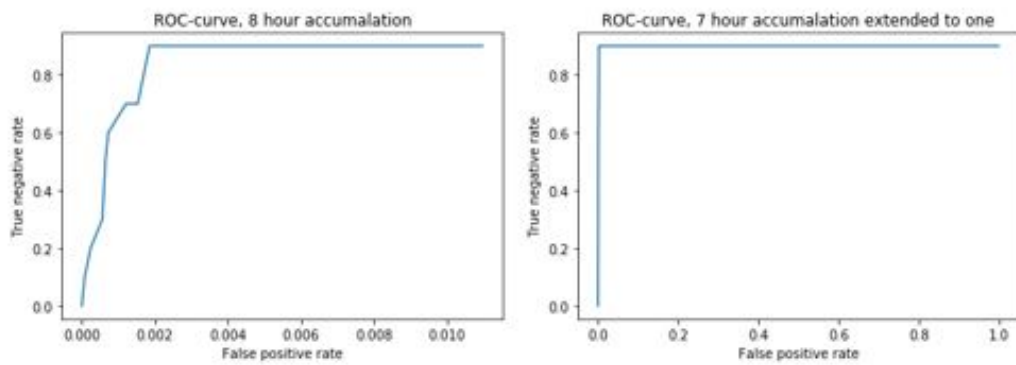
Surface area below curve, 6 hour accumulation: 0.8993143502460272

Equation: G.2: Illustration of the ROC-curves of the 4, 5 and 6 hours rainfall accumulation.



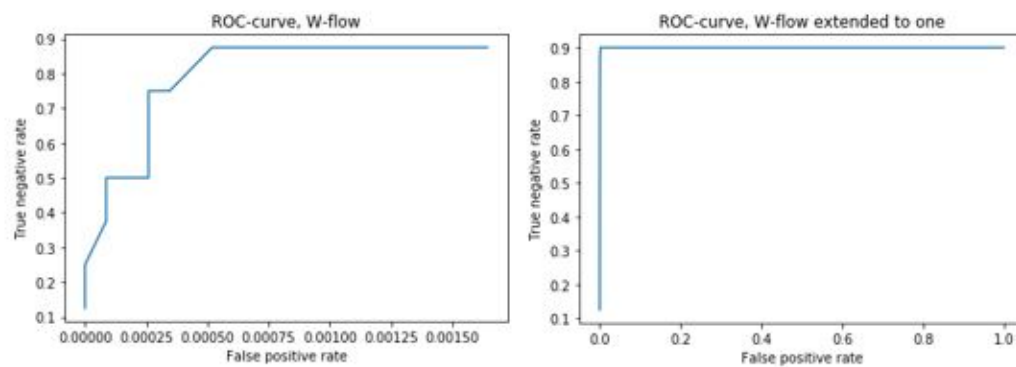


Surface area below curve, 7 hour accumulation: 0.899286117609099



Surface area below curve, 8 hour accumulation: 0.8992143502460272

Equation: G.3: Illustration of the ROC-curves of the 7 and 8 hours rainfall accumulation.



Surface area below curve, W-flow Model: 0.8998334631023445

Equation: G.4: Illustration of the ROC-curve composed of the W-flow model



# H

## Appendix H: Script used for training and validating both models

In this section the script used to determine the optimal time frame is stated. The script used for the relational and the hydrological model are stated separately. First script written for the W-flow model is stated. Second the script written for the relational model is stated. The scripts are written in Python in a Jupyter Notebook environment.

# Relational model

October 4, 2019

```
In [ ]: import pandas as pd
import numpy as np
import scipy.spatial
import matplotlib.pyplot as plt
from itertools import combinations
from scipy.spatial.distance import pdist
from scipy import optimize
import matplotlib.dates as mdates

In [ ]: df7 = pd.read_csv('run_gauges_laatste_goed_goed_goed.csv',
                        index_col='datetime', parse_dates=True)
df7.columns = ['datetime', 'nul', 'een', 'twee', 'drie', 'vier',
               'vijf', 'zes', 'zeven', 'acht',
               'negen', 'tien', 'elf', 'twaalf', 'dertien',
               'veertien', 'vijftien', 'zestien', 'zeventien',
               'achtien', 'hondertwee', 'honderddrie',
               'honderdvier', 'honderdvijf', 'honderdzes',
               'honderdzeven', 'honderdacht', 'tweehonderdeen',
               'tweehonderdtwee', 'tweehonderdvier',
               'tweehonderdvijf', 'tweehonderdzes',
               'tweehonderdzeven', 'tweeduizendeen',
               'tweeduizendtwee']

In [ ]: dt_forecastwindow = 24
dt_valid = 24
df7['point_start_flood'] = False
df7['Flood_in_process'] = False
df7['Lead_time_flood'] = False #
df7['nul'] = 0
event_dates = pd.DatetimeIndex([
    '2017-10-27 10:00:00',
    '2018-01-08 16:00:00',
    '2018-03-16 16:00:00',
    '2018-03-26 18:00:00',
    '2018-04-13 10:00:00',
    '2018-05-04 18:00:00',
])
for date in event_dates:
```

```

df7.loc[(df7.index == date), 'point_start_flood'] = True
df7.loc[(df7.index >= date - pd.Timedelta(dt_forecastwindow, unit='h'))
        & (df7.index <= date), 'Lead_time_flood'] = True
df7.loc[(df7.index > date) & (df7.index < date + pd.Timedelta(dt_valid,
        unit='h')), 'Flood_in_process'] = True

In [ ]: #working script for differentiatie in regenval

reset_1 = 0

resultsx = []
resultsy = []

for x in ['1H', '2H', '3H', '4H', '5H', '6H', '7H']:
    df7['rolling_sum'] = df7.twee.rolling(x).sum()

for i in [15,30,45,60,75,90,105,120,135,150,165,180,
        195,210,225,240,255,270,285,300,315,330,345,360,375,390,395]:

    df7['precipitation_shifted'] = df7.rolling_sum.shift()
    df7['precipitation_shifted_filled'] =
    df7['precipitation_shifted'].fillna(0)

    df7['Rainfall_Difference'] = (df7['rolling_sum']
        - df7['precipitation_shifted_filled'])

    df7['Warning_first'] = (df7['rolling_sum'] > i) == True

df7['Hit_Flood_True_Positive'] = ((df7['Warning_first'] == True )
    & (df7['Lead_time_flood'] == True)) #Hit + flood
df7['Hit_no_Flood_False_Positive'] = ((df7['Warning_first'] == True )
    & (df7['Lead_time_flood'] == False)) #Hit + no flood

for m in range(len(df7)):
    if df7.Hit_Flood_True_Positive[m] == True:
        reset_1 = 1
    if reset_1 == (dt_forecastwindow + 1):
        reset_1 = 0
    if reset_1 >= 1:

```

```

        df7.Hit_Flood_True_Positive[m + 1] = False
        reset_1 += 1

for k in range(len(df7)):
    if df7.Hit_no_Flood_False_Positive[k] == True:
        reset_1 = 1
    if df7.rolling_sum[k] < 1:
        reset_1 = 0
    if reset_1 == 1:
        df7.Hit_no_Flood_False_Positive[k + 1] = False

Hit_Flood_True_Positive = df7.Hit_Flood_True_Positive.sum()

print(Hit_Flood_True_Positive,x, i, 'Hit_Flood_True_Positive')

No_Hit_Flood_False_Negative = len(event_dates) -
Hit_Flood_True_Positive #No Hit + Flood
print(No_Hit_Flood_False_Negative,x,
      i, 'No_Hit_Flood_False_Negative')

Hit_no_Flood_False_Positive = df7.Hit_no_Flood_False_Positive.sum()

print(Hit_no_Flood_False_Positive, 'Hit_no_Flood_False_Positive')

No_Hit_No_Flood_True_Negative = (len(df7) -
(Hit_Flood_True_Positive + No_Hit_Flood_False_Negative +
Hit_no_Flood_False_Positive))

print(No_Hit_No_Flood_True_Negative,x, i,
      'No_Hit_No_Flood_True_Negative')

yy = Hit_Flood_True_Positive / (Hit_Flood_True_Positive +
                               No_Hit_Flood_False_Negative)
xx = Hit_no_Flood_False_Positive / (Hit_no_Flood_False_Positive
                                   + No_Hit_No_Flood_True_Negative)

resultsx.append([xx])
resultsy.append([yy])

resultsx.reverse()
resultsy.reverse()
np.trapz(resultsy, resultsx = x)

```

# Relational model

October 4, 2019

```
In [ ]: import pandas as pd
import numpy as np
import scipy.spatial
import matplotlib.pyplot as plt
from itertools import combinations
from scipy.spatial.distance import pdist
from scipy import optimize
import matplotlib.dates as mdates

In [ ]: df1 = pd.read_csv('All_Data_2.0.csv',
                        index_col='dateTimeUTC', parse_dates=True)

df1.columns = ['site', 'name', 'precipitation']
df10 = df1.loc[df1['site'] == 'TA00269']
df11 = df1.loc[df1['site'] == 'TA00270']
df12 = df1.loc[df1['site'] == 'TA00271']
df13 = df1.loc[df1['site'] == 'TA00272']
df14 = df1.loc[df1['site'] == 'TA00273']
df15 = df1.loc[df1['site'] == 'TA00494']
df16 = df1.loc[df1['site'] == 'TA00495']
df17 = df1.loc[df1['site'] == 'TA00493']

In [ ]: df20 = df10.loc[(df10.index >='2018-01-01 01:00:00')
                        & (df10.index <= '2019-06-01 23:00:00')]
df21 = df11.loc[(df11.index >='2018-01-01 01:00:00')
                & (df11.index <= '2019-06-01 23:00:00')]
df22 = df12.loc[(df12.index >='2018-01-01 01:00:00')
                & (df12.index <= '2019-06-01 23:00:00')]
df23 = df13.loc[(df13.index >='2018-01-01 01:00:00')
                & (df13.index <= '2019-06-01 23:00:00')]
df24 = df14.loc[(df14.index >='2018-01-01 01:00:00')
                & (df14.index <= '2019-06-01 23:00:00')]
df25 = df15.loc[(df15.index >='2018-01-01 01:00:00')
                & (df15.index <= '2019-06-01 23:00:00')]
df26 = df16.loc[(df16.index >='2018-01-01 01:00:00')
                & (df16.index <= '2019-06-01 23:00:00')]
df27 = df17.loc[(df17.index >='2018-01-01 01:00:00')
                & (df17.index <= '2019-06-01 23:00:00')]
```

```

df7 = pd.DataFrame(columns=['TA00269', 'TA00271', 'TA00273',
                           'TA00493', 'TA00494'])
df7.TA00269 = df20.precipitation
#df7.TA00270 = df21.precipitation
df7.TA00271 = df22.precipitation
#df7.TA00272 = df23.precipitation
df7.TA00273 = df24.precipitation
df7.TA00493 = df27.precipitation
df7.TA00494 = df25.precipitation
#df7.TA00495 = df26.precipitation

In [ ]: df7['TA00273'] = df7['TA00273'].shift(1)
df7['TA00269'] = df7['TA00269'].shift(1)
df7['TA00494'] = df7['TA00494'].shift(3)
df7['TA00271'] = df7['TA00271'].shift(6)
df7['TA00493'] = df7['TA00493'].shift(5)
#df7.head()
df7.fillna(0)
df7['totalprecipitation'] = (0.0718*df7.TA00269 + 0.240*df7.TA00271
                             + 0.098*df7.TA00273 + 0.196*df7.TA00493 + 0.39*df7.TA00494 )
df7['totalprecipitation'].fillna(0, inplace=True)

In [ ]: dt_forecastwindow = 24
dt_valid = 24
df7['point_start_flood'] = False
df7['Flood_in_process'] = False
df7['Lead_time_flood'] = False
df7['nul'] = 0
event_dates = pd.DatetimeIndex([
    '2018-01-08 16:00:00',
    '2018-03-15 16:00:00',
    '2018-03-25 10:00:00',
    '2018-04-13 10:00:00',
    '2018-04-16 10:00:00',
    '2019-03-03 10:00:00',
    '2019-04-19 10:00:00',
    '2019-05-06 17:00:00',
    '2019-05-07 08:00:00',
    '2019-05-14 02:00:00'
])
for date in event_dates:
    df7.loc[(df7.index == date), 'point_start_flood'] = True
    df7.loc[(df7.index >= date - pd.Timedelta(dt_forecastwindow,
        unit='h')) & (df7.index <= date), 'Lead_time_flood'] = True
    df7.loc[(df7.index > date) & (df7.index < date +
        pd.Timedelta(dt_valid, unit='h')), 'Flood_in_process'] = True

In [ ]: #working script for differentiatie in renewal

```

```

reset_1 = 0

resultsx = []
resultsy = []

for x in ['6H']:
    df7['rolling_sum'] = df7.totalprecipitation.rolling(x).sum()

    for i in [1,5,10,15,20,25,30,35,40,45,50,55,60,65]:

        df7['precipitation_shifted'] = df7.rolling_sum.shift()
        df7['precipitation_shifted_filled'] =
        df7['precipitation_shifted'].fillna(0)

        df7['Rainfall_Difference'] = (df7['rolling_sum']
            - df7['precipitation_shifted_filled'])

        df7['Warning_first'] = (df7['rolling_sum'] > i) == True

        df7['Hit_Flood_True_Positive'] = ((df7['Warning_first']
            == True) & (df7['Lead_time_flood'] == True))
        df7['Hit_no_Flood_False_Positive'] = ((df7['Warning_first']
            == True) & (df7['Lead_time_flood'] == False))

    for m in range(len(df7)):
        if df7.Hit_Flood_True_Positive[m] == True:
            reset_1 = 1
        if reset_1 == (dt_forecastwindow + 1):
            reset_1 = 0
        if reset_1 >= 1:
            df7.Hit_Flood_True_Positive[m + 1] = False
            reset_1 += 1

    for k in range(len(df7)):
        if df7.Hit_no_Flood_False_Positive[k] == True:
            reset_1 = 1
        if df7.rolling_sum[k] < 1:
            reset_1 = 0
        if reset_1 == 1:
            df7.Hit_no_Flood_False_Positive[k + 1] = False

Hit_Flood_True_Positive = df7.Hit_Flood_True_Positive.sum()

```

```

print(Hit_Flood_True_Positive,x, i, 'Hit_Flood_True_Positive')

No_Hit_Flood_False_Negative = len(event_dates) -
Hit_Flood_True_Positive
print(No_Hit_Flood_False_Negative,x, i, 'No_Hit_Flood_False_Negative')

Hit_no_Flood_False_Positive =
df7.Hit_no_Flood_False_Positive.sum()

print(Hit_no_Flood_False_Positive, 'Hit_no_Flood_False_Positive')

No_Hit_No_Flood_True_Negative = (len(df7) -
(Hit_Flood_True_Positive + No_Hit_Flood_False_Negative +
Hit_no_Flood_False_Positive))

print(No_Hit_No_Flood_True_Negative,x, i,
      'No_Hit_No_Flood_True_Negative')

yy = Hit_Flood_True_Positive / (Hit_Flood_True_Positive +
                               No_Hit_Flood_False_Negative)
xx = Hit_no_Flood_False_Positive / (Hit_no_Flood_False_Positive
                                     + No_Hit_No_Flood_True_Negative)

resultsx.append([xx])
resultsy.append([yy])

```

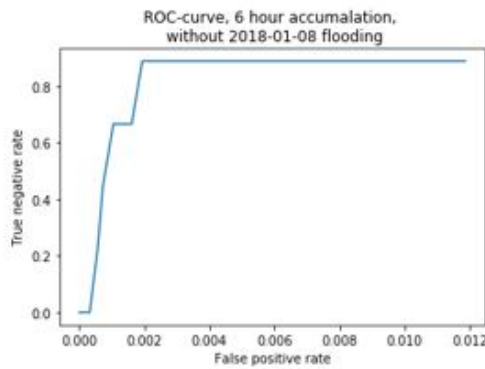


# I

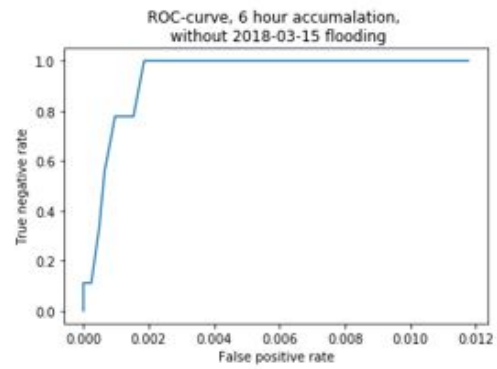
## Appendix I : ROC-curves leave one out method

In this chapter all ROC-curves are stated that are created for the leave on out method. Every ROC-curve is constructed of a new flooding event data string that differ from each other by the fact that for every ROC-curve one flooding event is left out. Make note that in this analysis the ROC-curves are not extended to the X and Y position of one. This is due the fact that the ROC-curves all stop at 0.12 mark at the False Positive Rate axis. Therefore, the calculated surface area's provided the right information in order to determine the surface area. The ROC-curves are illustrated in figure [I.1](#) and [I.2](#). The size of the surface area's calculated beneath the ROC-curves area also stated in the mentioned figures. Make note that the surface area beneath the ROC-curves do not have an unit. This is due the fact that both on the Y and X axis a probability rate is stated. The surface area is composed of both probability rates and has therefore no unit.

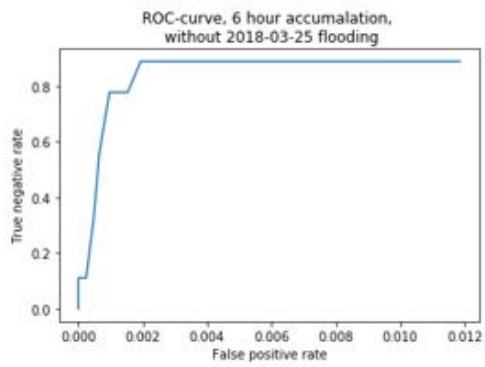
In this appendix the normal distribution of the surface area beneath the ROC-curves obtained by the Leave One Out method are also stated. In figure [I.3](#) the normal distribution is stated of all surface area's sizes beneath the ROC-curve obtained by the leave on out method, in figure [I.4](#) the normal distribution is stated of the surface area's beneath the ROC-curves with exception of the ROC-curve composed with the flooding event that occurred at 15-3-2018.



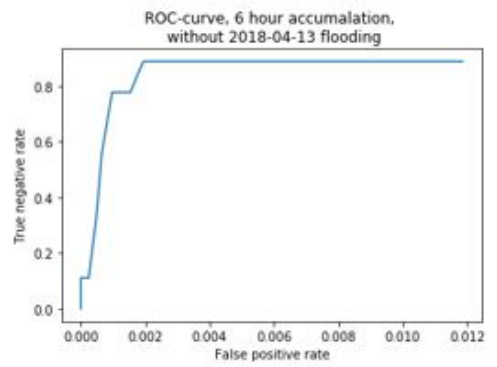
Surface area below curve, 6 hour accumulation: 0.009705866537613593



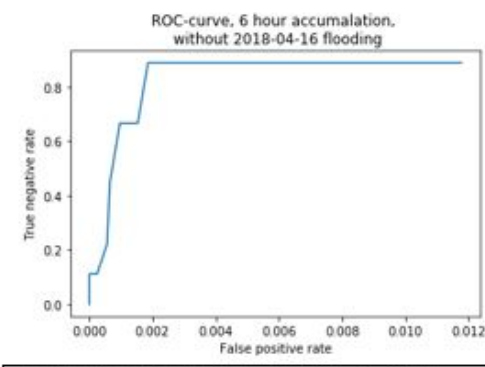
Surface area below curve, 6 hour accumulation: 0.011014321306303886



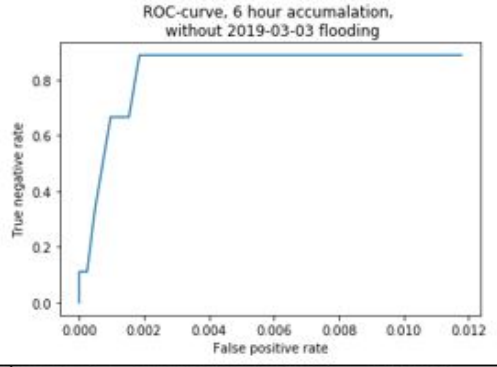
Surface area below curve, 6 hour accumulation: 0.009961284078077108



Surface area below curve, 6 hour accumulation: 0.009961284078077108

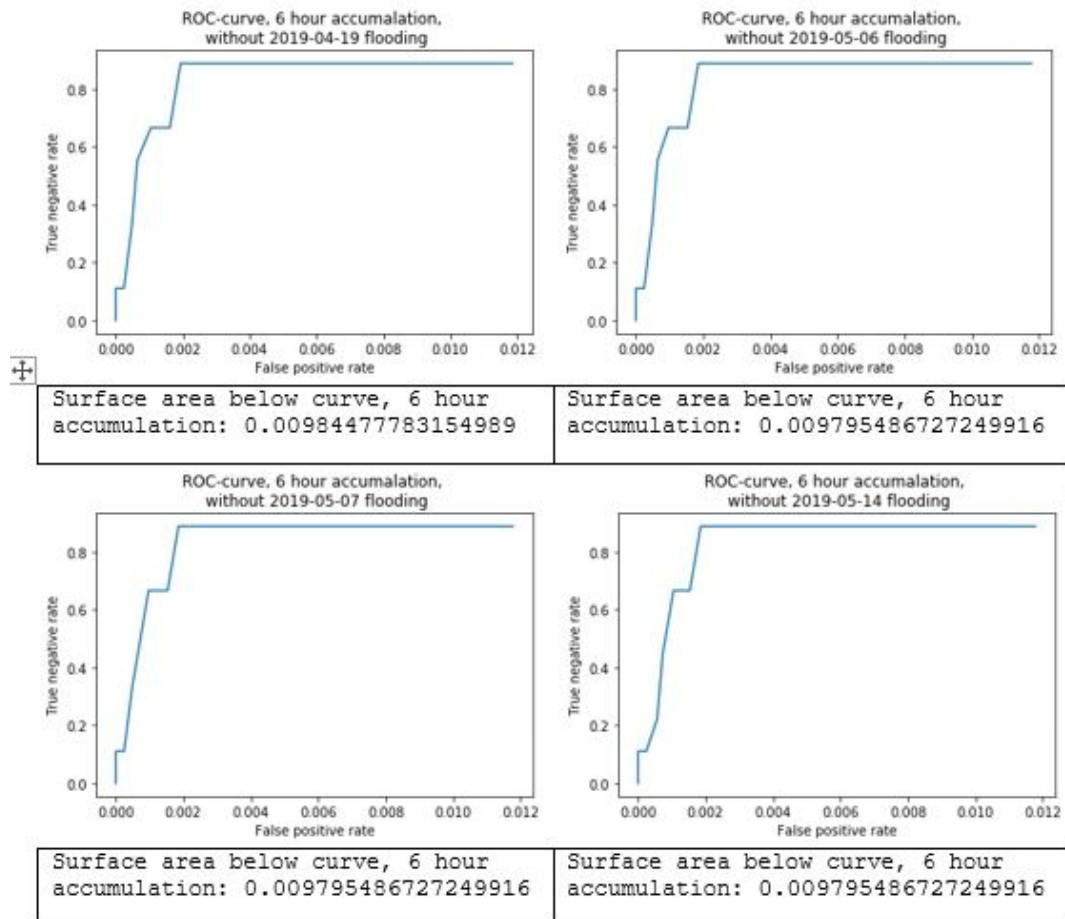


Surface area below curve, 6 hour accumulation: 0.00973275259450449

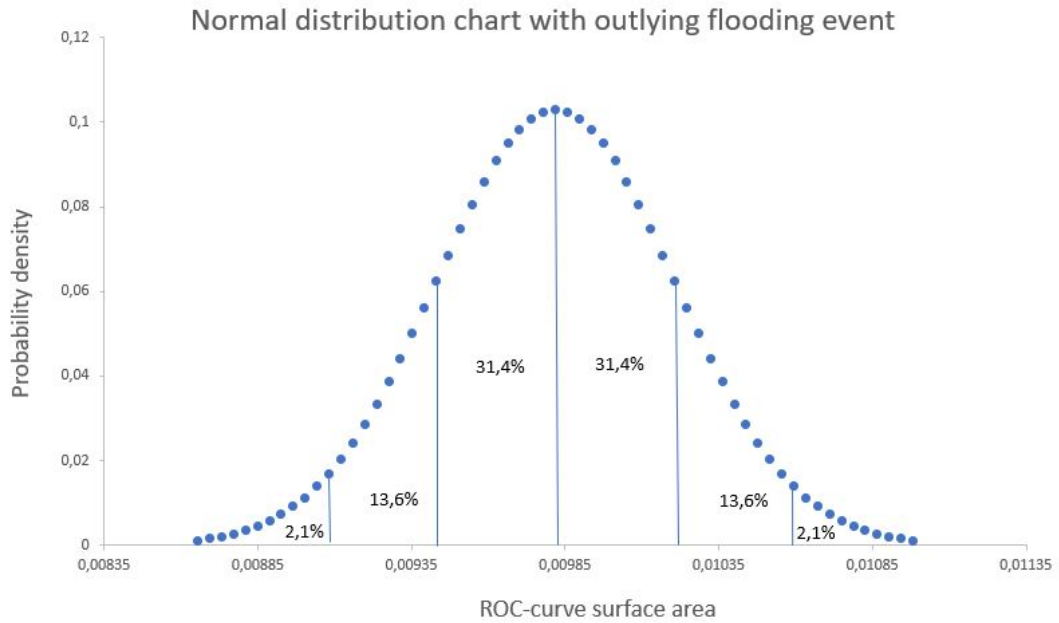


Surface area below curve, 6 hour accumulation: 0.009768600670359017

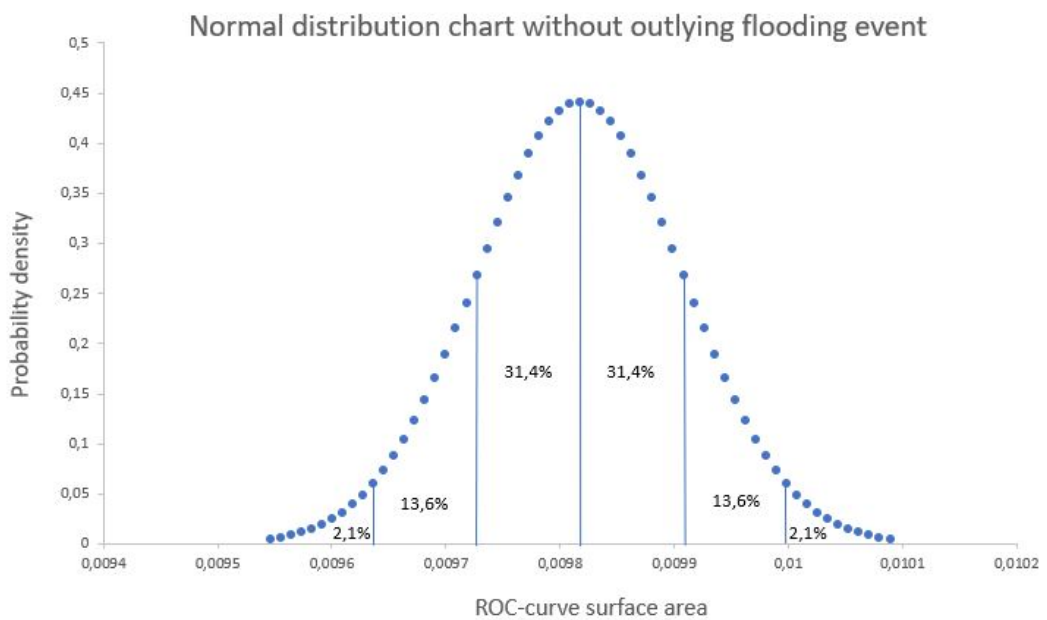
Equation: I.1: Illustration of the ROC-curves of the data strings with the following flooding event data point left out: 8-1-2018, 15-3-2018, 25-3-2018, 13-4-2018, 16-4-2018, 3-3-2019



Equation: 1.2: Illustration of the ROC-curves of the data strings with the following flooding event data point left out: 19-4-2019, 6-5-2019, 7-5-2019, 14-5-2019



Equation: I.3: Illustration of the normal distribution of the surface area beneath the 10 ROC-curves that were composed with the Leave One Out method.

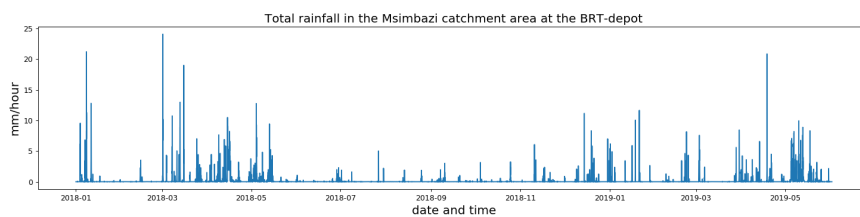


Equation: I.4: Illustration of the normal distribution of the surface area beneath 10 ROC-curves that were composed with the Leave One Out method with exception of the flooding event that occurred at 15-3-2018.

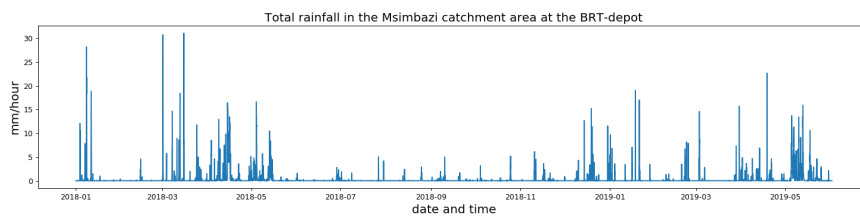
# J

## Appendix K: Rainfall in mm/h for full year, relational and hydrological model

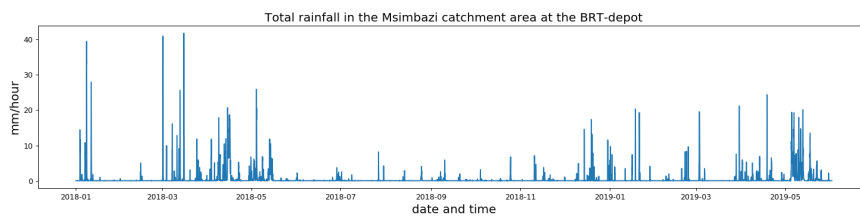
This appendix presents the plots of the historical rainfall data sets for all time frame accumulations.



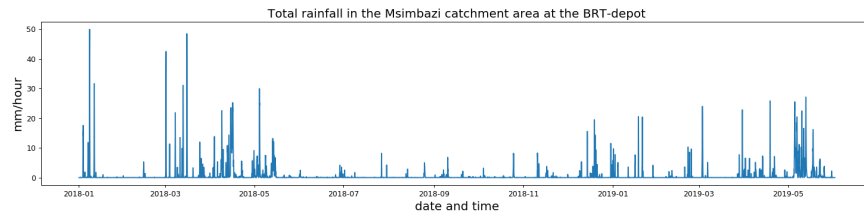
Equation: J.1: Relational model with rainfall accumulation of mm/1 Hour



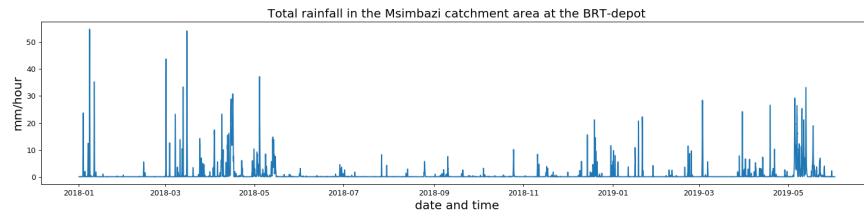
Equation: J.2: Relational model with rainfall accumulation of mm/2 Hours



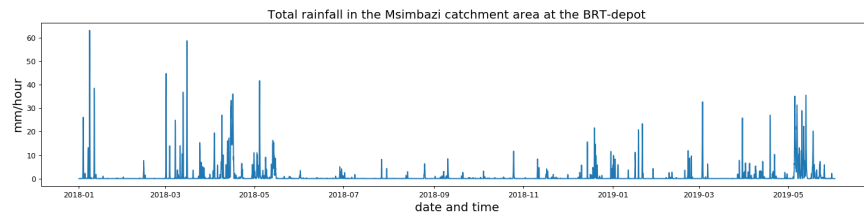
Equation: J.3: Relational model with rainfall accumulation of mm/3 Hours



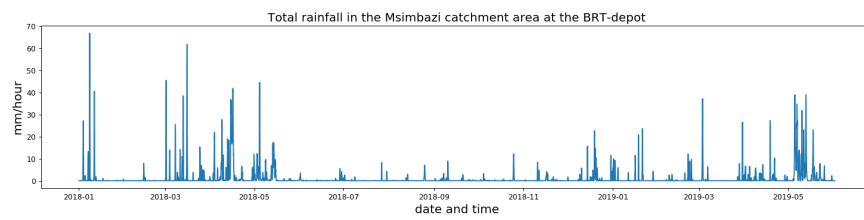
Equation: J.4: Relational model with rainfall accumulation of mm/4 Hours



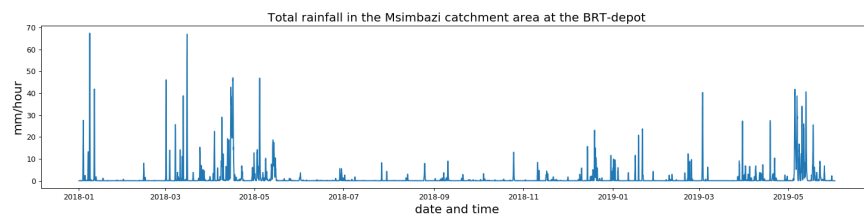
Equation: J.5: Relational model with rainfall accumulation of mm/5 Hours



Equation: J.6: Relational model with rainfall accumulation of mm/6 Hour



Equation: J.7: Relational model with rainfall accumulation of mm/7 Hours



Equation: J.8: Relational model with rainfall accumulation of mm/8 Hours

# References

- Ahferom, M. T., & Svensson, M. G. (2009). Sustainability assessment of a bus rapid transit (brt) system: The case of dar es salaam, tanzania. Lund University, Sweden.
- Arnell, N. W., & Gosling, S. N. (2016, Feb 01). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, 134(3), 387–401. Retrieved from <https://doi.org/10.1007/s10584-014-1084-5> doi: 10.1007/s10584-014-1084-5
- Berg, P., Moseley, C., & Haerter, J. O. (2013, Feb 17). Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, 6, 181 EP -. Retrieved from <https://doi.org/10.1038/ngeo1731>
- Chengula, D. H., & Kombe, K. (2017). Assessment of the effectiveness of dar es salaam bus rapid transit (dbrt) system in tanzania. *International Journal of Sciences: Basic and Applied Research*, 36(8), 10–30.
- Congedo, L., Munafò, M., & Macchi, S. (2013). Investigating the relationship between land cover and vulnerability to climate change in dar es salaam. Rome: Sapienza University.
- Cools, J., Vanderkimpen, P., Afandi, G. E., Abdelkhalek, A., Fockede, S., Sammany, M. E., ... Huygens, M. (2012). An early warning system for flash floods in hyper-arid egypt. *Natural Hazards and Earth System Sciences*, 12(2), 443–457.
- Darragh Coward, E. D., Edward Anderson. (2018). Tanzania urban resilience program, annual report 2018 (Tech. Rep.). World Bank.
- Egmann, E. T. (1986). Roughness coefficients for routing surface run-off. *Journal of irrigation and Drainage*, 112.
- Fawcett, T. (2006, 06). Introduction to roc analysis. *Pattern Recognition Letters*, 27, 861-874. doi: 10.1016/j.patrec.2005.10.010
- HEMA, E. (2019). Improving urban public transport in dar es salaam city through the implementation of bus rapid transit (brt) system. Resilient Tanzania summit.
- Hunt, A., & Watkiss, P. (2011, Jan 01). Climate change impacts and adaptation in cities: a review of the literature. *Climatic Change*, 104(1), 13–49. Retrieved from <https://doi.org/10.1007/s10584-010-9975-6> doi: 10.1007/s10584-010-9975-6
- Huvisa, T. L. (2012). National climate change strategy. DAR ES SALAAM TECHNICAL WORKSHOP.
- Jonkman, S. N. (2005, Feb 01). Global perspectives on loss of human life caused by floods. *Natural Hazards*, 34(2), 151–175. Retrieved from <https://doi.org/10.1007/s11069-004-8891-3> doi: 10.1007/s11069-004-8891-3
- Jury, M. R., Matari, E., & Matitu, M. (2009, Mar 01). Equatorial african climate teleconnections. *Theoretical and Applied Climatology*, 95(3), 407–416. Retrieved from <https://doi.org/10.1007/s00704-008-0018-4> doi: 10.1007/s00704-008-0018-4
- Ka'bange, A., Mfinanga, D., & Hema, E. (2014). Paradoxes of establishing mass rapid transit systems in african cities—a case of dar es salaam rapid transit (dart) system, tanzania. *Research in Transportation Economics*, 48, 176–183.
- Kebede, A. S., & Nicholls, R. J. (2011). Population and assets exposure to coastal flooding in dar es salaam (tanzania): vulnerability to climate extremes (Tech. Rep.). Global Climate Adaptation Partnership (GCAP).

- Kebede, A. S., & Nicholls, R. J. (2012). Exposure and vulnerability to climate extremes: population and asset exposure to coastal flooding in dar es salaam, tanzania. *Regional Environmental Change*, 12(1), 81–94.
- Kironde, J. (2016, 01). Governance deficits in dealing with the plight of dwellers of hazardous land: The case of the msimbazi river valley in dar es salaam, tanzania. *Current Urban Studies*, 04, 303-328. doi: 10.4236/cus.2016.43021
- Kost, C. (2018). Transforming urban mobility in east africa. ITDP Webinar.
- Koutsoyiannis, D. (2012). Clausius–clapeyron equation and saturation vapour pressure: simple theory reconciled with practice. *European Journal of physics*, 33(2), 295.
- Levinson, H., Zimmerman, S., Clinger, J., Rutherford, S., Smith, R. L., Cracknell, J., & Soberman, R. (2003). Bus rapid transit. Transit Cooperative Research Program Report, 90.
- Li, M.-H., & Chibber, P. (2008). Overland flow time of concentration on very flat terrains. *Transportation Research Record*, 2060(1), 133-140. Retrieved from <https://doi.org/10.3141/2060-15> doi: 10.3141/2060-15
- Liang, X., P. Lettenmaier, D., Wood, E., & Burges, S. (1994, 08). A simple hydrologically based model of land surface water and energy fluxes for gsms. *J. Geophys. Res.*, 99. doi: 10.1029/94JD00483
- Mtongori, H. I., Stordal, F., & Benestad, R. E. (2016). Evaluation of empirical statistical downscaling models skill in predicting tanzanian rainfall and their application in providing future downscaled scenarios. *Journal of Climate*, 29(9), 3231-3252. Retrieved from <https://doi.org/10.1175/JCLI-D-15-0061.1> doi: 10.1175/JCLI-D-15-0061.1
- Murphy, A. H. (1985). Decision making and the value of forecasts in a generalized model of the cost-loss ratio situation. *Monthly Weather Review*, 113(3), 362-369. Retrieved from [https://doi.org/10.1175/1520-0493\(1985\)113<0362:DMATVO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1985)113<0362:DMATVO>2.0.CO;2) doi: 10.1175/1520-0493(1985)113<0362:DMATVO>2.0.CO;2
- Ngana, J. (2010). Ruvu basin: A situation analysis: Report for the wami/ruvu basin water office. IUCN.
- Open Street Map, howpublished = <http://https://www.openstreetmap.org/#map=8/52.154/5.295>, note = Accessed: 2019-09-30. (n.d.).
- Pawlak, Z., Wong, S., & Ziarko, W. (1988). Rough sets: Probabilistic versus deterministic approach. *International Journal of Man-Machine Studies*.
- R.V. Sliuzas, C. L. S. G., A. Hill. (2016). Dar es salaam land use. Open Data Commons Open Database License / OSM (ODbL/OSM).
- Saha, A., Donoso, M., Mohamed, A., Masikini, R., Abbott, V., & Anderson, E. (2014). Water atlas of the wami/ruvu basin, tanzania.
- Secretariat, P.-A. S., et al. (2011). Urban poverty & climate change in dar es salaam, tanzania.
- Shemdoe, R. S., Rugai, D., & Fantini, L. (2016). 16. climate change adaptation in dar es salaam: Local government opinions and proposed interventions. In *Planning to cope with tropical and subtropical climate change* (pp. 290–303). Sciendo Migration.
- Suzuki, M. M. (2008). Dar es salaam transport policy and system development master plan.
- Svoboda, V., Máca, P., Hanel, M., & Pech, P. (2015, Jul 01). Spatial correlation structure of monthly rainfall at a mesoscale region of north-eastern bohemia. *Theoretical and Applied Climatology*, 121(1), 359–375. Retrieved from <https://doi.org/10.1007/s00704-014-1241-9> doi: 10.1007/s00704-014-1241-9
- Theis, S., Hense, A., & Damrath, U. (2005). Probabilistic precipitation forecasts from a deterministic model: a pragmatic approach. *Meteorological Applications*, 12(3), 257–268.
- TMA. (2011). Urban poverty climate change in dar es salaam, tanzania (Tech. Rep.). Tanzanian Metrological Agency.



- Venant Rwenyeri, G. K., Kissaka Huruma. (2015). Dar es salaam bus rapid transit system project-phase 2 (Tech. Rep.). AFRICAN DEVELOPMENT BANK.
- Verkade, J., & Werner, M. (2011). Estimating the benefits of single value and probability forecasting for flood warning. *Hydrology and earth system sciences*, 15(12), 3751–3765.
- Werner, B. R., H.C. Winsemius. (2018). A framework for establishing flow forecasting requirements: Application in the zambezi river basin.
- Zhu, Y., Tóth, Z., Wobus, R., Richardson, D., & Mylne, K. (2002). The economic value of ensemble-based weather forecasts. *Bulletin of the American Meteorological Society*, 83(1), 73–83.