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Hydrological modelling and flood risk in a data scarce country: Matola, Mozambique.

Tanja Katharina Sellick

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Department of

Physical Geography and Ecosystem Science

Lund University

Sölvegatan 12

S-223 62 Lund

Sweden

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Supervisor

Petter Pilesjö

Exam committee:

Andreas Persson

Abdulghani Hasan

Abstract: Flooding is a frequent natural hazard globally that is capable of major damage to society. The hazard is especially prevalent in Mozambique, in which many flood events with negative effects have occurred. Disaster risk management and research is therefore important in the country. However, as a developing country, it is subject to data scarcity. Matola is one of the most populous cities in Mozambique, and is located between two rivers (the Matola and Infulene) and the coastline of Maputo bay. Precipitation events frequently result in pluvial flooding in the city. This study aims to produce flood hazard maps (looking both at water depth and velocity) and disaster risk maps for Matola for the years 2000, 2020 and 2040 based on changes or projections in precipitation and urbanisation via the use of the hydrological model (TFM-DYN), its input data and population data. The input data required by the TFM-DYN includes land cover, a digital elevation model, precipitation, infiltration, and surface roughness. Land cover and digital elevation GIS data was gathered from the National Cartography and Remote Sensing Centre (CENACARTA). Precipitation was based on daily measurements in the catchments where a storm hyetograph was derived from an intensity-duration-frequency curve and the alternating block method. Infiltration and surface roughness are based on literature. Risk maps were produced as a combination of population density per neighbourhood and maximum water depth. Water velocity and depth maximums increase each year. Flood hazard and flood risk over the area did not differ by very much from each other, it is assumed this is because the flood risk only took two factors into account. The flood hazard maps can be a useful tool in risk assessment and disaster management in Matola. The flood risk maps show the possible changes in risk between 2000, 2020 and 2040, although the study recommends an improvement in data quality and the inclusivity of more factors in flood risk.

Keywords: hydrological modelling, flood hazard, TFM-DYN, climate change, Matola, Mozambique, data scarcity, pluvial flooding, flood risk.

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Abbreviations of organisations

GFDRR	Global Framework for Disaster Risk Reduction
INE	National Institute of Statistics (Mozambique)
INGC	National Institute of Disaster Management (Mozambique)
MH	Ministry of Health (Mozambique)
MICOA	Ministry for coordination of environmental action (Mozambique)
OCHA	Office for the Coordination of Humanitarian Affairs (UN)
OMS	World Health Organisation (France)
WMO	World Meteorological Organisation

1. Introduction

Occurrences of floods as disasters are increasing globally. Up until 1998 there were less than 100 floods recorded each year. After 1998 there have been more than 100 recorded floods per year (Ritchie and Roser 2020a). Flooding is the most commonly occurring natural hazard and causes the highest amount of economic damage out of all natural hazards (Wisner 2004; Batica and Gourbesville 2016). Floods can cause major damage in urban areas and some immediate consequences include injury, loss of life, damage to buildings and bridges, damage to drainage systems, and loss of running water and electricity. A common after effect of flooding in developing countries is disease, such as cholera from drinking water or malaria from increased mosquito breeding grounds (Wisner 2004). In addition, in areas more exposed to flooding health care is often lacking and herd immunity is low, encouraging disease outbreak after flood events (EM-DAT 2019). As urbanisation and the effects of climate change are set to increase (Winsemius *et al*. 2016), urban areas already prone to flooding in developing countries will experience increased risk of flooding. This is both in terms of greater floods and in terms of unsatisfactory flood protection measures alongside urbanisation. If immediate action is not taken to reduce flood risk, damage caused by flooding could increase globally by up to a factor of 20 by 2100 (Winsemius *et al*. 2016).

Mozambique is a country that is significantly affected by hazards, with a high INFORM risk rating of 6 from the GFDRR (2019). INFORM provides risk assessments that are measured out of 10, and are derived from the hazard and exposure, vulnerability, and coping capacity of a country. Cyclones, urban, coastal and river flooding are all occurring and are some of the highest impact primary hazards present, alongside wildfires and extreme heat (GFDRR 2019). Mozambique has a vulnerability factor of 6.5, Hazard and exposure are at 5.1 and the lack of coping capacity is 6.6. Mozambique's risk rating is greater than nearby countries, with the exception of Congo DR whose risk rating is 7.6. For perspective, Zimbabwe lies at 5.2, South Africa at 4.7, Tanzania at 5.6 and Madagascar at 5.1 (GFDRR 2019).

Climate change means that it is likely climate variability will increase, with extreme events becoming more common with larger magnitudes (Jongman 2018). In southern Africa, rain is expected to decrease (Kirtman *et al*. 2013). Winter and spring will become drier and drought events will increase in frequency (Kirtman *et al*. 2013). Increased drought events are set to cause slow accumulation of the population in coastal areas (Kirtman *et al*. 2013). Coupled with higher climate variability – extreme rainfall events becoming more intense, Mozambique is on a path to being more and more affected by harsher drought periods and a higher intensity in extreme precipitation events.

Urbanisation rates in Africa are high and have the potential to cause underlying issues in African cities. The total urban population on the continent is expected to triple from 2010 to 2050 (United Nations 2010). As of 2020, the majority of Mozambique's population is living in rural areas (approximately 70 %), and the country's population is expected to be mainly urban by 2050 (Ritchie and Roser 2020b). Rapid urbanisation can cause many issues in the infrastructure of cities in developing countries. Smaller cities in Mozambique are growing quicker than large cities like Maputo, causing potential problems in urban planning where essential services like waste management can be insufficient to keep up with the growing population (UN-Habitat 2020).

Cities that do have appropriate infrastructure to maintain the population may not be equipped to mitigate flood events. In order to visualise and identify possible areas in cities at risk of flooding, risk assessments are carried out. Flood modelling is a useful resource to aid in detecting the areas of greatest risk which can e.g. be useful in safely allocating social and economic infrastructure and the development of mitigation and adaptation measures in the municipality. Flood mitigation measures can be in terms of the awareness of the municipalities in risk informed planning and development, early warning systems, physical flood mitigation infrastructure and natural solutions (Aerts *et al*. 2014). Reductions in flood risk will result in a significant increase in the health and economy of the population (IPCC 2014).

Flood modelling via hydrological models shows the flow and accumulation of water in an area. The best output is at a high resolution, and so requires high resolution input data. Unfortunately, in developing countries it is often the case that this is not available or there are issues in the data. Data scarcity is an issue over much of Africa in many studies where natural hazards are often not well understood or studied (Nkwunonwo *et al*. 2020). This means that hydrological models with the most simple and variable inputs are preferred and may be the only option.

Matola, a city located near Maputo in southern Mozambique, is one of the most populous cities in Mozambique yet there is not much research into the flood issues the city faces (Noticias 2019; Jornal Noticias 2020a; O País 2020). The Maputo province is a high flood risk province and Matola is bordered by two rivers and the Indian Ocean coastline (INGC *et al*. 2011). Urbanisation in the city is horizontal, and land is constantly being transformed to urban and semi-urban areas. As is the case with many cities, much urban expansion is not planned and therefore important infrastructure such as drainage systems is not developed in many areas. Unplanned expansions do not account for land that is more exposed to hazards. Considering the damage caused by flooding and the inability to prevent their occurrence it should be a priority to develop flood mitigation and protection strategies.

Studies in areas with similar characteristics to Matola emphasize the necessity of research of flood risk in Mozambique (Augusta 2018; Zehra *et al*. 2019). A flood risk assessment study conducted in the neighbouring city Maputo by Zehra *et al*. (2019) concluded that there are many challenges faced in urban informal settlements in flood events including poor roads, poor drainage channels, and non-existent waste management resulting in restricted water flow. There is poor sanitation and much water contamination that allows Malaria and other water borne diseases to spread (Zehra *et al*. 2019). Augusta (2018) notes that many coastal areas in Mozambique are vulnerable to disasters, and that local populations are often ill-equipped to deal with natural disasters as they are dependent on natural resources. Nkwunonwo *et al*. (2020) emphasises the need to understand and model the relationship between flooding, urbanisation, and climate change in developing countries.

1.1 Study aim

The aim of this study is to (1) model urban pluvial flooding and (2) map risk in the city of Matola through the challenges of low data availability in three different years; 2000, 2020 and 2040. Through flood modelling, the maximum water depth and velocity over Matola will be based on:

- (2000) Major flooding in early February, the scenario is based on real distribution of precipitation that was recorded.
- (2020) The increase and the changes in land use/ land cover (LULC). This is modelled in the event that the same precipitation as in 2000 occurs in 2020.
- (2040) Increases in extreme precipitation events due to climate change, and changes in LULC.

Past, current, and future population data is used in the analysis of flooded areas in Matola, where population density in Matola's neighbourhoods will be combined with flood water depths to create disaster risk maps as a function of exposure and hazard.

The final production is flood hazard maps and flood risk maps for 2000, 2020 and 2040 over Matola. The study hopes to highlight the need for flood mitigation and protection measures in the city of Matola. It also hopes to present a methodology that can be replicated as an aid.

2. <u>Background</u>

2.1 The components of disaster risk

Disaster risk is generally defined as a function of hazard, exposure and vulnerability (PreventionWeb 2009; Zscheischler *et al*. 2018). Hazards are, in the context of this study, flooding from extreme precipitation events. Exposure is "The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas." (PreventionWeb 2009). To simplify, whatever lies in a flood-prone area is exposed to flooding. The normal occurrence of flooding is not usually a safety issue for people if no human activity is present, but becomes serious when there is a population, buildings, society etc. in the area. In this study, exposure is represented by population, where a higher population is indicative of more people exposed to hazards. The last defining aspect of disaster risk is vulnerability, or the susceptibility of a person, population, city etc. to hazards. Vulnerability is affected by a number of factors, such as e.g. according to Augusta (2018), where financial and societal capital are vital factors in the vulnerability of a population. Low income households are forced to live in areas prone to flooding, many women are malnourished compared to men who therefore are more susceptible to disease, and if the governing body can offer protection or services (Wisner 2004). The safety of individuals can be improved via their general standard of life in terms of where they live, their income, their opportunities etc. and therefore, in analysing natural hazards, the focus should ideally be placed not only on the natural hazard itself, but also on the social environment.

Risk is then defined by both climatic and non-climatic factors, where hazards are influenced by climate and exposure and vulnerability are influenced by non-climatic factors such as governance, mitigation and adaptation efforts, location etc. (Zscheischler *et al*. 2018).

2.2 Effects, and drivers and cases of flooding in Mozambique

In areas where humans are not heavily populated, floods perform a wide range of necessary tasks that benefit the local population; providing habitats for animals, providing nutrients to soil and water bodies, naturally irrigating agricultural land and transporting sediments that keep deltas and coastal areas maintained (Wisner 2004), especially important in Mozambique where water shortages are an issue. However, this natural phenomenon is capable of causing extreme damage as mentioned in Section 1.

Flooding in many parts of Mozambique is intertwined with culture and lifestyles. In rural flood plains people have adapted to living with flood hazards, showing interesting patterns in poverty and investments e.g. an avoidance of large possessions and animals, higher ownership rates of canoes and radios which are key assets in the warning and escaping of floods, and more building materials associated with poverty (choosing wood and grass over brick) (Artur and Hilhorst 2012). It is common that flood/drought events are considered controlled only by God, or that witches are influencing the rain patterns leading to violence (Artur and Hilhorst 2012). Education in rural and urban areas about the causes and patterns of floods/droughts can contribute to reducing vulnerability. Health is highly affected by education. Literacy levels are low, less than 45% of women in Mozambique can read, and there are only 6 doctors for every 100 000 people- a low number among sub-Saharan countries (Almeida and Guha-Sapir 2019).

The main mechanics of flood formation and causation is a period of increased frequency and intensity of rainfall, though there are other factors also relevant such as anthropogenic changes in the physical environment (Nkwunonwo *et al*. 2020). In Mozambique cyclones that form in the wet season are significant drivers of the increased frequency and intensity of rainfall causing flooding. This is largely due to the Mozambican Channel trough (MCT) which is influenced by the presence of Madagascar and causes specific cyclonic activity in the Mozambican Channel (Barimalala *et al*. 2018). However, there is little research into this climate phenomenon's effect on precipitation or how it might influence local future precipitation.

Pluvial flooding is the accumulation of water on the ground as a result of precipitation being higher than the infiltration rate of the ground. This type of flooding is a major cause of flooding in urban areas (Gaines 2016) where infiltration rates are often lower than other land cover due to increased ground coverage by impermeable surfaces. This means that areas that would not be expected to flood when rivers overflow are also at risk of flooding if the rainfall exceeds the infiltration for a period of time resulting in water run-off over the ground.

The El Niño-Southern Oscillation (ENSO) is known to have significant influences of general precipitation in southern Africa. In years where La Niña is occurring, in most cases, it correlates with a more extreme wet season and extreme tropical cyclones that reach land around the Mozambique Channel, and that El Niño is associated with much more subdued wet seasons and extreme dry seasons (Mavume *et al*. 2010; Hoell and Cheng 2018; Howard *et al*. 2019).

The MCT is a main driving force of precipitation patterns over Mozambique where warm sea surface temperatures (SST) and the southward migration of the inter-tropical convergence zone are triggers of its formation. Barimalala *et al*. (2020) showed that when the MCT is weak, it strengthens the South Indian Convergence Zone and so more water is transported from the south-western Indian Ocean to southern Africa. The trough shows around the beginning of the wet season and reaches its maximum in February (Barimalala *et al*. 2020), a period of the wet season typically associated with heaviest precipitation. It then dissipates at the end of April/ beginning of May (Barimalala *et al*. 2020).

There have been many flood events recorded in Mozambique in the 21st century. Noted are flood disasters that occurred in 2000, 2007, 2008, 2013 and 2019 (Table 1). Millions of people were negatively affected and in 2000 and 2019 the death toll was especially high (Table 1). In 2019 the flooding was associated with the arrival of cyclone Idai and Kennith (OCHA 2019; WMO 2019).

***Table 1**: Examples of extreme flood events recorded in Mozambique since 2000.*

Year	National consequences	Sources
2000	> 700 people died, ~650 000 people displaced, 4,5 million affected (25 % of Mozambique's population).	GFDRR (2014)
2007	285 000 people affected, 163 000 displaced	(OMS and MH 2008)
2008	> 110 000 people affected, 20 dead.	(OMS and MH 2008)
2013	Rainy season floods affected > 475 000 people, 186 000 displaced, and 117 dead.	(GFDRR 2014)
2019	> 600 people died, 1600 injured, 1,8 million affected.	(OCHA 2019; WMO 2019)

2.3 Study area

This study's focus is on Matola, a city in southern Mozambique (Figure 1). Located in the Maputo province on the coast in Maputo bay at the coordinates of 25°55'26''S, 32°27'56''E, it lies between two rivers, the Matola river and Infulene river, and is additionally bordered by the Indian Ocean on about 12 km of coastline. The Matola and Infulene rivers are two of four rivers that connect to the estuary "Estuário do Espírito Santo". The other two are the Tembe and much larger Mbuluzi river. However, the Tembe and Mbuluzi river do not directly connect to the Matola city area.

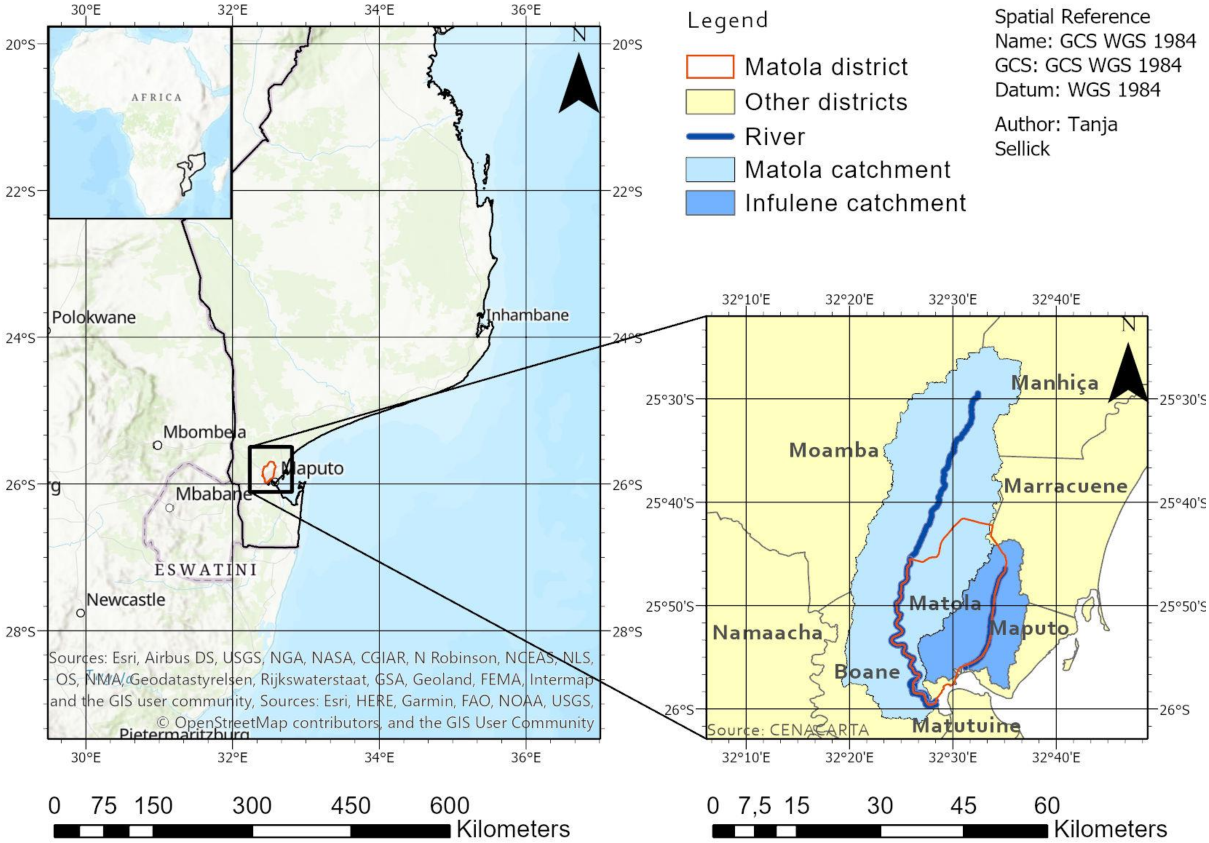


Figure 1: *The Matola city is located in southern Mozambique and is the capital of the Maputo province. It lies in the catchments of the Infulene and Matola river, and encompassess a short area of coastline in the Maputo Bay.*

The local climate is, according to the Köppen climate classification system (Arnfield 2020), a mix of hot semi-arid and tropical savanna with an average annual temperature of ~22 ° C and average annual rainfall of ~730 mm (Climate Data 2020). There are two seasons, a warm/wet and a cold/dry season. The former occurs from October/November to March/April (Figure 2). The mean annual maximum temperatures in areas surrounding the coast near the Matola city have risen 0.32 ° C per decade from 1970 - 2006, and the mean annual minimum temperature has decreased by 0.04 ° C per decade from 1970 –to 2006 (UN-Habitat 2020).

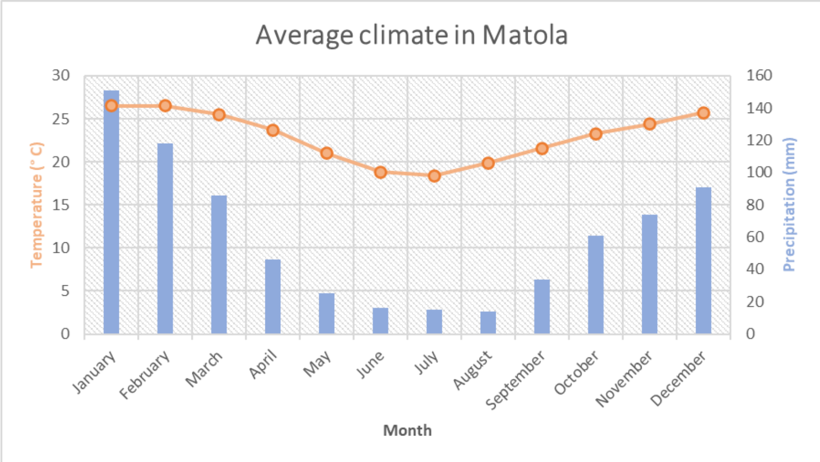


Figure 2: Average monthly temperature and precipitation in the Matola city (period 1982 – 2012), adapted from www.climate-data.org (Climate Data 2020).

The Matola city area was transformed from a district into a municipality with 41 neighbourhoods in 1998 (Preston 2002). Since then it has been an area of rapid population growth: the population was 420 000 people in 1997, and 1 million people in 2017 (ReliefWeb 2000; INE 2018). Since 1997 the population has more than doubled. This population increase has been unsurprisingly matched with rapid urbanization associated with the transformation of agricultural areas, low and floodable riverside areas, and wet/coastal protection areas into formal and informal settlements. Formal and informal settlements continue to illegally develop in areas prone to flooding without the added measures of infrastructures suitable for diverting, channelling and draining water (Neves 2018; Rádio Moçambique 2020)

Insight into the realities of flooding in the Matola city can be found through governmental websites and news articles. With every heavy precipitation event in the warm/wet season the city experiences flooding in many neighbourhoods because of low infiltration and poor water circulation due to the absence of sufficient drainage systems for rainwater collection (Jornal Noticias 2020a; O País 2020). This is seen especially in areas of lower elevation (DW 2020). High risk of flooding in urban areas of the Matola city and the Maputo city are warned of even when it is expected that there will not be high flood risk in the Maputo province (Portal do Governo 2019). Agricultural lands are also flooded, as in 2018 where > 570 hectares were under water (Jornal Noticias 2018).

In the flooding occurring in 2000, the Matola city was isolated as the water depth in the Matola and Infulene river rose over the bridges and cut off roads (Nevés, pers. comm). The drainage and water systems in the area are such that during flood events it can be that there are water shortages, causing people to use unsafe water from drainage channels (DW 2020). Forecasted flooding via precipitation is warned of by the National Institute for Disaster Management (INGC), where precautionary measures suggested include moving of important possessions to higher places, since citizens do not have much choice but to push through (O País 2019). Flooding in 2018 affected more than 8000 people in the Matola city (Jornal Noticias 2018). In February 2020 heavy precipitation caused one death and damage > 300 households (Jornal Noticias 2020b).

2.4 Future climate and population.

Future climate of southern-east Africa is uncertain and there are many contradicting studies. There are large disagreements between models on future projections of El Nino activity, and Global circulation models do not handle tropical cyclones well (McSweeney *et al*. 2010b, a). These are two large influences of Mozambique's precipitation patterns. According to Kirtman *et al*. (2013), global cyclone frequency will remain stable but the wind speed and precipitation rate will likely increase. It is also predicted that east Africa will experience more cyclone-related precipitation (Kirtman *et al*. 2013). Some projections in southern Mozambique indicate that flooding will become more intense, the number of cyclones reaching land will increase over the coming decades, and, between 1990 and 2090, and expected sea level rise by Mozambique's coast will range from 13-56 cm depending on the climate scenario (McSweeney *et al*. 2010b, a). A WMO (2019) report following tropical cyclone Idai stated that because of climate change, Mozambique will face an increase in maximum precipitation of tropical storms and category 4 and 5 tropical cyclones. However, according to Malherbe *et al*. (2013) southern Mozambique will experience fewer incidences of tropical cyclones reaching land as well as a general decrease in precipitation, particularly between January and March. Li *et al*. (2015) found that in southern Mozambique, an increased run off and evapotranspiration can be expected in the near future and that precipitation will increase east of 25° E. Past trends show that mean annual precipitation has decreased by 3.1% per month per decade between 1960 and 2006, though the proportion of precipitation occurring during heavy rainfall has increased at an average of 2.6 % with the biggest increases happening in December to February (McSweeney *et al*. 2010b, a)

The general consensus seems to be that annual precipitation is not expected to change by much, and that extreme precipitation events in the wet months as a result of cyclonic activity will increase, but there is a large uncertainty in how much.

Population projections performed by the National Institute of Statistics in Mozambique (INE 2007) indicate that the population in the Matola city will rise to 1.8 million people in 2040. This will be matched with an increase of urban areas, and the decrease of LULC that are permeable.

3. Data and Methods

This section describes the methodology concerning the hydrological model, TFM-DYN (Section 3.1), the input data required and the processes behind them (Section 3.2), and the production behind the risk maps (Section 3.3).

3.1 Model

A variety of different hydrological models exist to model the flow of water; however, many are not be readily accessible, are very complicated, or require hard-to-access input data (Nogherotto *et al*. 2019; Md Mominul *et al* 2019; Nkwunonwo *et al*. 2020). This study uses the TFM-DYN (triangular form-based multiple flow algorithm) model developed by Pilesjö and Hasan (2014). It requires few and readily available input data, and is also user-friendly.

TFM-DYN simulates flow and produces the depth and velocity of water in an area over time (Figure 3), and so allows the analysis of water depth and velocity over a temporal and spatial view. Elevation, precipitation, surface roughness, and infiltration in the form of ASCII raster data are required in order to run the model. In this case ArcMap v10.5.1 (With Spatial Analyst required) and Python v3.4 are used to process the data and run the code.

An advantage of the TFM-DYN is that the model includes a multiple flow algorithm (TFM), which allows water to flow from one cell in a grid representing the land surface to many cells whereas a single flow algorithm (SFM) restricts the flow by allowing water to only move to one cell (Zhou *et al*. 2011). In the TFM-DYN, each cell is divided into eight triangular segments of constant slope/ aspect from which flow can travel both between segments and into the cells surrounding it in a 3 x 3 cell block (Pilesjö and Hasan 2014).

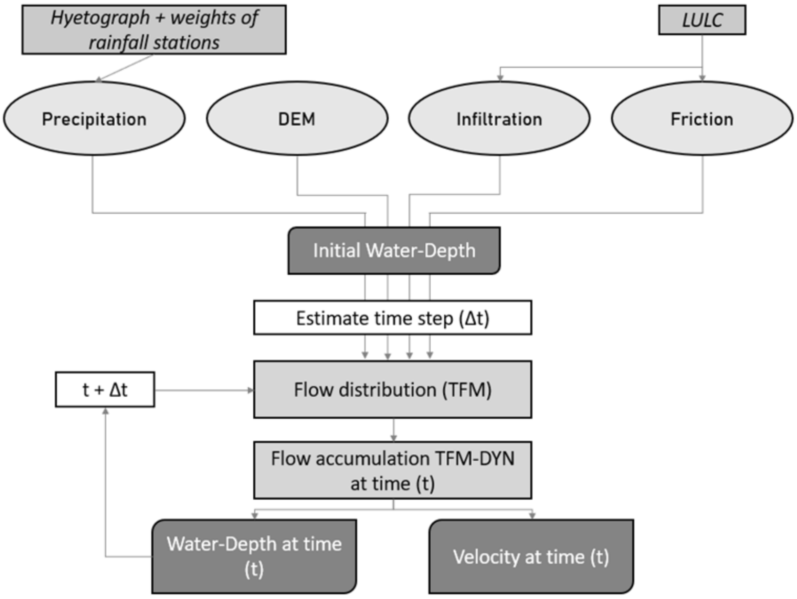


Figure 3*: Visualised process of the TFM-DYN model (Pilesjö and Hasan 2014).*

The time steps that the model ran with were kept constant at 1 second and the total time duration was 2,5 hours including a 2-hour storm duration and 30 minutes afterward of water flow with no precipitation. Output data were set to be saved at every 5-minute mark for the velocity and water depth starting at 00:00. Velocity is saved as the maximum of the 8 segments of each cell. The maximum water depth and velocity of each cell throughout the run were then derived from these 31 files. The water depth at the beginning of the model is set to 0 m. It is possible to run the model in a previous situation to create an initial water depth, but it is not under the scope of this study.

3.2 Data

The Matola city lies in the lower part of the catchments of the Matola and Infulene rivers (Figure 1). The two catchments are combined and included in the model in order to provide a higher quality result where incoming water flow from outside the Matola city is known.

3.2.1 Land cover

Land cover data are required in order for infiltration and surface roughness values to be allocated to different classes, as these variables change depending on the physical environments LULC characteristics.

LULC data covering the study area was constructed according to 30 m resolution satellite images from the year 2000 and 2020 from the United States Geological Survey (USGS). The LULC classes were classified based on classes from the National Cartography and Remote Sensing Centre in Mozambique (CENACARTA). CENACARTA is the main data provider for the National Institute of Disaster Management (INGC). The classes are named and described in Table 2.

Table 2: *LULC classes as per CENACARTA.*

LULC	Description
Water	Both natural and man-made water bodies.
Infrastructure	Urban, semi-urban and industry.
Agriculture	Includes irrigated and rain-fed agriculture.
Swamp	Flat areas of low vegetation that are semi-submerged in water.
Herbaceous vegetation and shrubs	Grasses and shrubs that are 10-50 cm in height.
Herbaceous vegetation, trees, and shrubs	Vegetation where trees are present, > 50 cm in height.

The LULC layers for 2000 and 2020 were classified using a maximum likelihood classification (MLC) (Figure 4a & b). This method is highly affected by human error and interpretations. However, the accuracy of the data is unknown. Uncertainties in the accuracy of the LULC data can be seen in Figure 9 where *water* covered 2% of the area in 2000 and decreased to 0.1% of the area in the 2020 classification.

Urban growth in the Matola city is almost completely horizontal, where agricultural and green areas are constantly replaced by planned housing and urban sprawl. The Matola city areas urbanisation patterns mean it will become urban in the majority of the area In addition, more people are favouring jobs in the industrial sector rather than agricultural. Unplanned housing often occurs in areas that would normally not be approved for residences, and are built using materials that offer little resilience to flooding. These areas are not well connected to drainage systems and the reduction of ground permeability is not addressed by the governing body (Neves, 2018; Matule *et al*, 2017). The industrial areas in the south are expanding as well, however, this study does not differentiate between semi-urban and urban areas.

Due to a lack of urbanisation data relevant for the Matola city area, urbanisation was simulated in ArcGIS 10.5 to create an estimation of LULC in 2040 (Figure 4c). The *Infrastructure* class was "expanded" with a range of 1 cell (30 m x 30 m) causing the 8 cells around any *Infrastructure* cell to be converted unless they were already the same class. *Infrastructure* increased by 25 % from 2020 to 2040 using this method. This was deemed sufficient horizontal expansion when compared to the increase of urban area from 2000 to 2020 which was 16 % (Figure 5).

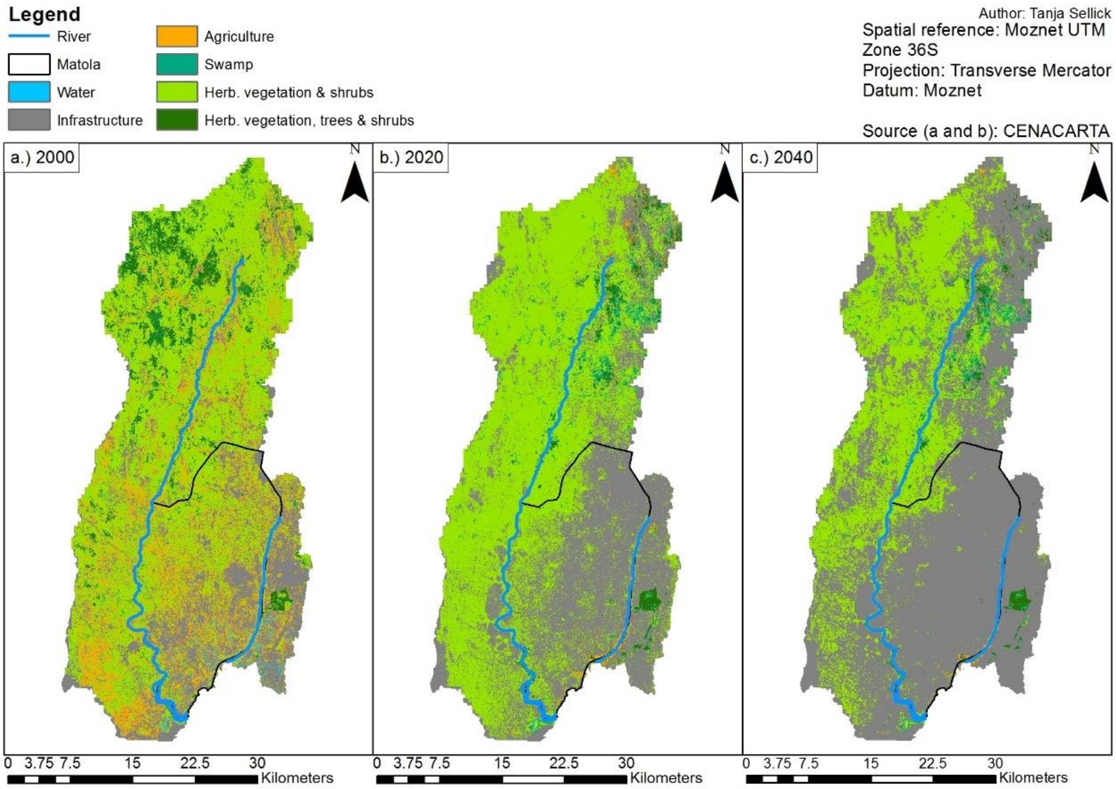
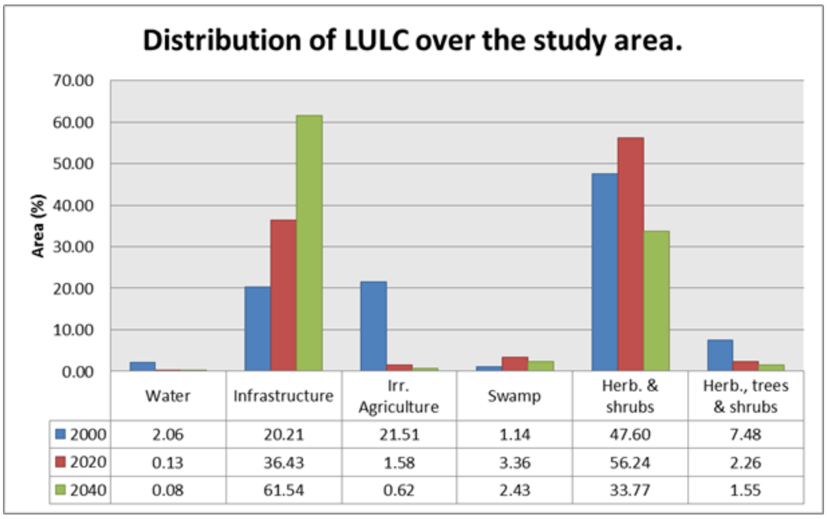


Figure 4: *LULC in the model study area in a.) 2000, b.) 2020 and c.) 2040.*



	Water	Infrastructure	Irr. Agriculture	Swamp	Herb. & shrubs	Herb., trees & shrubs
2000	2.06	20.21	21.51	1.14	47.60	7.48
2020	0.13	36.43	1.58	3.36	56.24	2.26
2040	0.08	61.54	0.62	2.43	33.77	1.55

Figure 5: *Percentage of area covered by each LULC class in 2000 and 2020.*

3.2.2 DEM

In urban flood modelling, high resolution elevation data in the form of a DEM (digital elevation model) is preferred as it better represents the real world than a more general model. High resolution is important in the x, y dimension as well as the z dimension. The higher resolution should make water flow more realistic as small topographical features such as small valleys and ridges are accounted for (Karlsson and Arnberg 2011). Digital elevation models are available in a format that is specific to hydrological models. HYDRO1K is an example of this that is accessible over Africa. It is a DEM that has been derived from the GTOPO30 (USGS 2007), where areas covered by water (rivers and lakes) are set to a value of 0, and other features included consist of flow direction and accumulation, slope, aspect, topographic wetness index, streamlines and basins (USGS 2007). This data is coarse with a resolution of 1 km and better suited to large scale studies. Other free use DEM's include the Shuttle Radar Topography Mission (SRTM) DEM and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM (Mehta 2017). A study by Karlsson and Arnberg (2011) in Mozambique investigated the accuracy of DEM's in flood modelling and showed that in hydrological modelling they should be critically evaluated for their accuracy, and that higher resolutions are better suited. This study makes use of the highest possible spatial resolution available, provided by CENACARTA, however the accuracy is unknown.

The DEM used in this study has a resolution of 30 m on the x, y dimension and 1 m on the z dimension. When the DEM was constructed by CENACARTA, the output was rounded as integer values instead of decimal values. A possible reason for this could have been to decrease the size of the data for efficient storage. The DEM, representing elevation as integer values of 1 m, did therefore not represent the real physical environment sufficiently for this study.

In order to compensate for the integer values, it was decided to change the vertical resolution of the DEM to centimetres instead of metres. Even though it could only be done based on the existing 1m integer DEM it was decided it would give a more realistic representation of the real physical environment. A 3 x 3 mean cells filter was applied on the original DEM. The result was a new DEM with decimal numbers with two decimals (equal to cm resolution).

By doing the 3 x 3 mean cells filter, the original DEM is “flattened out”, as sharp borders between x, y dimension cells due to the low z dimension resolution are removed. In the context of this study this was deemed to be an improvement to the representativity of the DEM, which itself is shown in Figure 6.

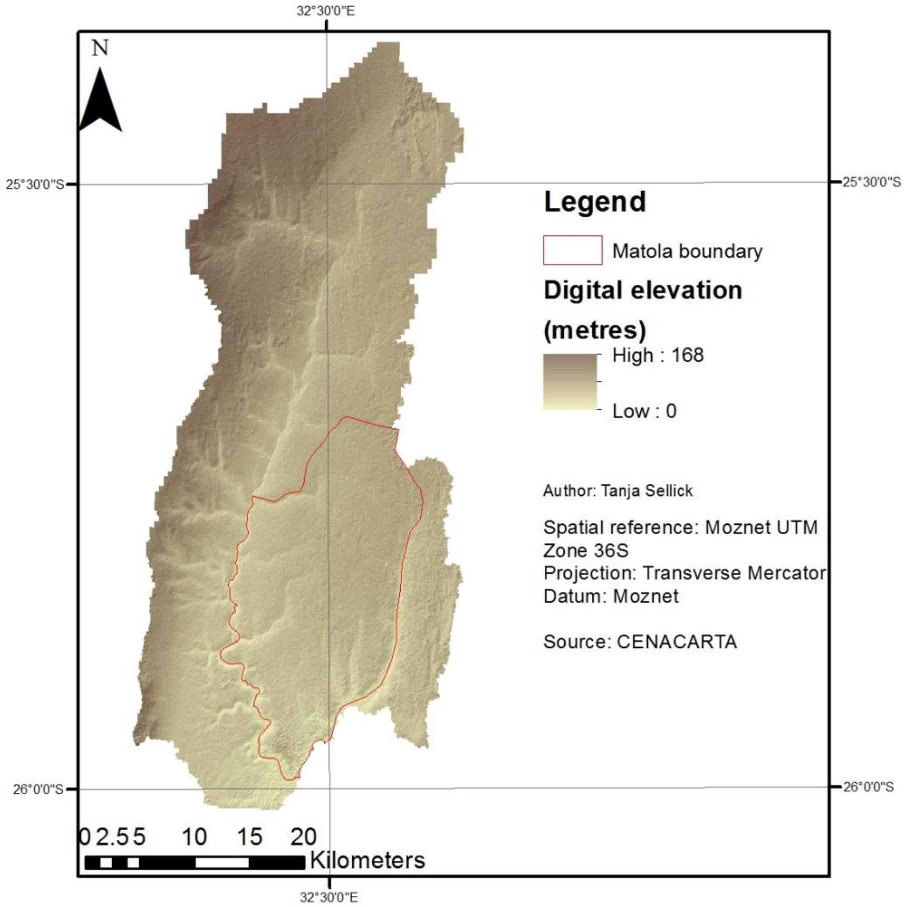


Figure 6: *Map of elevation in the Infulene and Matola river catchments.*

3.2.3 Precipitation

Daily Precipitation data over eight measurement stations in the Matola and Infulene catchments was available for the year 2000 from the South Regional Water Administration (ARA-SUL) of National Direction of Water (DNA), Mozambican water resource management institutions. The position of the eight stations used can be seen in Figure 7, where stations that were suitable are labelled. Suitable stations had available rainfall data for the 6th of February and were positioned close to the catchment with no topographical barriers separating them, such as a ridge. Rain gauges can underestimate precipitation in heavy rain events and so an additional 10 % was added to the data to compensate (Liang *et al*. 2012). The average precipitation measured on the 6th of February was 151,9 mm.

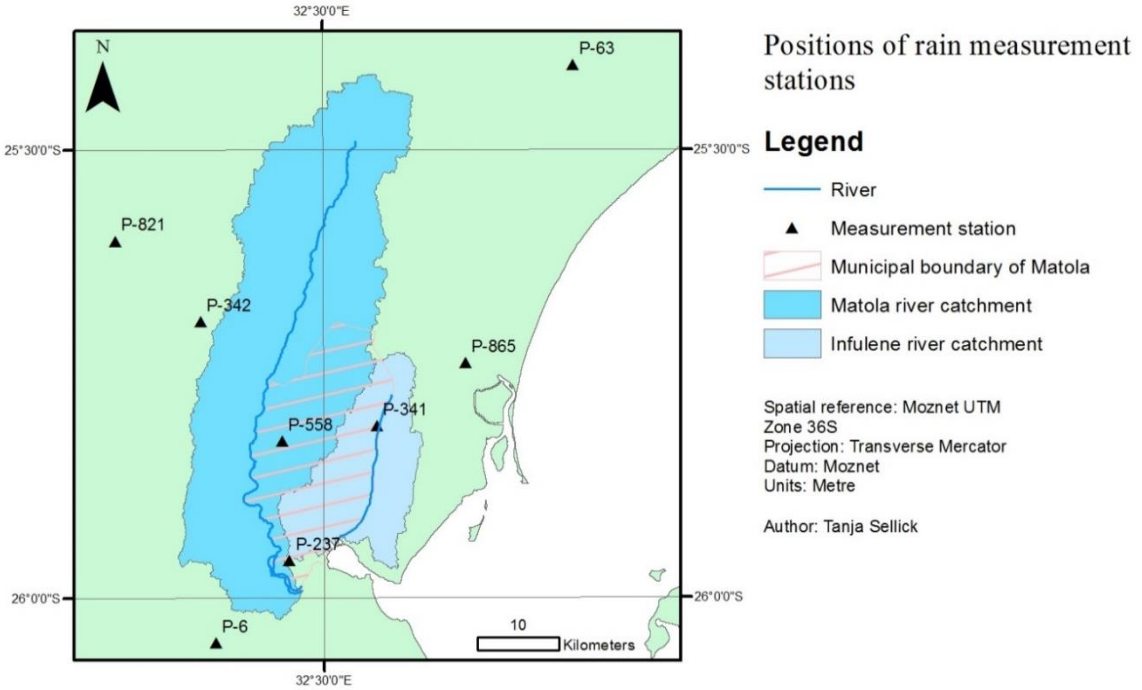


Figure 7: *Locations of rain stations within and around the catchments.*

The daily precipitation data was not in a high enough resolution to fit the standard method of TFM-DYN precipitation input data (a storm hyetograph), and this method would not work for multiple stations with varying measurements. To solve this, the precipitation input in the model was altered to accept a raster layer and a hyetograph where each cell in the raster layer is a weight of a standard storm hyetograph that is made based on the average precipitation (see below). In order to create a raster layer consisting of weights, each station was assigned a weight from the average precipitation and they were then interpolated to thiessen polygons in ArcGIS 10.5.1. The interpolated layer was then applied with a low pass filter to create a buffer zone about 1 km wide so that borders with large differences in weights were smoothed. The hyetograph was simulated using an Intensity-Duration-Frequency (I-D-F) curve and the alternating block method, which is a commonly used method of storm design (Chen *et al*. 2009; Awadallah *et al*. 2017). The I-D-F curve is calculated using the formula shown in Equation 1:

$$I = a * t^b$$

Equation 1: *I-D-F curve formula (MISAU et al. 2017)*

Where:

- I is the intensity of rainfall in mm/h
- a and b are coefficients that vary on location and return period (T)
- t is the time period in minutes

The a and b coefficients for Maputo/Matola (MISAU *et al*. 2017) were used in this study, and the return period was 50 years (a = 1,027 and b = -0.57749). The I-D-F curve is shown in Figure 8.

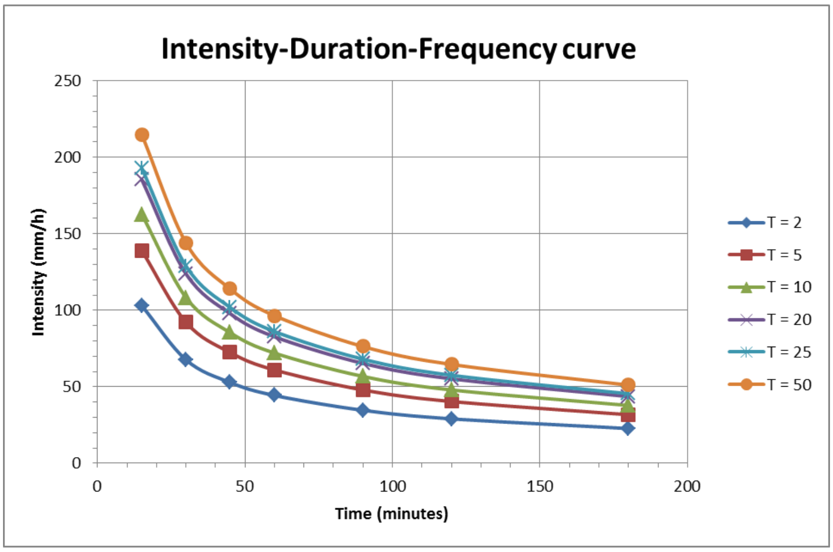


***Figure 8**: I-D-F curve for Maputo*

From an I-D-F curve, a design storm can be derived using different methods. The intensity *I* was calculated for 2 hours in 15-minute time steps, then re-arranged, scaled to the average precipitation in mm/ day on the 6th of February, and produced a graph as shown in figure 9. The alternating block method causes the rainfall to appear at its maximum in the middle of the storm, and then then decrease outwards to the storm beginning and end. This method provides a simple way for precipitation to vary both spatially and temporally in the TFM-DYN.

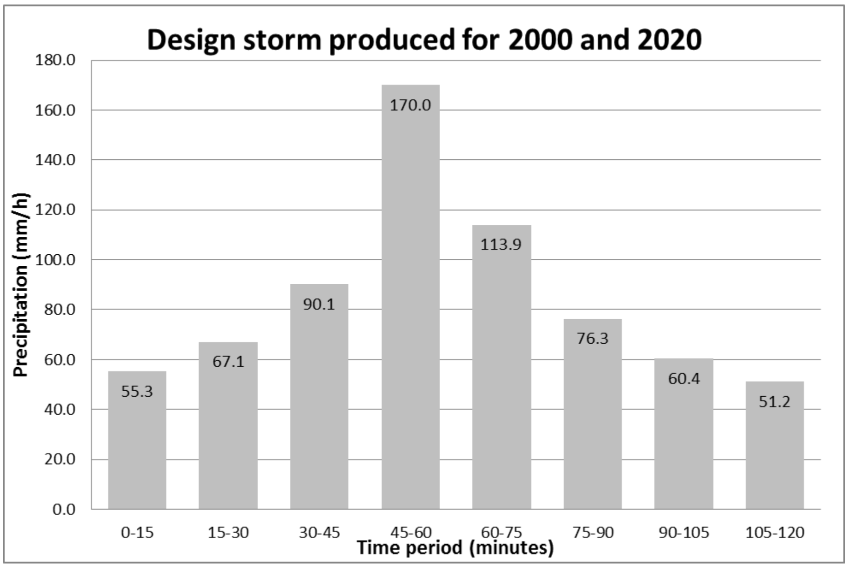


***Figure 9:** Intensity of rain in a 2-hour design storm for Maputo assuming a 50-year return period. Total average precipitation over the study area = 171.1 mm/day.*

As emphasized in Section 2.4, projections of precipitation changes are hard in Mozambique because of its unique position east of Madagascar and the Indian Ocean. What can generally be concluded is that while the total precipitation might not increase by very much, there is confidence in the increase of precipitation in extreme events, however big or small (Malherbe *et al*. 2013; Li *et al*. 2015; Lazenby *et al*. 2018; Dosio *et al*. 2019). A modest 10% increase in wet season extreme event precipitation from 2000/2020 (Figure 9) was therefore chosen in the study resulting in the hyetograph shown in Figure 10.

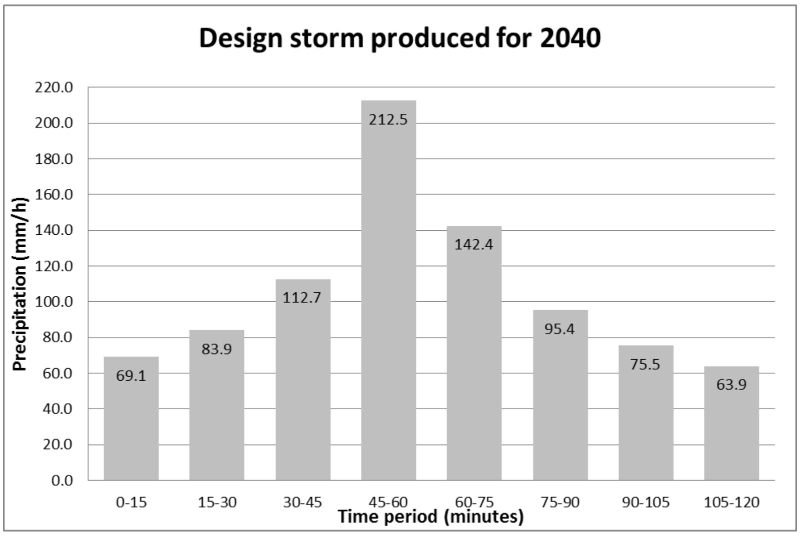


Figure 10: *Hyetograph showing a 10% increase in mm/h (from Figure 8) over a 2-hour storm period. Total average precipitation over the study area = 213.8*

<u>3.2.4 Surface Roughness</u>

Surface roughness affects the velocity of flow in the TFM-DYN. Manning's values (n) are commonly used to represent surface roughness in hydrological modelling (Kalyanapu *et al*. 2009; Mtamba *et al*. 2015). A greater value of Manning's n contributes to a higher water depth and slower flow, and inaccuracies in this component can lead to errors in water level estimation (Mtamba *et al*. 2015). Different methods that can be used to estimate Manning's n include visual inspection, a physically based approach, optimization techniques and a GIS or remote sensing approach (Kalyanapu *et al*. 2009). A GIS or Remote sensing approach is used in this study. It is the most appropriate when modelling a large area as it is normally less labour intensive than other techniques. In this method, Manning's' n values are commonly acquired from look-up tables in literature and they can then be assigned to a LULC dataset. Surface roughness was determined by look-up-tables in McCuen (1998), Mtamba *et al*. (2015) and Papaioannou *et al*. (2018). The end result Manning's coefficient for each LULC can be seen in Figure 2.

Table 2*: Listed LULC and their corresponding assigned surface roughness coefficients according to McCuen (1998), Mtamba et al. (2015) and Papaioannou et al. (2018).*

LULC	Manning's coefficient
Water	0.07
Infrastructure	0.02
Irrigated agriculture	0.04
Swamp	0.1
Herbaceous vegetation and bushes	0.15
Herbaceous vegetation, trees and bushes.	0.25

3.2.5 Infiltration

The infiltration of an area can change largely depending on what the soils and LULC present. Most of the study consists of arenosols, with fluvisols predominant along rivers. Arenosols are commonly found in arid and semi-arid environments (Dahlgren *et al*. 2008) and are classified by FAO as having a grain size content of more than 70 % sand and less than 15 % clay (Dahlgren *et al*. 2008). According to Savva and Frenken (2002), sandy soils in sub-Saharan Africa typically have an infiltration rate of 30 mm/ hr or more and a base infiltration rate of < 30 mm. The base infiltration rate is the steady state infiltration of a soil. This infiltration rate was chosen because the TFM-DYN model was run using a fixed infiltration rate. The Maputo/Matola city area have much low-lying wetlands and the surrounding soils have been described as hydromorphic sandy soils with poor drainage and a water table that lies close to the surface (FAO 1998). Flooding in the early months of the year is typically worsened by waterlogged soils due to frequent rainfall preceding an extreme rain event. Because of this, the infiltration rates shown in Table 3 were quite low, as the study assumes that previous saturation has caused a low infiltration. This was done because there was no concrete data on the infiltration between LULC in the area.

***Table 3**: Infiltration values assigned to each LULC according to information from Dahlgren et al. (2008), Savva and Frenken (2002) and FAO (1998).*

LULC	Infiltration (mm/h)
Water	0
Infrastructure	2
Irrigated agriculture	10
Swamp	14
Herbaceous vegetation and bushes	16
Herbaceous vegetation, trees and bushes.	16

3.3 Risk maps

Population density and the maximum water depth produced by the TFM-DYN model are used in the risk maps. Population data over the Matola city and the LULC were used to estimate population density in each neighbourhood. In 1997 the population was 424 662 people, in 2020 the population is 1.1 million people, and in 2040 it is projected to rise to 1.8 million people (INE 2007, 2018) (Table 5). 1997, being the closest year to 2000 with available population data is used for the 2000 scenario. The population distribution over the neighbourhoods was not available. Population density was therefore estimated using the urban distribution in the LULC data. Population density per *infrastructure* cell in the Matola city area was determined by dividing the total population by the cells, then, it was multiplied by the number of *infrastructure* cells in each neighbourhood which amounted to the population in each of them. The population density per neighbourhood could then be determined for each year and each neighbourhood was assigned their respective population density value. In order to determine risk, the population density per neighbourhood and the maximum water depth were both assigned linear fuzzy memberships where higher depths and densities were given a higher weight (where the minimum value was weighted as 0 and the maximum value was weighted as 1), and were then combined using the fuzzy logic AND function in ArcGIS 10.5.1.

***Table 5**: Total population in the Matola city in 2000, 2020 and 2040 (INE 2007, 2018).*

Year	Population
2000	424 662
2020	1 108 789
2040	1 859 104

4. Results

4.1 TFM-DYN

The TFM-DYN was run for the over the Matola and Infulene catchment, but the output data is shown only over the Matola city (which encompasses parts of each catchment). Shown in Figure 11 is the maximum water depth in the Matola city classed according to Table 6 (Moya Quiroga Gomez et al. 2018). The differences in water depth are slight when viewed over the whole area but can be noticed when looking at smaller areas (Bottom right and top left in Figure 11). The biggest difference is the distribution of flood depths. Over time, the class of depth between 0.01 and 0.5 metres (low depth) decreases (Figure 11 and Figure 12) while the very low (0 – 0.1), medium (0.5 - 1), high (1 - 2), very high (2 - 5) and extreme (> 5) classes increase in coverage over the three scenarios.

Along the southern areas of the Matola river, there is an increase in the low depth class from 2000 to 2020, even though the total amount of low depth decreases. It is also clear that much of the higher depth classes lie close to or in river channels. There are six of these noticeable channels reaching into the Matola and Infulene river, meaning that areas in between them are isolated or have one way to exit if trying to evacuate (as is done in heavy flood events).

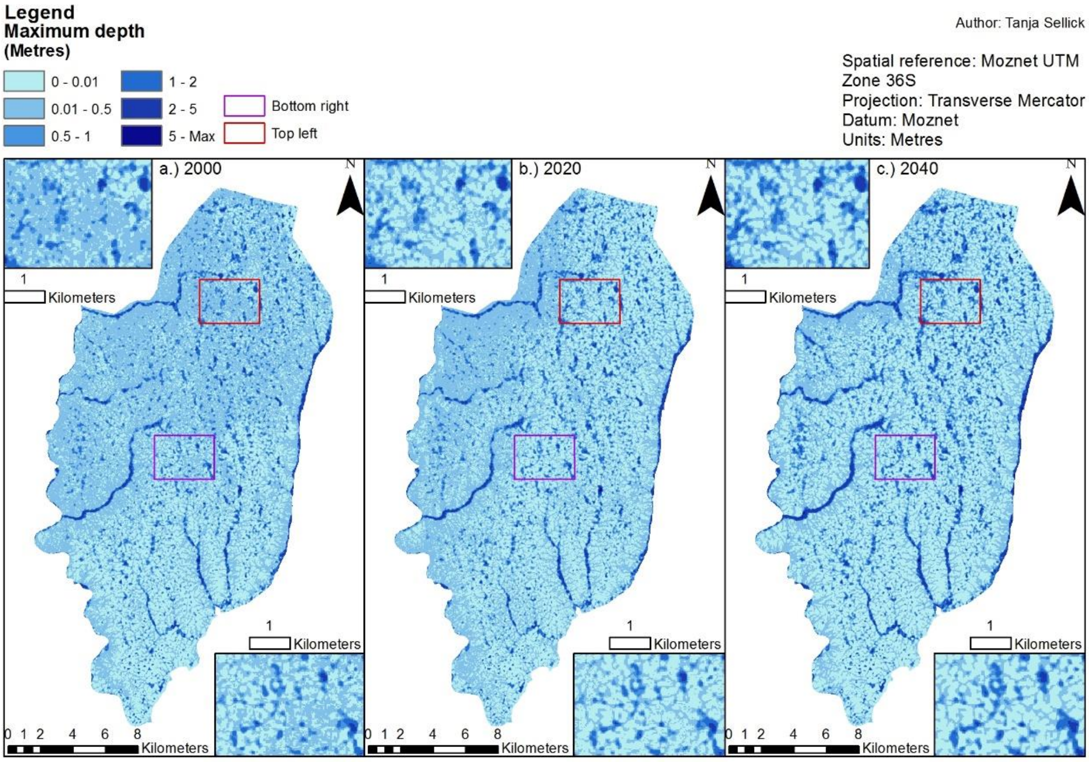


Figure 11: *Flood hazard map over the Matola city. Maximum depth for each cell over the storm period in a.) 2000, b.) 2020 and c.) 2040. Depths are classified according to Table 6. Higher depth appears with darker colour. Bottom right and top left show more detail in two areas of the Matola city where changes in depth each year can be more easily seen and compared.*

Table 6: *Depths classified into different hazard risk classes (Moya Quiroga Gomez et al. 2018).*

Depth (m)	Text classification
0 – 0.01	Very low
0.01 – 0.5	Low
0.5 – 1	Medium
1 – 2	High
2 - 5	Very high
> 5	Extreme

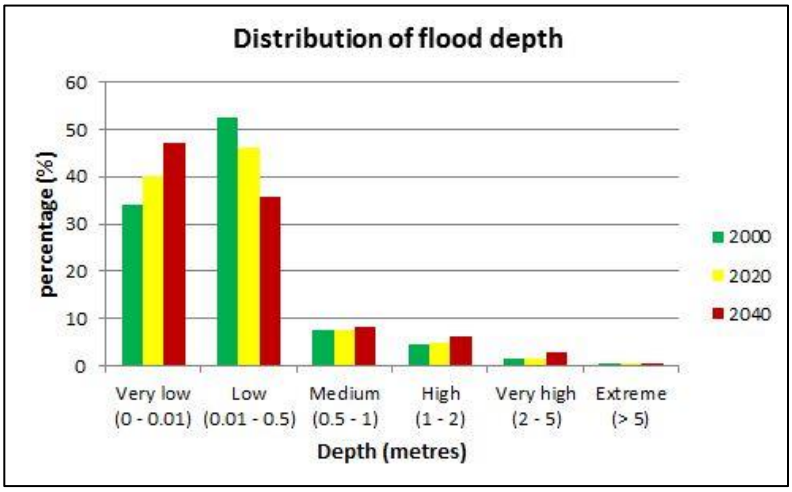


Figure 12: *Distribution of flood depth over the Matola city in relation to Figure 11.*

In Figure 13 we can see more clearly the changes that occur over four cells in the study area. The following points were generated randomly across two random northern and southern latitudes and four points are included here. Points a.), b.) and c.) fall along the same latitude in the northern area of the Matola city, and d.) lies in the southern part of Matola. From these we can see that the depth starts to rise sharply between 35 – 85 minutes into the event, mostly before peak precipitation is reached. In all graph a.) and b.) the depth is above 0.3 and 0.5 respectively for most of the storm duration. In Figure 13a.) We see that the pattern of flow appears different between 2000 and 2020 whereas it is the same between 2020 and 2040. This might indicate that the LULC has changed between 2000 and 2020 but not between 2020 and 2040. In Figure 13b.) The pattern of depth is similar between all years but at different magnitudes. Even though incoming precipitation stops at minute 120, the depth is rising from minute 120 - 150. The increase in urban area must be the difference between 2000 and 2020 in all cases. In 2040 the changes can be due to both increases in urban area as well as increases in precipitation. In Figure 13c.) and d.) the depths are lower (< 0.35 m). In c.), there is no inundation 2000, however this changes in 2020 and 2040 where changes in LULC in the cell or around the cell have caused more water to be directed to this location. In d.), a different pattern of depth is shown, where peak depth appears very early at 60 minutes and slowly decreases throughout the event.

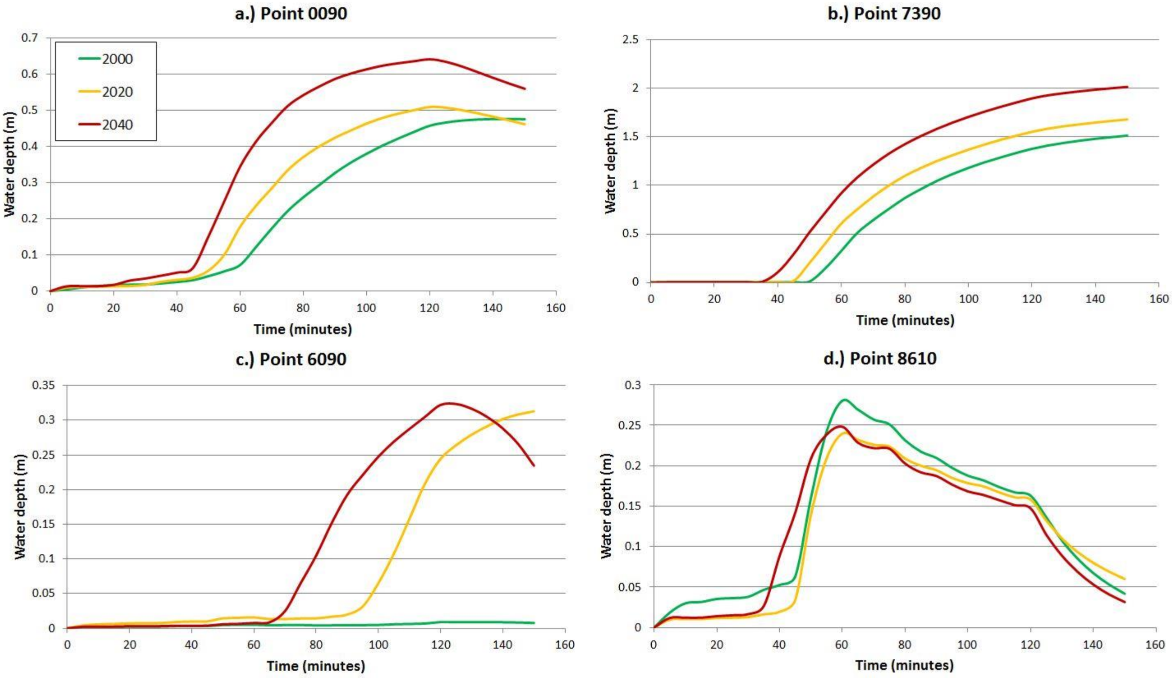


Figure 13: *Water depth recorded in 5-minute intervals over the 2,5-hour model duration in each year from time 00:00. Shown are four points generated randomly across two latitudes in the study area. a.), b.) and c.) are from the same latitude and d) is from another latitude.*

Figure 14 shows the maximum water velocity of each cell in the storm duration in a.) 2000, b.) 2020 and c.) 2040. The average maximum velocity for each year was 0.99, 1.18 and 1.68 m/s respectively. Water velocity is highest among drainage channels. The increase in urban areas has an increasing effect on the velocity of water flow in the model. This is more emphasized in the visible change between 2000 and 2020 where the incoming precipitation remains the same, but urbanisation has occurred. Cells with a maximum of 0 – 1 m/s have decreased each year (Figure 15), and cells with a maximum of more than 1 m/s increase each year.

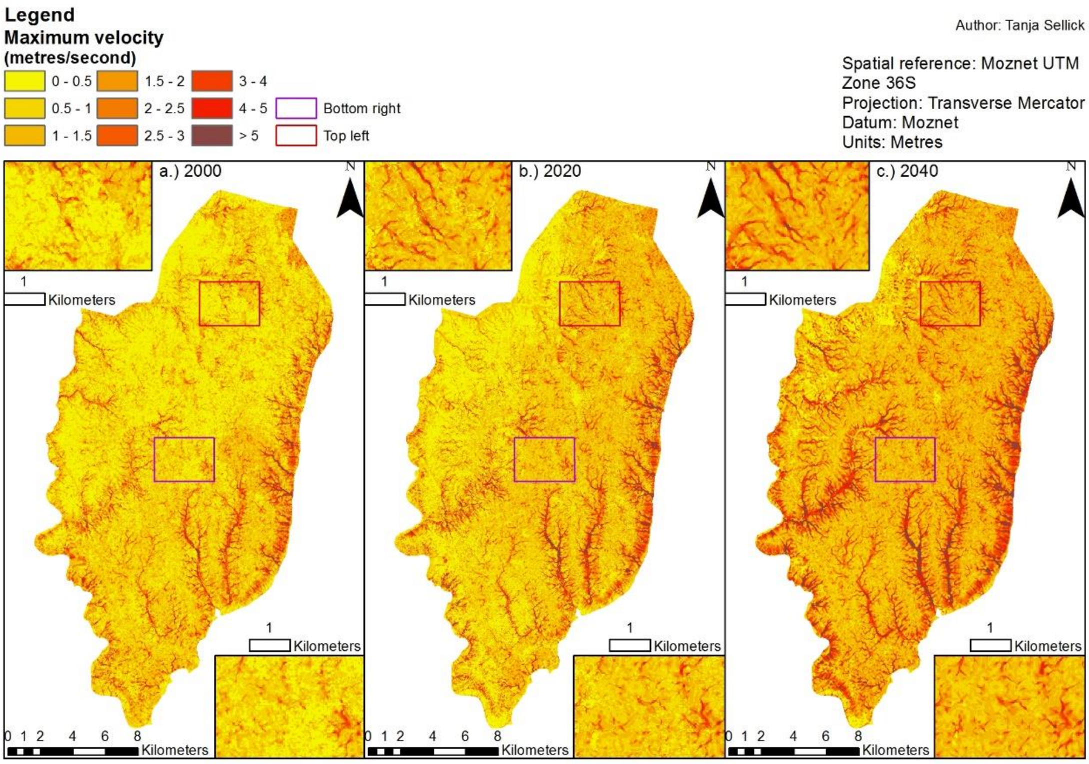


Figure 14: *Maximum velocity for each cell over the storm period in a.) 2000, b.) 2020 and c.) 2040. Higher velocities appear with darker colour. Bottom right and top left show more detail in two areas of the Matola city where changes in velocity each year can be more easily seen and compared.*

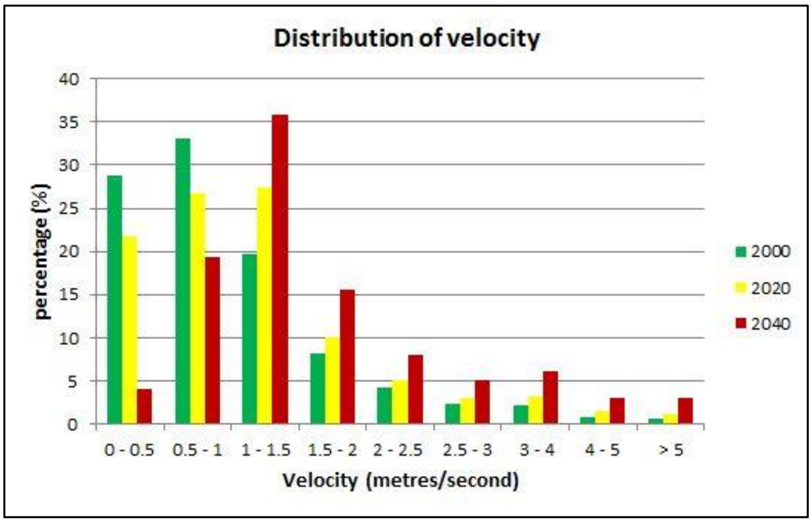


Figure 15: *Distribution of velocity over Matola in relation to Figure 14.*

Figure 16 shows the distribution of flood depths in 2020 over the DEM in the Ndlavela neighbourhood. We can see how the DEM's varying surface affects the water accumulation and explains why it appears in "pools" over Matola. Focus on the Ndlavela neighbourhood stems from its position as it contains the beginning of a water channel that connects to the Infulene river, which runs north-south in the middle of the neighbourhood seen by the areas of higher depth present and the DEM.

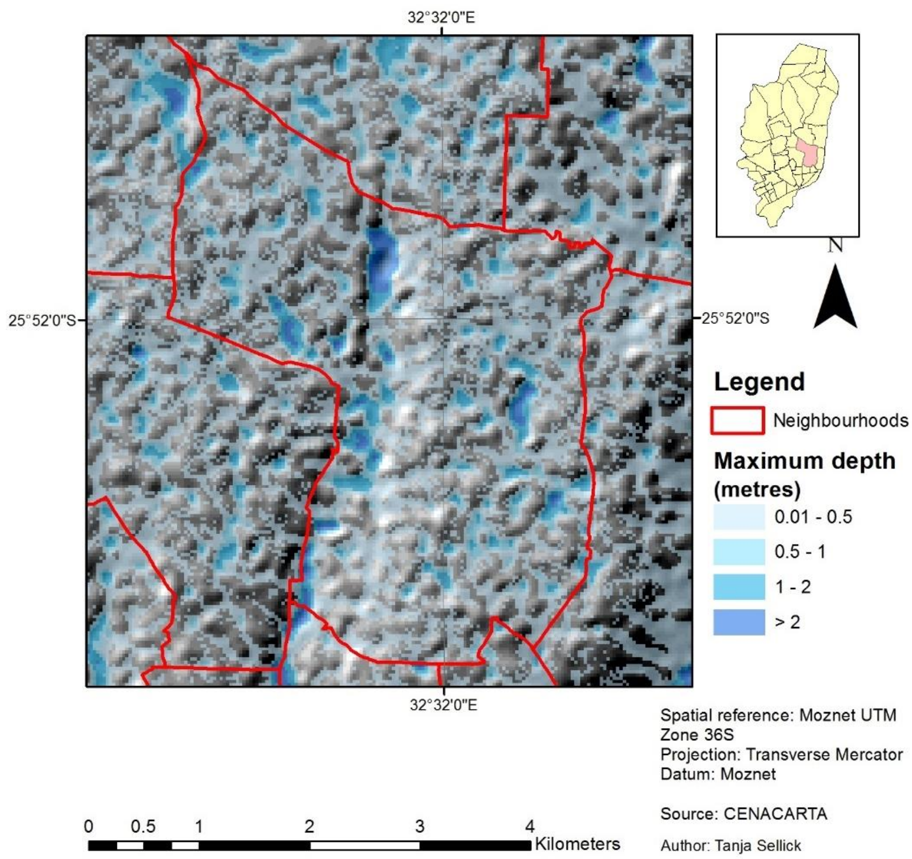


Figure 16: *Maximum depth in 2020 shown over the DEM (hillshaded) in the neighbourhood Ndlavela. The very low depths are not shown, and the very high and extreme depth class are shown together.*

Figure 17 shows an example where maximum water depths can be used in a practical way within a neighbourhood. Maximum depths over 0.5 m in 2020 are shown over a high-resolution satellite image through Google Earth, allowing the distribution to be more clearly seen and identified on a more local scale. On a smaller scale, using high resolutions and this simpler interface, neighbourhoods could perhaps identify areas that will have a higher water depth in flood events. This could, for example, be a useful tool in local flood risk assessments.

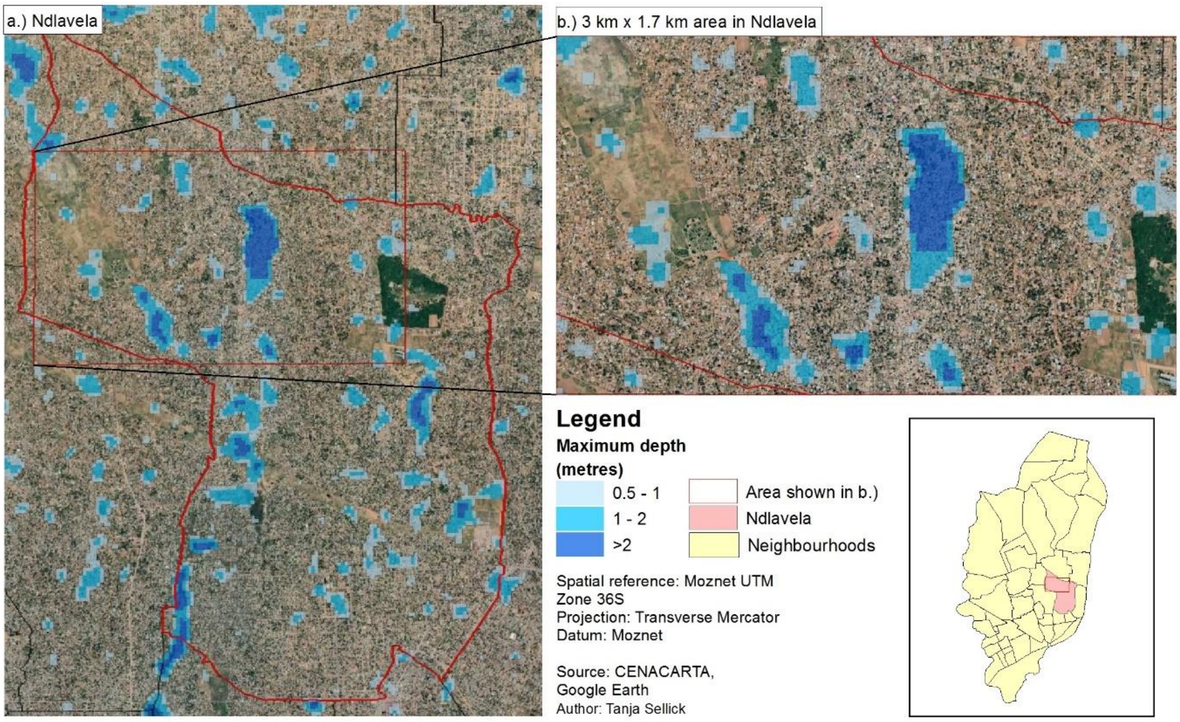


Figure 17: *Flood hazard/maximum water depth in the Ndlavela neighbourhood 2020 overlayed onto a Google Earth satellite image taken 18/12/2019. Shown in a.) is the whole neighbourhood and shown in b.) is a smaller 3 x 1.7 km area where locations are easier visualized. Maximum water depth under 0.5 m is not shown. Top left corner at b.) is at 32°30'36''E, 25°51'18''S.*

4.2 Risk maps

From 2000 to 2020 to 2040 the average number of people per 30 x 30 m cell rose/will increase from 3 to 4 to 5 in the Matola city. Shown in Figure 18 is risk over an area that underwent a large change in urban areas each year. We can see that most of the areas of highest risk lie near water channels. Highest risk in all of the Matola city mostly lies in and near the water channels present. Other areas of high risk appear throughout the Matola city as a result of lower elevation and the land cover present. In 2040, risk becomes the urban density is more similar through each neighbourhood in the Matola city due to urban cells being dominant in each neighbourhood, causing risk not to vary very much between neighbourhoods.

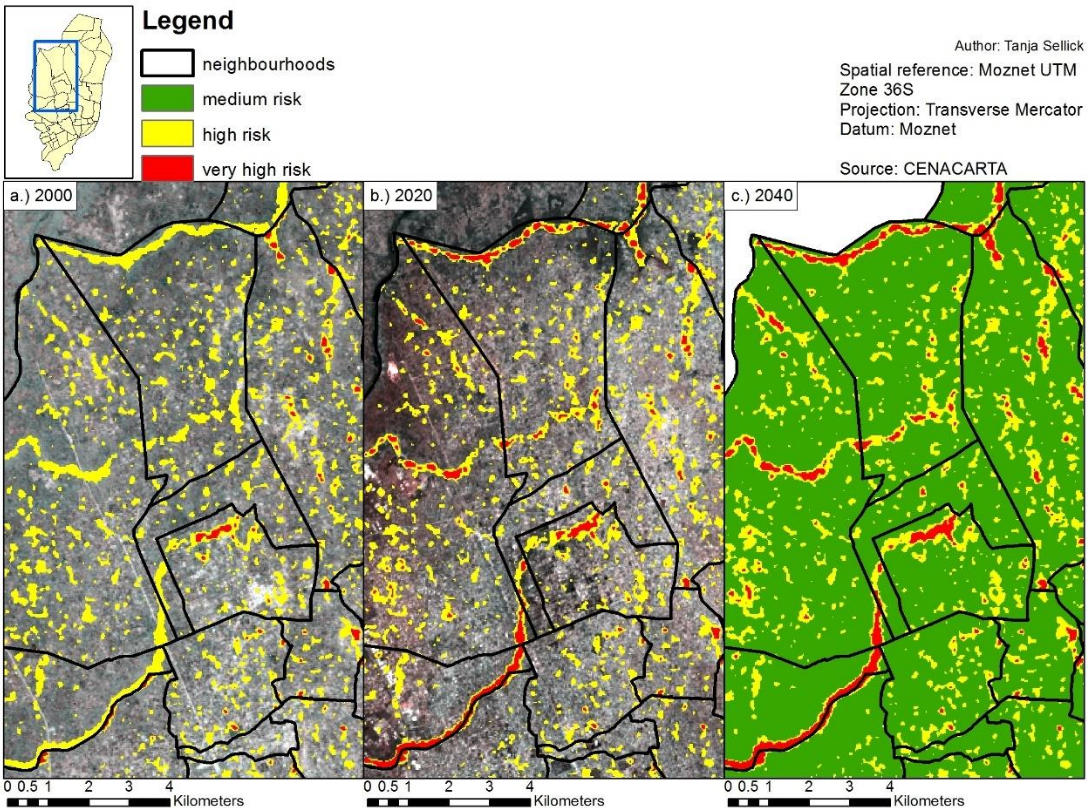


Figure 18: *Risk map of the western part of the Matola city is shown, an area where in a.) 2000, had little to no urban areas, and then in b.) 2020 and c.) 2040 had an increasing amount of urban areas. No satellite image exists for 2040. In a.) and b.) medium risk is not shown but is present in all areas that are not high/ very high.*

5. Discussion

From 2000 to 2040 we see an increase in areas flooded between 0 and 0.01 m, a decrease in areas that are flooded between 0.01 and 0.5 m, and an increase in areas flooded more than 0.5 m. The velocity of flow also has large increases from 2000 to 2040. More areas reach higher water depths and higher velocities, and this shows the effect of urbanisation on flood hazards in the Matola city.

This shift in the depths above is only due to the changes in land use over time in 2020, as the *infrastructure* class is increasing in each scenario, and infiltration and surface roughness are therefore decreasing. However, infiltration is already at a low level due to saturated soils and so surface roughness must be the main driving factor. Higher velocities can mean that less water accumulates at a depth between 0.01 and 0.5 m, it rather flows to areas of lower elevation which results in an increase of the medium, high, very high and extreme classes. It could also be that LULC changes are influencing flow direction and accumulation patterns due to the small changes in water flow that the velocity and infiltration can influence.

This study was very theoretical as many factors had to be estimated or assumed. A common and frustrating issue as mentioned earlier in the study, is that in many developing countries data is missing, coarse etc. In addition, in all modelling, there are uncertainties due to the results only representing what could happen according to the input data, and the results are hard to validate.

The TFM-DYN model does not follow the reality of flooding in some respects. Water can only enter the model through precipitation and flow out through infiltration, when in reality other processes are influencing water transport as well, such as evapotranspiration. The infiltration is kept constant throughout the event duration which would not occur in reality. This effect could be reduced by lowering the infiltration, increasing the precipitation, and/or decreasing the event duration. In this study, the infiltration was slightly reduced, and the event duration was kept to 2-hours of precipitation, and 30 minutes post precipitation. The infiltration changes were not deemed to affect the Municipal area greatly, as much of the area was urban. In addition, it is a drawback of the model that it runs with the assumption that the area has no water present on the surface at time 00:00. This can be changed by introducing an initial water depth; however, this was not under the capabilities of this study.

In regard to the input data, much was estimated, or the accuracy could not be validated. The DEM was very coarse, and its initial vertical resolution was not fit for water flow. However, even though the altering of 1 m integer values in the original DEM can be argued to be inappropriate (as it does not improve the quality of the data), in this case the positive effect, improved representation of the physical landscape, is believed to be worth the risk of decreasing the DEM's quality. This is because integer values are more unrealistic than the interpolated decimal values in cm. The LULC was created with a maximum likelihood classification and lacked a measure of its accuracy. It may therefore have not been a good enough representation of the study areas surface.

The risk maps showed that higher risk areas were mostly located around water channels. They are mostly characterized by being surrounded with agriculture and unplanned housing. However, the risk maps were only a product of two factors. While they show areas where higher densities of population and higher depth of flow are located, and the expansion of risk areas, they do not provide much new findings. An example of its use could be in the prioritization of certain neighbourhoods in mitigation efforts. Velocity was not considered as a factor in the risk maps, as it can reduce risk in cells that have a high depth but low velocity, and water depth is a better indicator of possible damages (Kreibich 2009). A more complex analysis where multiple aspects of exposure and vulnerability are included will produce a better indicator of risk.

The social environment has a large influence on vulnerability (Parnell and Walawege 2011; Artur and Hilhorst 2012; WMO 2019; Zehra *et al.* 2019). Such as a scenario where those who have only the means to live off agriculture must, in many cases, reside in areas by river channels that become inundated in a serious flood event. Vulnerability to flooding can be reduced via e.g. societal development, which in turn reduces risk.

Further improvements to the methodology are recommended. Higher than 1-day resolution manually collected precipitation data did not exist, and though the method of estimation used in the study is common for storm design, it would be beneficial to install higher quality measurement forms that e.g. measure precipitation every 30 minutes and are automatic. A higher resolution DEM would improve the results accuracy greatly, making areas of higher flood depths more trustworthy. These two issues are possible to access, though have costs and time involved. Considering that these data can be useful for the Matola city and Maputo city together, two of the most populous cities in Mozambique, the costs can be justified. Another recommended improvement is the land use, which in this study had an unknown accuracy. This might have affected both the distribution of surface roughness and infiltration, as well as the population density. The risk maps can therefore not be fully trusted to be accurate. In addition, the differentiation between urban and semi-urban areas would be beneficial to the population distribution and detail of the infiltration and surface roughness.

The results of the model could not be validated. An on-site investigation into which areas have experienced the highest flood depths and at what depths these typically have been would be beneficial for the study. In addition, detailed information about flood events that have occurred can be compared with the study's results where possible. Hydrograph data from the Matola and Infulene rivers would also have been useful since they are commonly used in the validation and calibration of hydrological models (Wambura *et al*. 2018) and data are existing for some hydrometric stations in rivers in the neighbouring Incomati catchment (Okello 2019). Another possible method of flood model validation is the comparison of the model output against remotely sensed images taken during flood events (Nogherotto *et al*. 2019).

There are many uncertainties in the future of Mozambique's climate as climate change indicators in southern Africa have large spatial and temporal variability in the near future (Li *et al*. 2015). In particular, the precipitation in Mozambique is highly dependent on cyclones. In turn, the cyclones are influenced by the Mozambican Channel Trough, where the presence of Madagascar makes Mozambique's climate more influenced by different factors than many other places in Southern and Eastern Africa. In addition, coastal cities in general will be affected by sea level rise in the future; most of Matola's industrial areas are located on areas close to the small coastline. It is highly likely that increasing magnitudes of extreme precipitation and sea level rise can both be affecting Matola in the future.

Future improvements and changes in the exposure to flooding as influenced by the municipality's plans are not known and are not accounted for. However, future investments in urban areas of Mozambique show a focus on the construction and maintenance of infrastructure (MICOA 2013). This includes but is not limited to roads and bridges, protection against rising sea levels, pipelines, water supply and treatment facilities. In addition, concerns are made on how to ensure that the investments are themselves resilient to climate change and natural hazards. A report by the (World Bank 2017) used the Greater Maputo Areas plans for drainage and sanitation in analysis of flood prone areas.

Luu *et al*. (2020) produced a risk assessment map where many relevant factors were included: Flood hazard represented by water depth; exposure represented by land use, distance to river and population density; and vulnerability represented by road density and poverty rate. According to Houston *et al*. (2019), effective communication and education of flood risk and mitigation can change people's behaviour towards flood events, where higher confidence in risk management and willingness to follow recommended precautions can be seen. Education may reduce vulnerability in situations such as when people often return to their homes after being evacuated and/or refuse to leave (Artur and Hilhorst 2012) or continue to illegally spread housing into flood prone areas of the city.

6. Conclusion

It is a reality in many countries that high quality data is not available. This study aimed to model pluvial flooding over the city of Matola through a combination of coarse data, estimations and assumptions based on literature. The model's focus was on water depth and velocity. Maximum water depth over Matola was modelled but was unable to be validated. Water velocity increases for every year but was not included in the risk. Highest water depths and velocities are present in water channels, of which there are around six that connect to the Matola and Infulene river. The risk maps for each year show how changes in population density because of horizontal urban expansion over the city may affect the risk in the neighbourhoods. These maps showing maximum water depth and risk are possible to create in Matola, or another city in Mozambique, and can be utilized as an aid in risk assessment or in disaster risk management of flood hazards. Improvements and additions to the methodology are recommended in the form of higher accuracy/ higher resolution data in the TFM-DYN, and the inclusivity of more "risk factors" in the flood risk map. This could allow for a more accurate flood hazard map, and a more comprehensive and reliable risk map.

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