Flood Risk Assessment of the Crocodile River, Mpumalanga

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A dissertation submitted to the School of Geography, Archaeology and Environmental Studies, Faculty of Science at the University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2016

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed by: *Miss S. Sauka (0504584n)*

ABSTRACT

The Crocodile River East in Mpumalanga Province, South Africa, has seen three major floods in a twenty-four-month period, specifically January 2011, January 2012 and January 2013. The damage included the loss of life, damage and/or loss of public or private properties, agricultural land loss, and damage to biodiversity and river geomorphology.

The purpose of this study was to understand the consequences and risks to livelihoods and river basin systems due to flooding of the river. The study focused on a segment of the Crocodile River East, between Riverside and Tekwane.

The study used historic hydro-climatic data for the Crocodile River to determine the critical threshold for past flood events and to predict the extent of future flood events. Hydrological modelling coupled with the HEC-RAS hydraulic model enabled the simulation of these future flood events. The use of orthophotos and digital elevation models (DEMs) allowed for a spatial representation of the areas affected during the flood events. Flood hazard maps and flood risk maps were then developed for the identified flood events within a Geographical Information System (GIS). The maps enabled the identification of high risk and flood prone areas along this segment of the Crocodile River Basin.

The results showed that when discharge reaches 241.75 m^3/s, both locations (Riverside and Tekwane) are at risk to flooding. This is therefore the threshold for which the two locations are likely to be flooded.

This study provides a methodology to determine the spatial extent of past and modelled future river flood events. As such, outcomes of this study may aid in the understanding of flood hazard extent and flood prone areas, and may thus help catchment management authorities and institutions in flood reconstruction and flood risk management. The employed methodology can aid effective spatial planning, and can also be extended at the basin scale through integration with the existent flood warning system to gain an estimate of flood extent and flood risk.

ACKNOWLEDGEMENTS

I want to thank Prof. Jasper Knight for his valuable support and constantly guiding me throughout this research. In particular, I would like to thank him for providing critical and valuable comments and advice that informed this research. In spite of my relocation, he was accommodative and extremely adaptable, for which I will forever be grateful for. His help has been indispensable and I cannot imagine how I would have achieved this research without his guidance, patience and support.

I would like to thank the NASA Land Processes Distributed Active Archive Centre User Services and the Customer Services Department at the USGS Earth Resources Observation and Science (EROS) for their assistance with obtaining Digital Elevation Models (DEMs) for my research. Your assistant with the various packages and with navigating the USGS website was indispensable.

And lastly, I would also like to thank the Department of Water Sanitation (DWS) for making hydrological and meteorological data available on their website, without which this study would have been impossible.

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CHAPTER 1 - INTRODUCTION

1. INTRODUCTION

Within the next 50 years, the number of people facing water stress will increase dramatically (Arnell, 2004). This is because economic development, human settlement patterns, population distribution and infrastructure requirements are drawn to places where fresh water resources are abundant. However, freshwater ecosystems, especially river systems, have experienced rapid degradation due to the past century of water resources development and are particularly vulnerable to the added effects of climate change (Palmer *et al.,* 2008; Pittock *et al.,* 2008; Vorosmarty *et al.,* 2010).

Freshwater ecosystems in Africa are at risk from anthropogenic land use change, over-extraction of water and diversions from rivers and lakes, and increased pollution and sedimentation loading in water bodies (Vörösmarty *et al.*, 2005; Vié *et al.*, 2009; Darwall *et al.*, 2011). Climate change is also beginning to affect freshwater ecosystems (Niang *et al.*, 2014). Small variations in climate can cause wide fluctuations in the thermal dynamics of freshwaters (Odada *et al.*, 2006; Stenuite *et al.*, 2007; Verburg and Hecky, 2009; Moss, 2010; Olaka *et al.*, 2010), seasonal flow, and climate extremes (i.e. floods and droughts).

There are numerous factors that result in the fluctuation of hydrological systems. These include changes in weather patterns, land use and agricultural practices, infrastructure developments along the river basin, surface and groundwater dynamics, temperature variability and evaporation, as well as changes in the intensity and frequency of rainfall. The inter-connected nature of hydrological systems results in a cause and effect relationship between the fore-mentioned factors. For example, impacts of land use practices on surface water can be divided into (i) impacts on the overall water availability or the mean annual runoff, and (ii) impacts on the seasonal distribution of water availability (such as impacts on peak flows) (Kiersch, 2001).

According to the 2014 IPCC Africa Report (Niang *et al.,* 2014), the weather patterns on the African continent are predicted to become more variable, with extreme events becoming more frequent and severe. This includes an increase in inland flooding, as well as the inundation of coastal areas due to sea-level rise. Future precipitation projections show changes in the scale of the rainfall probability distribution, indicating that extremes of both signs may become more frequent in the future (Kay and Washington, 2008). Climate extremes are attributed to changes in relative humidity and increased global mean temperature, which affects parameters such as wind velocities, soil moisture and erosion, vegetation cover and precipitation patterns; these factors ultimately influence the occurrence of floods, hurricanes, droughts, storms and landslides.

In recent years, there has been a significant increase in floods around the world, in both developed and developing countries. Not only the frequency, but the severity of floods has increased to such an extent that 100-year floods are becoming annual occurrences (UNISDR, 2004; Wisner *et al.*, 2004; Shamaoma *et al.*, 2006; Alho *et al.*, 2008; Klijn, 2009). There has also been an increase in the number of El Niño-related high rainfall events, coastal inundation, and storm surges. Changes in tropical cyclone landfall from the southwest Indian Ocean have resulted in intense floods in Eastern Africa during the 20th Century (Kay and Washington, 2008).

As a result of changing weather patterns, people, assets and river basin characteristics will be exposed to water-related disasters at an increasing rate. This is of concern as development strategies are currently not able to counter current climate risks. There is increased knowledge of maladaptation risks from narrowly conceived development interventions and sectoral adaptation strategies that decrease resilience in other sectors or ecosystems. Given multiple uncertainties in the African context, successful adaptation will depend on building resilience (Niang *et al.*, 2014).

Therefore, in order to understand the risks to human livelihood and river basin characteristics that may be caused by flood events, this study focuses on providing a spatial representation that identifies flood prone areas along the Crocodile River Basin in Mpumalanga Province, South Africa. The approach taken in this study is to initially define the flood risk paradigm and the climate change impacts on water resources. By using historic hydro-climate data and future rainfall projections, future hydrological scenarios were created and used to predict possible future flood events. The use of the HEC-RAS hydraulic model allowed for the spatial distribution of previous and predicted flood events to be simulated. Flood maps were then created within a Geographical Information System (GIS) for each of the studied future flood events. This enabled the identification of areas at risk during flooding of the Crocodile River Basin under certain future climatic scenarios.

The outcomes of this study may be valuable to catchment management authorities and institutions for decision making processes such as identifying possible flood extent and flood prone areas.

1.1 Problem Statement

A high proportion of people have settled on or near river banks. This is because water resources provide drinking water, and allow for the development of essential products and services such as agriculture, energy and transportation. This growth in population and settlements has resulted in the development and growth of urban and rural centres along river banks, and ultimately floodplains.

Naturally occurring rainfall events in the lowlands may be augmented by human interventions in the floodplains, such as road and river embankments (Kiersch, 2001). Highly populated floodplains are potentially dangerous to occupants during flood events, and can result in a loss of life and infrastructure. In order to minimise the risk to formal and informal settlements, current and future spatial and land-use planning should be informed by effective flood hazard assessment and flood zone planning. It is essential to steer developments and critical infrastructure away from hazard-prone areas through better land use planning and zoning (Asian Development Bank, 2013).

Flood events can have disastrous impacts in developing countries, which is mainly due to inadequate flood adaptation capacity. The consequential damages may include loss of life and public or private properties, agricultural land loss, and economic or monetary loss due to the shutdown of business and industry (Khan and Igbal, 2012). In Pakistan, the major source of frequent flooding is the Indus River system that comprises the major rivers of Pakistan (Khan and Igbal, 2012). It is reported that in Asia between 1996 and 2005, 472 flood-disasters killed 42,570 people and affected 1.3 billion people, resulting in economic losses estimated at USD$ 129 billion (Satterthwaite, 2007). Similarly, over the same period, there were 290 flood-disasters in Africa alone, which left 8,183 people dead and 23 million people affected, resulting in economic losses of USD$ 1.9 billion (Musungu *et al.*, 2012).

According to Midgley *et al.* (2005), floods are a major natural hazard in South Africa. Climate change could cause floods to increase due to fewer but more severe rainfall events (Midgley *et al.,* 2005). According to the Southern Africa Risk and Vulnerability Atlas (2011), climate change is likely to alter the magnitude, timing, and distribution of storms that produce flood events. Therefore, an increasing occupancy of floodplains and river banks may increase the risk of, damage and loss of life caused by flood events.

In South Africa, the principal state organisation, the Department of Water and Sanitation (DWS), is responsible for water resource management, planning, and guidance for water-related events including flooding. Local scale water management is performed by catchment management agencies (CMAs), which often have constraints such as large management areas and not enough resources. Thus, flood mapping is currently limited to historical maps created from previous flood events. Rural and sparsely located areas that are not considered as economic hubs or development zones are even more neglected, although some of these areas are prone to flood hazards and are highly influenced by flood events. These areas have even fewer flood assessments, flood maps, records of data and land-use change, and spatial planning systems.

In the recent past, the Crocodile River East in Mpumalanga Province has seen three major floods in a twenty-four-month period, in January 2011, January 2012 and in January 2013. The frequent flood events can be attributed to rainfall events from Indian Ocean cyclones that result in larger than usual volumes of water flowing into the river. This caused flooding of parts of the river basin, with associated erosion, loss of life and damage to infrastructure. Under climate change, similar flood events are likely. Understanding the spatial distribution of past flood events and projected future flood events is, therefore, the focus of this research.

1.2 Research Question, Aims and Objectives

The main objective of this research was to assess the spatial distribution of previous flood events along the Crocodile River Basin, to predict how future flood events are likely to be distributed, and to provide a spatial representation of flood-prone areas along the river basin.

1.2.1 Research Question

The research project was framed by the following research question:

What is the spatial extent of historic flood events on the Crocodile River Basin and which areas along the river banks are most at risk during future flood events of varying magnitudes?

1.2.2 Research Aims

Based on the above research question, this project had the following aims:

Aim 1: To evaluate the extent of previous flood events and identify the characteristics of the rainfalls that caused them.

Aim 2: To determine how these previous flood events have affected the Crocodile River Basin (e.g. impacts on settlements, human and physical characteristics).

Aim 3: To develop discharge and water level scenarios for possible future flood events for the Crocodile River, based on these historical events.

Aim 4: To develop flood maps for these future scenarios that identify flood-prone areas along the Crocodile River Basin.

Aim 5: To determine how future flood events are likely to affect the settlement patterns, human and physical characteristics of the Crocodile River Basin.

1.2.3 Research Objectives

In order to reach the above-mentioned research aims, the following research objectives have been set:

Objective 1: Conducting a high-level assessment of flood reports that highlight the flood events and flood prone areas over a 10-year period (August 2004 - April 2014). *(This objective is linked to Research Aim 1)*

Objective 2: Using the identified flood events and the discharge and water levels associated with these events to define the several characteristics of floods in the Crocodile River. *(This objective is linked to Research Aim 1)*

Objective 3: Creating flood maps of the Crocodile River Basin for these previous flood events. *(This objective is linked to Research Aim 2)*

Objective 4: Defining discharge and water level scenarios for possible future flood events for the Crocodile River, in the context of climate change. *(This objective is linked to Research Aim 3)*

Objective 5: Creating flood maps of the Crocodile River Basin for possible future flood events of various magnitudes. *(This objective is linked to Research Aim 4)*

Objective 6: Highlighting specific high-risk areas on the flood map by conducting a high-level spatial risk assessment of the Crocodile River Basin. *(This objective is linked to Research Aim 5)*

This research may be valuable in increasing knowledge of flood risk assessment, projecting future flood events under climate variability, predicting flood prone areas and guiding planning and decision making.

1.3 Research Methodology

This research was aimed at understanding flood events over the previous decade (2004 to 2014), the spatial distribution of flood events, as well as understanding the potential risk to the Crocodile River Basin under scenarios of increased rainfall. A graphical representation of the methodology that was used to meet the aims of this research is provided in Figure 1.1.

The historic rainfall and hydrological data for the Crocodile River Basin over the last decade (2004 to 2014) were sourced from the Hydrological Information System (HIS), a database belonging to the Department of Water and Sanitation (DWS), and analysed. In parallel, a review of written records of flood events on the river was used to identify and assess previous flood events over the last decade. The rainfall and hydrological characteristics of the identified past flood events were then assessed. These data, together with spatial data (i.e. topographic data), were then used as input data for hydraulic modelling, which was used to simulate the spatial distribution of these past flood events. For future flood events, current rainfall and hydrological data, as well as future climate projections, were used to create future hydrological scenarios. This was based on a rainfall-runoff assessment of the past data. The projected hydrological data, together with the spatial data that represent the river basin characteristics, were then used as input data for hydraulic modelling. This enabled the simulation of the spatial extent of future scenarios of flood events.

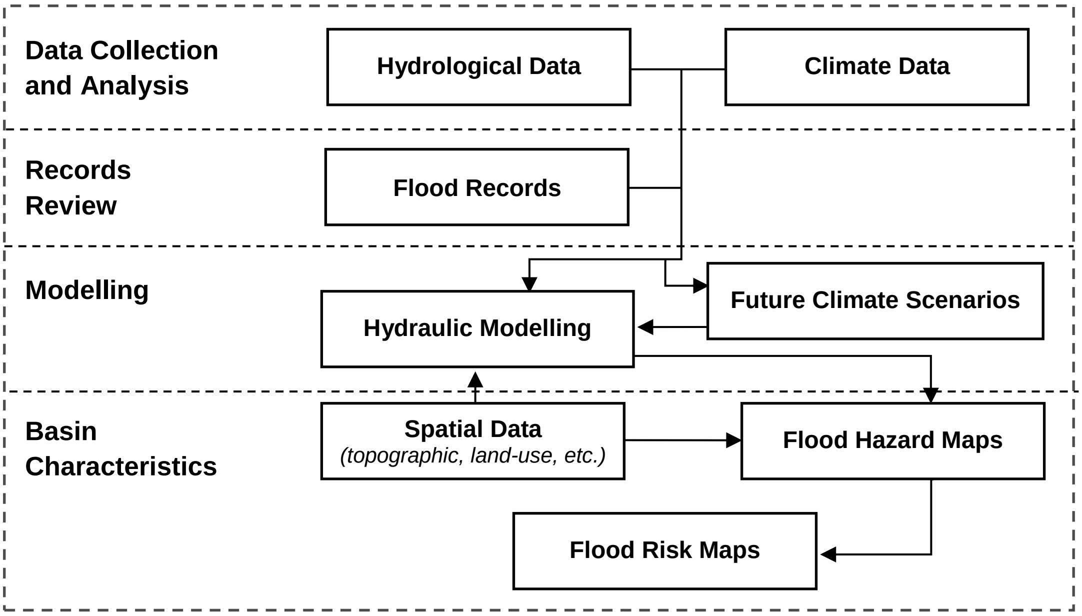


Figure 1.1: Flowchart Representation of the Methodology used in this Study

The use of orthophotos and digital elevation models (DEMs) allowed for spatial representation of flood extent during individual flood events. Flood hazard maps were then developed for the identified flood events. The flood hazard maps, together with detailed topography and other spatial data (e.g. land-use), were used to develop flood risk maps for each of the identified flood events along the Crocodile River Basin.

The study focused on a 30 km segment of the Crocodile River East, between Riverside and Tekwane. This research did not take into account all natural processes affecting the catchment such as landslides or geology, but instead focused mainly on rainfall and runoff variability. A detailed analysis of the social characteristics of the basin was also not conducted with respect to vulnerability. These analyses require a wider and more complex framework, which was beyond the scope of this research.

Lastly, although data were available for more than 10 years for some gauging and weather stations (as illustrated in Chapter 4), the limited written records of flood events on the river made it difficult to analyse previous floods events. Therefore, a more recent time period was selected (i.e. 2004 to 2014) as this would enable a comparison and analysis between flood records and the hydro-climatic data.

1.4 Structure of Dissertation

Following this introductory chapter (Chapter 1), the remainder of this research will consists of eight chapters.

Chapter 2 provides the theoretical framework for the research project. This includes an investigation into different types of floods, focusing primarily on river floods, the flood risk framework, as well as the flood risk assessment framework. A description of the uses of hydraulic modelling and GIS for flood risk mapping is conducted. In addition, the climate change implications on flooding in South Africa, particularly the Mpumalanga province, will be explored.

In Chapter 3, an overview of various characteristics that influence flooding on the Crocodile River Basin is provided. This includes a description of the topography, geology, soils, ecology, land-use types and settlement patterns. In addition, the climatic and hydrological properties of the basin are discussed.

Chapter 4 provides a description of data acquisition, analysis and processing for the rainfall, hydrological characteristics (namely discharge and water levels), land-use characteristics and topography (i.e. DEMs). This includes an assessment of the decadal trend in rainfall experienced at weather stations in the Inkomati-Usuthu Water Management Area (WMA), as well as the runoff (i.e. discharge and water levels) readings at gauging stations along the Crocodile River. In addition, a description of the analytical approaches and software that were used to collect and analyse the data and the quality of the data is provided.

Chapter 5 provides an assessment of historic flood events. Two flood events are discussed, and their associated rainfall and hydrological characteristics are analysed. In addition, a brief description of the impacts of the floods is provided.

Chapter 6 provides an estimate of future flood events through the development of hydrological and flood scenarios. In addition, a brief description of the methodology employed for estimating flood events is provided.

Chapter 7 provides flood extent maps for the identified past and future flood events. This is based on the use of a hydraulic model and GIS to provide a spatial representation of the extent of the two previous flood events. The flood maps highlight flood prone areas along the Crocodile River.

Chapter 8 contains a discussion of the results and highlights the findings from the research. This discussion is focused on the flood risk maps of the locations along the segment of the Crocodile River.

In Chapter 9, the conclusions of the research are provided. The chapter also includes the limitations to the study, including data accuracy and completeness, and the availability of high-resolution DEMs. In addition, recommendations are made for aspects to be considered for further research.

Lastly, several appendices have been provided. The appendices provide additional information that supports the material provided in this dissertation.

CHAPTER 2 - LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Introduction

Floods are natural phenomena that are defined as the temporary inundation of normally dry land areas resulting from overflowing of the natural or artificial confines of a river or other body of water, including groundwater (Wisner *et al.*, 2004; Martini and Loat, 2007; EC, 2009a; Klijn, 2009). Hydrologists define floods as a peak in the water level due to an increase in discharge (Els, 2011). Nurritasari *et al.* (2015) defines floods as water inundation over the sub-catchment caused by overflowed water. The inundated water will recede through run off to a lower area or channel (Nurritasari *et al.*, 2015).

As stated by Eleutério (2012), floods are one of the most damaging natural events in the world. Statistics show a continuous increase of hydrological disaster events since 1980. In 2008, the Munich Re’s database documented 750 loss events, with 292 of which being floods and landslides (Taubenböck *et al.*, 2011). The most adverse consequence of flooding is the impact on human health, resulting in psychological problems, injuries and loss of human life. There is also an additional loss of goods and disruption of activities and infrastructure as well as ecosystems and environmental issues which indirectly impact human livelihoods. Although floods are often viewed as negative and disastrous events, in some cases floods can generate benefits, such as in the case of the Nile floods that resulted in the fertilisation of floodplains (Eleutério, 2012).

Climate change and urbanization are arguably the most dramatic driving forces of global change. The combination of a climatologically driven increase of natural hazards, uncontrolled urban sprawl and changing urban patterns results in an increasing risk of flood events. Growing population trends, particularly in urban areas, imply a dimension of quantitative growth, a high concentration of people, and urban sprawl into potentially hazardous locations, such as mountain slopes or river floodplains. This high pressure on urban space and, hence, fast and uncontrolled spatial growth and densification, creates settlements in inappropriate areas most likely to be exposed to natural hazards (Taubenböck *et al.*, 2011).

2.2 Flood Typology

The flooding phenomenon is defined by meteorological, hydrological and landscape parameters; a flood event is thus caused by several factors, individually or in combination, that promote the difference between events in different contexts (Eleutério, 2012). Floods can be described according to the water source (origin), the geography of receiving area, the cause and the speed of onset. The water source of floods can originate from the ocean (coastal floods), rivers (fluvial floods), from underground (groundwater floods) and from rain (pluvial floods) (EC, 2009b; Klijn, 2009). The various types of floods are described in more detail in Table 2.1.

Table 2.1: Flood Typology

Pluvial floods
Pluvial floods are caused by high to extreme rainfall that leads to the accumulation of rain water in low-lying (relatively flat) areas. These floods have a slow onset and can be forecast days ahead, although they can cause major damage, especially in urban areas, but rarely with fatalities (Klijn, 2009). In addition to pluvial floods, the limited or poor drainage of rain water in urban environments can lead to an increase in flooded areas even during normal rainfall periods.
Riverine (fluvial) floods
Riverine (fluvial) floods occur when the rate of rainfall exceeds the maximum capacity for storm water drains to remove the water and/or the maximum capacity for the surface to absorb water is exceeded (Vogel and Mgquba, 2004). Put differently, fluvial floods occur when the rainfall that is often transformed into runoff and can normally be removed by the drainage systems, remains on the impervious surface and flows as overland flow into topographic or local depressions to create temporary ponds (Els, 2011). The flood onset is sometimes slow, and the river flow exceeds the carrying capacity of the river, causing water to over flow onto the flood plains. This type of flood is often characterised by slow velocities and large inundated areas (Klijn, 2009). This type of event is the most devastating of all the different types of floods due to the high flow, as well as the number of people and aspects exposed to it.
Flash floods (or fast floods)
Flash floods (or fast floods) are caused by continuous rainfall in the same areas, or by intense rainfall over a short time period. This type of flood occurs mainly in mountainous or hilly locations, when excessive rainfall occurs at the upper reaches of the river, or in urban areas where anthropogenic surfaces cannot absorb the surface water. The floods form when rainfall falls too fast or too abundantly for the ground to absorb it. The high velocity and debris load of flash floods (Martini and Loat, 2007; Wright, 2008) often results in high fatalities and severe damages (Klijn, 2009). The difficulty in forecasting them make early warning and evacuation very difficult (Bunn and Arthington, 2002).
Coastal (marine) floods
Coastal (marine) floods are caused by coastal storms or large waves caused by physical earth processes such as tsunamis. This type of flood affects large areas and causes huge losses in human life and livelihoods, as the flooding is accompanied by waves, high velocity water and floating debris that result in beach erosion and extensive damage to infrastructure along the coast (Wright, 2008). The onset of coastal storms can usually be forecast between days to a few hours ahead (Klijn, 2009) while possible storm surges can occur within four to eight hours after the storm has started (Wright, 2008).
Groundwater floods (seepage
Groundwater floods (seepage) are caused by water rising to the ground surface due to a high water table (Klijn, 2009). This type of flood has a slow onset, and is formed during periods where the soil is saturated by water.

2.2.1 Flood Prone Areas

Environments that are vulnerable to floods include alluvial fans, low-lying inland shorelines, low-lying deltas, coasts and low-lying parts of major floodplains (Smith, 2004). Flood prone areas can be defined as the areas that are vulnerable to floods along a river, and can be either a floodway or a floodplain (Els, 2011), as illustrated in Figure 2.1.

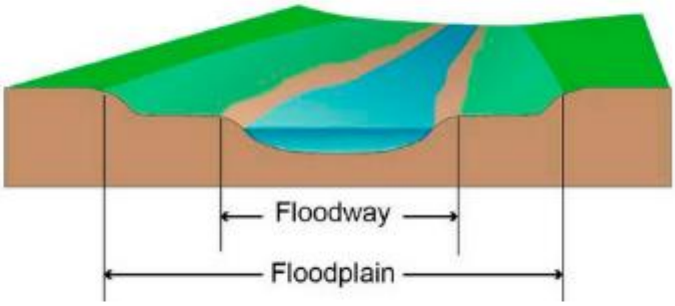


Figure 2.1: A floodway within a floodplain (FEMA, 2006)

A floodplain represents all areas surrounding the river channel that can be inundated during the occurrence of a flood (FEMA, 2008; Wright, 2008). The probability of floods decreases as the slope of the floodplain increases (Alexander, 2000). Floodplains are, therefore "flood-prone" and are hazardous to development activities if the vulnerability of those activities exceeds an acceptable level of sustainable water resource use within the catchment (Penning-Rowsell, 1996).

A floodway is the minimum area within a floodplain that is required to provide sufficient passage for a given volume of water during periods of high rainfall that cause river basins to over flow, or during flood events. The floodway can be differentiated from the floodplain by its deep water level, high flow velocity and containing turbulent and sediment rich flow, which often causes erosion (Els, 2011). No development should take place in the floodway and only critical infrastructure such as bridges should be allowed within it (UNISDR, 2004; Wright, 2008).

2.2.2 Flood Frequency

Flood frequency analysis is used to determine the probability of the occurrence of a flood event of a particular magnitude. Flood lines are an indication of the water level of a flood with a specified annual exceedance probability (Alexander, 2000). A flood line is shown as a line on a spatial representation (e.g. map, drawing) where the water surface level intersects with the land surface. It depicts water levels likely to be reached by a flood that is predicted to recur after a certain time-period.

The recurrence interval is based on the inverse of the probability that the given flood event will occur once or more in any given year (Baer, 2008; Wright, 2008; Haarhoff and Cassa, 2009; USGS, 2009). Therefore, the recurrence interval is a statistical average for annual recurrence and not the number of years between flood occurrences of the same magnitude (Wright, 2008; Haarhoff and Cassa, 2009; NOAA, 2009). For example a 50 year flood has a 1/50 (0.02) or 2% chance of being exceeded in any one year, and does not mean that a 50 year flood will happen only once in 50 years.

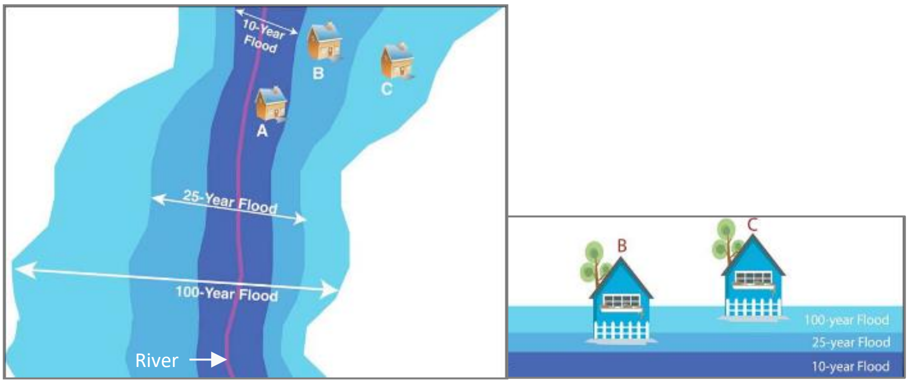


Figure 2.2: Flood lines with different return periods (10-, 25- and 100-year flood lines) on a floodplain (Wright, 2008).

2.3 Causes of Floods

According to Smith (2004), the two most significant types of physical causes of flood include environmental hazards such as catchment characteristics (e.g. vegetation, slopes and soil types) and atmospheric hazards (e.g. rainfall intensity or duration) that creates a large amount of rainfall. In addition, causes of floods can also include catastrophic events such as dam burst or the effect of volcanic eruptions (Alexander, 1995), as well as tropical depressions, hurricanes and heavy rainfall from monsoons (Koutroulis and Tsanis, 2010), and technical related aspects such as poor storm water drainage system or channels that are not optimised for high water levels. The severity of floods, on the other hand, is influenced by four factors, which include antecedent catchment status of moisture, catchment processes, fixed catchment characteristics and rainfall characteristics (Alexander, 2000).

- Antecedent moisture status is based on the moisture saturation of the catchment soil or groundwater immediately before the start of rainfall that produces floods.
- Catchment processes include channel storage, pondage storage and the rate of potential infiltration (Hewitt, 1997). Channel storage is the proportion of the overland flow which is necessary for the flood passage in the system. Pondage storage is the proportion of the overland flow that is trapped in pools that are caused by unevenness of the ground surface.
- Fixed catchment characteristics include land cover, shape, slope and catchment size (Alexander, 2000), geology and soils.
- Rainfall characteristics include the direction of rainfall, intensity of rainfall and the duration of rainfall.

2.3.1 Weather Systems

Meteorological causes of floods include snowmelt, rain, combined rain and melt, and ice melt. Coastal storm surges and estuarine interactions between stream flow and tidal conditions also entail partly meteorological causes (Alexander, 2000). The meteorological processes that are mainly responsible for flooding in South Africa are discussed in Table 2.2.

Table 2.2: Meteorological Processes responsible for Floods in South Africa

Mid-latitude cyclone
A mid-latitude cyclone is a low pressure system that develops in the mid-latitudes and moves in an easterly direction. They occur together with cold fronts that create a cold mass of air in front of warmer air (Alexander, 2000; Tyson and Preston-Whyte, 2000; Halloway *et al.*, 2010; CSAG, 2011). This moving mass of warm air forces cold air to rise, causing a very unstable atmosphere, resulting in rain (Alexander, 2000; Tyson and Preston-Whyte, 2000; Haarhoff and Cassa, 2009; Halloway *et al.*, 2010; CSAG, 2011). Cyclones are mostly responsible for winter rainfall in the Western Cape and are associated with gale force winds and snow on high-lying areas (Alexander, 2000; Tyson and Preston-Whyte, 2000; Halloway *et al.*, 2010; CSAG, 2011). In May 2010, a mid-cyclone passing through Cape Town resulted in flooding (Halloway *et al.*, 2010).
Cut-off low pressure systems
Most of the major floods in South Africa are caused by cut-off low pressure systems. A cut-off low is a mid-latitude cyclone that becomes detached from the main circulation or pressure wave. In South Africa, a cut-off low detaches from a westerly pressure wave to the south and rotates off independently (Alexander, 2000; Tyson and Preston-Whyte, 2000; Halloway *et al.*, 2010). A cut-off low can remain stationary for days

as it loses all momentum during the detachment from the westerly flow. The instability and strong convection updrafts associated with cut-off lows cause severe weather conditions (e.g. heavy rainfall, strong winds, and snow across mountains) (Alexander, 2000; Tyson and Preston-Whyte, 2000; Halloway *et al.*, 2010). Examples of floods that were caused by cut-off low pressure systems are the 1968 flood in Port Elizabeth, the 1970 flood in East London, the 1981 flood in Laingsburg, as well as the 2007 and 2008 floods in the Western Cape (Halloway *et al.*, 2010).
Convective storm
A convective storm is formed when air moves upward due to the heating of the earth surface and the lower atmosphere. These storms occur mostly in the summer when the surface temperatures are high and more often inland than in the coastal areas, due to the cooling effects of the ocean (Halloway *et al.*, 2010). It seldom causes major floods but these can occur (Alexander, 2000). Convective storms often occur with other severe weather conditions (e.g. lightning, hailstorms, and tornadoes) (McKnight and Hess, 2007), and are common to the Highveld in South Africa during the summer season. Such weather systems can be the cause of localised flooding, particularly in urban areas with low surface permeability. For example, the 2009 flood in Gauteng was caused by a convective storm.
Tropical cyclones
Tropical cyclones have a closed low pressure circulation with a pressure gradient that increases from the centre to the periphery of the system (Tyson and Preston-Whyte, 2000; CSAG, 2011). Tropical cyclones are formed from small clusters of convection clouds over the tropics and energy from high sea surface temperatures (Tyson and Preston-Whyte, 2000). This causes extremely strong winds, large waves and abnormally high tides along the coastlines (McKnight and Hess, 2007; CSAG, 2011). Tropical cyclones begin over the eastern Indian Ocean, east of Madagascar, and then move into a westerly direction (Tyson and Preston-Whyte, 2000). Their influence on the South African rainfall is very limited as they do not occur often and when they do, they only last for a few days and will never exceed a horizontal dimension of 400 to 650 km (Alexander, 2000; Tyson and Preston-Whyte, 2000). They occur mainly in the summer months over the KwaZulu-Natal and Mpumalanga regions (CSAG, 2011). The 2012 and 2013 floods that resulted in extensive damage in the Mpumalanga, Gauteng and Limpopo Provinces, as well as in Mozambique we caused by tropical cyclones.

2.3.2 Land-Use and River Basin Characteristics

The significance of the river basin as a hydrological unit of study in water resource management has been identified by many researchers in different disciplines and in different areas of the world (Gregory and Walling, 1973; ICRAF, 2001; Clark *et al.*, 2003; Dollar and Rowntree, 2003). This is because the severity of riverine floods is determined by the characteristics of the catchment area, the drainage network and the river channel (Görgens, 2003).

Gregory and Walling (1973) and Peckham (2003) describe a catchment as a physical, ecological, biological and climatic entity, where a hydrological balance can be struck when one considers inflow and outflow of moisture and energy. In other words, it provides an essential geomorphic unit for analysing hydrological input and output. A catchment (also known as a river basin) is therefore defined as an area of any size that drains into a river, stream, lake or any other water body (Goudie and Viles, 2005). A catchment originates at the top or ridge of a mountain or hill (called a watershed or divide) and runs down the slopes into the river valley. Water runoff flows into major streams and rivers of the catchment and then joins other rivers of surrounding catchments which eventually flows into the ocean (Hill and Verjee, 2010).

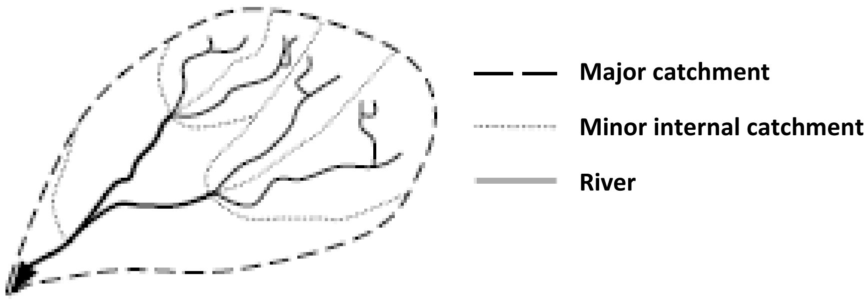


Figure 2.3: Categorisation of catchments (White *et al.,* 1992)

Hydrological changes, mainly increasing runoff and resultant flooding in the river basins, have been a motivation for increased investigation of the geometric characteristics of the drainage basin as a unit of landscape analysis (Hardy, 2005). The most commonly examined geometric characteristics are the topology of the stream networks, and quantitative descriptions of the drainage texture, pattern, shape, and relief (Baker *et al.*, 1988).

Dollar and Rowntree (2003) cite five important hydrological factors necessary to consider when evaluating a drainage basin, namely: (1) morphometry of the drainage network; (2) soil characteristics, particularly those related to infiltration; (3) geology as it is related to structure and terrain erodibility; (4) vegetation as it affects erosion, infiltration and surface detention; and (5) meteorological-climatic conditions that control the nature of rainfall input.

Channel characteristics such as slope, flood control and river regulation works influence the water level, course and velocity of water. An increase in channel slope combined with the presence of control measures and river regulation networks results in an increase in the velocity and energy of floodwaters. The speed of the surface runoff and the infiltration is determined by the basin slope. Steep slopes cause the infiltration rate to decrease while the speed of surface runoff increases, and vice versa (Smithson *et al.*, 2002).

Water flow within basins is determined by the characteristics of the basin, such as area, shape and slope. The larger the area of a basin, the more surface runoff can be expected during a rainfall event; the smaller the basin, the more susceptible to floods it becomes (Smithson *et al.*, 2002) due to limited surface area to enable water absorption. The shape of the basin will also influence the surface runoff; an elongated basin will have less surface runoff arriving at the channel at a given time than a more circular basin during the same time period. The latter will experience possible flooding due to the simultaneous arrival of surface runoff at the same point in the channel (Hill and Verjee, 2010).

Streams come together to form a large network of streams. Within this network exists a stream order where the first order refers to the smallest streams without any tributaries (McKnight and Hess, 2007). First-order streams unite to form second-order streams and so on. The stream network develops certain drainage patterns that can be described as dendritic, trellis, radial, centripetal, annular and parallel. Complex drainage patterns can hinder the absorption of water and could cause flooding to occur (McKnight and Hess, 2007). The type of surface will determine how much of the surface runoff is temporarily retained in the network surface before it becomes part of the stream flow. Thus, a high surface storage, within the river channel, surface, lake or pond, can decrease the likelihood for flooding (Waugh, 2009).

The amount of water absorption is influenced by the network characteristics, such as pattern, surface storage, under-drainage, channel length and bifurcation ratio (Smithson *et al.*, 2002). The ratio between the numbers of streams in two sequential hierarchies of basins is referred to as the bifurcation ratio, and is an indication of the drainage characteristics of the stream network. Chances for flooding will increase if this ratio is low, since water flow can concentrate in one river (Waugh, 2009). In addition, the climate, geology, soil type and vegetation cover influence the storage capacity, infiltration and transmissibility of the catchment. The type of rock and soil in the network will determine the under-drainage, as more permeable rock and soil will allow more drainage and a reduced possibility of flooding. Under-drainage refers to the drainage of soils through drains that are placed underneath the surface (Waugh, 2009). Peak flows can increase as a result of a change if the infiltration capacity of the soil is reduced (e.g. through soil compaction or erosion, or if drainage capacity is increased) (Kiersch, 2001).

The linkage between deforestation and its associated impact on flooding has led to a growing debate among researchers, some of whom have questioned the evidence that suggests that loss of forest cover exacerbates runoff, causing flooding (Calder and Aylward, 2006; Cui *et al.*, 2007). However, there is evidence that deforestation can be linked to the erosion of river beds and a decrease in water infiltration. This can increase the velocity and energy of floodwaters.

Irrespective of whether floods are natural or human induced or a combination of both, they generally have a direct or indirect impact on people and the economy (Calder and Aylward, 2006). This is evidenced, by example, by the extensive damage to infrastructure or loss of life, the changes in water quality, or the increases in water-borne diseases during flood events.

2.4 Flood Risk

2.4.1 Flood Risk Framework

Scientific literature shows that the concept of flood risk has at least two aspects, namely a hazard and the vulnerability of a system. The concepts such as hazard, risk and vulnerability are the most commonly used terms to describe the potential threats that natural disasters pose to human life, the environment and infrastructure (Pistrika and Tsakiris, 2007). As flood risk is a function of flood hazard, the value of the properties of river systems that are exposed, and their vulnerability, the increase in flood losses must be attributed to changes in some or all of these aspects (Kron, 2003).

“Hazard” is generally associated with a causal factor, i.e., a flood event is described by its magnitude and the probability of occurrence. On the other hand, risk is linked to the exposure of a system to the said hazard. Thus, flood risk evaluation requires an understanding of climatological and hydrological conditions (i.e. the causing factor) along with the terrain characteristic (i.e. the elements at risk) (Mani *et al.,* 2013). The terms ‘hazard’ and ‘vulnerability’ are also used to question the coping capacity of various structural and non-structural measures, which are applied for protection from these threats. An understanding and quantification of the terms is essential to obtain a holistic view of the probability of a flood occurring, and likely extent (and associated impact) of floods. This requires that one understands the water body, as well as the potentially vulnerable systems.

2.4.1.1 Hazard

A hazard may be defined as a source of potential harm, or a threat or condition that may cause loss of life or initiate any failure to natural, modified or human systems. Hazards may thus be classified as either of natural origin (e.g. excessive rainfalls, floods) or of anthropogenic and technological nature (e.g. sabotage, deforestation, industrial site of chemical waste) (Pistrika and Tsakiris, 2007).

The flood hazard can be independent of natural phenomena. Natural floodplains have been modified over time in order to adapt the landscape for receiving human populations and their activities. Although the modification of water bodies helps society to protect goods from natural phenomena, anthropogenic infrastructure (e.g. dykes and embankment) may create the conditions for a hazard. These hazards can be associated with, or completely dissociated from, natural climate and hydrological aspects (Eleutério, 2012).

The most common terms that are used to differentiate between different types of hazards are ‘natural’ and ‘anthropogenic’ hazards. Floods can therefore be caused by natural or anthropogenic hazards, or by a combination of both. However, it is a recognised practice to use the classification by the UNISDR (2002), as given below.

- **Natural hazards** are natural processes or phenomena occurring in the biosphere that may constitute a damaging event. Natural hazards are typically classified as either geological, hydrometeorological or biological hazards. Geological hazards refer to natural earth processes or phenomena in the biosphere that include geological, neotectonic, geophysical, geomorphological, geotechnical and hydrogeological nature. Hydrometeorological hazards refer to natural processes or phenomena of atmospheric, hydrological or oceanographic nature. Biological hazards refer to processes of organic origin or those conveyed by biological vectors, including exposure to pathogenic microorganisms, toxins and bioactive substances.

- **Technological hazards** are dangers originating from technological or industrial accidents, dangerous procedures or certain human activities, which may cause loss of life or injury, property damage and social and economic degradation.

- **Environmental degradation** involves processes induced by human behaviour and activities (sometimes combined with natural hazards) that damage the natural resource base or adversely alter natural processes or ecosystems.

Floods can be caused by the existence of any of one these hazards or a combination of several hazards. Therefore, the initiating causes of a hazard may be either an external (e.g. earthquake, rainfall or human agency), an internal event (e.g. an embankment breach) with the potential to initiate a failure of the coping capacity of the system, or a combination of several factors.

Full comprehension of flood hazard requires an understanding of the frequency of the flood events as well as their magnitudes (and thus their anticipated flood damages) (Alexander, 1991). This will allow for the understanding of the flood risk, and the probability of occurrence of a flooding event, taking into account hydrometeorological and technological aspects (Eleutério, 2012).

A hazard is, therefore, a physical event that has the potential to cause human injury, damage to property or damage to the environment. However, not all hazards lead to disasters and not all incidents are regarded as disasters. A hazard only has the potential of becoming a disaster event when it occurs in populated areas where it can cause loss of life or major economic losses (Allen, 1992). A disaster is defined as a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses that exceed the ability of the affected community or society to cope using its own resources (UNISDR, 2002). Disasters may be either natural, for instance a flood, or human induced such as a nuclear accident. Disasters may further be classified as slow-onset disasters, such as a drought, or as sudden disasters, such as an earthquake (RAVA, 2002). The possibility or chance of harmful consequences, or expected loss (of lives, people injured, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human induced hazards and vulnerable conditions are defined as the disaster risk (UNISDR, 2002).

2.4.1.2 Vulnerability

The development of human society is closely linked to the water cycle and the availability of water resources. One of the consequences is that the majority of civilisations have settled near water-bodies. Unfortunately, a great percentage of city areas are still located inside flood zones, increasing the exposure of people and goods to floods, such as in the Netherlands and Bangladesh. The concept of vulnerability is complex and controversial, and goes far beyond the simple concept of exposure of assets to floods (Green *et al.*, 1994; Barroca *et al.*, 2006; Messner and Meyer, 2006).

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Thus, the vulnerability to climate change and the capacity for adaptation and mitigation are strongly influenced by livelihoods, lifestyles, behaviours and cultures (IPCC, 2014). The IPCC (2007) defines vulnerability as “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity”.

Vulnerability is a central theme in hazard research, yet there is very little consensus on its meaning or exactly how to assess it. Questions of geographical scale and social characteristic (i.e. individual, household, community, society) add to the confusion (World Bank, 2000). In the context of this study, vulnerability may be described as a set of conditions or processes resulting from physical, social, economic and environmental factors, which may increase the susceptibility of a community or location to the impacts of hazards. It is also important to remember that vulnerability is dynamic, not static; the vulnerability of a community may change due to changing climate, the improvements or degradation of social, environmental and economic conditions, as well as interventions specifically aimed at reducing vulnerability, such as disaster mitigating actions (Zschau and Küppers, 2003). A vulnerability analysis in the event of a flood hazard considers the population and structures at risk within the affected area (Pistrika and Tsakiris, 2007).

Turner *et al.* (2003) recognised that holistic studies on vulnerability that are meant to have an input into decision making should include all the hazards affecting the system, as an assessment of how the system gets exposed to the hazard, as well as the coping capacity of the system. Variations in these indicators will invariably result in different levels of vulnerability. This is mainly because the incidence of disasters tends to be higher in poor communities, which are more likely to be in areas vulnerable to hazards such as flooding. There is evidence that the low quality of infrastructure in poor communities increases their vulnerability (May, 1998).

The resilience of the various human systems will determine their resistance to floods. The IPCC (2007) defines resilience as “the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.” Similarly, Greenberg *et al.* (2007) defined resilience as the ability of a society (within a physical system) to adapt and recover from a shock. Therefore, the resilience of a system to floods refers to the potential of a system to recover from the effects of flood hazard events, thus reducing the long-term negative consequences of the events. The understanding of this aspect of the risk is proving to be essential for flood management purposes.

2.4.1.3 Flood Risk

The word risk is may have multiple and different meanings. Risk as e a technical meaning refers to a chance or probability of an event happening, such as risk from exposure, a consequence or impact, an example being the risk from smoking, or a perilous situation like a nuclear power plant that creates a risk (Gerrard *et al.*, 2001). Therefore, the definition of “risk” may vary in different research contexts depending on the application of the term, and the field in which it is used.

The “common sense” understanding of the concept is the notion that risk is connected to a particular hazard, and lies in the consequences caused by that particular hazard, increasing with both its frequency and severity; it is also clear that these consequences depend on what is exposed to the hazard and its vulnerability (Fedeski and Gwilliam, 2007). Thus, risk is defined as the possibility of suffering harm from a hazard that can cause injury, disease, economic loss or environmental damage. Risk can be expressed in terms of probability, a mathematical statement about how likely it is that some event or effect will occur, or frequency, the expected number of events occurring in a unit time (Allen, 1992; Miller, 2004). Risk as a simple definition then refers to uncertain events that can damage the wellbeing of an individual or group (Scoones, 1996).

Flood risk is a complex process that combines human and natural factors. It is characterized by the conjunction of the probability of floods to take place and the potential consequences associated with them. Floods only cause damage when flood zones are occupied by vulnerable human systems (Eleutério, 2012). Therefore, even though nature is the source of many risks, including floods, human actions very often amplify the consequences (Gerrard *et al.*, 2001).

The European Union Flood Risk Management Directive (2007/EC/60) for flood management defines "flood risk" as the likelihood of a flood event, together with the actual damage to human health and life, and the environment and economic activity associated with that flood event. In this context, flood risk can be considered as the actual threat or the real source of flood hazard to the affected areas (Messner *et al.*, 2007).

As discussed above, a hazard is the presence of water in a specific place and time, and the vulnerable systems would include humans, infrastructure, environment and all kind of things that are exposed to the hazard. Therefore, flooding is a natural process that considers a flood risk as any aspects of human added value that are potentially affected by floodwater. Therefore, the main purpose of risk analysis is to understand and measure the possible consequences associated with the occurrence of flooding in areas occupied by vulnerable systems (Eleutério, 2012), and refers to the potential or likelihood of an event occurring.

2.4.2 Flood Risk Assessment

In general, approaches to flood risk assessment recognise that floods can often not be stopped from occurring, and emphasis should, therefore, be placed on reducing the vulnerability of, and the impact on, various catchment aspects such as human settlements and infrastructure. Flood assessment is thus aimed at understanding and assessing possible consequences of flood events in areas occupied by vulnerable systems (Eleutério, 2012). This approach is shared by the European Union Flood Risk Management Directive (2007/EC/60), which states that flood management plans need to consider first the harmful potential of floods, and then identify tangible measures to reduce exposure and sensitivity to floods, while improving risk governance.

Risk assessment involves determining the types of hazards involved, estimating the probability of each hazard occurring, estimating how many people are likely to be exposed to it and how many may suffer serious harm (Miller, 2004). The risk assessment process involves the use of data, hypotheses and models to estimate the probability of harm to human health, to society or to the environment that may result from exposure to specific hazards (Miller, 2004). In this context, the flood risk is considered as the combination of hazard and vulnerability, as illustrated in Figure 2.4.

Figure 2.4: Flood Risk as the Combination of Hazard and Vulnerability (Eleutério, 2012)

The impact of a flood event depends on the characteristics of both the system and the hazard. Even though each system has its own characteristics, we can consider that the vulnerability concept is also intrinsically linked to the hazard characteristics (Eleutério, 2012). Thus, a risk assessment emphasises the estimation and quantification of risk to determine acceptable levels of risk and safety; in other words, to balance the risk of a technology or activity against its social benefits to determine its overall social acceptability (Cutter, 1993).

Disaster risk is defined as the possibility or chance of harmful consequences on a system or expected loss (of lives, people, injury, livelihoods, economic activity disrupted or environmental damage) resulting from interactions between natural and human induced hazards and vulnerable conditions (UNISDR, 2002). The disaster risk assessment is a process that analyses the nature and extent of the risk by considering the potential hazard, the vulnerability and the resilience of the community that might be affected (UNISDR, 2010). In general, it is agreed that risk is a function of hazard, vulnerability, resilience, capacity to cope and exposure. Therefore, in order to ensure that populations can adequately adapt to disaster risk, it is essential that a disaster risk assessment is completed. This will allow for the identification of high-risk areas where adaptation is required.

The South African National Disaster Management Framework (Republic of South Africa, 2005) provides certain guidelines on the execution of a disaster risk assessment and specifically instructs that the level of risk associated with a hazard is estimated to determine whether it is a priority or not. This should be completed by initially collecting information regarding all existing hazards and prevailing conditions in the area, on aspects such as climate, demography, groundcover, land use, infrastructure and topography. In addition, the assessment of the hazard should be conducted, by analysing previous incidences and impacts, and predicted future hazards. Similarly, the ANCOLD Guidelines (2003), provide a methodological framework for risk identification and estimation. This framework can be generally be summarised by the following steps:

- **Risk identification**, which refers to the spatial and qualitative identification of the hazard source.

- **Risk analysis or risk estimation**, which involves estimation of the probability of occurrence of the hazardous phenomenon, estimation of the actual consequences, and the vulnerability estimation of the affected system over the selected hazard scenarios.
- **Risk evaluation**, which refers to identification of the local society's tolerable risk policies and criteria as well as to the comprehension of the local society's perception of the hazard impacts by decision makers.
- **Risk assessment**, which refers to evaluation of tolerability of estimated risks based on the local society's acceptability criteria. The comparison of the estimated risk with acceptable risk results in the decision of what risk will be acceptable in the particular affected system and what risk reduction measures may be applied. This process is also often referred to as 'risk prioritisation'.

Once the risk assessment has been conducted, the flood risk areas should be mapped in order to provide a risk profile for the area. This spatial assessment should be incorporated as part of the regional flood assessment, planning and management processes.

Flood risk assessment is a challenge in terms of providing scientific knowledge and using it to provide essential tools for land-use planning, flood management initiatives, and infrastructure investment. There is considerable disagreement over the use of risk assessment. Most of these conflicts centre on scientific issues of measurement, inference and use of quantitative data. In theory, risk assessments are objective attempts to numerically define the extent of human exposure to all the hazards they face. Unfortunately, science is not always objective; scientists tend to disagree on the interpretations of the quantitative evidence. This lies at the centre of many debates on risk assessments (Lofstedt and Frewer, 1998).

2.5 Flood Distribution and Flood Mapping

The European Union Flood Risk Management Directive (2007/EC/60) stipulates that disaster and flood risk management should be supported by the production of hazard and risk maps. Flood maps are the base of flood risk analysis and can be used to regulate land-uses as well as to support project design to alleviate floods.

Flood maps bring the spatial dimension of flood analysis and are crucial for project appraisal. Different types of flood maps are currently used to support flood management (Eleutério, 2012). The use of these different tools is crucial and has gained importance over time (Penning-Rowsell and Green, 2000).

There are several methods for flood mapping based primarily on hydrologic, meteorologic and geomorphologic approaches. In developing countries where hydro-meteorological data are commonly insufficient and inaccurate to generate flood models, the geomorphologic method may be more effective and appropriate (Wolman, 1971; Lastra *et al.*, 2008). This can be based on aerial photo interpretation and field investigation of flood extent (Ho *et al.*, 2010). A geomorphologic map provides an overview of the extent of inundation area, and changes in river channels through land reforms and sediments deposited by repeated floods. Hence, they enable an understanding of the nature of past floods and the likely characteristics of floods occurring in the future (Oya, 2002).

The availability of new technologies for the measurement of surface elevation has partially addressed the lack of high-resolution elevation data. The increasing availability of digital elevation models has given a strong impulse to the development of the so-called DEM-based hydro-geomorphic models (Williams *et al.*, 2000; Gallant and Dowling, 2003). This approach of flood investigation, i.e. flood modelling, has been verified significantly where the channel system and floodplain morphology of rivers change dynamically and have high erosive potential and substantial sediment supply (Lastra *et al.*, 2008). Moreover, as hydrological and meteorological data to develop a flood model are commonly restrictive, a method for flood hazard zonation based on the geomorphologic approach (Ho *et al.*, 2010) may have to be considered. This is studied further below.

2.5.1 Hydrological Modelling

Whenever rainfall occurs, a part of it is intercepted by trees and evaporates without reaching the surface, and the remainder appears as runoff (Maity, 2009), is stored in soil or below the surface (as groundwater), or may evaporated from the surface.

This concept is explained in detail by Horton (1933) and Beven (2004). According to Horton (1933), infiltration divides rainfall into two parts, which pursue different courses through the hydrologic system. One part goes via overland flow and stream channels to the sea as surface runoff. The other part initially goes into the soil and then through groundwater, and then finally into the stream or is returned to the air by evaporative processes. The soil therefore acts as a separating surface, and various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall as so divided, separately (Horton, 1933; Beven, 2004).

The conversion of rainfall into runoff and its routing through the slope and river come under the ambit of hydrological modelling (Knocke, 2011). According to Allaby and Allaby (1999), hydrological modelling refers to the use of small-scale physical models, mathematical analogues, and computer simulations to characterize the likely behaviour of real hydrologic features and systems.

2.5.1.1 Hydrological Models

Hydrological models have the five basic components that include governing laws, watershed geometry, input, output and boundary conditions (Knocke, 2006). The interaction between water network, soil, vegetation, geomorphology, land geology and the atmosphere is very complex and makes developing and carrying out the models very difficult (Pilgrim and Cordery, 1993).

a) Runoff Estimation

In order to estimate runoff in a river basin, various approaches have been developed that analyse the relationships between the rainfall over a catchment area and the resulting flow in a river. These approaches should, therefore, be used when attempting to obtain or predict runoff, and are discussed in Table 2.3.

Table 2.3: Runoff Estimation Methods

Conceptual models
Conceptual models incorporate the important hydrological processes using mathematical approximations. Conceptually these types of models usually involve interconnected storage volumes receiving recharge and discharge as appropriate for representations of component processes of the hydrological cycle (Kokkonen and Jakeman, 2001). The more component processes that are represented in the conceptual model, the larger the risk of over-parameterization (Tedela, 2009).

Physically-based models
Physically-based models have a theoretical basis that simulates hydrological responses based on the governing hydrodynamic and transport equations. A physically-based model is one for which parameters and variables of the governing equations are measurable in the field (Beven, 1983). Physically-based models are appealing because of the mathematical approximations of real phenomena that are derived from first principles (Tedela, 2009).
Lumped, semi-distributed, or fully distributed models
Lumped, semi-distributed, or fully distributed models are classifications of the conceptual or the physically-based rainfall-runoff models (Tedela, 2009). • The lumped-parameter model ignores spatial heterogeneity of the catchment response to achieve an important advantage of simplicity (Ponce and Hawkins, 1996). • Semi-distributed models lump parameters with similar properties together for simplicity and convenience (Tedela, 2009). • Distributed models attempt to simulate most of the heterogeneous response at a local scale (Beven, 1989; O'Connell, 1991; Garbrecht *et al.,* 2001).
Metric (or empirical) models
Metric (or empirical) models are directly based on observations to characterize runoff and are formulated with little or no consideration of the hydrologic cycle (Kokkonen and Jakeman, 2001) or river systems, so that the model has no theoretical basis. Strictly limited to the range of data used to formulate the model, empirical models have two basic uses. Firstly, interpolations over the range of data used to derive the model are feasible in that the computer codes serve to estimate a response between observations. Secondly, the form and structure of metric models provide insight into the formulation of conceptual models or the derivation of physically based models, making extrapolation beyond the original observations possible (Tedela, 2009). The unit hydrograph (Sherman, 1949), formulated as a linear relationship between rainfall excess and streamflow, was one of the first metric rainfall-runoff models developed (Kokkonen and Jakeman, 2001). Another empirical method is the rational method, which uses an empirical linear equation to compute the peak runoff rate from a selected period of uniform rainfall intensity. Originally developed more than 100 years ago, it continues to be useful in estimating runoff (New Jersey Department of Environmental Protection, 2004). The conditions of constant temporal and spatial rainfall, storm duration exceeding time of concentration, and overland flow as the dominant runoff mechanism, dictate that the rational method be restricted to small basins (Tolland *et al.,* 1998).
Semi-empirical models
Semi-empirical models have a strong empirical origin, but also have some conceptual basis so that these cannot be clearly classified as empirical or conceptual models. The curve number method is the best example of a semi-empirical model (Tedela, 2009). The curve number method relates watershed rainfall to runoff in engineering drainage design (McCuen, 2005), and was derived from the principle that water is conserved in a watershed during a storm (Tedela, 2009). The ad hoc popularity of the technique follows from the lumping the complexity of runoff generation into a single watershed potential maximum retention parameter easily expressed as the curve number (Nachabe, 2006). Important uses include estimation of runoff volume from gauged and ungauged watersheds, determination of hydrologic effects of changes in land use and treatment, and as a calibration parameter in watershed models (Tedela, 2009).

a) Design Storm Method

Flood design generally requires the estimation of flood discharges of a given return period at a site. If long stream flow records are available, the flood estimates can be derived directly from data by frequency analysis. If no or limited stream flow data are available, or floods associated with very large return periods are of interest, design floods are generally estimated based on design storms (Viglione and Blöschl, 2009).

In this procedure, one or more storms of a given return period are used as an input to a rainfall-runoff model, and it is then assumed that the simulated peak discharge has the same return period (Viglione and Blöschl, 2009). The idea of the design-storm procedure is to estimate a flood of a selected return period from rainfall intensity-duration frequency (IDF) curves for the site of interest (Viglione and Blöschl, 2009). A flood event may be described by a multivariate function of the peak, volume and duration, as a joint distribution of their marginal distributions (Mediero *et al.*, 2010).

There are a number of “parts” that need to be considered in the design storm method which include storm rainfall intensity, storm duration, temporal and spatial storm patterns, and antecedent soil moisture conditions (Viglione and Blöschl, 2009). In addition, a pair of peak and volume values will have a different return period than that of their marginal distributions. Therefore, peaks and volumes cannot be utilized independently as thresholds to assess risk. The threshold must be defined as a given water level in the reservoir, so that the return period is the inverse of the probability of exceeding that reservoir water elevation in any given year (Mediero *et al.*, 2010). The problem is complex and a set of hydrographs can have the same design return period (Mediero *et al.*, 2010).

Alfieri *et al.* (2008) assessed the accuracy of design hyetographs in producing flood peaks with the same return period as the storms, and provided a correction factor to obtain more robust estimates of the design flood. In South Africa, the developmental effort in this regard by Alexander (2002) led to the development of a numerically calibrated version of the Rational Method (RM), known as the Standard Design Flood (SDF) method, which incorporates engineering factors of safety to accommodate the uncertainties in hydrological analyses at a regional level. The identification of representative, homogeneous flood-producing regions, which followed the boundaries of the drainage regions as depicted by the Department of Water Affairs and Forestry (DWAF) (1995) (Gericke and du Plessis, 2012). These regions are referred to as SDF basins and a total of 29 basins in South Africa were identified (Alexander, 2002). This was a major step in the development of the SDF method (Gericke and du Plessis, 2012).

This study utilised the design storm method to predict runoff for future flood events at the Crocodile River Basin. This is due to the simplicity of the model, as well as the data required for implementation.

2.5.1.2 Uncertainties in Hydrological Modelling

Large-scale hydrological modelling has become a focal point in hydrological research in recent years and is of fundamental importance for understanding continental and global water balances, impacts of climate and land-use changes, and for water-resources management (Werth and Guntner, 2010; Jung *et al.,* 2012; Li *et al.,* 2012; Mulligan, 2012). However, hydrological modelling and analysis of large spatial domains is severely constrained by data availability and quality (Arnell, 1999; Decharme and Douville, 2006; Doll and Siebert, 2002; Fekete *et al.*, 2004; Guntner, 2008; Hunger and Doll, 2008; Widen-Nilsson *et al.*, 2009; Peel *et al.,* 2010). In addition, the modellers' knowledge of the quality and limitations of large-scale datasets is often inadequate, which restricts the possibility to distinguish informative from dis-informative data. In a hydrological context, dis-informative data are data that are physically inconsistent and therefore misleading when these are met for model inference and hydrological analyses (Kauffeldt *et al.*, 2013).

Uncertainty is also created by the method that is used. The statistical methods used and the considerations made when processing existing data can also strongly influence the determination of discharge for specific frequencies (Eleutério, 2012). This will thus create uncertainty in the data and assumptions used for hydrological analysis. Therefore, uncertainty acceptance levels (or confidence intervals) for hydrological analysis and modelling should be considered when analysing flood risks and when producing flood maps.

According to the NRC (2009), flood frequency analysis of stream gauge records is the most reliable hydrological approach in flood risk evaluation process (NRC, 2009). The objective of flood frequency analysis is to provide the quantiles of maximum peak flow or daily discharge corresponding to a given return period (Chow *et al.*, 1988). The gauges record length plays a critical role on the liability of the quantiles of maximum peak flow corresponding to a given return period (NRC, 2000; Xu and Booij, 2007).

2.5.2 Hydraulic Modelling

Hydraulics has its basis in fluid mechanics and is aimed to better understand the actual behaviour of water movement in river channels based on the physical nature of the system, i.e. water flow in time and space as it moves through the system. Hydraulic modelling has the ability to replicate many features of complex river flow in various river reaches to support operational decisions of flood management and prediction (GHD, 2013). Therefore, hydrological modelling involves the technical process consisting of the reproduction of surface flow dynamics using physical and/or mathematical models (Patterson, 2013). In a river basin context, these models are used to simulate flows in river channels and on floodplains and in wetlands, to account for the operation of regulating structures (e.g. weirs); while the hydrological processes are computed from hydrological models (GHD, 2013).

2.5.2.1 Hydraulic Models

In general, hydraulic models are used in the prediction of the stream flow (output) of a catchment or river basin (system) in response to the precipitation (input). A hydraulic model is an important tool used in planning, simulation and management of runoff processes and rainfall as it is designed in a simplified way for both qualitative and quantitative modelling of any hydrological processes (Maity, 2009).

There are simple techniques in the applications of flood prediction which are available for modelling. These hydraulic models are classified according to their temporal and spatial scale, underlying modelling process and method of solution (Singh, 1995). The models simulate natural properties of river systems such as sediment, the flow of water, nutrients, microbial organisms and chemicals (Singh and Frevert, 2006). The spatial and temporal variations of both input and system are considered as the driving forces of physically-based hydraulic modelling (Pelling, 1999).

The modelling of fluids (i.e. runoff) is complex due to the three dimensions involved and the accompanying time-dependency (ADWR 2002; Munson *et al.,* 2010). Models are classified according to the number of dimensions involved in a physical space where the flow variables are considered. It is, therefore, possible to construct one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) models (ADWR, 2002; Dyhouse *et al.*, 2003; Hunter *et al.*, 2007).

Each of these applications start with some amount of rainfall over the catchment area, excess runoff that is found after the removal of all abstractions that include infiltration and surface storage, and the application of the hydraulic model that has been chosen for the simulation of runoff hydrographs (Knocke, 2006). The process of identifying and mapping possible areas at flood risk can then be identified in three steps. In a first step, return periods of discharge of particular values are determined. Inflow and outflow hydrographs are then created for these selected return periods. In a second step, water levels associated with these discharge values are determined through the use of numerical methods and numerical codes, and finally the computed elevations are used to create flood maps. Derivation of flood maps can be realized with different types of approaches, ranging from less complex (1D, quasi-2D model) to complex two and three-dimensional modelling codes (Werner and Lambert, 2007). These approaches are discussed in Table 2.4.

Table 2.4: Hydraulic Models

One-dimensional (1D) Modelling
One-dimensional flood modelling considers the flow in only one of the three coordinate dimensions (ADWR, 2002), namely along the central streamlines in the channel (Franzini and Finnemore, 2001), where streamlines intersect with cross sections at right angles which are parallel to each other (Dyhouse *et al.*, 2003). In fluid mechanics, the downstream direction of flow, parallel to the channel, is considered as the one-dimensional coordinate, thus longitudinal (ADWR, 2002). All the points in the fluid have the same velocity and direction at a specific time (Franzini and Finnemore, 2001; Munson *et al.*, 2010). The boundaries for such models are usually the catchment runoff and dry weather flow at the inlets and water levels at the outlets. This is a simplified flow analysis where the assumption is made that the velocity components in the other two directions are negligible (Franzini and Finnemore, 2001; Dyhouse *et al.*, 2003; Munson *et al.*, 2010). This analysis is suitable for most open channel hydraulic flows (Dyhouse *et al.*, 2003). These models are available in software packages such as MOUSE (DHI, 1986), SWMM (US EPA, 1988), INFOWORKS (Wallingford, 2002) and MIKE URBAN (DHI, 2004), and are widely used by research organizations, consulting companies and local authorities (Hénonin *et al.*, 2010). One-dimensional hydraulic models have been the preferred approach for several decades since their principles are simple to apply and there is a wide selection of software packages available. Furthermore, these models require fewer data inputs and minimum computational power to perform the analysis (Pappenberg *et al.*, 2005). However, such models are not suitable to reproduce the network overflow phenomenon. As this kind of model does not simulate the surface flood routing and the water level calculated in the virtual storage is not linked to any realistic behaviour of the overflow water, it logically leads to an overestimation of flood depth (Maksimovic, 2000; Mark *et al.*, 2004).

Quasi One-dimensional (1D-1D) Modelling
A variation of the 1D model is the 1D-1D model, which involves a coupling between a 1D collection system model and a 1D representation of the surface flow path (usually streams). This modelling approach is also known as dual drainage approach (Wisner *et al.*, 1982; Stephenson, 1998; Djordjevic *et al.*, 1999). The computed runoff can be distributed either directly into the drainage system or on the surface network, depending on the local context. The exchange between the two networks is handled through coupling links (Hénonin *et al.*, 2010). The development of this model involves large amounts of data with detailed GIS dataset including high-resolution DEM (Digital Elevation Model) or DTM (Digital Terrain Model). The pre-processing and verification of both the surface flow paths and storage functions have to be done carefully and can be particularly time-consuming, although automatic GIS procedures can be used (Maksimovic and Prodanovic, 2001; Mark *et al.*, 2004; Boonya-Aroonnet *et al.*, 2007).
Two-dimensional (2D) Modelling
In two-dimensional models the velocity of the flow changes along the longitudinal and lateral directions in the channel (Janna, 2009). Thus, gradients of the velocity exist in two dimensions of the horizontal plane (Franzini and Finnemore, 2001; Janna, 2009; Munson *et al.*, 2010). Two-dimensional models are used for the modelling of more complex flood parameters (e.g. flow velocity, flood wave propagation, inundation duration, flow direction and water rise rate). Additional data about the flood wave characteristics are required to determine the duration and peaks in the advanced modelling (Büchele *et al.*, 2006; De Moel *et al.*, 2009). The availability of more powerful computers and more accurate data have made the two-dimensional models a suitable option where more complex analysis is needed (FEI, 2007).
Quasi Two-dimensional (1D-2D) Modelling
The flow is still modelled in 1D but the surface flow is computed with a 2D engine. The 2D model is used to reproduce accurately the urban surface topography, including buildings, ponds, various structures, etc. The hydrodynamic flow computation with the 2D surface model allows calculations such as flow velocities with 2-directions components. The surface water level is no longer calculated from an interpolation formula but the result of 2D modelling of the flow behaviour (Hénonin *et al.*, 2010). This kind of coupled modelling has been used in a number of studies and is now available in commercial software packages such as INFOWORKS (Wallingford, 2006), MIKE FLOOD (DHI, 2005) and HEC-RAS. The exchanges between the collection system and the surface are still handled through coupling links as for the 1D-1D coupling, but the nodes of the collection system network are connected to cells of the 2D surface model. Thus, an issue of such 1D-2D models is the accuracy and resolution of the 2D surface model; the accuracy of the 2D model is highly dependent of the input data resolution, i.e. topographic data resolution such as density and elevation (Prodanovic *et al.*, 1998; Mark *et al.*, 2004). GIS pre-treatments are usually required to ensure that the main topographic features will be properly taken into account into the 2D model (Hénonin *et al.*, 2010) *This study utilised the Quasi Two-dimensional (1D-2D) model to simulate the flood extent for the Crocodile River Basin. This is due to the availability of data, and the advantages offered by this modelling approach. The approach employed is discussed in Chapter 4 and Appendix B.*
Three-dimensional (3D) modelling
Three-dimensional modelling considers the velocity changes in all three dimensions of the channel (Dyhouse *et al.*, 2003; Janna, 2009) and is applied at nodes in the river network. This model is normally applied to complicated reaches as it requires detailed data input, significant computer power and engineering expertise (Dyhouse *et al.*, 2003).

One-dimensional models cannot represent the true river basin and limits the modelling of the complex conditions of extreme flood events (ADWR, 2002; Merwade *et al.*, 2008; Pappenberg *et al.*, 2005), especially the simulation of flood waves (Hunter *et al.,* 2007) and the spreading flows on alluvial fans or unstable alluvial channels (ADWR, 2002). Although high quality data are available, it would have no effect on the quality of the flood lines generated, as cross-sections across the river network are used (Merwade *et al.*, 2008).

The use of two-dimensional modelling codes provides the best approach to flood extent modelling (e.g. with MIKE 21, TELEMAC-2D). These codes have the ability to represent complex floodplains topography, dynamic wetting and drying of the floodplain, and prediction of the exchange of momentum between channel and floodplains (Horrit *et al.*, 2007). Although two-dimensional models are far more realistic than 1D models to represent the surface flow behaviour, 1D-2D models still require more computation time than 1D-1D models. Thus, 1D-2D models are currently used for off-line applications only, while 1D and 1D-1D models can be used online for real-time forecast applications. Some ongoing research projects are investigating the feasibility of 1D-2D online models use for real-time applications, focusing on model enhancements methods to reduce computation time (Hénonin *et al.*, 2010).

However, common problems regarding the two-dimensional approach are data requirements and significant computational time. Due to these inconveniences, a new method was developed: coupled one and two-dimensional unsteady hydraulic model (Patro *et al.,* 2009; Tuteja and Shaikh, 2009). The flood modelling packages include MIKE FLOOD and SOBEK 1D2D, which offer the possibility to dynamically link a 1D breach model to a 2D floodplain model (Vanderkimpen and Peeters, 2008). Similarly, HEC-RAS has the ability to perform 2D hydrodynamic flow routing within the unsteady flow analysis portion of the software package. Users can perform 1D unsteady-flow modelling, 2D unsteady-flow modelling (Full Saint Venant equations or Diffusion Wave equations), as well as combined one-dimensional and two-dimensional (1D/2D) unsteady-flow routing (Brunner, 2014).

The availability of high-resolution data and more computational power has increased the use of complex models (Hunter *et al.,* 2007). As natural flows are known to be three-dimensional, the use of three-dimensional methods may appear obvious. However, some shortcomings have been identified in the complex models. Expert knowledge is required to set up complex models according to the requirements of the end user (Dyhouse *et al.*, 2003; Hunter *et al.,* 2007) and appropriate data for the verification of these complex models are very limited

(Hunter *et al.,* 2007). Complex models are also more expensive (Dyhouse *et al.*, 2003).

2.5.2.2 Uncertainties in Hydraulic Modelling

The selection of hydraulic models is typically based on a trade-off among the different factors of physical realism, computational efficiency, consistency with the quantity and quality of input and observation data, and objectives of the specific study (Mukolwe *et al.,* 2014). The accuracy of the hydraulic model will depend on the modelling approach that is employed. However, Dottori *et al.* (2013) discuss a number of important issues that should be taken into account in works related to flood modelling. These include the large number of uncertainty sources in model structure and available data; the difficult evaluation of model results, due to the scarcity of observed data; computational efficiency; as well as false confidence that can be given by high-resolution outputs, as accuracy is not necessarily increased by higher precision. Dottori *et al.* (2013) also state that the extreme precision of highly resolved models and data sets may lead non-expert users to become overconfident in the model results, disregarding a number of issues that have importance in performing reliable flood analyses.

The achievement of ‘as accurate as possible’ characteristics of the flood hazard is a research challenge that is widely addressed (Mukolwe *et al.,* 2014). Flood mitigation methodologies to deal with prior flood warning, quantification of envisaged disasters, uncertainty in flood risk management tools and coping mechanisms are continuously being researched (e.g. Pappenberger and Beven, 2006; McCarthy *et al.,* 2007; Montanari, 2007). These initiatives are bolstered by the availability of ever-increasing computer power and new models developed to analyse hydro-meteorological inputs and generate flood warnings and estimates of flood extent and other specific hazard characteristics; new information sources such as spatial data derived from satellite imagery are also increasingly becoming available (Di Baldassarre *et al.*, 2009a, 2009b; Schumann *et al.*, 2009; Bates, 2012). These improvements in flood risk management tools and methodologies can result in a reduction of flood risk (Mukolwe *et al.,* 2014).

It has been widely accepted by hydrologists that the most effective way to reduce future flood damages is to restrict development in areas that are subject to flooding (Dingman, 1984). However, the role of uncertainty in the production of flood maps and flood damage assessment is highly significant and cannot be neglected (de Blois and Wind, 1995; Merz *et al.*, 2010), which creates difficulty when planning for an uncertain future. Indeed, there are several studies that highlight the importance of hydrological uncertainty on the global uncertainty of flood damage estimations (de Blois and Wind, 1995; Merz *et al.*, 2010).

2.5.3 Geographical Information Systems

The main advantage of using Geographic Information Systems (GIS) is its ability for developing powerful models at different temporal and spatial scales, which involve complex interaction among dynamic phenomena and static geographical entities through which these entities evolved (Longley *et al.*, 1999). Therefore, the spatial dimension provided by GIS-based analyses is crucial for mapping processes and natural hazard management issues (Zerger, 2002; Köhler *et al.*, 2006). However, a great amount of data and knowledge are needed to produce and use these maps (Merz *et al.*, 2007; NRC, 2009).

GIS can be used in every step of the flood risk assessments for visualisation, data management and modelling (Robayo and Maidment 2005; Goodchild, 2006). Data preparation and results visualisation as well as data transfer methodologies can be achieved in the flexible GIS environment (Kiesel *et al*, 2013). Hydrological and hydraulic models benefit from GIS because of integration of the models and the spatial representation aspects that are offered by the software.

Three issues need to be considered when GIS is integrated with hydraulic and environmental modelling. These include considerations of the issue of systems that include user interfaces, GIS functionality, data models GIS design; issues of modelling that include developing and structuring of models; and issues of spatial data that include accuracy, resampling, common formats, access and availability (Knocke, 2006). Several complexities associated with data requirements need to be overcome in order to use GIS.

- Hydrological and geographical data can be very complex as they need to include information about possible topological connections of objects which have been recorded, together with their attributes (Ogden *et al.*, 2001).
- Weather and hydrological data comes in different formats and storage structures (Carrara *et al.*, 1999).
- Land use and infrastructural data are available, and are important as they provide the baseline information for a hazard assessment, as it is possible to map the extent of a hazard (Zschau and Küppers, 2003), and then to consider the land-uses and infrastructure affected.

It is, however, usually not easy to transform such data into the correct format for each specific model platform. This can require the users to use an external device, which can format the data, or to collect the required data in other formats. But, this can be overcome by using GIS (Knocke, 2006), as GIS has the ability to analyse and incorporate spatial characteristics in different formats. GIS allows for accurate spatial representation of a hazard event, thus enabling disaster management, police, medical, fire and other managerial personnel to make decisions based on data they can see and judge for themselves. This spatial or geography-based method presents essential information in a way that is more understandable than any other method (Greene, 2002).

Even though several methods are currently used to evaluate flood risks, the construction of comprehensive databases and the harmonisation of methods in national and international contexts remains great challenges for researchers and practitioners alike (Köhler *et al.*, 2006; Merz *et al.*, 2007). Often, when more complex modelling is required, the modelling is extended outside GIS by using another software package (Longley *et al.,* 2005). This is generally the approach in flood modelling, where external hydraulic software is used to determine the flood magnitude. Here, GIS is only used for visualisation and data management (Pilon 2004; Klijn 2009), as GIS technology is regarded as a computer method for the creation of digital maps, digital analysis, and creation of a database for spatial features and visualisation of spatial data. By using GIS, it is possible to understand the geographic extent of hazards as they very often occur in predictable locations. Once the possible extent of a hazard is known, it is then possible to identify communities, resources and infrastructure at risk (Zschau and Küppers, 2003).

Lastly, GIS also helps during all stages of Disaster Management of floods, including pre and post-disaster activities, mitigation, prevention and preparation (Haile, 2005). It helps in the provision of user-friendly, spatial data that are interactive and powerful.

Chau *et al.* (2013) used GIS to present a geospatial assessment of flood impacts on agricultural land in Quang Nam province, Vietnam. The study demonstrated how the results can inform economic assessments of natural disaster impacts and associated policy responses to mitigate extreme weather events. The use of GIS is supported also by Musungu *et al.* (2012), who used the spatial capabilities of the software to conduct a case study of an informal settlement in Cape Town. This study proposed a methodology of integrating community-based information obtained through a participatory multi-criteria evaluation into a GIS that can be used by the Cape Town City Council for risk assessment. This methodology ensures that different aspects are considered when conducting the risk assessment, and that the vulnerability of this study area is correctly assessed. Flood risk management approaches can, therefore, be localised and adapted to suit the specific area.

2.5.4 Flood Hazard Mapping

Flood hazard maps describe the magnitude and/or probability of a flood where the flood risk assessment provides information about the consequences of the flooding (Alho *et al.,* 2008; Zimmermann, 2008; De Moel *et al.*, 2009; Klijn 2009). Bründl *et al.* (2009) summarise flood hazard maps that indicate the locations of flood events with certain return periods. Flood hazard mapping can be integrated to analyse and map the vulnerabilities and the resulting risk to a community (Lechtenbörger, 2006; Martini and Loat, 2007).

Flood hazard maps can play an integral part in all the phases of flood risk assessment as they can communicate the extent of the flood and other flood parameters to different stakeholders. The community and disaster management role-players can better understand and visualise the characteristics of a possible future flood event when using GIS (Hardmeyer and Spencer, 2007). The requirements or needs of the stakeholders will determine the flood parameters to be mapped in the flood hazard map (Hardemeyer and Spencer, 2007; Martini and Loat, 2007; De Moel *et al.*, 2009). It is, however, important that the information gathered is communicated in an uncomplicated yet accurate format, easily understandable to experts and laymen alike (Greene, 2002). The basic types of flood hazard maps are indicated in Figure 2.5.

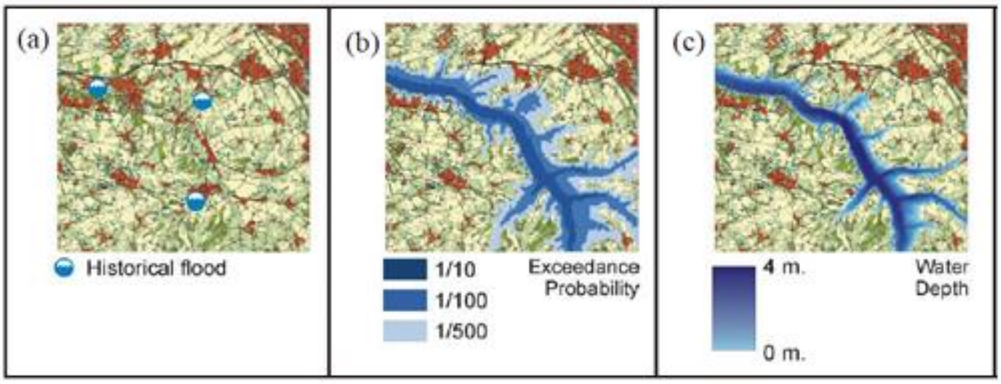


Figure 2.5: Types of flood hazard maps - (a) historical (event) maps, (b) extent maps and (c) flood depth maps. (Source: De Moel *et al.*, 2009).

As shown in Figure 2.5, the basic types of flood hazard maps are:

a) historical (event) maps, indicating the locations of historical events with point symbols on a map (De Moel *et al.*, 2009).
b) extent maps, which display the inundated areas of a flood event that can either be historical or hypothetical; different probabilities of occurrence need to be determined for the latter, namely 10 and 50 years for high, 100 years or greater for a medium, and 1000 years for low probabilities (Büchele *et al.,* 2006).
c) flood depth maps, displaying the water depths (levels) derived from one- and two-dimensional models for river flooding (De Moel *et al.*, 2009).

Other types of flood maps include:

- flow velocity maps, indicating the velocity of the water flow determined by two-dimensional models – one-dimensional models can also be used but this will be more complex (Büchele *et al.,* 2006).
- flood wave maps, displaying the movement of waves, as determined by two-dimensional models (Büchele *et al.,* 2006).

- inundation maps, indicating the area that was or may be under water (De Moel *et al.*, 2009).

Flood hazard mapping consists of the quantification of hydraulic parameters and their intersection with digital terrain models (DTM) and land use data (Büchele *et al.,* 2006; De Moel *et al.*, 2009). Thus, the modelling of the flood hazard consists of three main steps, namely (Büchele *et al.* 2006; De Moel *et al.*, 2009):

- the collection of historical data of water levels or inundation zones and calculating the return period for certain discharge values;
- the modelling of water levels using hydraulic models, either one- or two-dimensional; and
- the modelling of water levels with the DTM or DEM using one- or two-dimensional models.

There is a wide variety of flood models that can be used to this end. However, modelling may be erroneous due to erroneous, incomplete or missing input data. Moreover, many of these models have been designed for large scale applications, although their results are also used on a local scale to determine flood hazard and/or risk (Pappenberger *et al.*, 2007).

Flood hazard maps can be differentiated from flood risk maps in that flood hazard maps contain information about the probability and/or magnitude of a flood event, e.g. flood extent and water depth distribution; whereas flood risk maps contain additional information about the potential consequences of floods, e.g. economic loss, human injuries and environmental impacts (de Moel *et al.*, 2009). Both flood hazard and risk maps are essential for flood risk assessment and flood management.

2.6 Floods under Changing Climate Futures

Climate variability is the natural cycle through which the earth and its atmosphere accommodate the change in the amount of energy received from the sun. Changes in temperature also influence rainfall, but the biosphere is also able to adapt to a changing climate if these changes take place long time periods (Mukheibir and Sparks, 2005).

The concept of climate variability is an important factor in its own right, but especially in regard to its significance within the context of climate change (*S*chulze, 2011). It is therefore important to distinguish between the two concepts;

- ***Climate Variability*** signifies any deviation from the long-term expected value. It is an entirely natural phenomenon, is *reversible* and *non-permanent*. An example would be the droughts in Southern Africa which are associated with the El Niño - Southern Ocean (ENSO) phenomenon. Climate variability has time scales which can range from diurnal to daily to intra-seasonal to inter-annual and to decadal (*S*chulze, 2011).

- ***Climate Change***, on the other hand, is *irreversible* and *permanent*, where a (positive or negative) trend over time is superimposed over naturally occurring variability. A commonly cited example of climate change is anthropogenically forced global warming, and the associated trends in increased temperature which result from the enhanced greenhouse effect through increased atmospheric emissions of greenhouse gases. The time scale of this climate change is decades to centuries and the trend is more likely to occur in steps than linearly over time (*S*chulze, 2011). However, it is important to note that climate change can also be an entirely natural process. Naturally induced climate change occurs at a slower rate of change than with anthropogenically forced global warming.

2.6.1 Southern Africa

Climate is controlled by complex maritime and terrestrial interactions that produce a variety of climates across a range of regions and continents (Mukheibir and Sparks, 2005). Africa is considered to be one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity (IPCC, 2007; Davis, 2010). As the livelihoods of people in Africa, including South Africa, are often directly linked to the climate of the area (Davis, 2010), livelihoods are likely to be affected. This is because climate influences agriculture, the environment, water availability and thus the economy of primary sector-dependent countries all over the world (Mukheibir and Sparks, 2005).

Over Southern Africa a reduction in late austral summer precipitation has been reported over the western parts, extending from Namibia, through Angola, and toward the Congo, during the second half of the 20th Century (Hoerling *et al.*, 2006; New *et al.*, 2006). The drying is associated with an upward trend in tropical Indian Ocean Sea Surface Temperatures (SSTs). Modest downward trends in rainfall are found in Botswana, Zimbabwe, and western South Africa. Apart from changes in total or mean summer rainfall, certain intra-seasonal characteristics of seasonal rainfall such as onset, duration, dry spell frequencies, and rainfall intensity as well as delay of rainfall onset have been identified (Tadross *et al.*, 2005, 2009; Thomas *et al.*, 2007; Kniveton *et al.*, 2009).

An increasing frequency of dry spells is accompanied by an increasing trend in daily rainfall intensity, which has implications for run-off characteristics (New *et al.*, 2006). Over Southern Africa, unusually dry austral summers as occurred during 2002/2003 have become more likely, whereas unusually wet austral summers like that of 1999/2000 have become less likely due to anthropogenic climate change. There is some tentative evidence that the risk of extreme high 5-day precipitation totals (as observed in 1999/2000) have increased in the region. These results are consistent with CMIP5 models projecting a general drying trend over SAF during December–January–February (DJF) but also an increase in atmospheric moisture availability to feed heavy rainfall events when they do occur (Bellprat *et al.*, 2015).

Climate projections over Southern Africa show a drying signal in the annual mean temperature over the climatologically dry south-west, extending north-eastward from the desert areas in Namibia and Botswana (Moise and Hudson, 2008; Orlowsky and Seneviratne, 2012; James and Washington, 2013). Similarly, Lu *et al. (*2015) found that the projected temperature shows an increasing tendency over Southern Africa in the near future, especially in the eastern part, while the precipitation changes are varying between different months and sub-regions. An increase in runoff (and evapotranspiration) is projected for eastern part of Southern Africa, i.e. Southern Mozambique and Malawi, while a decrease was estimated across the driest region in a wide area encompassing Kalahari Desert, Namibia, southwest of South Africa and Angola (Lu *et al.*, 2015).

During the summer months, dry conditions are projected in the south-west, while projections indicate wetter conditions in the south-east of South Africa and the Drakensberg mountain range (Hewitson and Crane, 2006; Engelbrecht *et al.*, 2009). Drier winters are projected over a large area in Southern Africa by the end of the 21st century as a result of the poleward displacement of mid-latitude storm tracks (Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; Shongwe *et al.*, 2009; Seth *et al.*, 2011; James and Washington, 2013). Rainfall decreases are also projected during spring months, implying a delay in the onset of seasonal rains over a large part of the summer rainfall region of Southern Africa (Shongwe *et al.*, 2009; Seth *et al.*, 2011).

The strongest climate change signals are found over humid tropical areas, i.e. north of Angola and Malawi and south of Democratic Republic of Congo (DRC). Large spatial and temporal variability of climate change signals is found in the near future over Southern Africa (Lu *et al.*, 2015). Enhanced heat wave probabilities are associated with deficient rainfall conditions that tend to occur during El Niño events (Niang *et al.*, 2014). Large uncertainties surround projected changes in tropical cyclone landfall from the south-west Indian Ocean that have resulted in intense floods during the 20th Century. Future precipitation projections show changes in the scale of the rainfall probability distribution, indicating that extremes of both signs may become more frequent in the future (Kay and Washington, 2008).

2.6.2 South Africa

South Africa is a country that experiences a wide range of different weather conditions. These include thunderstorms of the Highveld, frontal rain over the south-western Cape, berg winds along the Eastern Cape coast, and widespread flooding over north-eastern South Africa, caused by tropical cyclones making landfall over Mozambique (Archer, 2011).

Mean annual temperatures have increased by at least 1.5 times the observed global average of 0.65°C over the past five decades and extreme rainfall events have increased in frequency (Ziervogel *et al.*, 2014). Rainfall variability is particularly pronounced over the dry western parts of South Africa, where a dry year can have significant economic repercussions. Furthermore, extreme dry years tend to be more frequent in the driest regions of the country (Mukheibir and Sparks, 2005).

Rainfall patterns over the country display well-pronounced intra-annual and inter-annual variability mainly due to the ENSO (Davis, 2010). In the El Niño (dry) years, the rainfall is considerably low, whereas in the La Niña (wet) years, rainfall is relatively higher (Mukheibir and Sparks, 2005). Steyn (1984) argued that there are also other influences on the climate variability of the region, such as changes in macro pressure over the interior and adjacent oceans that impact on the weather and climate and result in wet and dry spells, and the location of troughs of standing westerly waves (Steyn, 1984).

Climate change is expected to impact the earth's atmosphere through increases in temperature and resultant perturbations to rainfall regimes, including increases in rainfall variability. This may lead to increases in the intensity and frequency of extreme rainfall events of both short duration and long duration and, with that, associated flooding (IPCC, 2007). The IPCC (2007) and DEA (2013) suggest warming relative to 1986–2005 of 3-6°C by 2081-2100 in the interior, yet less certain precipitation changes in terms of both direction and magnitude (Ziervogel *et al.*, 2014). There are significant geographical differences in projected rainfall changes. Drier conditions are predicted for the south-west of the country in both seasons. Rainfall intensity is likely to increase, but will not necessarily imply an increase in total rainfall (Davis, 2010).

Many questions arise about climate change and climate variability and how they affect South Africa. South Africa's water resources, already subjected to high hydro-climatic variability both over space over time, are a key constraint to the country's continued economic development and the sustainable livelihoods of its people (*S*chulze, 2011). Water resources will continue to be affected, where South Africa's industrial, domestic and agricultural users are highly dependent on a reliable supply of water (Mukheibir and Sparks, 2005). A changing climate is likely to have considerable impacts on the water sector, with different regions of the country likely to be affected in many different ways. For this reason alone, local scale analyses are needed to assess potential impacts (Andersson *et al.*, 2009).

Streamflow, or channel flow, which refers to the flow of water in streams, rivers and other channels, is expected to experience changes in the concentration and timing of high and low flows due to changes in rainfall patterns (Archer, 2011), and feedbacks through land-use changes and soil characteristics. Changes in mean annual streamflow and its variability are anticipated, with an increase in variability into the intermediate future of around 20 to 30%, except in the south-Western Cape where variability is projected to decrease (*S*chulze, 2011).

DEA (2013) states that preliminary projections indicate changes in runoff ranging from a 20% decrease to a 60% increase by as early as 2050, while other projections indicate changes in runoff ranging from a 5% decrease to a 20% increase. Spatially, the eastern seaboard and central interior of the country are likely to experience increases while much of the Northern and Western Cape are likely to experience decreases in runoff (Ziervogel *et al.*, 2014). In the latter part of the century a strong decrease in absolute variability of annual streamflow is projected not only in the south-west, but also in the south and in parts of the north of South Africa (*S*chulze, 2011).

Greater evaporation rates are likely to increase drought incidence and intensity (as defined by the response of available soil moisture and available free water), possibly even in regions where total rainfall increases (Davis, 2010). A projected increase in extreme events is expected to have a negative impact on the quantity and quality of groundwater reserves and surface water. The risk that water resources face due to the increase in extreme events, droughts and heavy precipitation can be categorised by: a decrease in water quality due to saltwater intrusion; an increase in the occurrence of international water conflicts; a decrease in water quality due to run-off and erosion; and a decrease in agriculture production due to droughts (Archer, 2011).

2.6.3 Mpumalanga Province

With projected changes in global climates into the future, changes in the South African water sector will be inevitable (*S*chulze, 2011). For the north-eastern region of the country, which includes Gauteng, Limpopo and Mpumalanga provinces, an increase in overall rainfall is projected. Figure 2.6 illustrates the projected change in mean annual precipitation for the north-eastern region of South Africa. CSIR (2010) states that future rainfall is expected to increase by between 85 and 303 mm per annum for the north-eastern region as a whole, and the total rainfall is expected to range from 301 mm to 758 mm per annum by 2100 (CSIR, 2010). The majority of the increased rainfall that is projected is expected to fall during the summer months (December to February). An extension of the rain season may occur into early spring due to the increase in rainfall predicted for September to November. The number of rain events is expected to increase, which could infer that the chances of floods may increase (CSIR, 2010).

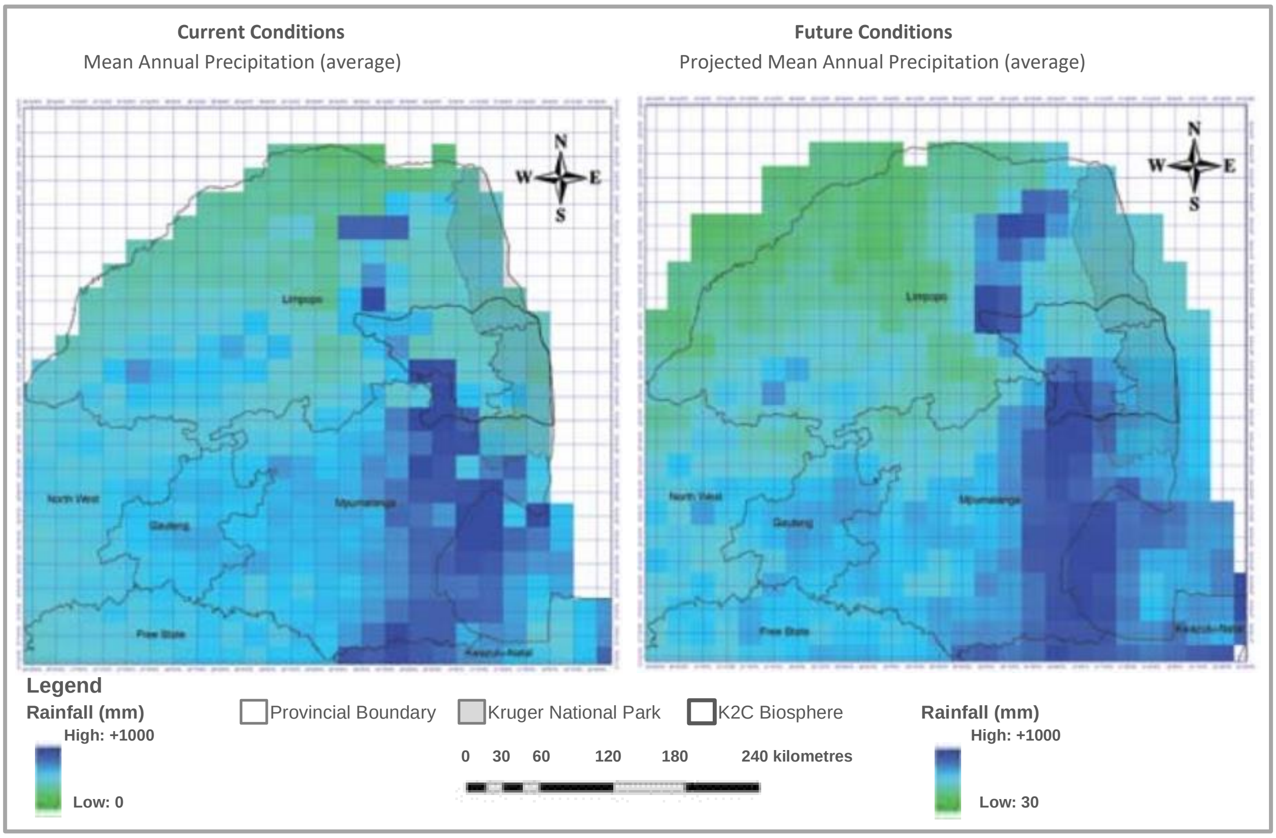


Figure 2.6: Current and Projected Mean Annual Precipitation by 2100 (Source: Davis, 2010).

The majority of rain events are expected to occur in November to January, which have the highest number of rain days. The number of rain days per month is expected to increase by between 1.036 and 2.188 days. This small change in the number of rain days per month compared with the increase in rainfall demonstrates that the intensity of rain events and possibly the severity of rain events may increase (Davis, 2010). The risk of flooding during rain events is also likely to increase.

2.6.4 Limitations and Uncertainties of Future Climate Projections

While there is sufficient confidence in the scientific community about climate change and the associated global patterns of surface temperatures that are controlled by thermodynamics, there is little confident in circulation aspects of climate change, which are primarily controlled by dynamics that exert a strong control on regional climate. Model projections of circulation-related fields (including precipitation) show a wide range of possible outcomes, even on centennial timescales (Shepherd, 2014). Projections of future climate change by Global Climate Models (GCMs) may provide insight into potential broad-scale changes in the atmosphere and ocean, such as shifts in the major circulation zones and the magnitude of sea-level rise. However, because these models are computationally expensive, they are often integrated at relatively coarse horizontal resolutions, where the regional details of climate (such as the characteristics of orographic precipitation and thunderstorms) and climate change cannot be sufficiently described (Davis, 2010). In addition, due to the costs, most studies tend to rely on a few GCMs. This, therefore, creates uncertainty in climate projections.

Daly (2006) cautioned over the tendency to equate resolution with realism in climate modelling, as climate-forcing factors assumed to be unimportant at coarser resolutions may become significant if the scale is refined. Guentchev *et al.* (2010) pointed out that developers of spatial climate data sets should always communicate the strengths and limitations of their data sets. For example, the climate projections discussed in Section 2.6.1 are based on a CSIR study that used two dynamic regional climate models (PRECIS and MM5) and future precipitation variables were obtained from ten statistically downscaled GCMs. The use of different GCMs to those employed, more GCMs, or GCMs with a higher resolution would likely provide different projections for Mpumalanga. Therefore, it is imperative that climate projections are read as estimates of what the future may look like, instead of a certainty of what future climate will be.

2.7 Conclusions

Floods are among the most recurring and devastating natural hazards, impacting human lives and causing severe economic damage throughout the world. It is understood that flood risks will not subside in the future, and with the onset of climate change, flood intensity and frequency will threaten many regions of the world (McCarthy *et al.*, 2001; Jonkman, 2005). However, because global data and models are generally tailored to relatively coarse spatial (and to a smaller degree temporal) resolutions, the local character and short timescale of floods makes prediction difficult (at the global scale). Moreover, the impact of local scale floods is dependent on the spatial overlap between a flooded area and the exposed assets and inhabitants in the region. The spatial variability of such exposures is often large, and there are many examples where they are in fact concentrated in flood-prone regions (Winsemius *et al.*, 2013).

It should be noted that flooding is not the only risk associated with climate change; it is also likely to impact the country through other feedbacks, such as changes in vegetation, land-use, urbanisation, groundwater levels and soil types. Due to the interlinkages between these spheres, changes in these characteristics will result in changes in river systems and hydrological processes, and therefore changes in the basin's responses to future rainfall, upstream dam releases, and flood events. This will have a direct impact on the magnitude of floods.

In the South African context, the major risks to water resources include decreased availability of water in rivers as a result of the net effect of increased temperatures and increased evaporation, coupled with shifts in the timing and amounts of rainfall; changes in the concentration and timing of high and low flows due to changes in rainfall; increased incidence of floods as the incidence of very heavy rain events increases; and increased risk of water pollution and decreased water quality linked to erosion and runoff (Davis, 2010). It is clear that climate change, variability and associated increased disaster risks will seriously hamper future development (Mukheibir and Sparks, 2005), and potentially harm human, natural and physical systems in high risk areas and along river banks.

CHAPTER 3 – STUDY AREA

3. STUDY AREA

3.1 General Description of Study Area

To facilitate the management of water resources, South Africa's National Water Resources Strategy (NWRS) divided the country into nineteen catchment-based water management areas (WMAs). However, as part of the second National Water Resources Strategy (NWRS 2), the nineteen WMAs have been amalgamated to nine WMAs. The Inkomati-Usuthu WMA, where the Crocodile River (East) is located (as is shown in Figure 3.1.), is the focus area for this research.

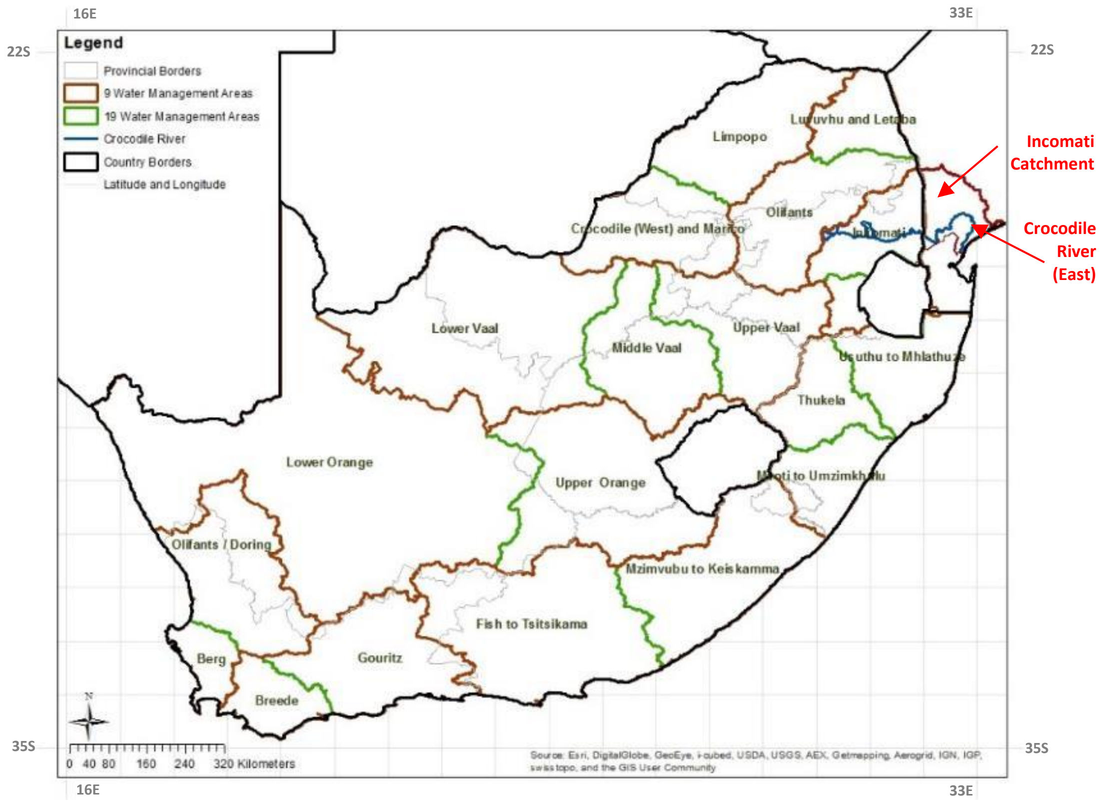


Figure 3.1: Location of the Crocodile River (East) in North-East South Africa

The Inkomati-Usuthu WMA falls almost completely in the Mpumalanga Province of South Africa. It is managed by the Inkomati-Usuthu Catchment Management Agency, and consists of four major catchments, namely the Komati, Crocodile, Sabie-Sand catchments (DWA, 2011) and the recently amalgamated Usuthu catchment. The Incomati catchment (Figure 3.2), is comprised of the Crocodile River, Inkomati River, as well as the Sabie, Komati, Massintonto, Uanetze and Mazimechope Rivers.

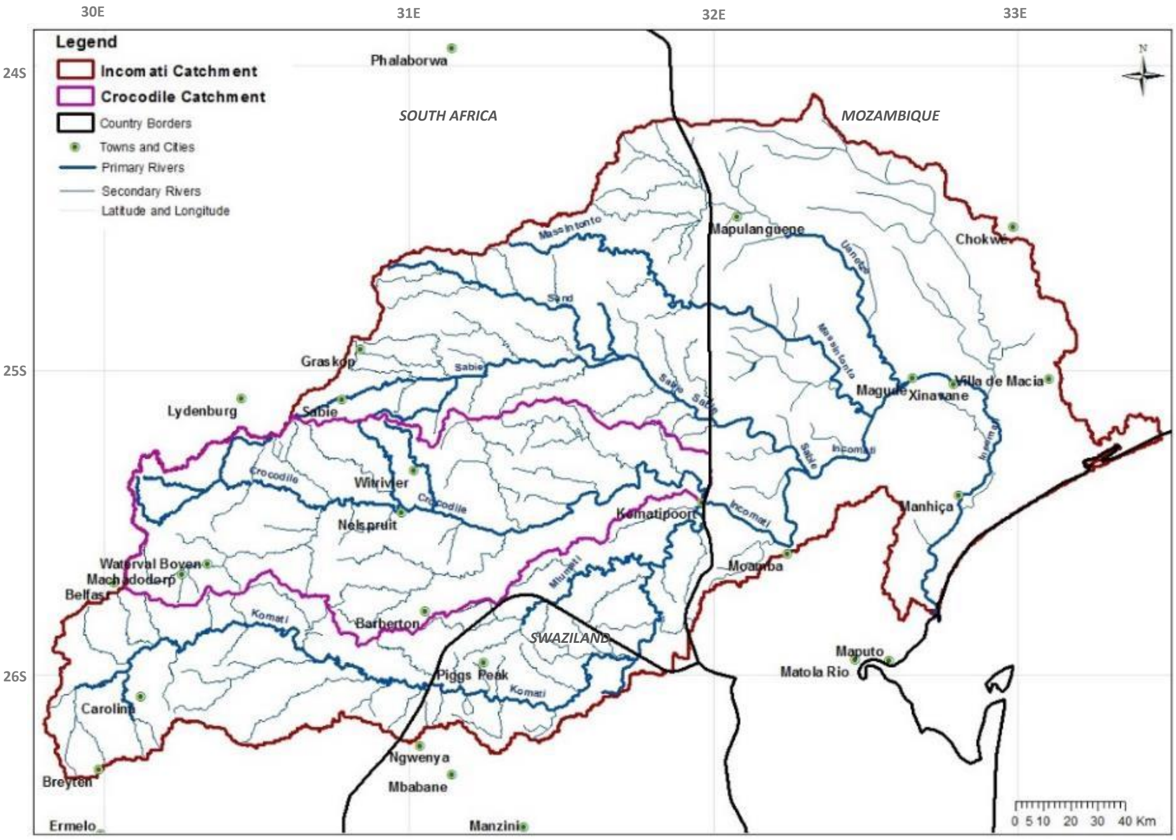


Figure 3.2: The Incomati Catchment

The Crocodile River, which is the focus of this research, is a perennial river that originates at Steenkampsberg, north of Dullstroom, in the western part of Mpumalanga. It has a relatively large river basin with a total river length of approximately 320 km draining a catchment area of about 10 450 km^2 from its source to its confluence with the Komati River. At Komatipoort, the Crocodile River and the Komati River converge to form the Incomati River which cuts through the Lebombo Mountains into Mozambique between the border towns of Komatipoort and Ressano Garcia. The Incomati River then flows across the Mozambique coastal plain for approximately 250 km before reaching the sea at the Incomati Delta at Marracuene, approximately 20 km north-east of Maputo. Its main tributaries include the Elands, Sand, White and Kaap Rivers (CSIR, 2001), while the minor tributaries include the Nsikazi (or Sigasi) River and the Mbiyamiti River (in the Kruger National Park).

The focus of this research will, however, be on the South African portion of the Crocodile River (as shown in Figure 3.3). This is mainly due to data availability and the consistency of how data are captured and recorded. Inconsistencies in the data that are used would impact the accuracy of this research.

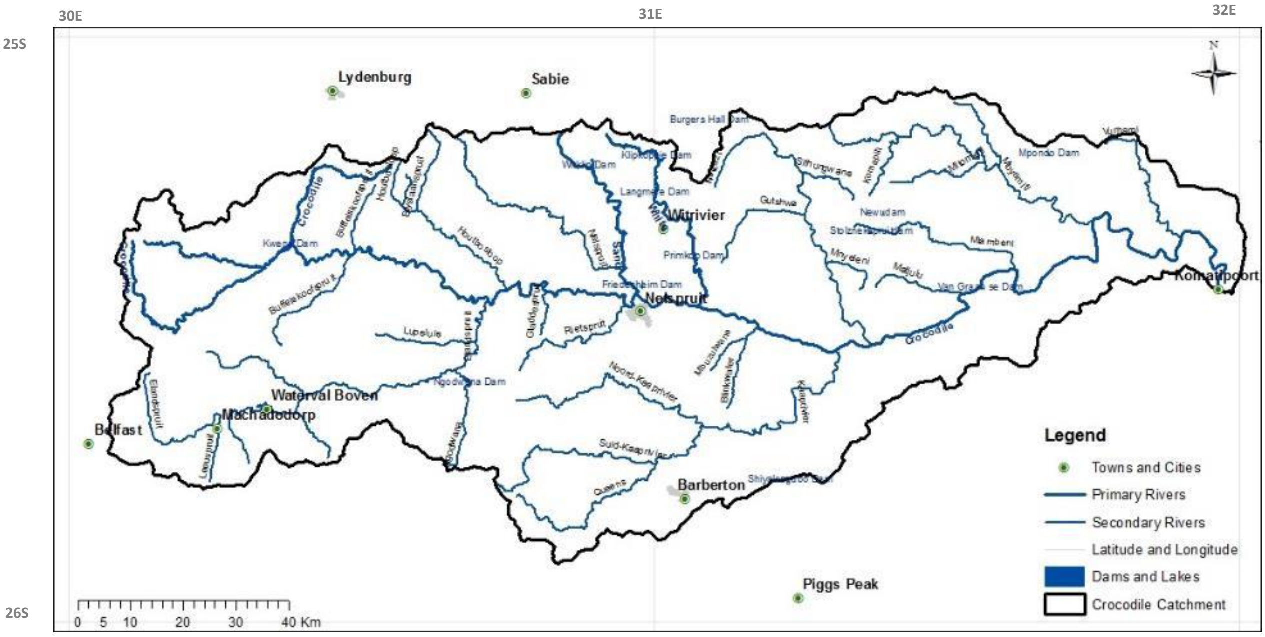


Figure 3.3: The Crocodile River (East) in South Africa

3.2 Physical Properties of the Study Area

3.2.1 Topography

The Crocodile River rises at an altitude of approximately 2 000 metres above sea level (m.a.s.l.) near Dullstroom in the Steenkampsberg Mountains. The upper catchment consists of steep-sided valleys, often with sharply defined cliff slopes on the eastern edge of the escarpment. From the escarpment, the Crocodile River levels out into the basin of the Kwena Dam, and then winds along the valleys of the Drakensberg Mountains (Schoemanskloof) to Montrose Falls and the confluence of the Elands River (Roux *et al.,* 1999). The topography of the catchment is illustrated in Figure 3.4. The high interior plateau and the low-lying region have relatively flat rolling terrain, while the escarpment zone is mountainous with scarps and steep valley flanks (RHP, 2012).

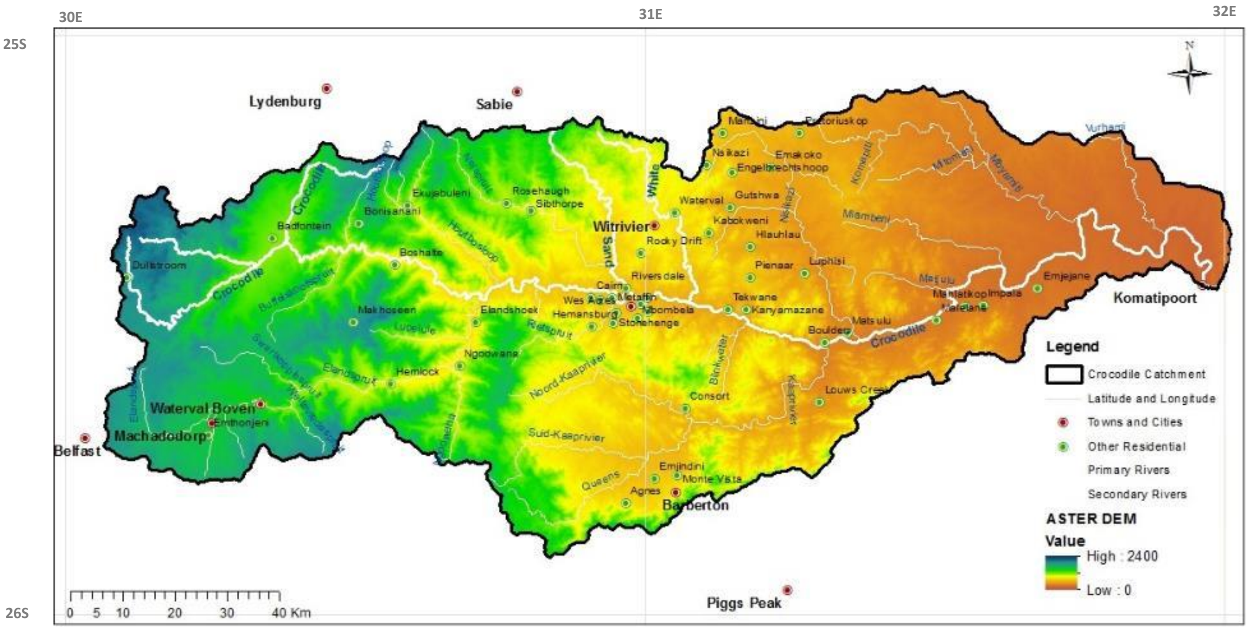


Figure 3.4: Topography of the Crocodile Catchment (shown in metres above sea level (m.a.s.l.)) (Data Source: USGS, 2014)

The changes in altitude can be represented through a longitudinal profile through the main trunk of the river, which recognises changes in the longitudinal characteristics of the river. The longitudinal profile of the Crocodile River is illustrated in Figure 3.5.

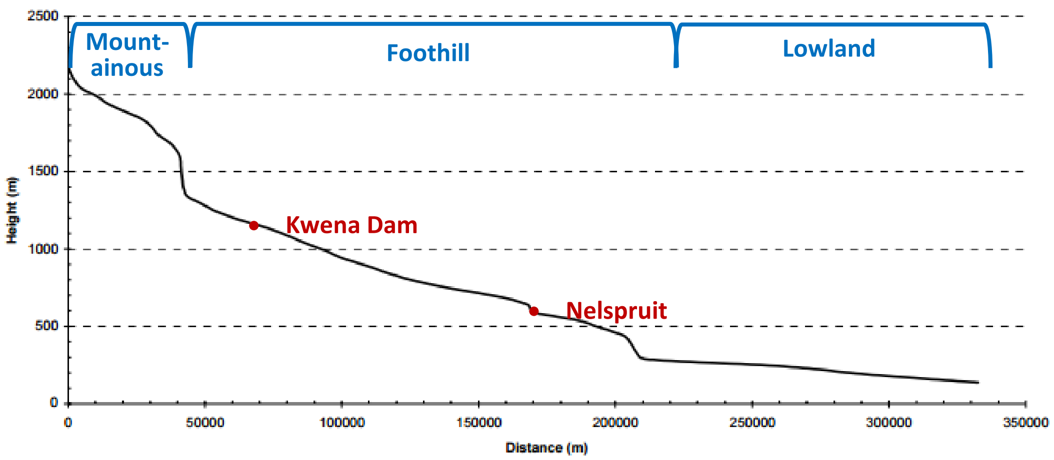


Figure 3.5: Longitudinal Profile of the Crocodile River, showing the Mountainous, Foothill and Lowland Zones (Adapted from DWA, 2002)

Between Montrose Falls and Nelspruit, the Crocodile River is slightly incised into a broad, flat-bottomed valley. Further downstream the steep sided river banks are densely covered with riparian vegetation and reed beds. Downstream of its confluence with the Kaap River, the gradient of the Crocodile River flattens out until its confluence with the Komati River at the town of Komatipoort (Roux *et al.*, 1999).

3.2.2 Geology

The Crocodile River is a slow flowing river whose channel flows over mainly bedrock or sandy pools (Roux and Selepe, 2013). The geology of the Crocodile catchment is complex, as is illustrated in Figure 3.6.

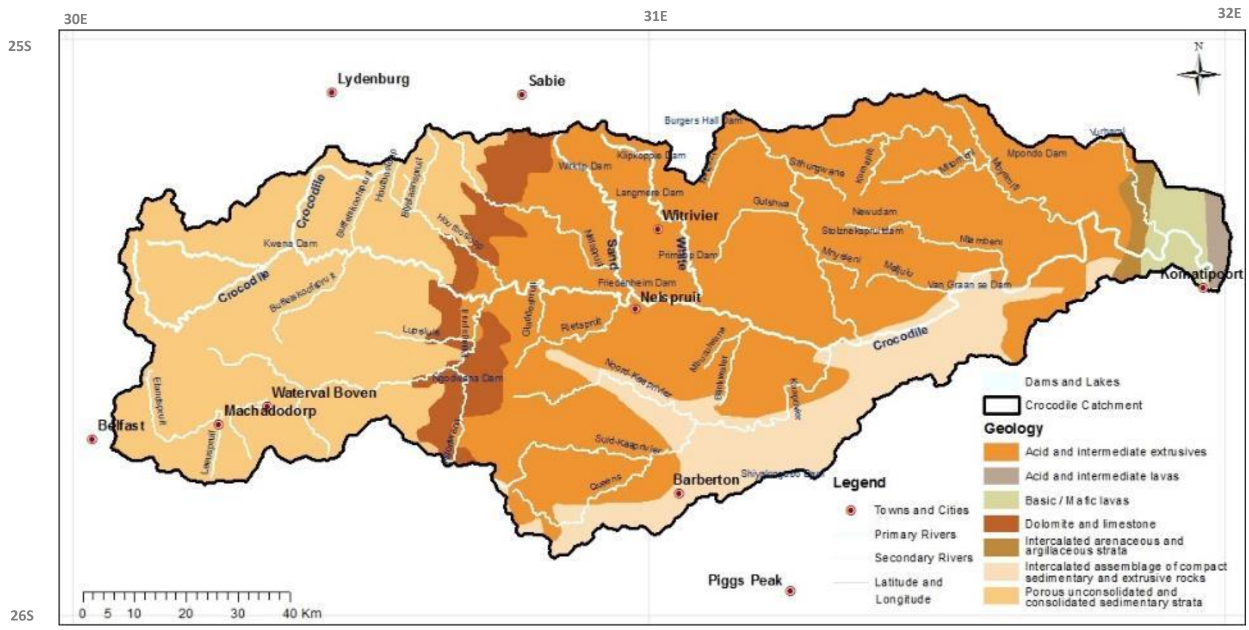


Figure 3.6: Geology of the Crocodile Catchment (Data Source: WRC, 2011)

It is characterized in the south by sedimentary rocks (such as arenite) and volcanic rocks (mainly lavas) of the Barberton sequence. In the west, it is composed of a complex mixture of sedimentary rocks (such as arenite and shale), volcanic (mainly andesite) and dolomitic rocks of the Transvaal sequence. In the east, it contains a very small area of sedimentary rocks (such as shale) and volcanic rocks (mainly basalt and rhyolite) of the Karoo sequence (Mussá *et al.*, 2015).

The wider Lowveld has developed as the younger overlying sediments have been eroded away, exposing the older granitic geology. The topography associated with the granite is thus typically gently undulating, which has had a concomitant effect on the type of drainage present in the area (SANRAL, 2012). The Kruger National Park contains rocks that represent the earliest parts of South Africa's geological history. Archaean rocks present in the KNP include both Archaean granitoid intrusions and Archaean greenstone belt fragments (Robb *et al.*, 2006).

3.2.3 Soil Typology

The catchment is characterised by plains with moderate slopes and highveld grasslands on deep red to yellow sandy soils, overlying granites, quartzites and basalts (CSIR, 2013). The soils are highly variable, ranging from moderately deep clayey loam in the west, to moderately deep sandy loam in the central areas and moderately deep clayey soils in the east (Okello *et al.*, 2015). Figure 3.7 illustrates that the dominant soil textures in the catchment, are sandy loam to loamy sand (LmSa-SaLm), sandy clay to clay (SaCl-Cl) and sandy clay loam (SaClLm). The type of soil in the river basin determines the saturation level of the riverbed because the soil type determines whether rainfall will infiltrate and impact the ability of vegetation to grow. (Water infiltrates sand quicker than loamy and clayey textures. Clayey textures have the lowest infiltration rate.) This will impact the characteristics of the river basin, such as the vegetation and anthropogenic factors.

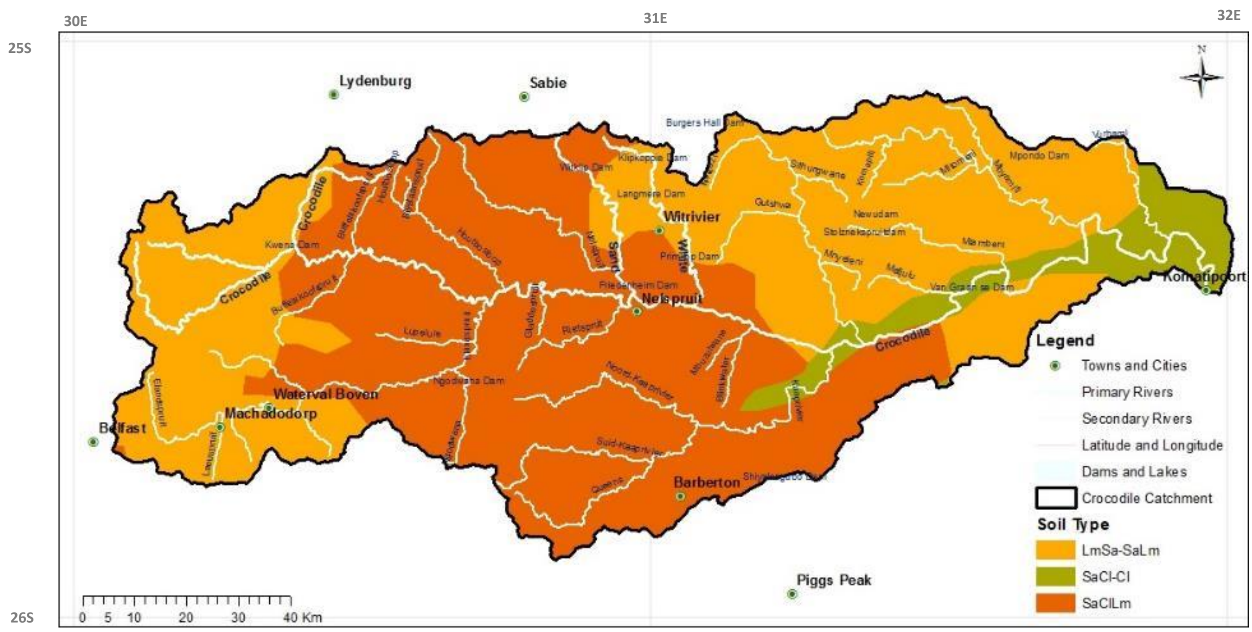


Figure 3.7: Soil Types in the Crocodile Catchment (Data Source: WRC, 2011)

3.2.4 Ecology

The natural ecology of the study area consists of savannah-type vegetation, i.e. very open woodland with a grassy understorey. Dense thickets and large trees occur along drainage lines, wetlands and rivers in the study area (SANRAL, 2012). There are 3 major biomes in the study area, grassland, savanna (bushveld) and forest (Figure 3.8). The grasslands are found predominantly on the higher altitude plateaus and slopes, and the bushveld is dominant in the lower plains. Patches of afromontane forest are found on the Drakensberg Escarpment - the western half of the catchment has the largest number of exotic plantations. The area below 250 m altitude falls within the typical Bushveld (Roux and Selepe, 2013).

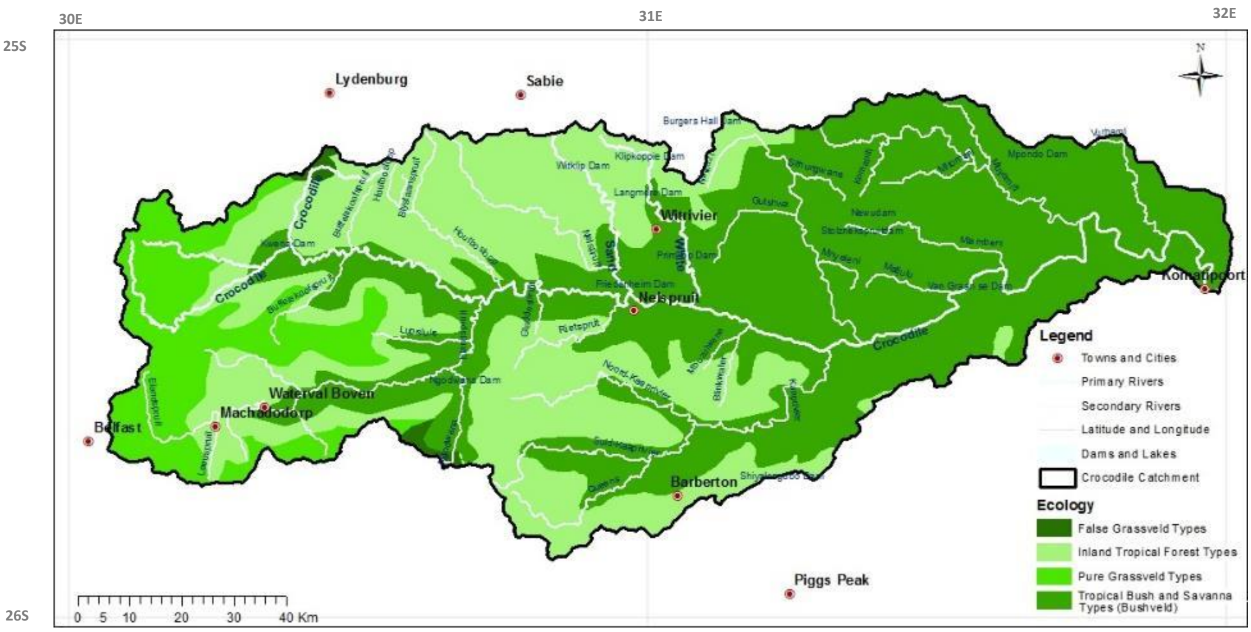


Figure 3.8: Ecology of the Crocodile Catchment (Data Source: WRC, 2011)

3.2.5 Land Cover and Land Use Typology

A large proportion of the study area has been modified or transformed from its natural condition (CSIR, 2001). The increase in modified areas results in changes in the relationship between land-use and environmental impacts. For example, an increase in urban areas results in an increase in surface runoff and consequently erosion and flooding, which is a result of the increase in high flows in localised areas. Therefore, the land cover types in the area, illustrated in Figure 3.9, will likely influence the possibility and magnitude of flooding.

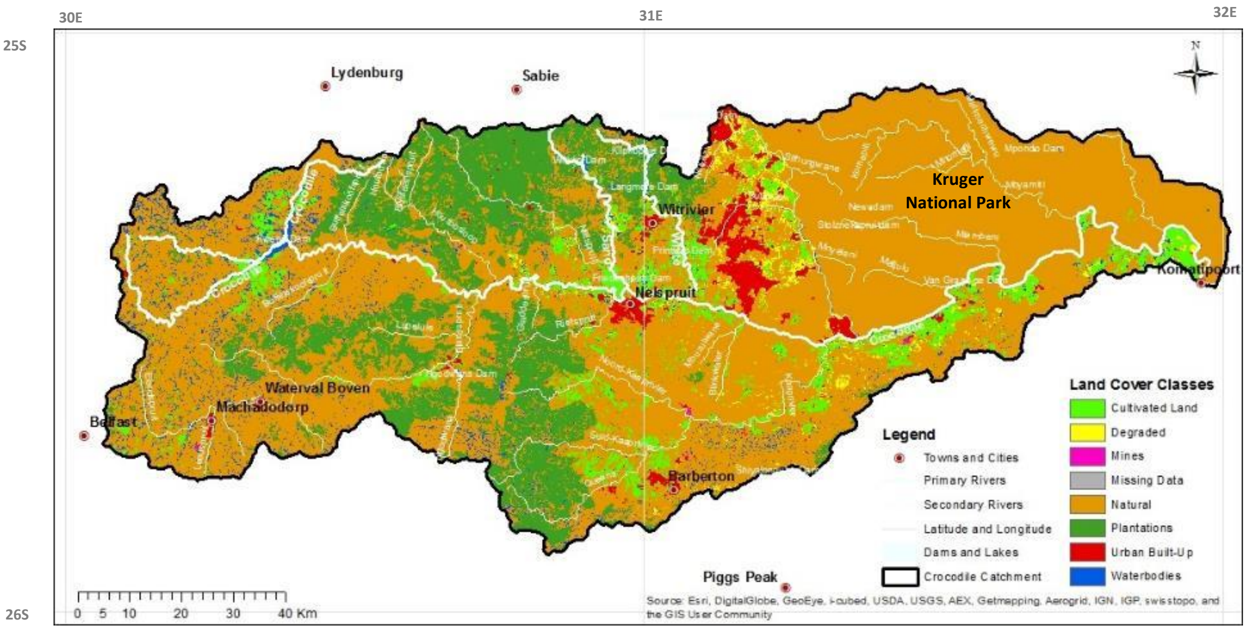


Figure 3.9: Land Cover Types in the Crocodile Catchment (Data Source: NLC, 2009)

The area is characterised by agriculture (pasture, dryland or irrigated cultivation), conservation areas and forestry, as well as mining and industrial activities (RHP, 2012). The Kaap River sub-catchment has been intensively mined (Heath, 1999). Commercial agriculture predominates, with much of the area in the vicinity of White River being utilised for the production of subtropical fruit, in particularly citrus, as well as sugarcane (SANRAL, 2012).

In certain areas, small compartments of commercial forestry occur (SANRAL, 2012). In the low-lying region, there are large conservation areas such as the internationally renowned Kruger National Park (CSIR, 2001). In addition, there are extensive areas of exotic afforestation in the upper and middle areas of the catchment (Heath, 1999).

3.2.6 Settlement Patterns

The area is largely rural, although there are a few towns, and urbanisation is rapid (RHP, 2012). The major settlement in the catchment is Nelspruit, although parts of the area to the north-west of Nelspruit have a low population density. Other ‘transformed’ parts of the study area include urban areas (residential, retail and light industrial as well as a newly-developed informal settlement component), with a number of transport links in the form of road and rail (SANRAL, 2012). Settlement patterns along the river basin are illustrated in Figure 3.10.

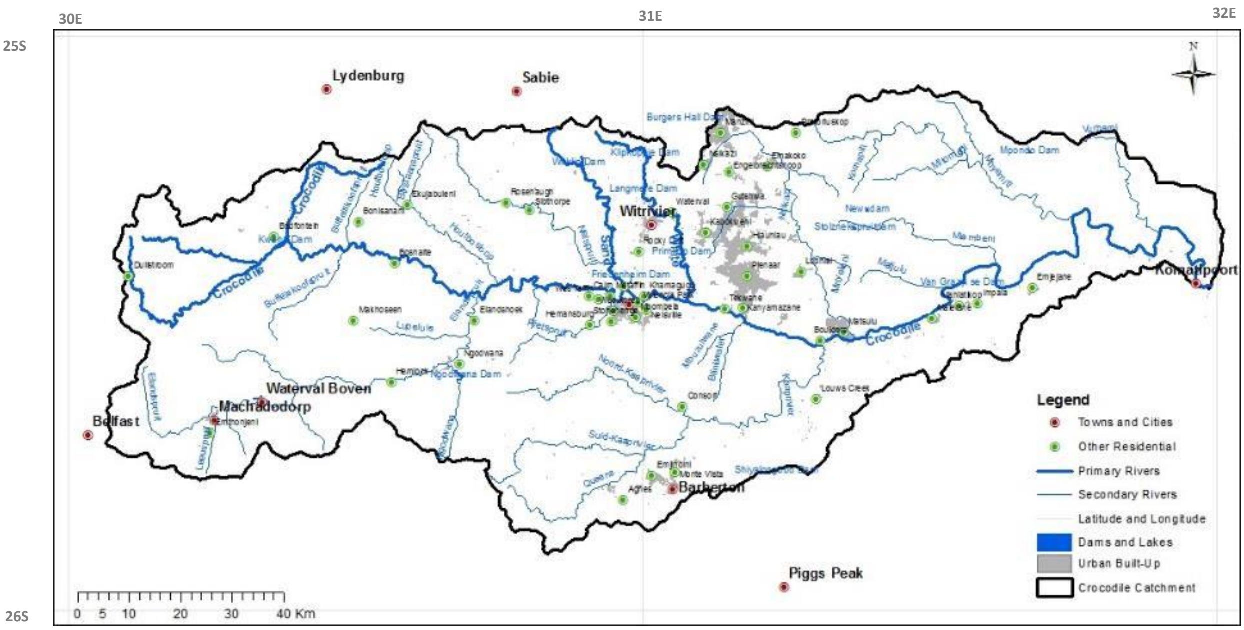


Figure 3.10: Settlement Patterns along the Crocodile Catchment (Data Source: NLC, 2009 and Google Imagery, 2014)

The Middle Crocodile River sub-catchment is impacted by intensive urbanisation around Nelspruit, aNyamazane and Matsulu (Heath, 1999). Approximately 1.5% of the study area is under urban development, although this is expanding rapidly. There are concerns about this in terms of loss of natural habitat and increased generation of pollution and waste (CSIR, 2001), leading to an increase in vulnerability to flood events.

3.3 Climatological Properties of the Study Area

3.3.1 Rainfall

There is a typical rainfall gradient between the escarpment and the lower lying areas, with rainfall decreasing as one moves eastward away from the escarpment into the Lowveld. The location of parts of the study area within the foothills of the escarpment means that these areas have a higher rainfall than other surrounding lower-lying areas (SANRAL, 2012). The region, therefore, has variable rainfall distribution due to the large variation in altitude and relief. The mean annual rainfall (i.e. precipitation) over the river basin is illustrated in Figure 3.11.

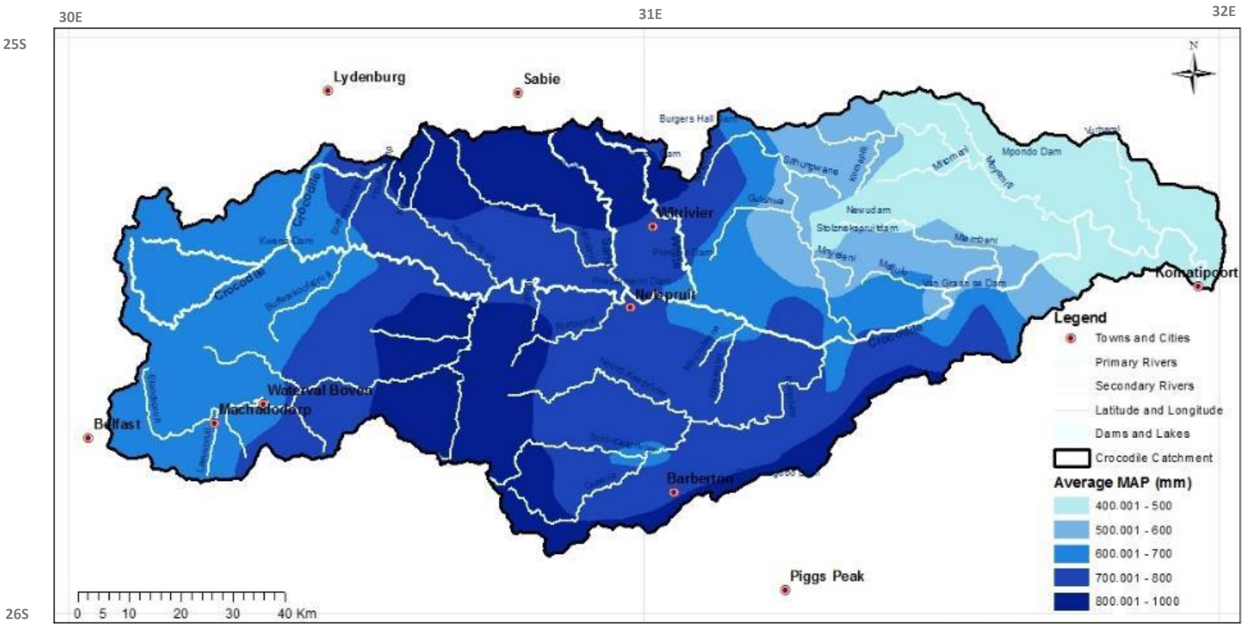


Figure 3.11: Mean Annual Precipitation (MAP) in the Crocodile Catchment (Data Source: WRC, 2011)

Rainfall is highly seasonal with rainfall predominantly occurring in the summer months (SANRAL, 2012). The Highveld region experiences high rainfall, which is mostly received in the form of summer storms (RHP, 2012) as peak rainfall months are December through January (DWAF, 2004). The mean annual rainfall for the southern part of the study area ranges between 775 and 795 mm per annum. To the higher-lying ground to the north, rainfall gradient increases to around 875 mm per annum (SANRAL, 2012). On the escarpment, the rainfall is generally higher (in excess of 600-1200 mm per annum), while the low-lying areas are drier (400-600 mm per annum) (RHP, 2012).

Inter-annual fluctuations in rainfall are large, however, and extremes of flooding and drought are not uncommon (RHP, 2012). High variability is also common seasonally, and high rainfall events that result in flooding are analysed further in Chapter 4.1. This high seasonality of precipitation has implications for the hydrology of the area, and means that river flows are typically much higher in the summer months (SANRAL, 2012).

3.3.2 Temperature

The Crocodile River Basin region has variable temperature due to the large variation in altitude and relief. The area typically experiences hot summer temperatures, whilst winters are generally mild with a low incidence of frost (SANRAL, 2012). The Highveld region is cool (10-18°C), while the escarpment varies from 10-12°C to 20-22°C (Figure 3.12). In the low-lying areas temperatures are generally warmer, with an annual average of 22°C (RHP, 2012). Maximum temperatures are experienced during the summer season in January, while minimum temperatures are experienced during the winter season in June.

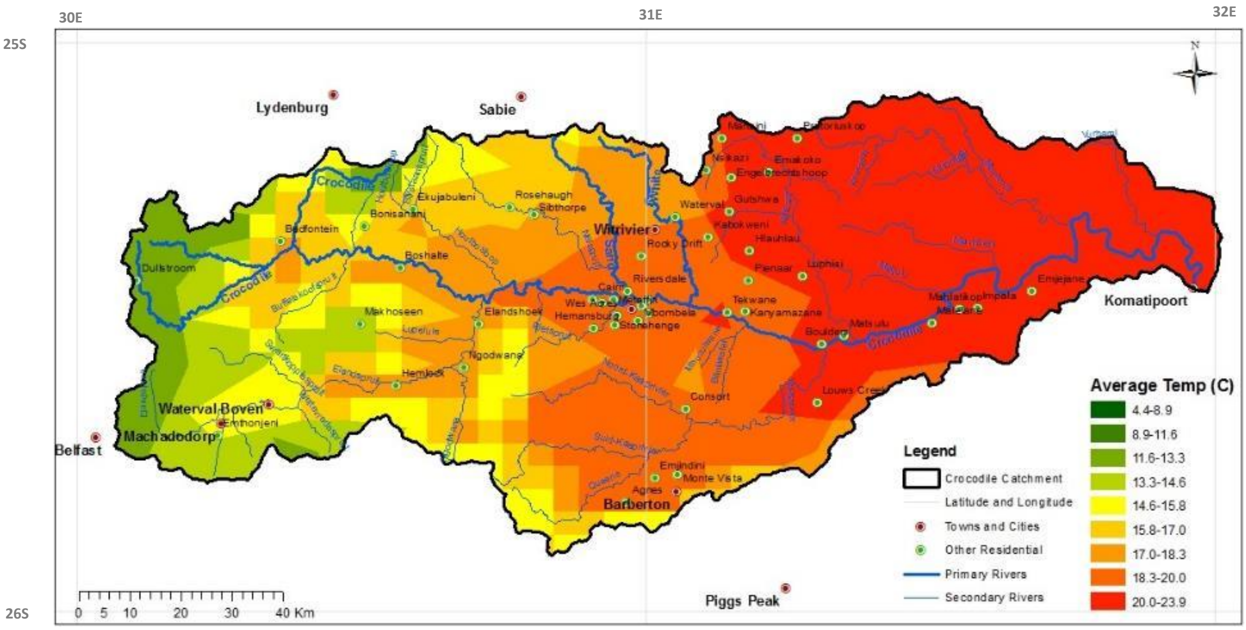


Figure 3.12: Average Temperature in the Crocodile Catchment (Data Source: ArcGIS Gallery, 2015)

Due to the high and dry temperatures of the region, evaporation is relatively high. Potential evaporation decreases from downstream (low altitudes) to upstream (high altitudes) (Mussá *et al.,* 2015). Average potential annual evaporation ranges from 1 600 mm in the south-west to 2 000 mm in the east. The highest evaporation occurs in January (approximately 203 mm) and the lowest in June (101 mm).

3.4 Hydrological Properties of the Study Area

The maximum of *usable surface water*, existing groundwater use and usable return flows that can be abstracted from the system (taking into account storage and natural runoff), is 859 million m^3/a (RHP, 2012). This is referred to as the estimated maximum yield, as defined in the NWRS (2004).

The Crocodile Catchment has a natural mean annual runoff (nMAR) of 1 200 million m^3/a. This is the *total flow* calculated for a specified period of time (i.e. 1 October to 30 September) in the catchment's natural state. The mean annual runoff (MAR) for each of the sub-catchments in the Crocodile Catchment, which is the *average flow* calculated for a specified period of time for a specified area, is illustrated in Figure 3.13.

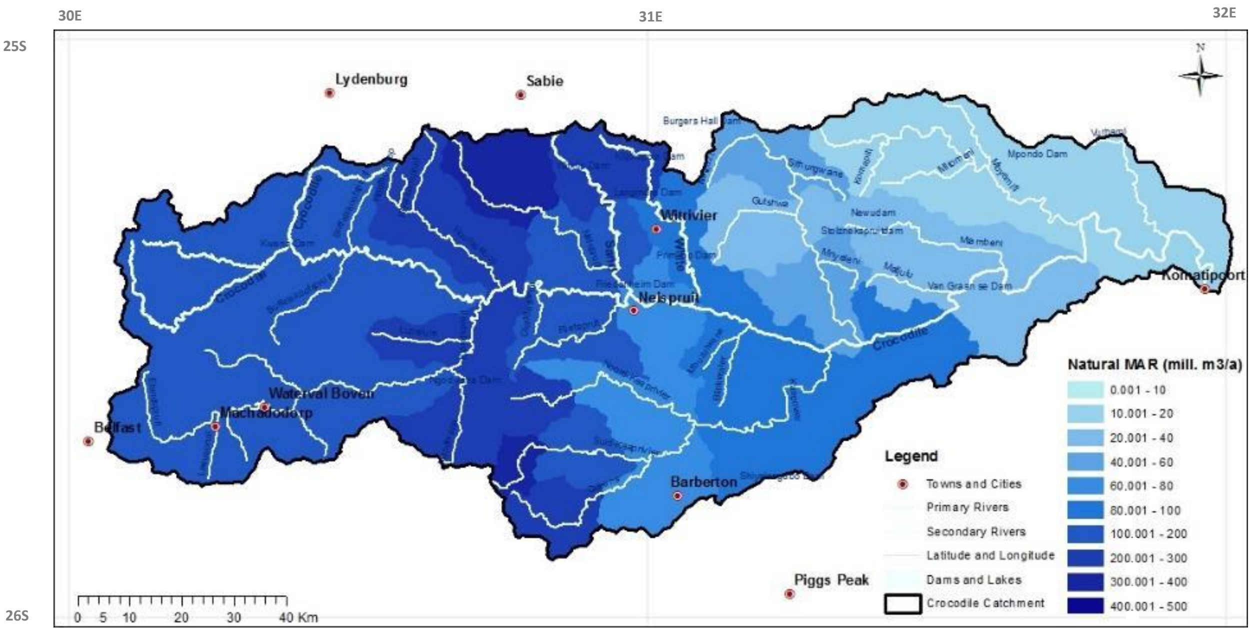


Figure 3.13: The Natural Mean Annual Runoff (million m^3/a) for the Sub-Catchments in the Crocodile Catchment (Data Source: WRC, 2011)

As illustrated in Figure 3.13, the MAR in the western and northern parts of the catchment varies between 200 and 500 million m^3/a, which can be attributed to the Kwena and Witklip Dams that regulate the flow. The eastern part of the catchment, where the Kruger National Park is located, has a MAR of less than 10 million m^3/a. This is mainly attributed to the forested areas, which reduce the runoff that would have flowed in the river under natural conditions.

3.5 Conclusions

While the Crocodile River catchment is characterized by a semi-arid climate, precipitation is highly seasonal. More than 80% of the annual rainfall falls during the summer half-year (October to March) and also varies over the catchment - it is higher in the middle parts and lower in the upstream and downstream regions (Mussá *et al.*, 2015). In addition, there is increasing development along the Crocodile River, including rural communities, urban areas, industries and agricultural changes. This may increase flood risk, as these natural and hydro-climatic characteristics create a possible flood hazard for the basin, which may result in flood-related impacts on settlements and industries, as well as on vegetation cover, fluvial and sediment systems). This relationship is investigated further in Chapters 5 to 8.

CHAPTER 4 - DATA ACQUISITION, ANALYSIS AND METHODOLOGY

4. DATA ACQUISITION, ANALYSIS AND METHODOLOGY

The availability of data determines the methodology and the flood parameters to be modelled in flood hazard mapping (Zimmermann, 2008). In order to perform flood modelling, the data requirements need to be determined and sourced. These data requirements include:

- Historical climate and hydrological data that describe the flood event,
- Topographic data that describe the topography of the study area,
- Land cover, land use and other spatial data that provide a spatial description of the river basin characteristics.

The data are required for hydraulic modelling to show flood parameters such as extent and depth. In addition, the accuracy of the data is important as it influences the accuracy and reliability of the resulting flood hazard maps.

4.1 Hydro-Climatic Data

4.1.1 Data Acquisition

The Department of Water and Sanitation (DWS) is the custodian of all hydrological data in South Africa, while the South African Weather Service (SAWS), the DWS, as well as agricultural organisations are custodians of meteorological data. However, as rainfall directly impacts the hydrological characteristics, namely water level and discharge (or flow) of a system, DWS also maintains meteorological data.

Monitoring information needs to be stored in an information system that is accessible and comprehensible to decision-makers and water managers (de la Harpe, 1998; Republic of South Africa, 1998). The Hydrological Services at DWS are responsible for providing hydrological data and information. Their Hydrological Information System (HIS) consists of various databases that include data on river stations, river flow and other related information. More than 800 gauging stations for river flow exist and each station has one or more monitoring points (DWA, 2009). This information system aims to provide various water role-players with information for research and development, planning, environmental impact assessments, determining water resource status, improving public safety, and disaster management (de la Harpe, 1998; Republic of South Africa, 1998).

The data for the relevant weather and gauging stations are contained on DWS's online HIS. Table 4.1 shows the weather stations in the Inkomati Water Management Area, while Table 4.2 shows the gauging stations. As several stations are currently non-operational, they have been excluded from this analysis. As stipulated above, the gauging stations record various hydrological data. For this research, the water level and discharge rates were deemed as the most suitable data entries, and the daily readings were downloaded from DWS's HIS. Table 4.1 and Table 4.2 also show the period for which there are available records for weather and gauging stations respectively.

Table 4.1: Weather Stations in the Inkomati WMA (Data obtained from DWS's HIS at www.dwaf.gov.za/hydrology/. Accessed: 31 May 2014)

Station No	Name	Daily Data Availability	
X1E003	Nooitgedacht Dam	02/08/1961	30/04/2014
X1E006	Vygeboom Dam	31/07/1970	01/04/2014
X1E007	Driekoppies Dam	06/11/2004	30/04/2014
X2E010	Witklip Dam	31/07/1970	30/04/2014
X2E013	Kwena Dam	02/12/1979	30/04/2014
X3E005	Inyaka Dam	31/07/2002	30/04/2014

Table 4.2: Gauging Stations along the Crocodile River (East) (Data obtained from DWS's HIS at www.dwaf.gov.za/hydrology/. Accessed: 31 May 2014)

Station No	Name	Daily Data Availability	
X2H006	Karino	02/10/1929	30/04/2014
X2H013	Montrose	21/01/1959	30/04/2014
X2H016	Tenbosch	24/08/1960	30/04/2014
X2H032	Weltevrede	15/09/1968	30/04/2014
X2H046	Riverside	04/09/1985	30/04/2014
X2H070	Badfontein	09/11/1979	30/04/2014

The weather and gauging stations provided in Table 4.1 and Table 4.2 were mapped in order to obtain a spatial perspective of their distribution. As the weather stations provided in Table 4.1 are for the Inkomati WMA, several of the stations (i.e. X1E003, X1E006, X1E007 and X3E005) fall outside of the Crocodile

Catchment and were thus excluded from the analysis. The weather and gauging stations that fall within the catchment are illustrated in Figure 4.1.

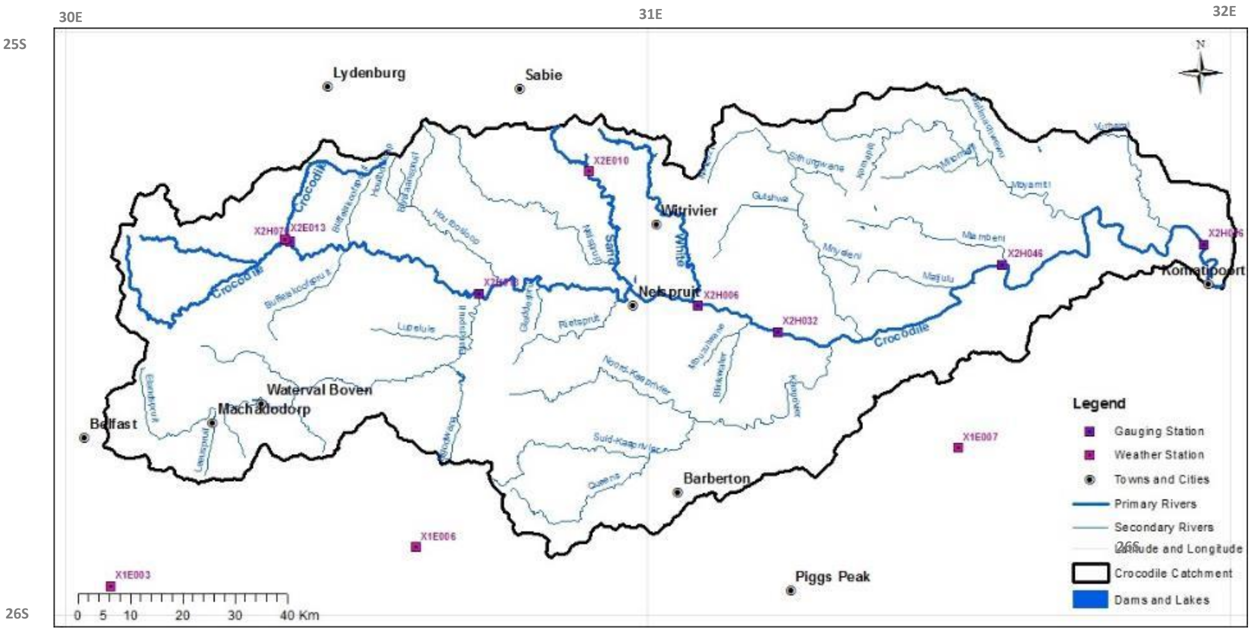


Figure 4.1: Weather and Gauging Stations in the Crocodile Catchment

The analysis of the weather and gauging stations is provided below. In addition, the discussion of which weather and gauging stations will be used for the remainder of this research and the reasoning behind the selection is also provided.

4.1.2 Data Analysis

As the accuracy of the flood modelling relies on the accuracy of the data, it was essential that the quality of the data was assessed. Table 4.3 provides an overview of the quality codes that are used by DWS to describe the quality of the data. Only the applicable quality codes (i.e. codes that are relevant for the data points for the weather and gauging stations in Table 4.1 and 4.2), and the associated descriptions, have been provided in Table 4.3.

Table 4.3*: *Description of Quality Codes for Data Entries (Data obtained from DWS's HIS at www.dwaf.gov.za/hydrology/. Accessed: 31 May 2014)

Quality Code	Description
Quality Code 1	Good continuous data
Quality Code 2	Good edited data
Quality Code 4	Unaudited

Quality Code 26	Audited Gauge Plate Readings / dip level readings
Quality Code 60	Above Rating
Quality Code 64	Audited Estimate
Quality Code 65	Unaudited Estimate
Quality Code 151	Data Missing
Quality Code 170	Permanent Gap

The quality codes show that codes 1 and 2 are the most desirable quality codes as they represent good, continuous and edited data. Codes 4 and 26 are less desirable as they represent unaudited data and gauge plate readings or dip level readings. Codes 60, 64 and 65 are undesirable as they represent data estimates. Codes 151 and 170 represent data gaps, and can therefore not be used for the analysis. Based on these quality codes, the quality of the data for each of the weather and gauging stations is shown in the Table 4.4 and Table 4.5 respectively.

Table 4.4: Analysis of All Data Records for Weather Stations (Data Range: 02 October 1929 – 10 April 2014)

Station No	Total Entries	Quality Code 1	Quality Code 4	Quality Code 26
X1E003	**3 560**	3 287	273	0
X1E006	**3 529**	2 800	729	0
X1E007	**3 438**	0	0	3 438
X2E010	**3 560**	3 135	425	0
X2E013	**3 560**	3 287	273	0
X3E005	**3 560**	3 287	273	0
TOTAL	**21 207**	**15 796**	**1 973**	**3 438**

Table 4.5: Analysis of All Water Level and Discharge Rate Data Records for Gauging Stations (Data Range: 02 October 1929 – 10 April 2014)

Station No	Total Entries	Quality Code 1	Quality Code 2	Quality Code 4	Quality Code 60	Quality Code 64	Quality Code 65	Quality Code 151	Quality Code 170
Water Level									
X2H006	**94 484**	84 909	81	9 494	0	0	0	0	0
X2H013	**65 491**	55 641	1 412	8 294	0	143	0	0	1
X2H016	**94 405**	78 641	2 556	6 613	0	0	6 593	0	2
X2H032	**67 133**	50 231	5	16 500	4	389	0	2	2
X2H046	**96 644**	84 693	785	11 160	0	0	0	3	3
X2H070	**96 469**	85 454	2 736	8 279	0	0	0	0	0
TOTAL	**514 626**	**439 569**	**7 575**	**60 340**	**4**	**532**	**6 593**	**5**	**8**
Discharge Rate									
X2H006	**94 483**	83 642	81	8 560	2 200	0	0	0	0
X2H013	**65 491**	55 641	1 412	8 294	0	143	0	0	1

X2H016	**94 405**	78 641	2 556	6 613	0	0	6 593	0	2
X2H032	**67 133**	50 231	5	16 500	4	389	0	2	2
X2H046	**96 644**	81 821	785	7 765	1 666	4 601	0	3	3
X2H070	**96 469**	85 433	2 736	8 279	21	0	0	0	0
TOTAL	**514 625**	**435 409**	**7 575**	**56 011**	**3 891**	**5 133**	**6 593**	**5**	**8**

Importantly, although data were available for more than 10 years for the gauging and weather stations, as discussed in Section 4.4 the limited written records of flood events on the river made it difficult to analyse previous floods events. Therefore, a more recent time period (i.e. August 2004 to April 2014) was selected to enable a comparison and analysis between flood records and the hydro-climatic data. The months of August to April were selected to coincide with the rainfall season (i.e. summer months), as discussed in Chapter 3.

The selection of the weather and gauging stations was based on the quality of the data, as well as the spatial distribution of the stations. A summary of the quality of the data (02 October 1929 to 10 April 2014) is provided in Table 4.6, while the spatial distribution is discussed below.

Table 4.6: Summary of the Data Quality of All Stations (Data Range: 02 October 1929 – 10 April 2014)

Station No	Good Quality		Average Quality		Poor Quality		Total Entries
	Total	%	Total	%	Total	%	
Weather Stations							
X2E010	3 560	100	0	0	0	0	3 560
X2E013	3 560	100	0	0	0	0	3 560
Gauging Stations (Water Level)							
X2H006	84 990	90	9 494	10	0	0	94 484
X2H013	57 053	87	8 294	13	144	0	65 491
X2H016	81 197	86	6 613	7	6 595	7	94 405
X2H032	50 236	75	16 500	25	397	1	67 133
X2H046	85 478	88	11 160	12	6	0	96 644
X2H070	88 190	91	8 279	9	0	0	96 469
Gauging Stations (Discharge Rate)							
X2H006	83 723	89	8 560	9	2 200	2	94 483
X2H013	57 053	87	8 294	13	144	0	65 491
X2H016	81 197	86	6 613	7	6 595	7	94 405
X2H032	50 236	75	16 500	25	397	1	67 133
X2H046	82 606	85	7 765	8	6 273	6	96 644
X2H070	88 169	91	8 279	9	21	0	96 469

The two weather stations, namely X2E010 (at Witklip Dam) and X2E013 (at Kwena Dam) have 100% of good quality data entries. The two weather stations are located relatively far apart, with Station X2E013 located in the western part of the catchment, and Station X2E010 located in the northern-central part (see Figure 4.2). As weather patterns of the entire catchment will influence the Crocodile River, both weather stations will be used for this dissertation.

The gauging stations do not all have good quality data entries. Station X2H006 (at Karino) and X2H070 (at Badfontein) have the highest number of good quality data entries for the water level (90% and 91% respectively) and discharge rate (89% and 91% respectively), while the X2H032 (at Weltevrede) has the lowest number (75% for both water level and discharge rate). Station X2H016 (at Tenbosch) has the highest number of poor quality data entries (7%) for both the water level and discharge rate.

As this research focuses on a segment of the Crocodile River (as discussed in Section 4.4.1), gauging stations that are located upstream of the segment. i.e. Station X2H013 (at Montrose), and along the segment, i.e. Station X2H006 (at Karino), were selected. The segment, weather and gauging stations that will be used for the remainder of this research are illustrated in Figure 4.2.

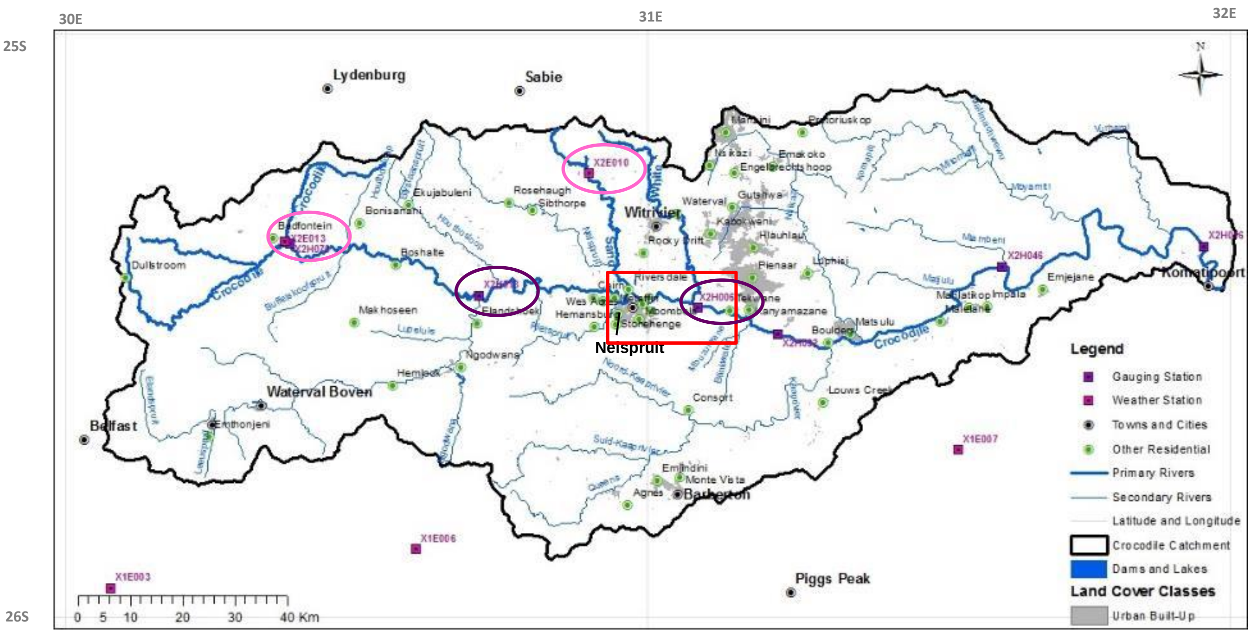


Figure 4.2: The Selected Segment (Red Rectangle), Weather (Pink Circles) and Gauging Stations (Purple Circles)

The X2E010 Weather Station

The daily rainfall at X2E010 weather station at Witklip Dam is illustrated in Figure 4.3. The figure illustrates that the highest daily rainfall event was 210 mm, which was experienced on the 17th of January 2012, and the second highest was 184 mm, which was experienced on the 3rd of February 2009.

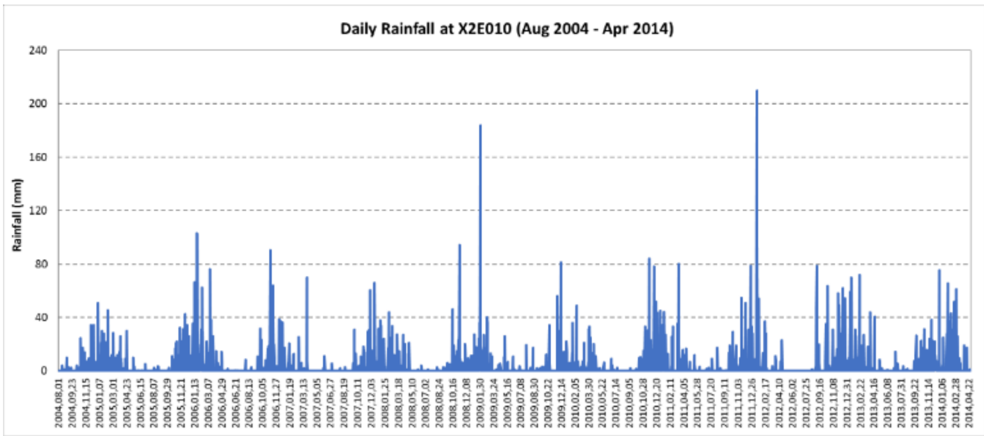


Figure 4.3: Daily Rainfall for the X2E010 Weather Station at Witklip Dam (1 Aug 2004 - 30 Apr 2014)

The X2E013 Weather Station

The daily rainfall at X2E013 weather station at Kwena Dam is illustrated in Figure 4.4. The figure illustrates that the highest daily rainfall event was 74 mm, which was experienced on the 28th of December 2013, and the second highest was 66.4 mm, which was experienced on the 4th of January 2010.

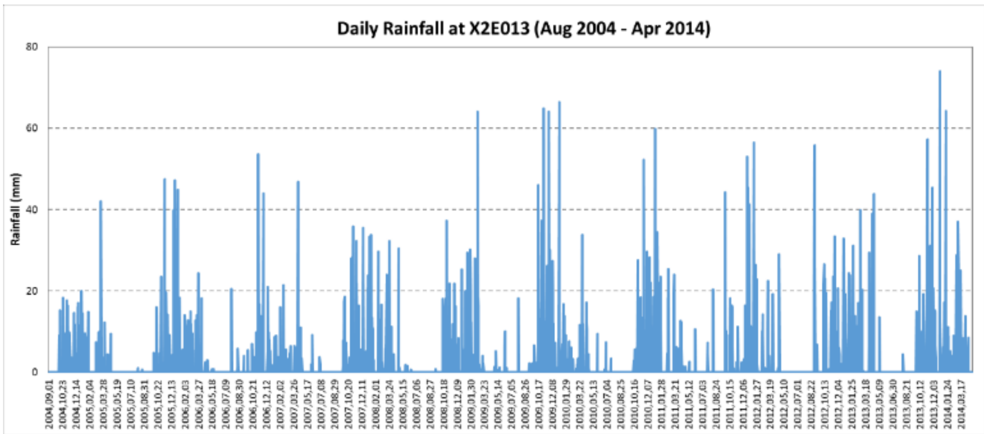


Figure 4.4: Daily Rainfall for the X2E013 Weather Station at Kwena Dam (1 Aug 2004 - 30 Apr 2014)

For both weather stations, seasonal variations in the rainfall patterns are evident, with rain falling during the spring and summer seasons and almost no rainfall in the winter and autumn seasons.

The X2H006 Gauging Station

The water levels at the X2H006 gauging station at Karino (circled in purple in Figure 4.2), are illustrated in Figure 4.5, while the discharge rates are illustrated in Figure 4.6.

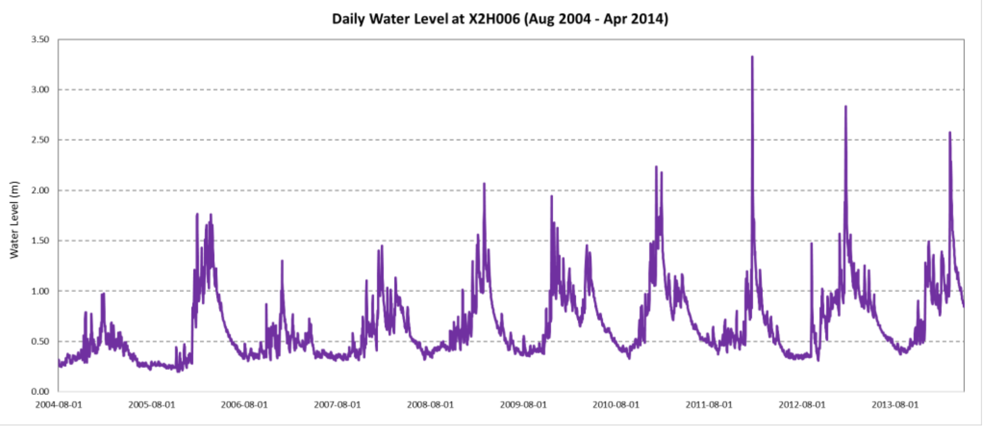


Figure 4.5: Daily Water Levels at the X2H006 Gauging Station at Karino (1 Aug 2004 - 30 Apr 2014)

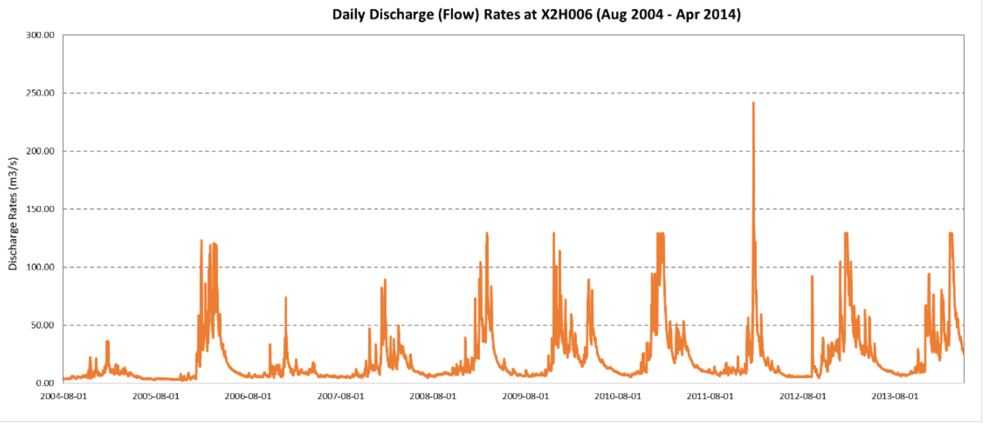


Figure 4.6: Discharge (Flow) Rates at the X2H006 Gauging Station at Karino (1 Aug 2004 - 30 Apr 2014)

The X2H013 Gauging Station

The water levels at the X2H013 gauging station at Montrose (circled in purple in Figure 4.2), are illustrated in Figure 4.7, while the discharge rates are illustrated in Figure 4.8.

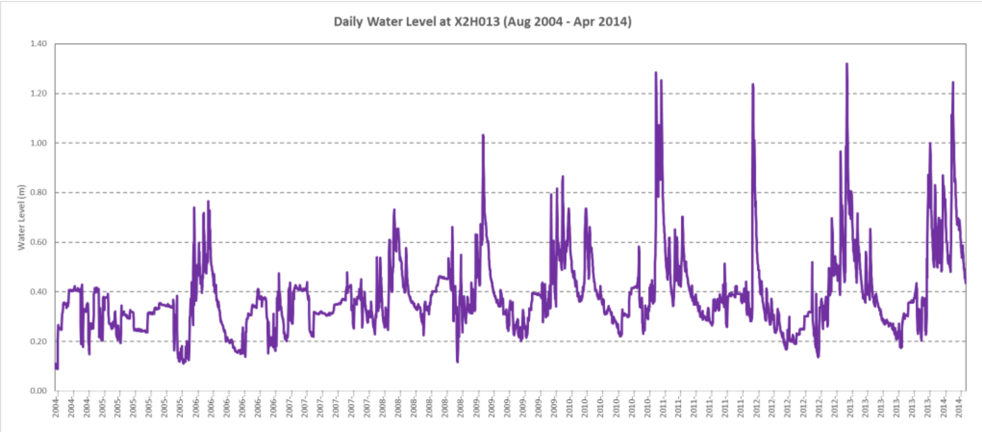


Figure 4.7: Daily Water Levels at the X2H013 Gauging Station at Montrose (1 Aug 2004 - 30 Apr 2014)

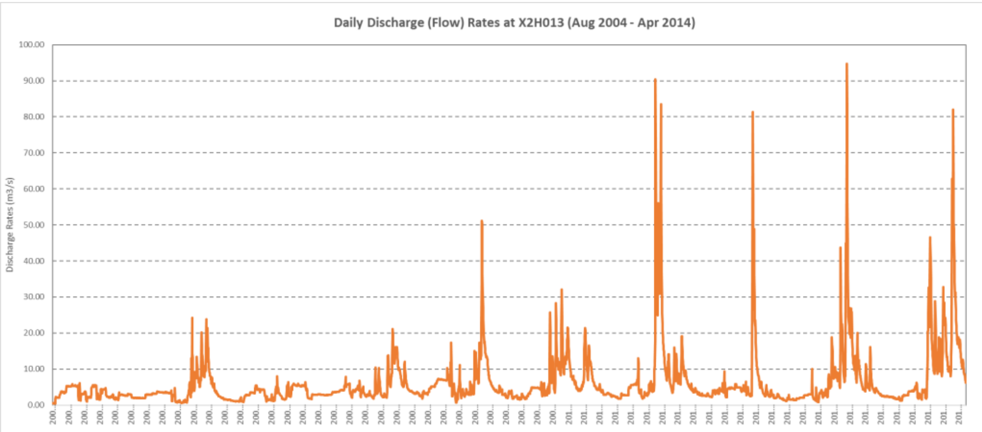


Figure 4.8: Discharge (Flow) Rates at the X2H013 Gauging Station at Montrose (1 Aug 2004 - 30 Apr 2014)

The water level and discharge series for both gauging stations exhibit significant variations although an annual cycle is evident (i.e. peaks during the spring-summer periods).

4.1.3 Data Processing

The hydro-climatic data were analysed through the use of the Microsoft Excel software package. This involved an analysis of the daily records, mean values, trends, and the development of scenarios (as discussed further in Chapter 6).

4.2 Topographical Data

4.2.1 Data Acquisition

Topographical data are required to describe a river and its surrounding area (Maidment, 2002; Martini and Loat, 2007). DEMs and contours are examples of data sources that can be used for topographical data.

In the past, expensive and time consuming ground surveys and photogrammetric data collection had to be done to collect topographic data for study areas (Heywood *et al.*, 2002). With the arrival of remote sensing, especially airborne laser altimetry (Marks and Bates, 2000) and interferometric synthetic aperture radar (SAR) (Maidment and Djokic, 2000; Smith, 2002), topographic data for flood modelling analysis can be easily obtained. In European countries, the collection of this high resolution data is done periodically (Hunter *et al.,* 2007). This is also the same for other developed countries such as those located in North America. The topographical data sources that exist in South Africa, are provided in Table 4.7.

Table 4.7: Topographical data sources in South Africa

Data Sources	Resolution or Interval	Coverage
Contours		
CD: NGI 1: 10 000 scale topographic mapping	5 m - 20 m interval	South Africa
CD: NGI 1: 50 000 scale topographic mapping	20 m interval	South Africa
DEMs Derived from Satellite Platforms		
LiDAR	1 m vertical resolution	Global
Worldview 1 & 2, GeoEye-1, Pleiades 1A/1B	1 m vertical resolution	Global
ASTER GDEM	2 m - 30 m resolution	Global
CD: NGI DEM	25 m - 50 m resolution	South Africa
SANSA	30 m resolution	South Africa
SRTM DEM	30 m - 90 m resolution	Global
GTOPO 30	1 km resolution	Global

There are several national and international topographical data sources that are available:

- The Chief Directorate: National Geo-spatial Information (CD: NGI) provides 5 m and 20 m interval contours for partial and national coverage respectively. DEMs are available from CD: NGI at 25 m and 50 m grid with partial coverage of South Africa and a vertical accuracy of 2.5 m (CD: NGI, 2011a).
- Light detection and ranging (LiDAR) offers DEMs at 1 m resolution with a vertical accuracy of 0.15 m to 0.25 m.
- The Worldview 1 and 2, GeoEye-1, and Pleiades 1A/1B satellites offer DEMs at 1 m resolution with a vertical accuracy of 0.5 m to 2 m. The data are available from the United States Geological Survey (USGS) website.
- The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global digital elevation model (GDEM) provides DEMs of 2 m up to 30 m resolution, with a vertical accuracy of up to 15 m. The data are available from the USGS website. (This dataset was used for this dissertation, as discussed in Section 4.2.2.)
- The South African National Space Agency (SANSA) provides DEMs at 30 m resolution, with a vertical accuracy of 5 m.
- The Shuttle Radar Topography Mission (SRTM) DEM has a 30 m to 90 m resolution, with a vertical accuracy of 10 m. The data are available from the USGS website.
- The Global 30 Arc-Second Elevation (GTOPO 30) is a global digital elevation model (DEM) that provides DEMs at 1 km resolution, with a vertical accuracy 30 m. The data are available from the USGS website.

The quality of the topographical data source is an important factor in the accuracy and reliability of the final flood hazard map (Martini and Loat, 2007; Sane and Huokuna, 2008; De Moel *et al.*, 2009), thus it is important to select the most suitable topographic data source. Martini and Loat (2007) recommends a 0.5 m vertical resolution and a 10x10 m (possibly even 5x5 m) horizontal resolution as minimum requirements for a DEM. Where contours are used to generate a DEM, the contours should at least be at 1 m vertical intervals (Martini and Loat, 2007).

4.2.2 Data Preparation

From Table 4.7 above, it is evident that very limited data at the required resolution are available for South Africa. Therefore, it will be essential to obtain data from international sources. The USGS website provides access to various DEMs. A search on this database provided two DEMs for the study area, ASTER Global DEM (GDEM) Version 2 and SRTM, which both provided 1 Arc-Second (30 x 30 m) grids. Both DEMs were downloaded and uploaded on the HEC-RAS software package. This enabled a comparison of the two models, and a selection of the most precise model. For this study, the ASTER DEMs provided the most precise representation of the study area. In addition, the file type was compatible with the software packages. The two ASTER DEMs that were downloaded for use are illustrated by the red squares in Figure 4.9.

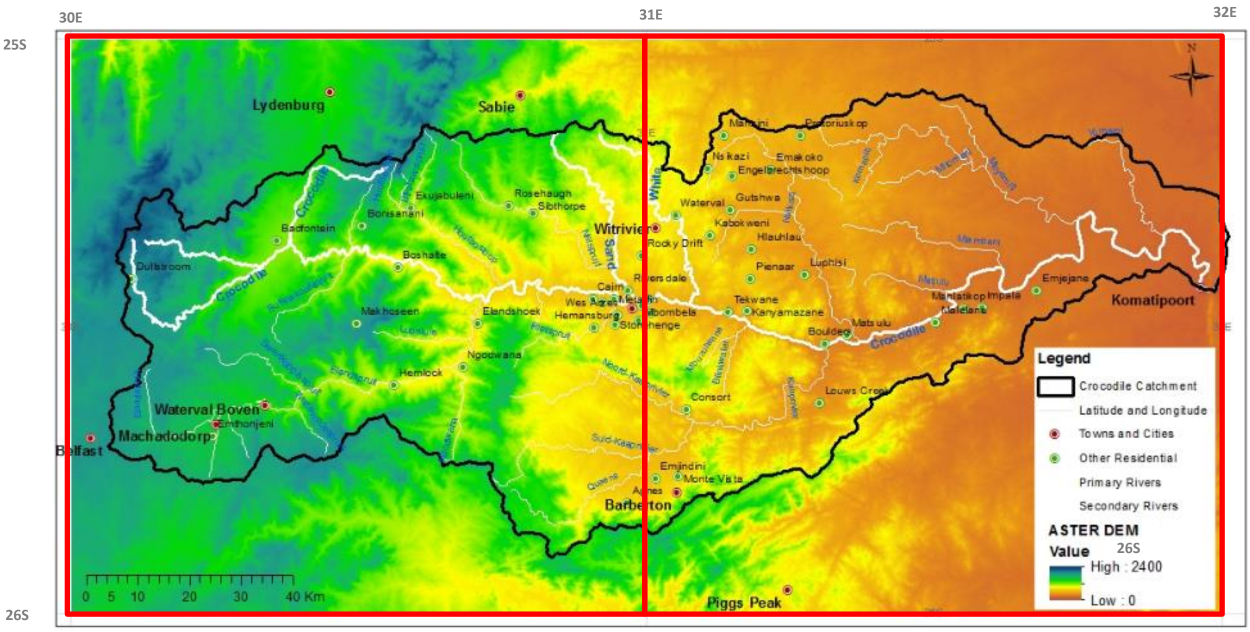


Figure 4.9: The Two ASTER DEMs (Red Squares) used for this Research (Data Source: USGS, 2014)

The two DEMs were used for hydraulic modelling. This enables the development of flood maps based on an accurate spatial representation of the topography. To enable this, the two DEMs where converted from raster to tin format as this is the format required for input into the hydraulic modelling software. The converted DEMs are illustrated by the red squares in Figure 4.10.

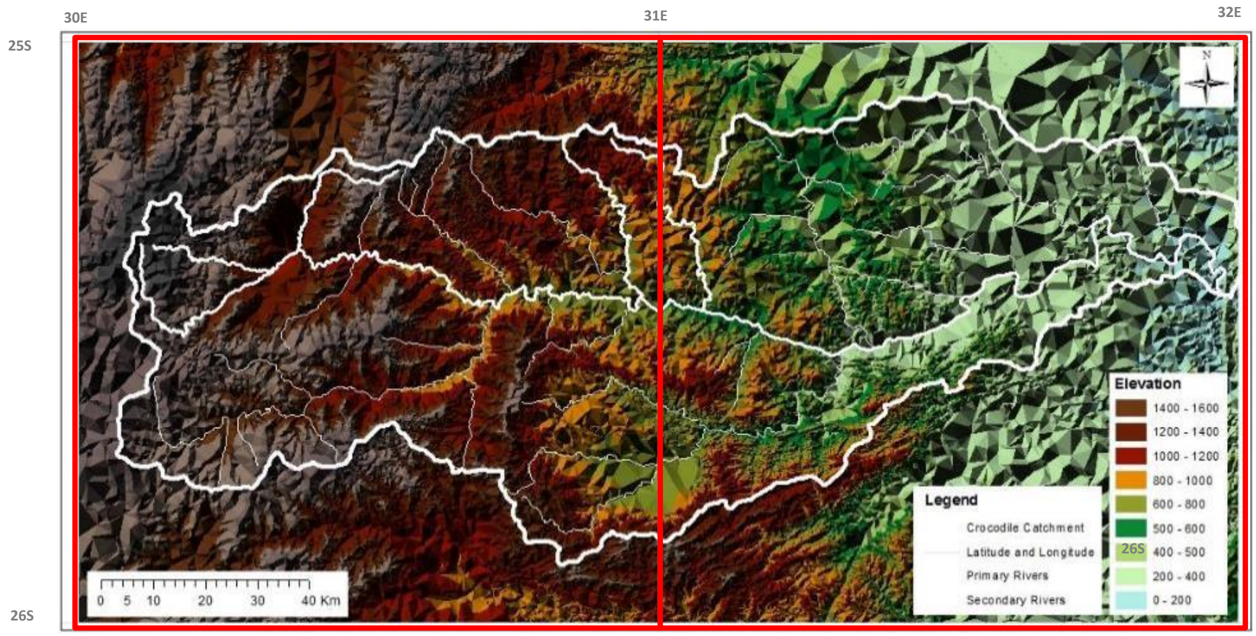


Figure 4.10: The Two Converted DEMs (Red Squares) used for this Research

4.2.3 Data Processing

There are various software packages that can be used for the modelling of flood events. As flood modelling has various processing requirements, a combination of software packages is often required. This includes flood modelling software, and spatial analysis software to prepare flood maps. A detailed explanation of flood modelling software packages is provided in Section 2.5.2, while an explanation of spatial analysis and flood mapping software packages is provided in Section 2.5.3.

The software packages that were be used for this research are the HEC-RAS 4.1.0 package for flood modelling, and ArcGIS 10.3.1 for spatial analysis and flood mapping.

- HEC-RAS is a dynamically coupled modelling environment that is used for modelling 2D flow. It can be utilised with numerous software packages that are produced by the US Army Corps of Engineers (i.e. RAS Mapper and HEC-GeoRAS), and thus combines the advantages offered by the individual packages. RAS Mapper offers 2D modelling capabilities, while HEC-GeoRAS allows the preparation of geometric data for import into

HEC-RAS and also enables processing of post-simulation results exported from HEC-RAS.

- ArcGIS is a collection of spatial analysis software that is produced by ESRI (e.g. ArcMap, ArcScene), and can thus be used for 3D analysis, geospatial data preparation and map creation. DEMs such as raw LiDAR data can be converted to a 3D layer by using the spatial analysis toolbox offered by the software package. In addition, the HEC-GeoRAS software package is loaded as an extension to ArcGIS, and is therefore accessed through the package.

4.3 Land Use and Land Cover Data

4.3.1 Data Acquisition

Land use refers to the human activity (e.g. industry, agriculture) associated with a specific land unit, while land cover refers to all natural features (e.g. vegetation (natural or planted), water, ice, bare rock) and anthropogenic features (e.g. buildings, roads) on the surface of the earth (Thompson, 1996). These two terms are often used interchangeably. However, in order to provide the comprehensive catchment characteristics, both sets of data need to be considered.

South Africa has four main land cover data sets available:

- The National Land Cover (NLC) 1994, was released in 1996 by the Council for Scientific and Industrial Research (CSIR). It is a manually digitised data set based on the Land Remote-Sensing Satellite (Landsat) Thematic Mapper (TM) satellite imagery collected from 1994 to 1996. This vector data set contains 31 land cover classes (Schoeman *et al.*, 2010).
- The National Land Cover (NLC) 2000 was released in 2005. It is based on the Landsat 7 Enhanced Thematic Mapper (ETM) satellite imagery for the period 2000 to 2001. This raster dataset contains 45 land cover classes (Schoeman *et al.*, 2010).
- The National Land Cover (NLC) 2009 and released during 2010. It was based on the merging of the NLC 2000 as a base layer with other more recent national land cover datasets that were developed by other state

organisations or parastatal institutions (SANBI, 2010). This raster dataset has a final classification of eight classes (SANBI, 2009).

- The Environmental Potential Atlas (ENPAT) was developed for the Department of Environmental Affairs (DEA) by the University of Pretoria in 2001. It provides land cover at a scale of 1:250 000, and was developed to provide guidance in decision-making regarding environmental impact assessments (ENPAT, 2001).

The NLC 2000 contains 45 classes and was carried out at a scale of 1:50 000 over the entire country. On the other hand, the NLC 2009 is the most recent dataset. However, the fact that the NLC 2009 only contain 8 classes does not make it suitable. Both of these datasets were downloaded and analysed, as this enabled an assessment of which dataset provided the most detailed representation of the catchment.

Other spatial information will also be required. This includes data and/or shapefiles showing vegetation, soil types, as well as spatial characteristics (including settlement patterns, land use types, administrative boundaries and socio-economic data). The data and/or shapefiles were obtained from various databases, such as the South African National Biodiversity Institute (SANBI), the Water Research Commission (WRC), ArcGIS Gallery and other online GIS databases. The Department of Water and Sanitation (DWS), Chief Directorate Surveys and Mapping (CDSM), National Geo-spatial Information (NGI), a component of Department of Rural Development and Land Reform (DRDLR).

Satellite imagery is used to capture the surface of the earth at a particular time, and can be classified into three categories according to their spatial resolution:

- low/medium resolution (30 m - 1 000 m);
- medium resolution (10 m - 30 m); and
- high resolution (0.1 m - 10 m) (Altan *et al.,* 2010).

There is a wide range of satellite imagery available for South Africa that is distributed by local and international custodians (as shown in Table 4.8). Table 4.8 also indicates the imagery that is used for this dissertation.

Table 4.8: Aerial and Satellite Imagery Available for South Africa. The imagery used for this dissertation is indicated in italics.

Name	Horizontal Resolution or Scale	Coverage
Aerial Photo		
CD: NGI Panchromatic (Pan)	1: 20 000 - 1: 150 000	South Africa
CD: NGI Colour	*1: 20 000 - 1: 30 000*	*South Africa*
Orthophotos		
CD: NGI Colour	*1: 10 000*	*South Africa*
Satellite Imagery (optical)		
WorldView-3 (2014 - to date)	0.31 m	Global
GeoEye-1 (2008 - to date)	0.46 m	Global
WorldView-1 and WorldView-2 (2007 - to date)	0.46 m	Global
Pleiades-1A and Pleiades-1B (2011 - to date)	0.5 m	Global
QuickBird (2001 - 2015)	0.65 m	Global
IKONOS (1999 - date)	0.82 m	Global
SkySat-1 and SkySat-1 (2013 - to date)	0.9 m	Global
SPOT-6 and SPOT-7 (2012 - to date)	1.5 m	Global
FORMOSAT-2 (2004 - 2015)	2 m	Global
ALOS (2006 - 2011)	2.5 m	Global
CARTOSAT-1 (2005 - to date)	2.5 m	Global
SPOT-5 (2002 - 2015)	2.5 m - 5 m	Global
RapidEye (2008 - to date)	5 m	Global
SPOT-1, SPOT-2, SPOT-3 and SPOT-4 (1986 - to date)	10 m	Global
Landsat-8 OLI (Operational Land Imager) (2013 - to date)	30 m	Global
Landsat-7 and Landsat-8 Enhanced Thematic Mapper Plus (ETM+) (1999 - to date)	15 m	Global
ASTER (1999 - to date)	*15 m*	*Global*
CBERS-2 and CBERS-CCD (2003 - to date)	20 m	Global
Landsat-4 and Landsat-5 - Landsat Thematic Mapper (TM) sensor (1982 - to date)	30 m	South Africa
Landsat 1-5 Multispectral Scanner (MSS) (1972 - to date)	60 m	South Africa
Terra (MODIS) (1999 - to date)	*250 m, 500 m, 1 km*	*Global*
NOAA AVHRR (1981 - to date)	1 km	Global

The type and scale of the flood hazard map will determine the geometric resolution of the imagery. For example, low resolution (250 m) Moderate Resolution Imaging Spectroradiometer (MODIS) images are used when the flood extent is large and mapped at a national scale (e.g. 1: 500 000) (Altan *et al.,* 2010). Medium resolution can be considered for monitoring food events at regional scales (e.g. 1: 25 000 to 1: 50 000), while high resolution is best suited for local applications (e.g. 1: 5 000 to 1: 25 000); both medium and high resolution imagery can be obtained from the

Chief Directorate: National Geo-spatial Information (CD: NGI). Therefore, a combination of MODIS and CD: NGI imagery will be used in this research.

A concern, however, is that high-resolution imagery is not captured daily. For example, the Landsat Thematic Mapper (TM) sensor, the Landsat Enhanced Thematic Mapper Plus (ETM+) sensor, as well as the Landsat 8 sensors collect images of the Earth with a 16-day repeat cycle. Therefore, depending on the day for which imagery is required, there is a possibility that no imagery will be available.

4.3.2 Data Analysis

Land use and land cover data, as well as any other relevant data and shapefiles, were downloaded from the relevant sources as discussed above. Through the use of the shapefiles and Google Imagery, the spatial characteristics of the area were identified and analysed. This enabled the selection of a segment for the dissertation, as discussed in Section 4.4.

An online search of satellite imagery from the CD: NGI and MODIS database was also conducted. In addition, the USGS website, which houses daily global satellite imagery was also searched. Challenges were however experienced with the available satellite imagery. This was mainly due to the fact that images for South Africa are not captured daily. Although several Landsat 7 ETM+ (30 m resolution) satellite images could be found, there were no clear images available for the day of the flood events (5 February 2009 or 19 January 2012). (The cloud cover on the days after the flood resulted in the images being unclear and unusable.) The high resolution images that were available were when the flood had already receded, and could therefore not be used to compare the flood distribution. In addition, the MODIS images that were available on the flood events were of a poor resolution, and could thus not be used to compare the flood distribution. Therefore, as no satellite imagery was found for the flood events, no data analysis was conducted.

4.3.3 Data Processing

ArcGIS is a powerful GIS software package that provides a variety of opportunities for spatial modelling and analysis, 3D visualization, and developer tools to enable high quality map production. Google Imagery also enabled a representation and identification of spatial characteristics. However, as no satellite imagery was found for the flood events, no data processing of satellite imagery was conducted.

4.4 Flood Mapping

4.4.1 Segment Identification

The methodology applied in this research was restricted by the available data (as discussed in Section 4.1 - 4.3). As discussed in Section 4.1, only a 30km segment of the Crocodile River was analysed through hydraulic modelling, and for which flood maps were created. Along the segment, two different types of locations were selected for detailed analysis, namely 1) Tekwane, a village located approximately 25 km East of Nelspruit, and 2) Riverside, a suburb situated in Nelspruit. The two locations are shown as squares in Figure 4.11, while the segment is the shown as a pink line.

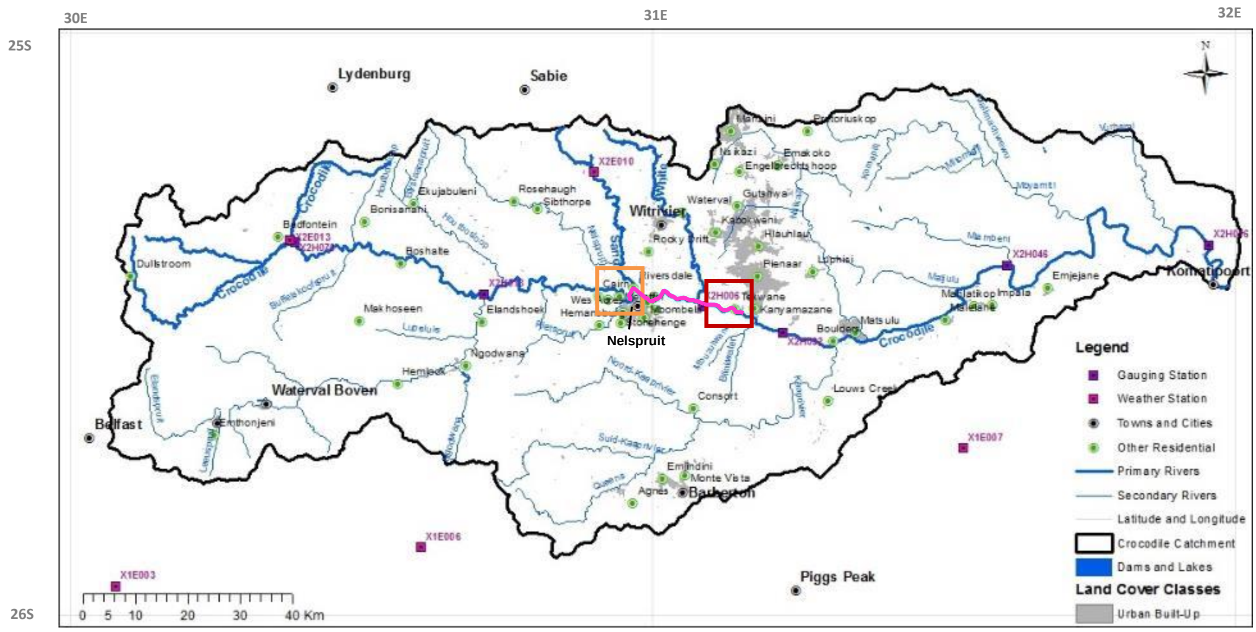


Figure 4.11: Location of Segment along the Crocodile River (Pink Line). The Red Square Indicates Tekwane and the Orange Square Indicates Riverside

The enlarged (large scale) map of the segment is shown in Figure 4.12, while the satellite image is shown in Figure 4.13.

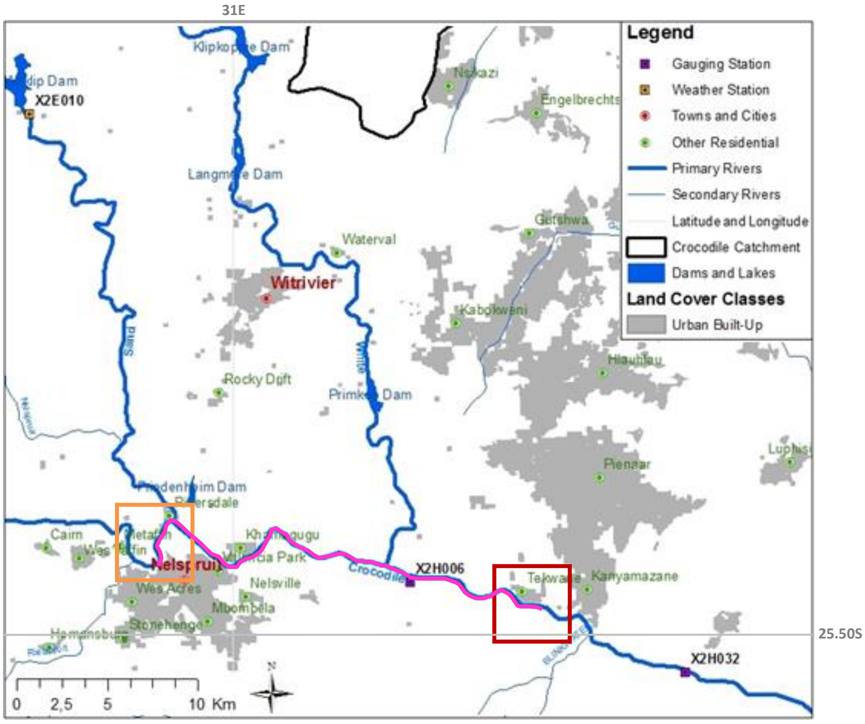


Figure 4.12: Location of the Selected Segment along the Crocodile River (Pink Line)

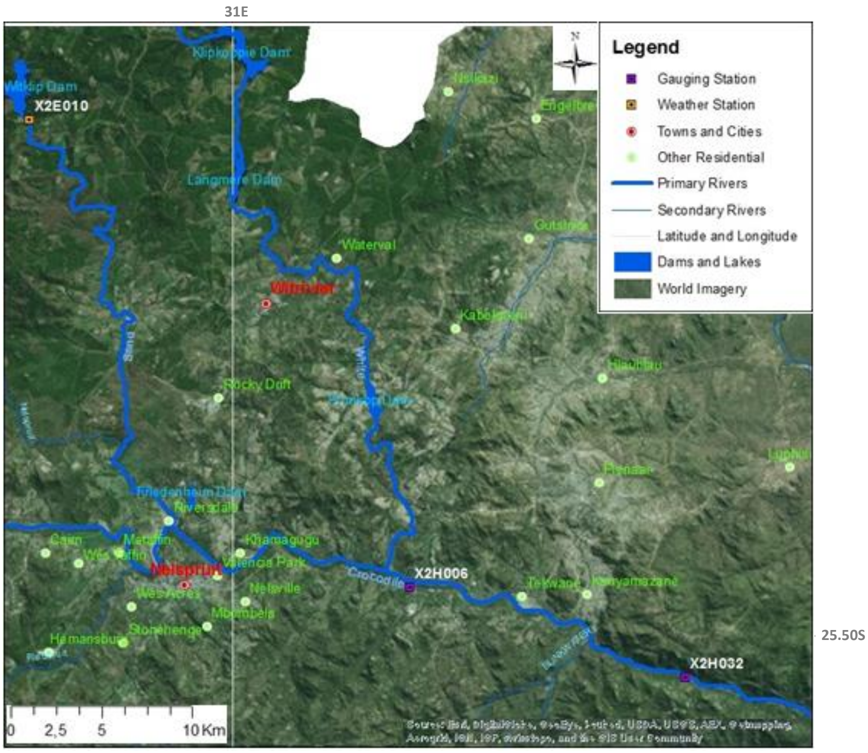


Figure 4.13: Satellite Map of the Selected Segment along the Crocodile River (Pink Line)

Close up Google Earth Imagery of the two locations, Tekwane and Riverside, are shown in Figure 4.14 and Figure 4.15. In addition, the longitudinal profile of the two locations are shown below the images. It should however be noted that the resolution provided by Google Earth Imagery is low and the elevations therefrom cannot therefore be used for quantitative analysis purposes.

Figure 4.14: Google Map Imagery and the Longitudinal Profile of Location 1 (Tekwane) along the Crocodile River

Figure 4.15: Google Map Imagery and the Longitudinal Profile of Location 2 (Riverside) along the Crocodile River

Tekwane is a rural population, while Riverside is urban and industrial. The relationships between elevation (as indicated in Figure 4.14 and 4.15), and the risk of flooding is investigated further in Chapters 7 and 8.

4.4.2 Historical Flood Map

In order to determine the flood events that have occurred in the previous decade (Aug 2004 - Apr 2014), it was essential to conduct a high level desktop research exercise. This included flood reports from the WRC, DWS and news reports. In addition, an online search of satellite imagery for the each of the identified flood event (as discussed in Section 4.2) was conducted. When historical flood data are used, images captured before and during the disaster are required to allow for proper identification of previously existing water levels for calibration and validation purposes (Altan *et al.,* 2010). The flood extent image should preferably be captured within 8 to 24 hours after the flood event has occurred (GMES, 2010).

Sources of historical data can include dated flood maps, water level records of rivers, gauge station records (for velocity), newspaper articles about past flood events, historical reports or books about flood events, and aerial and satellite photos (FEI, 2007; Martini and Loat, 2007). However, the capturing of data on hazard events, both spatially and non-spatially, is very limited in South Africa (Halloway *et al.,* 2010). In addition, flood maps and flood reports are often not produced for flood events (Sakulski, 2007). Therefore, to enable this research, details of historical events are mainly obtained from online news websites, newspaper articles and South African Weather Services (SAWS) reports.

4.4.3 Hydraulic Modelling Overview

An overview of the approach that was employed for the hydraulic modelling is illustrated in Figure 16. There are three main phases in flood modelling analysis, namely data preparation, hydraulic analysis, and post-processing.

- Data preparation involved GIS data development and generating the RAS import file. This was performed in ArcGIS with the HEC-GeoRAS extension.
- Hydraulic analysis involved utilising the GIS import file, running the hydraulic modelling using instrumental flow data, and generating the RAS

GIS export file. This was performed within HEC-RAS. An important input into this phase was flood scenarios with varying discharge rates. These scenarios are discussed in detail in Chapter 6.

- Post-processing involved using the RAS GIS export file, processing the results and creating flood maps. This was performed in ArcGIS with the RAS Mapper extension.

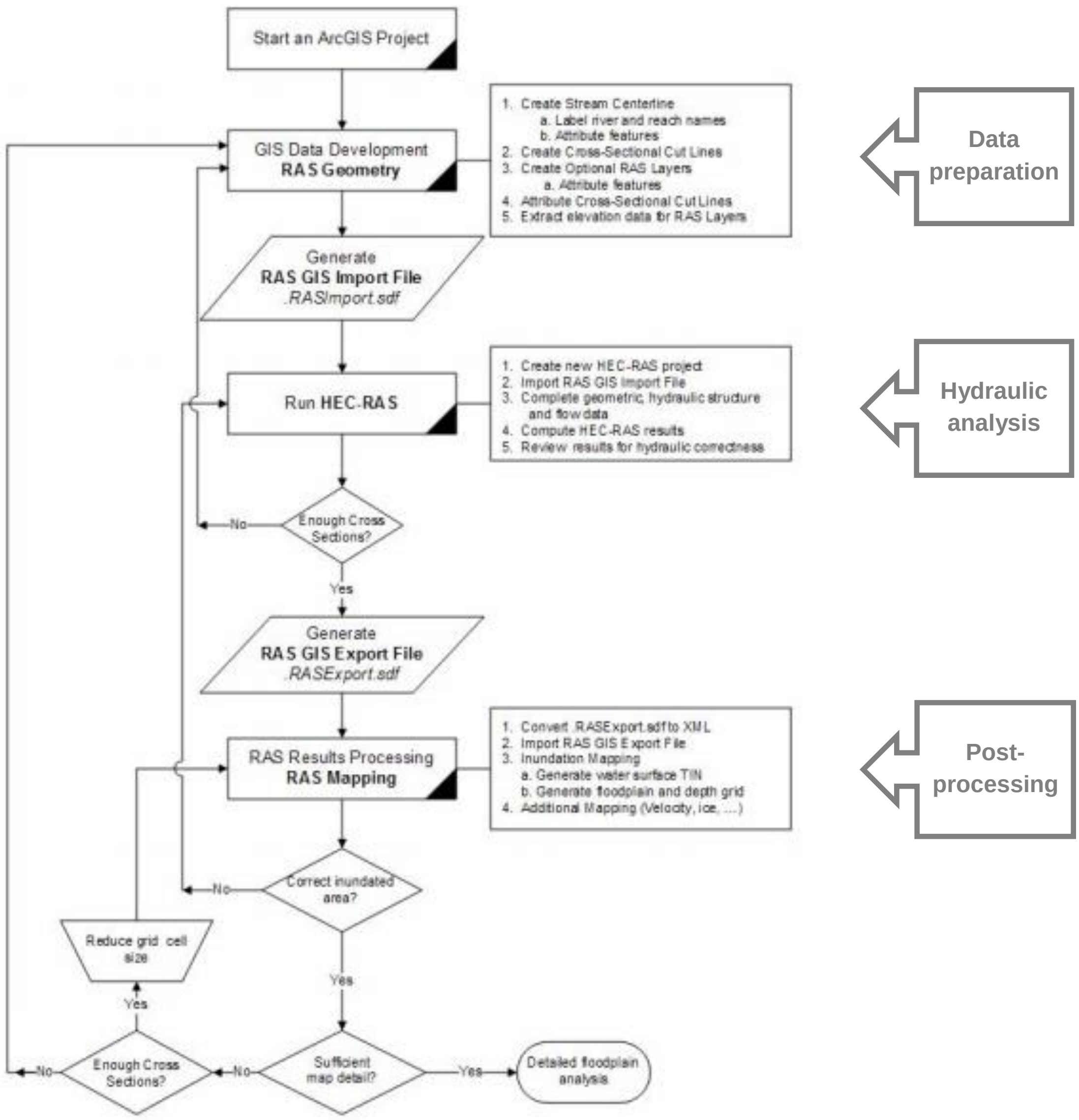


Figure 4.16: Process flow diagram for using ArcGIS, HEC-GeoRAS and HEC-RAS (Adapted from USACE, 2009)

Utilising the process illustrated in Figure 4.16, the flood events were modelled and the flood hazard maps for the two locations were then created. Layers of spatial features were added through ArcGIS, which allowed for the representation of areas on the flood maps. Useful guidance for using HEC-RAS and ArcGIS for hydraulic modelling and flood hazard mapping was provided by the HEC-RAS 4.1.0 River Analysis System User Manual (2010) and the HEC-GeoRAS User Manual (2009) developed by the US Army Corps of Engineers, as well as the Tutorial on Using HEC-GeoRAS 10.1 with ArcGIS 10.1 and HEC- RAS 4.1.0 for Flood Inundation Mapping in Steady and Unsteady Flow Conditions by Leon (2013). An overview of the hydraulic modelling process is provided in Appendix B.

4.5 Flood Risk Identification

4.5.1 Assessing Risk

The approach that was adopted for the flood risk assessment follows the approach developed by Gilard (1996), which is divided into the hazard component and the vulnerability component. However, as a detailed analysis of the social characteristics of the basin was not within the scope of this research, the vulnerability analysis only consists of a spatial vulnerability component. The results of these two analyses are then combined for the flood risk assessment (Gilard, 1996; Manadhar, 2010). This process is summarised in Figure 4.17 and Table 4.9.

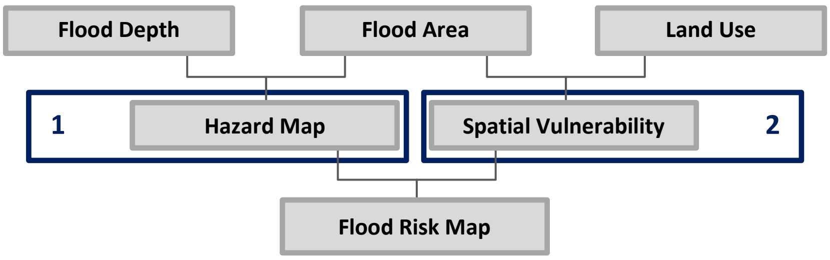


Figure 4.17*:* Approach for Conducting a Flood Risk Assessment, involving (1) a Hazard Component and, (2) a Vulnerability Component

Table 4.9: Approach for Conducting a Risk Assessment (Text adapted from: Gilard, 1996; Shrestha *et al.*, 2002; Manadhar, 2010)

STEP 1: Flood Hazard Analysis
The hazard aspect of the flood risk is related to the hydraulic and the hydrological parameters. This implies that the same flood will affect a particular area with the same hydraulic properties regardless of the land use. Hazard level may be defined by the parameters like flood extent, flood depth and exceedance probability of a particular flood magnitude. In this study, the hazard level is determined by reclassifying the flood grid polygons bounding the water surface for different discharge rates (as defined in Appendix B).

STEP 2: Flood (Spatial) Vulnerability Analysis
The flood (spatial) vulnerability is affected by the land use characteristics of the areas under the influence of flood. That is to say, a flood of the same exceedance probability will have different levels of vulnerability according to the land-use characteristics and potential for damage. This excludes social vulnerability, as a detailed analysis of the social characteristics of the basin was not within the scope of this research. The vulnerability analysis, therefore, consists of identifying the land use areas under the potential influence of a flood of particular discharge. For this, vulnerability maps are prepared by clipping the land use themes of the floodplains with the flood area polygons for each of the flood events being modelled. This depicts the vulnerability aspect of the flood risk in the particular area in terms of the presence or absence of flooding of a particular return period.
STEP 3: Flood Risk Analysis
The flood risk analysis includes the combination of the results of both the vulnerability analysis and the hazard analysis. This is defined by the relationship between the land use vulnerability classes and the flood extent hazard classes in a particular area. For this, the flood risk maps are prepared by overlaying the flood extent grids with the land use map. The flood extent polygons prepared during the hazard analysis are intersected with the land use vulnerability polygons. This hence depicts potential flood areas in terms of both the land use vulnerability classes and water extent. ArcGIS enables the identification of these classes by shading polygons red for a high risk area, orange for medium risk, and green for low risk (as defined in Section 8.1).

This process enables a spatial risk assessment for flood extent. Although the process is simple, it is deemed sufficient for this research. This is particularly important as this research has several analytical components.

4.5.2 Identification of Flood Risk Areas

The flood maps that were created for each of the identified flood events portrayed areas that were, or may be, impacted during flood events. Using ArcGIS, flood risk areas were identified on the flood maps. This was achieved through a risk rating system. Using the standard traffic light system, high risk areas are identified as red, medium risk areas are identified as orange, and low risk areas are identified as green) (as per Table 4.9. and Section 8.1). Therefore, the final output of the flood modelling exercise was numerous flood maps, showing high, medium and low risk areas along the Crocodile River basin.

4.6 Conclusions

This chapter provided an overview of the data used for this research, focusing on how the data were analysed and the various software packages utilised to enable this research. The outcome of the research, as well as the various challenges that were experienced during this research, are discussed further in Chapters 8 and 9.

CHAPTER 5 - HISTORIC FLOOD ASSESSMENT

5. HISTORIC FLOOD ASSESSMENT OF THE CROCODILE RIVER

5.1 Background

Despite the obligation imposed by the EU Floods Directive 2007/60/EC that the assessment and management of floods and flood risk should be based on a collection and assessment of information about previous flood events, in South Africa these records are often hard to find. The capturing of data on hazard events, both spatially and non-spatially, is very limited. Information can be derived from municipal and provincial reports, interviews and actual field research. However, it is constrained by protracted lag times between the occurrence of the events and the provision of funding for post-impact research. This has happened despite the recurrent and costly nature of many storms, and the fact that such studies are explicitly required by both national and provincial disaster management frameworks (Halloway *et al.*, 2010).

While the meteorological and hydrological conditions leading to floods are well documented and analysed, the spatial evolution of floods and the assessment of the impacts of floods are quite limited. Therefore, daily satellite imagery, South African Weather Services (SAWS) reports and news events are often relied on to determine the spatial distribution of floods and the impact of flood events, respectively.

The remainder of this chapter provides an overview of two previous flood events in the Crocodile catchment (i.e. February 2009 and January 2012). This includes an assessment of their meteorological and hydrological characteristics, and the flood news reports that give information on the extent and impacts of these floods.

5.2 Identified Flood Events

An online search of flood events revealed that several floods have been experienced in the Crocodile River over the past 10 years. This includes January

2006, February 2009, January 2011, January 2012 as well as January 2013. An analysis of the dataset in Section 4.1 indicated that the two highest rainfall events in the past decade were in February 2009 and January 2012. As stated above, flood events were also experienced during these two rainfall periods. These two events are particularly significant as they coincided with the highest river discharge, which resulted in significant flooding in the region. Therefore, these two flood events (i.e. February 2009 and January 2012) were investigated in more detail.

5.2.1 The February 2009 Flood

Figure 5.1 illustrates the total rainfall that was measured at the X2E010 and X2E013 weather stations over a 20-day period, from 26 January to 14 February 2009. The highest daily rainfall (i.e. 184 mm) was measured on 3 February at the X2E010 weather station.

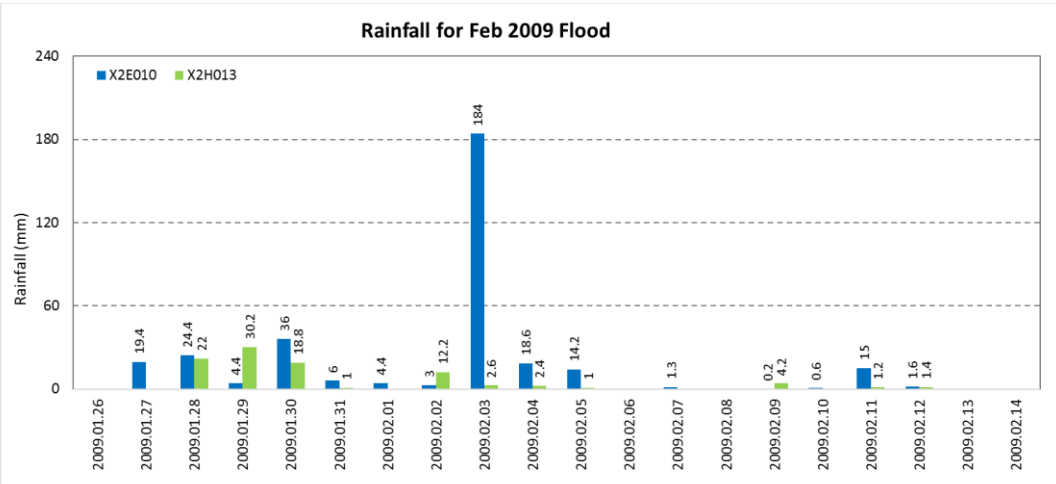


Figure 5.1: Daily rainfall during the February 2009 Flood (in mm)

Changes in the water level and discharge (flow rate) are shown in Figure 5.2. As evident from Figure 5.2, although lower values for water levels and discharge rates are observed at the X2H013 gauging station, similar trends can be observed for both stations. The water level and discharge (flow) rate at the X2H006 and X2H013 gauging stations were the highest on 31 January and on 5 February.

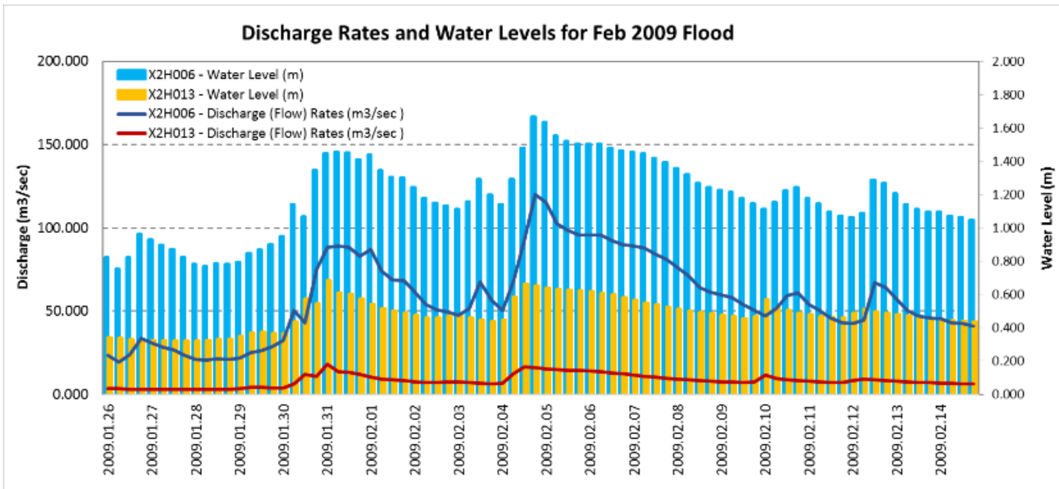
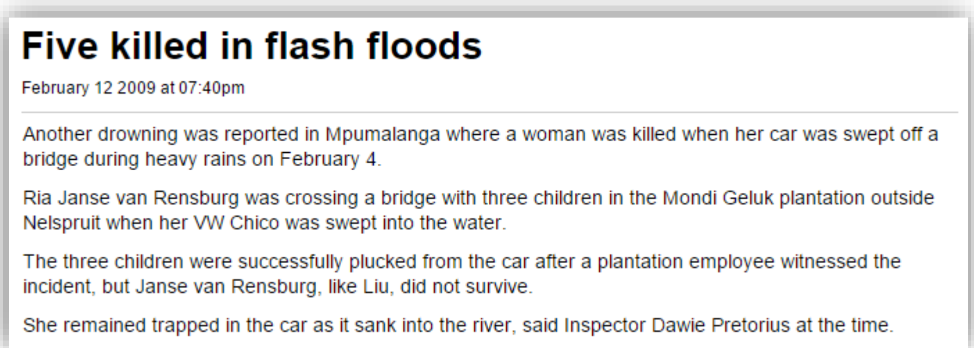


Figure 5.2*:* Discharge (flow) rates and water levels during the February 2009 flood

On 5 February 2009, the provincial government of Mpumalanga issued a flood alert for residents in low lying areas and next to flood lines. This was due to large amounts of rain falling over the preceding days, causing larger than usual surface runoff. Communities and road users were particularly warned to move to higher road, and to be careful as roads were wet, with surface water, and some areas experienced rocks falling on to the road. As can be seen from Figure 5.3, the flood caused extensive damage in the catchment resulting in death and extensive damage to infrastructure (causing outlying communities to be cut off for a number of days). Flood hazard maps for the February 2009 flood event are shown in Chapter 7.



Five killed in flash floods

February 12 2009 at 07:40pm

Another drowning was reported in Mpumalanga where a woman was killed when her car was swept off a bridge during heavy rains on February 4.

Ria Janse van Rensburg was crossing a bridge with three children in the Mondi Geluk plantation outside Nelspruit when her VW Chico was swept into the water.

The three children were successfully plucked from the car after a plantation employee witnessed the incident, but Janse van Rensburg, like Liu, did not survive.

She remained trapped in the car as it sank into the river, said Inspector Dawie Pretorius at the time.

Figure 5.3: Extract from a news report on the February 2009 flood (Source: ioL News, 2009)

5.2.2 The January 2012 Flood

Figure 5.4 illustrates the total rainfall that was measured at the X2E010 and X2E013 weather stations over a 20-day period, from 7 January 2012 to 26 January 2012. The highest daily rainfall (i.e. 210 mm) was measured on the 17 January at the X2E010 weather station. The changes in the water level and discharge (flow rate) are shown in Figure 5.5.

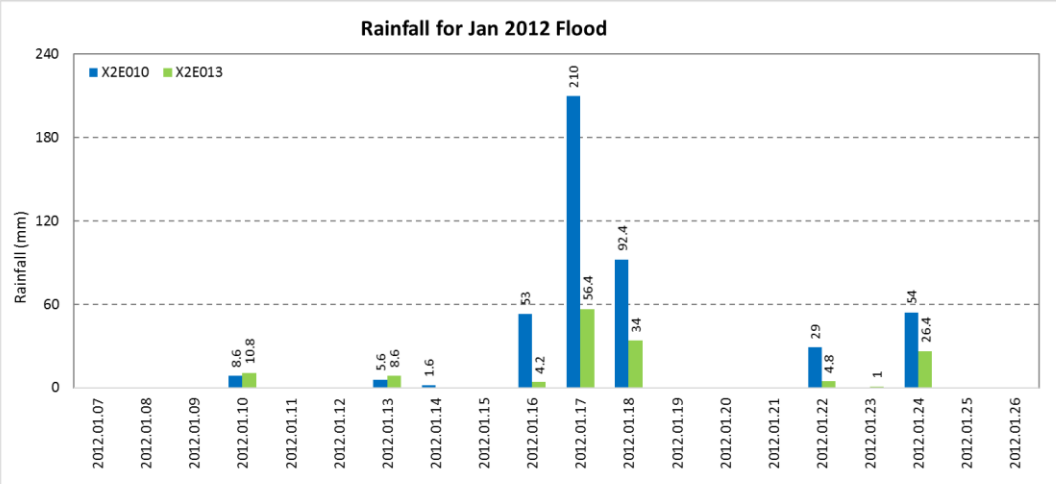


Figure 5.4: Daily rainfall during the January 2012 flood (in mm)

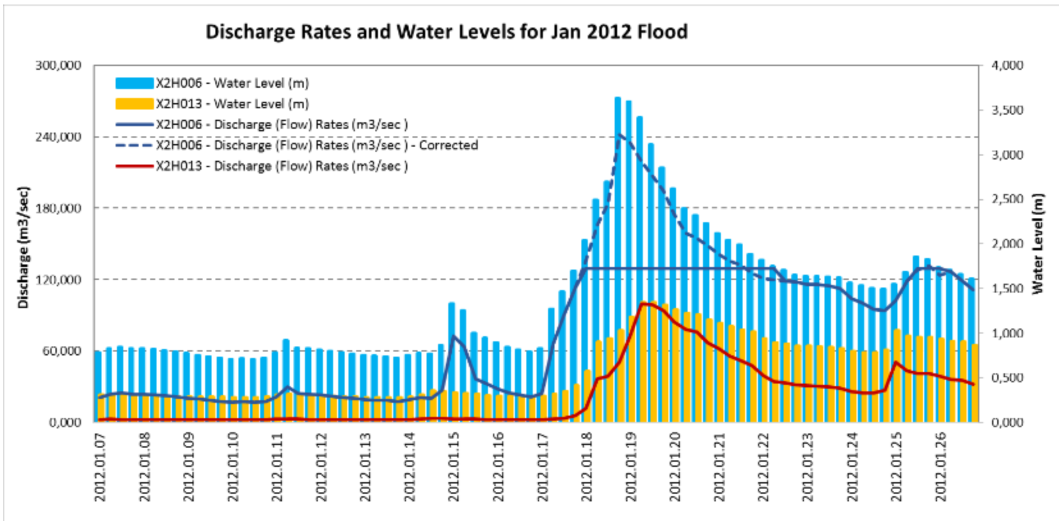


Figure 5.5*:* Discharge (flow) rates and water levels during the January 2012 flood

As evident from Figure 5.5, although lower values for water levels and discharge rates are observed at the X2H013 gauging stations, similar trends can be observed for both stations. The water levels and discharge (flow rate) at the X2H006 and X2H013 gauging stations were the highest on 17 January. Although the gauging station malfunctioned during the flood event (as shown by the straight blue line between 18 and 22 January), the study performed by the Kruger National Park (on Setting the Thresholds of Potential Concern for River Flow and Quality) estimates the discharge rate at high flow to vary between 225 m^3/s at Malelane to 255 m^3/s at Nkongoma (at an average of 240 m^3/s, as illustrated by the dotted line in Figure 5.5). Therefore, a peak rate of approximately 240 m^3/s can be estimated for the flood event.

On 19 January 2012, the Department of Water Affairs (through the provincial government of Mpumalanga) issued a flood alert for residents in low laying areas and next to flood lines. This was due to large amounts of rain falling over the preceding days, causing dams to spill over and larger than usual surface runoff at the Komati and Crocodile Rivers. Communities located in low lying areas were particularly warned to move to higher road, while some members of the population were evacuated to ensure their safety. An extract of the media release is shown in Figure 5.6.

January 19, 2012

MEDIA RELEASE

FLOODING IN MPUMALANGA AND DAM LEVELS UPDATE

The Department of Water Affairs is closely monitoring the situation in the Mpumalanga Province where heavy rains have caused wide spread flooding. A team from the Department has been deployed to the affected areas and is working with the local authorities and disaster management units to bring the situation under control.

The levels of the Komati and Crocodile Rivers have risen substantially but have not as yet broken their banks. The Driekoppies Dam is spilling, while Maguga Dam in Swaziland along Komati River is almost 100% full. Affected communities downstream of the dams are being warned to move to safety on higher ground. Some families were evacuated by local disaster management in conjunction with other government department.

Figure 5.6: Extract from a Media Briefing by the Department of Water Affairs on the January 2012 Flood (Source: Mpumalanga Provincial Gov., 2012)

The flood caused extensive damage in the region (as well as neighbouring catchment) resulting in death and extensive damage to infrastructure, and causing outlying communities to be cut off for a number of days. Damage was particularly severe in downstream areas, and at the Kruger National Park, resulting in road closures and restricted access to the National Park. Figure 5.7 illustrates some the areas that were inundated during the January 2012 flood event. Flood hazard maps for the January 2012 flood event are shown in Chapter 7.

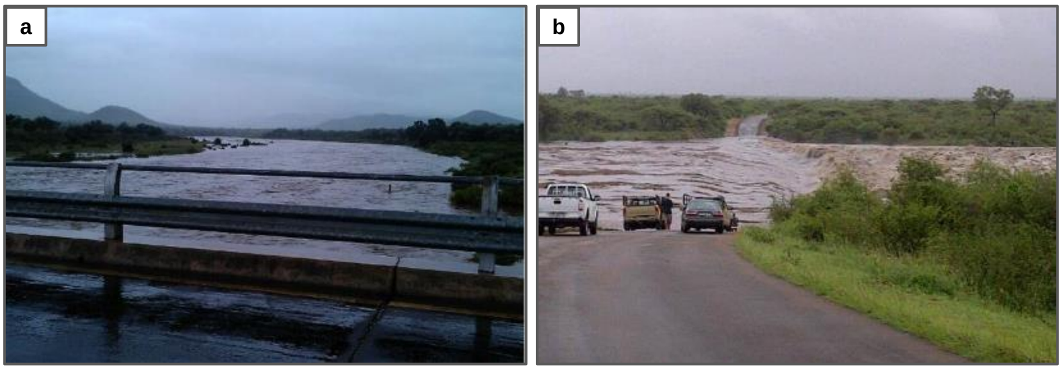


Figure 5.7: Images of the January 2012 Flood: a) Crocodile River at Malelane Gate; b) Crocodile Bridge Gate (Source: SAGR Forum, 2012)

5.3 Conclusions

This chapter provided an overview of two previous flood events in the Crocodile catchment, namely the February 2009 and January 2012 events. This included an assessment of the meteorological and hydrological characteristics, research on flood reports and news reports published. It is, however, unfortunate that public flood reports for the selected flood events from state institutions (e.g. DWS, WRC, or Disaster Management Institutions) were not available. Therefore, the analysis provided above is only based on news reports and press releases from the Mpumalanga provincial department. Details such as the total number of deaths, the total damage to infrastructure or the economic losses as a result of the flood were largely not available.

An overview of previous flood events provides a useful starting point in predicting future flood events, which is conducted in Chapter 6. Spatial representation of the flood events is provided in Chapter 7.

CHAPTER 6 - DETERMINING FUTURE FLOOD EVENTS

6. DETERMINING FUTURE FLOOD EVENTS FOR THE CROCODILE RIVER

6.1 Estimating Future Rainfall Events

According to Ampitiyawatta and Guo (2009), precipitation is a good long-term indicator of changes that may impact on water resources. Furthermore, changes in precipitation patterns are very important for water resource managers who deal with water resource planning and management (Odiyo *et al.*, 2015).

Several studies, such as Hewitson and Crane (2006), Engelbrecht *et al.* (2009) and Schultz (2011), have been undertaken on rainfall changes in South Africa, including in the Mpumalanga Province. As illustrated in Section 2.6, in the north-eastern region of the country, which includes the Gauteng, Limpopo and Mpumalanga provinces, an increase in overall rainfall is projected. Under future climate change scenarios, rainfall is expected to increase by between 85 and 303 mm per annum for the region as a whole, and is expected to range from 301 mm to 758 mm per annum by 2100 (CSIR, 2010). This equates to an increase in rainfall of between 20% and 40% by 2100.

The majority of the increased rainfall that is projected is expected to fall during the summer months, namely December, January and February (DJF) (CSIR, 2010). An extension of the rain season may occur in early spring with an increase in rainfall predicted between September to November. The number of rain events is expected to increase, which could infer that the chances of floods may increase based on wetter antecedent conditions (CSIR, 2010).

6.2 Estimating Runoff during High Rainfall Events

The Long-term Adaptation Scenarios (LTAS) Study conducted by the Department of Environmental Affairs (DEA) and the South African National Biodiversity Institute (SANBI) (2013) provided an estimate of the projected changes in catchment runoff. These runoff projections are illustrated in Figure 6.1.

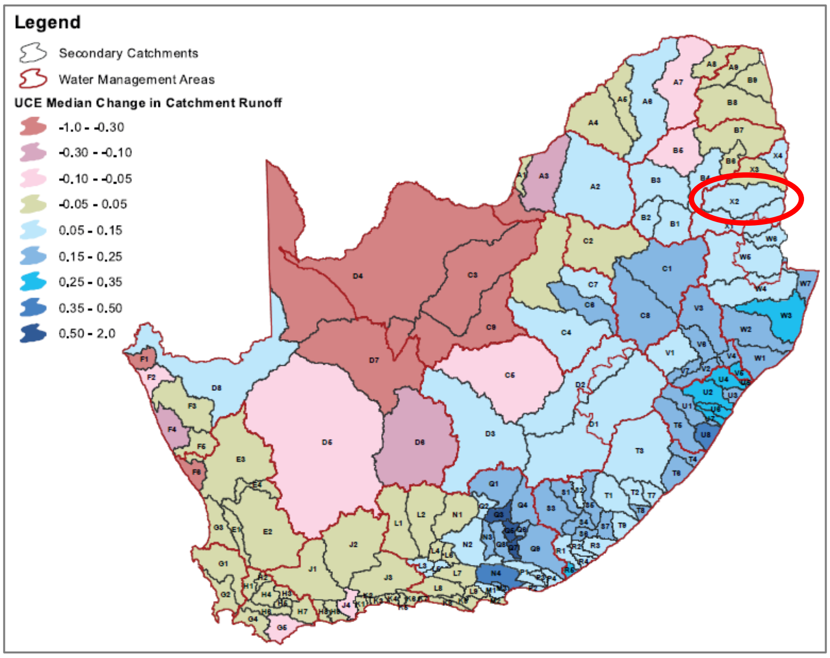


Figure 6.1: Median impact of climate change on the average annual catchment runoff for the period 2040–2050. The Crocodile (East) catchment is circled in red (Source: DEA, 2013)

The estimates suggest that, for the Crocodile (East) catchment (i.e. red circle in Figure 6.1), an increase of 5% to 15% in annual catchment runoff is projected. The Mpumalanga Province is also noted to show the highest risks of extreme runoff related events, together with KwaZulu-Natal and the Eastern Cape. It should however be noted that these projections are annual averages, and may not be applicable at the sub-daily or daily time interval of a flood occurrence.

In order to estimate the rainfall events for this study, two scenarios were selected. Section 6.1 estimates an increase in rainfall of between 20% and 40%. However, as stated in Appendix A, which provides background context to the rainfall-runoff relationship, only a portion of the rainfall is converted to runoff (i.e. the runoff coefficient). According to the Food and Agriculture Organization (FAO), the runoff coefficient (K), can be represented mathematically as:

$$K = Runoff/Rainfall \qquad \text{[Equation 1]}$$

Therefore, to estimate runoff when rainfall and the runoff coefficient (K) is available, the following equation can be used:

$$Runoff = K \times Rainfall$$ [Equation 2]

Alexander (2002) calculated the runoff coefficient for the Inkomati catchment to be estimated at 5% for a 2-year return period and 40% for a 100-year return period. Therefore, for the two identified rainfall scenarios (i.e. a 20% or 40% increase in rainfall), the associated estimate runoff can be determined. By applying Equation 2, i.e. multiplying the runoff coefficient with the rainfall, an estimate of the future increase in runoff can be obtained (as shown in Table 6.1).

Table 6.1: Estimating a Percentage Increase in Runoff

Projected Increase in MAP	K = 5%	K = 40%
20%	Runoff = (0.05 * 0.2) = 1%	Runoff = (0.4 * 0.2) = 8%
40%	Runoff = (0.05 * 0.4) = 2%	Runoff = (0.4 * 0.4) = 16%

An increase in runoff of 1% and 2% can be estimated for a 20% and 40% increase in rainfall respectively for a 2-year flood return period, and an 8% and 16% increase in runoff for a 20% and 40% increase in rainfall respectively for a 100-year flood return period.

The 100-year projections (i.e. an 8% and 16% increase in runoff for a 20% and 40% increase in rainfall) are similar to those provided by the LTAS Study (provided in Section 6.2), which project an increase of 5% to 15% in annual catchment runoff. Therefore, the two flood scenarios that were selected for the remainder of this dissertation are the two ranges provided in the LTAS Study, which have been accepted by the national regulating authority, namely a 5% to 15% increase in runoff for the Crocodile River catchment.

6.3 Rainfall and Hydrological Scenarios

In Chapter 5, two base scenarios, namely the February 2009 and January 2012 flood events, were identified. As shown in Figure 5.1 and Figure 5.4, the rainfall data measured at the X2E013 weather station is significantly less than that measured at the X2E010 weather station. This is because, as illustrated in Figure 3.13, the X2E013 weather station is located in an area with less MAP than the

X2E010 weather station. Due to the interconnected nature of catchment process, the runoff of the Crocodile River will be affected by the weather patterns throughout the catchment. However, as this dissertation estimates flood events by using the runoff coefficient, i.e. estimating runoff by using projected rainfall, the high rainfall measured at the X2E010 weather station will provide higher runoff estimations for flood events. Therefore, to serve the purpose of this dissertation, only the X2E010 weather station will be used.

The X2H013 gauging station is located approximately 40 km upstream of Riverside and approximately 50 km upstream of Tekwane, whereas the X2H006 gauging station is located approximately 10 km downstream of Riverside and approximately 10 km upstream of Tekwane. The peak discharge recorded at the X2H013 gauging station is 17.953 m^3/s for the February 2009 flood event, and 99.419 m^3/s for the January 2012 flood event. For the X2H006 gauging station, the peak discharge is 119.967 m^3/s for the February 2009 flood event, and 241.750 m^3/s for the January 2012 flood event. Therefore, to fulfil Objective 2 of this dissertation, which is "using the identified flood events and the discharge and water levels associated with these events to define the several characteristics of floods in the Crocodile River", only data from the X2H006 gauging station will be used to create flood scenarios. However, to ensure completeness, the 99.419 m^3/s discharge recorded at the X2H013 gauging station (for the January 2012 flood event) will also be modelled. This will serve as an integral part of the spatial risk assessment, which is provided in Chapter 8.

The runoff (m^3/s) for the two base runoff scenarios are shown in Figure 6.2, where X represents the February 2009 flood event, and Y represent the January 2012 flood event. The two runoff scenarios identified above (i.e. a 5% and 15% increase in runoff) were applied to each of the base scenarios, resulting in a total of four scenarios (this is explained in detail in Appendix A.2). The resulting runoff for the four future flood events is provided in Figure 6.2, where X1 and Y1 represent a 5% increase in runoff for base scenario X and Y respectively, and X2 and Y2 represent a 15% increase in runoff for base scenario X and Y respectively. In addition, as indicated earlier, the discharge recorded at the X2H013 gauging station will also be used for the hydraulic modelling. This is shown as scenario Z in Figure 6.2.

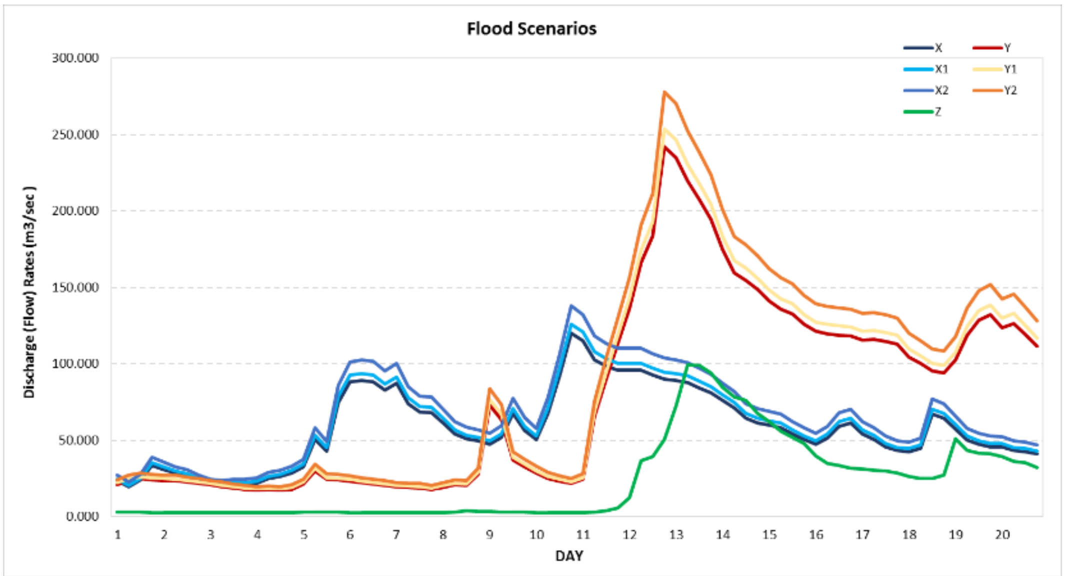


Figure 6.2: The seven scenarios for hydraulic modelling (given as m^3/s)

The peak runoff value for each of the four scenarios, as well as the runoff for the two base scenarios, is provided in Table 6.2. As in Figure 6.2, X1 and Y1 represent a 5% increase in runoff for base scenario X and Y respectively, and X2 and Y2 represent a 15% increase in runoff for base scenario X and Y respectively. The 99.419 m^3/s discharge recorded at the X2H013 gauging station is shown as scenario Z. The peak runoff for the seven identified flood events is provided in Table 6.2, and provided in detail in Table A.1.

Table 6.2: Peak runoff for the scenarios for hydraulic modelling (values are given as m^3/s)

Scenario	Base Scenario	Scenario 1	Scenario 2
X	119.967	125.965	137.962
Y	241.750	253.838	278.013
Z	99.419		

6.4 Conclusions

This chapter provided four scenarios for future flood events. The runoff for each of the flood events was projected, based on rainfall projections. The scenarios were developed using the accepted rainfall projections provided by the LTAS study, namely a 5% to 15% increase in runoff for the Crocodile River catchment. Although the projections are based on uncertainties, and the methodology utilised is simple, the scenarios provide an estimate of the probable magnitude of floods in the Crocodile River basin (i.e. the magnitude of future floods). These projections should not be taken as facts, but as an indication of what the future may look like.

As the water level is determined by river discharge, the associated changes in water level for each of the identified scenarios will be modelled through hydraulic software, and provided in the following chapter. In addition, the flood extent of the identified flood events, as well as the base scenarios, will be determined. A spatial flood risk assessment of the Crocodile River basin will then be provided.

CHAPTER 7 – FLOOD EXTENT MAPPING

7. FLOOD EXTENT MAPPING

7.1 Introduction

Chapter 5 provided an overview of two previous flood events in the Crocodile River Catchment (i.e. February 2009 and January 2012). Chapter 6, on the other hand, provided four scenarios for future flood events, where the runoff of each base scenario was projected based on a projected increase in rainfall. An additional scenario was also provided, based on the discharge recorded at the X2H013 gauging station.

The aim of this chapter is to simulate the flood extent and provide flood extent maps for each of the seven identified flood events. No detailed analysis is done for the seven flood events – the flood risk assessment (conducted in Chapter 8) provides a detailed analysis of the two locations selected along the segment of the Crocodile River.

For hydraulic modelling purposes, complex analyses were not possible since the required detailed data for both the topographic representation and flow are not available in South Africa. Therefore, coupled one and two-dimensional hydraulic modelling (i.e. HEC-RAS) was used to determine flood parameters such as flood extent. The detailed process that was undertaken to develop the flood extent maps is provided in Appendix B. The advantages offered by this hydraulic method are discussed in detail in Chapter 2.

7.2 Previous Flood Events

As discussed in Chapter 5, numerous floods have been observed in the Crocodile River (East) River basin. However, only two of these floods were discussed in detail in Chapter 5. The two identified flood events also happened to be the flood events with the highest observed rainfall in ten years (i.e. during August 2004 - April 2014). The remainder of this section discusses the extent of these flood events.

7.2.1 Base Scenario X (in February 2009)

As provided in Chapters 5 and 6, the peak discharge for base scenario X (in February 2009), is 119.967 m^3/s. Floods were experienced in the area on 5 February. The flood extent was modelled through HEC-RAS software, and is illustrated in Figure 7.1. Although several Landsat 7 ETM+ (30 m resolution) satellite images could be found, there were no images available for 5 February 2009 or any day immediately after. The images that were available are when the flood had already receded, and could therefore not be used to compare the maximum flood extent.

Figure 7.1*: *Flood extent map for the Base Scenario X

7.2.2 Base Scenario Y (in January 2012)

As provided in Chapters 5 and 6, the peak discharge for base scenario Y (in January 2012), is 241,750 m^3/s. Floods were experienced on 19 January. The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.2. Although several Landsat 7 ETM+ (30 m resolution) satellite images could be found, there were no images available for 19 January 2012 or any day immediately after. The MODIS images that were available on 20 and 21 January were of a poor resolution, and could thus not be used to compare the flood extent. High resolution images that were available are when the flood had already receded, and could therefore also not be used to compare the maximum flood extent.

Figure 7.2*: Flood extent map for the Base Scenario Y*

7.2.3 Scenario Z (in January 2012)

As provided in Chapters 5 and 6, the peak discharge for scenario Z (in January 2012), is 99.419 m^3/s. Floods were experienced in the area on 19 January. The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.3. As identified in Section 7.2.2., satellite images for the flood event were not available.

Figure 7.3*: Flood extent map for the Scenario Z*

7.3 Future Flood Events

In Chapter 6, four scenarios for future flood events were developed. The runoff for each of the flood events was projected, based on the two previous flood events (i.e. February 2009 and January 2012). This was achieved by applying two runoff increase projections, namely a 5% increase in runoff and a 15% increase in runoff, resulting in 4 future flood scenarios. The four scenarios were modelled, and the remainder of this section discusses the extent of the flood events.

7.3.1 Flood Event: Scenario X1

As provided in Chapters 5 and 6, the peak discharge for scenario X1 is 125.965 m^3/s. This scenario represents a 5% increase in runoff for base scenario X (i.e. 119.967 m^3/s). The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.4.

Figure 7.4*:* Flood extent map for the Scenario X1

7.3.2 Flood Event: Scenario X2

As provided in Chapters 5 and 6, the peak discharge for scenario X2 is 137.962 m^3/s. This scenario represents a 15% increase in runoff for base scenario X (i.e. 119.967 m^3/s). The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.5.

Figure 7.5*:* Flood extent map for the Scenario X2

7.3.3 Flood Event: Scenario Y1

As provided in Chapters 5 and 6, the peak discharge for scenario Y1 is 253.838 m^3/s. This scenario represents a 5% increase in runoff for base scenario Y (i.e. 241.750 m^3/s). The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.6.

Figure 7.6*: Flood extent map for the Scenario Y1*

7.3.4 Flood Event: Scenario Y2

As provided in Chapters 5 and 6, the peak discharge for scenario Y2 is 278.013 m^3/s. This scenario represents a 15% increase in runoff for base scenario Y (i.e. 241.750 m^3/s). The extent of the flood was modelled through HEC-RAS software, and is illustrated in Figure 7.7.

Figure 7.7*: Flood extent map for the Scenario Y2*

7.4 Synthesis: Flood Extent

The extent of each of the flood events was modelled as illustrated in Section 7.2 and 7.3. For each flood event, the total area that is likely to be flooded is provided in Table 7.1 (ranked from the smallest discharge to the lowest). The total area under water for Scenario Z is 1.92 km^2. This is the smallest flood extent area, and it also corresponds to the smallest discharge. The largest flood extent area is 8.77 km^2, which corresponds to Scenario Y2. This also corresponds to the largest discharge.

Table 7.1: The area flooded under each scenario (values are given as km^2)

Scenario	Z	X	X1	X2	Y	Y1	Y2
Discharge (m^3/s)	99.419	119.967	125.965	137.962	241.750	253.838	278.013
Area (km^2)	1.92	2.24	3.44	3.73	5.78	6.68	8.77

Graphically (as shown in Figure 7.8), the change in area, based on a change in discharge, more or less follows a linear trade for all scenarios expect Scenario Y2 (i.e. 278.013 m^3/s). Similarly, if you exclude Scenario X1 and X2, the change in area follows an exponential trend and not a linear trend. This means that while the area flooded during a flood event with a predetermined discharge can be roughly estimated, an accurate representation of flood extent requires a detailed hydrological and hydraulic analysis (as conducted in this dissertation).

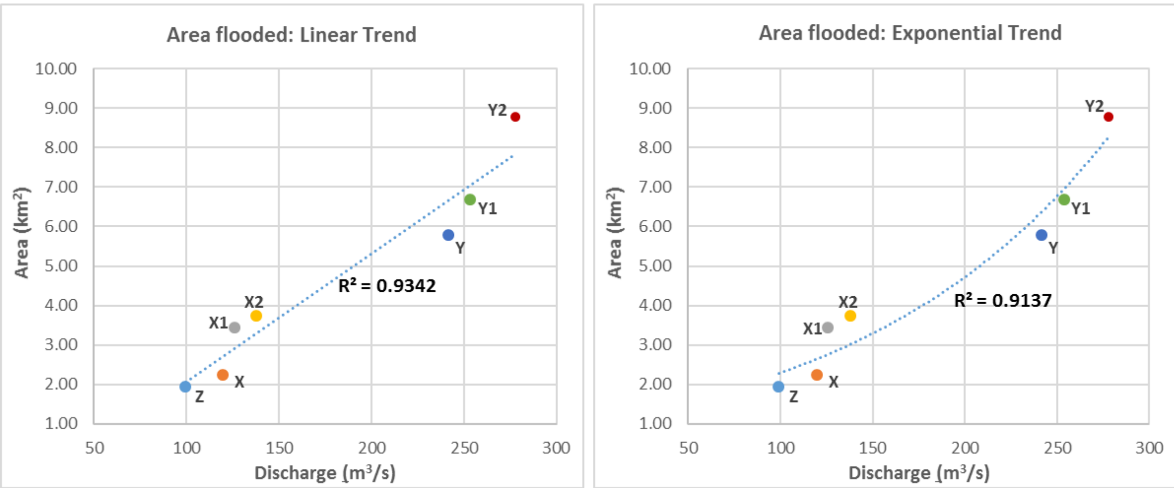


Figure 7.8*:* Change in the area flooded (i.e. flood extent) under each scenario

7.5 Conclusions

This chapter provided an overview of the flood extent of identified flood events. Flood hazard maps were created for each of the identified flood events. This will enable the identification of high risk areas along the Crocodile River basin, which is discussed in Chapter 8.

A major limitation of this study was the quality of the elevation data. This created various inconsistencies in the elevation profile for the study area, which ultimately affected the simulated flood profiles. Availability of high quality data would have increased the accuracy of the flood simulation.

The aim of this chapter was also to compare the simulated extent of previous flood events with the observed distribution. However, due to the unavailability of archived satellite imagery at an adequate resolution, the flood extent for the previous flood events could not be validated.

CHAPTER 8 – SPATIAL FLOOD RISK ASSESSMENT

8. SPATIAL FLOOD RISK ASSESSMENT

8.1 Introduction

This chapter discusses the flood extent maps that were produced in Chapter 7. The aim of the chapter is to identify high flood risk areas along the Crocodile River Basin. This risk assessment is based on the likelihood of the basin area being flooded during flood events, and therefore includes the elevation of the basin (as discussed in Chapter 4), the simulated flood extent (as discussed in Chapter 7), the flood scenarios (developed in Chapter 6) and the flood frequency (as discussed in Chapters 5 and 6). This will enable a spatial risk assessment, using the methodology provided in Chapter 4 and Appendix B.

The analysis of the likelihood of an area to be flooded by a flood event of particular discharge was conducted using ArcGIS. This was done by intersecting the seven polygons that represent the discharge of the seven flood events. As illustrated in Table 8.1., when an area is intersected by seven polygons (one polygon for each of the flood events), this area is likely to be flooded by all seven flood events, and is therefore at very high risk during flood events. Similarly, an area identified as medium risk is intersected by four polygons, and is likely to be flooded by four flood event. The areas with the lowest risk are likely to be flooded by one flood event. Using the standard traffic light system, high risk areas are identified as red, medium risk areas are identified as orange, and low risk areas are identified as green.

Table 8.1: Risk Rating System

Risk Categories		Description
Minimal		Intersected by 1 polygon
Low		Intersected by 2 polygons
Low-Medium		Intersected by 3 polygons
Medium		Intersected by 4 polygons
Medium-High		Intersected by 5 polygons
High		Intersected by 6 polygons
Very High		Intersected by 7 polygons

ArcGIS enables the identification of different risk categories by shading polygons based on the risk categories. As there were seven profiles modelled, seven risk categories were determined (as shown in Table 8.1). Layering the polygons on the land use map enabled an identification and discussion of flood risk for each of the two locations along the segment of the Crocodile River. Rather than create a risk map for each of the flood events, the polygons were overlain (as discussed above) and an overall risk assessment was conducted. This approach enabled a comparison between the different flood events, and a spatial risk assessment (showing the seven risk categories). For each location, a discussion of the flood risk is provided, which includes the discharge that is associated with the flood event(s).

It should be noted, due to the challenges experienced during the floodplain process of the hydraulic modelling exercise (as discussed in Appendix B.2), the standard method (i.e. developing a water surface and floodplain inundation polygon for each water surface profiles using HEC-GeoRAS) could not be used. Therefore, the water extent polygons (which are relevant for this dissertation) were created in ArcGIS manually by joining the flood extent points on each cross section.

8.2 Future Food Risk Profile

8.2.1 Segment 1: Tekwane

The spatial flood risk profile for Tekwane is illustrated in Figure 8.1. As illustrated, the left bank (i.e. the top part of the figure) is at a higher risk than the right bank. This is because the elevation of the right bank is higher than the left bank, particularly the lower right portions of the area that was modelled. The yellow area (identified as low-medium risk) illustrates areas that are at risk to flooding when discharge reaches 241.75 m^3/s. The areas in orange and red are at a higher risk to flooding (identified as medium to very high risk), and are at risk to flooding even when discharge is less than 137.96 m^3/s. These areas are however largely unpopulated. Therefore, there is a minimal risk to the population of Tekwane when the discharge is less than 241.75 m^3/s.

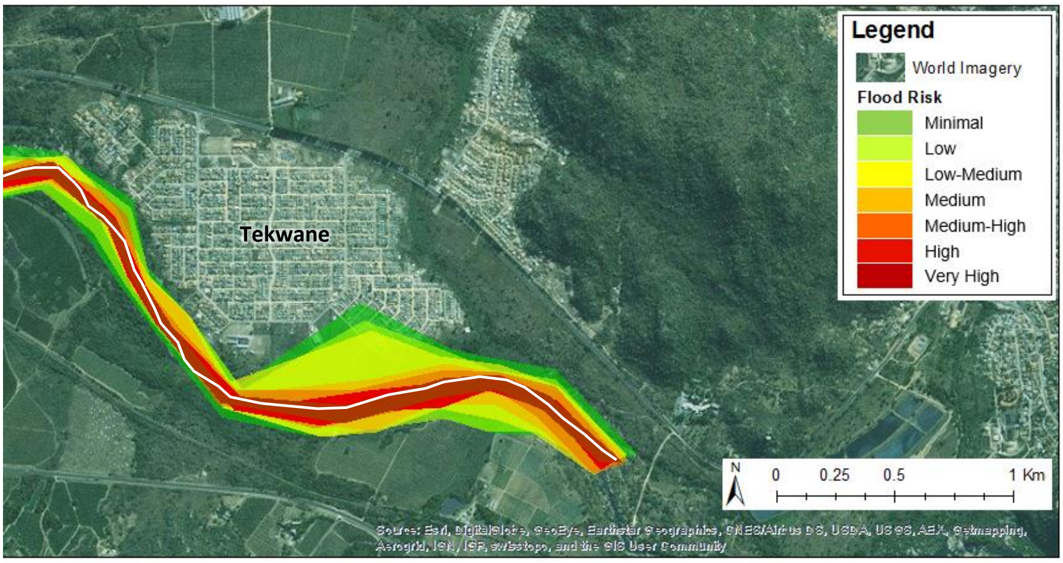


Figure 8.1*:* Spatial Flood Risk Profile for Tekwane, with the Crocodile River shown as a white line

On the right bank, the area is largely agricultural, with a low population density. However, the left bank is populated with rural settlements. Rural settlements are often more sensitive to flood events as they are often directly exposed to climatic events, such as floods. Houses are often poorly built, are poorly located, or lack flood and lightning protection, efficient water systems, or damp-proofing, which make them more vulnerable to floods (DEA, 2013).

In addition, rural households which have a lower ability to cope with flood events than their urban counterparts due to lower adaptive capacity. Households without access to electricity, water, sanitation and waste management services are more impacted by climate extremes, while factors such as poverty and unemployment reduce the ability of households to recover from climate shocks (DEA, 2013). In addition, from a spatial planning perspective, the population at Tekwane should be located at a higher elevation. This is particularly important as climate projections indicate that intense floods are likely to be a regular feature of the Crocodile River (East) (as discussed in Section 2.6).

While rural settlements inherently have a lower adaptive capacity than urban settlements, it is the ability of an individual household to cope with flood hazard that determines its overall risk to flooding (International Institute for Environment and Development, 2013). Although this is largely determined by financial circumstances, innovative strategies to flood management have the ability of increasing the ability of rural households to cope to flood events. Therefore, further assessment of the rural settlements would provide a more detailed assessment of the flood risk to the Tekwane population.

As indicated in Chapter 2, flood risk can only be determined when the sensitivity and adaptive capacity of a system is determined. However, the assessment of the individual adaptive capacity, as well as the sensitivity of a system to a hazard, which have an influence on the overall impact and impact to a system, is not in the scope of this study.

8.2.2 Segment 2: Riverside

The spatial flood risk profile for Riverside is illustrated in Figure 8.2. As illustrated, the right bank is more at risk than the left bank in the higher reaches of the Crocodile River. This is because the elevation of the right bank is higher than the left bank, particularly the upper portion of the area that was modelled.

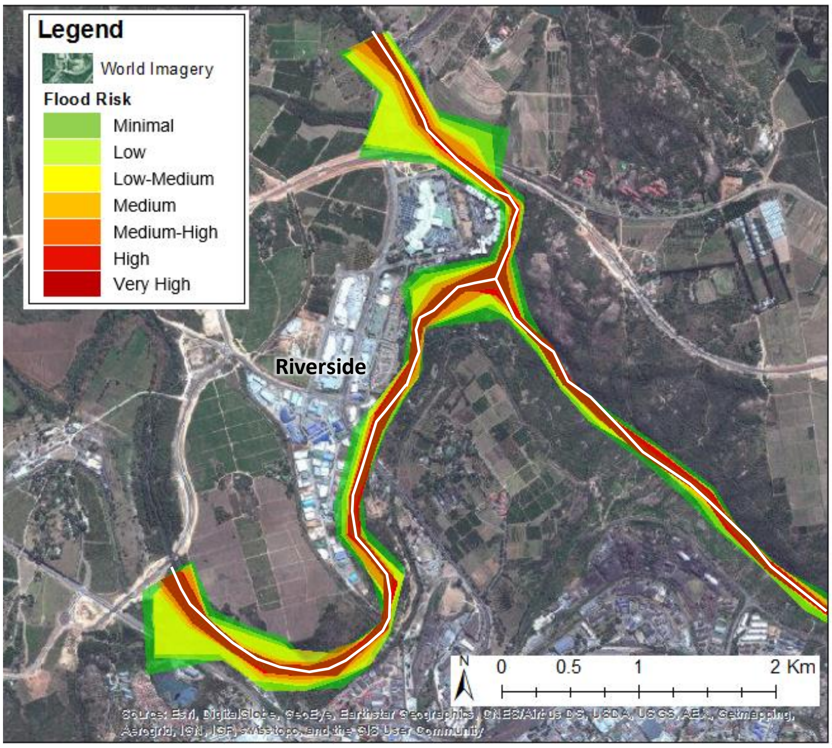


Figure 8.2*: Spatial Flood Risk Profile for Riverside, with the Crocodile River shown as a white line*

The yellow area (identified as low-medium risk) illustrates areas that are at risk to flooding when discharge reaches 241.75 m^3/s. Similar risk areas can also be identified on the northern parts of Riverside along the Sand River tributary. The areas in orange and red are at a higher risk to flooding (identified as medium to very high risk), and are at risk to flooding when discharge is less than 137.96 m^3/s. These areas are however largely unpopulated. Therefore, similarly to Tekwane, there is a minimal risk to the population of Riverside when the discharge is less than 241.75 m^3/s.

The right bank is largely unpopulated, with small agricultural patches located close to the river banks. This means that even if these areas do get flooded, there will be a minimal impact to human livelihoods and lives. Higher elevations are largely urbanised, and have not been identified as being at risk to flooding. However, medium risk areas have been identified on the left and right portions of the river banks. These areas currently contain urban, industrial and agricultural areas.

In addition, the sensitivity of a system to flood events is also important. (Industrial sites are, for example, often deemed as more sensitive to floods than agriculture, as they are less able to absorb the impacts of flood events.) Therefore, in order to minimise the sensitivity of the area as a whole, flood management interventions need to be implemented. The determination of the individual adaptive capacity and the sensitivity of the various systems within the basin is therefore required. This is however, not in the scope of this study.

Alternatively, the adaptive capacity of the population can be increased. The overall capacity of the urban population to cope with flood events is usually deemed higher than the rural population, as there are often more options, solutions and interventions available to cope with flood events. However, as previously indicated, individual households and industrial sites will have varying adaptive capacity. Interventions such as effective storm management systems can play larger part in mitigating the impacts of flood events in urban areas. In addition, spatial planning, such as locating residential and industrial areas at a higher elevation will also be effective at minimising the impacts of flood events.

8.3 Discussion

The two locations are at risk to flooding when discharge reaches 241.75 m^3/s. This is based on Section 8.2, which indicates that when discharge reaches 241.75 m^3/s, areas at both Tekwane and Riverside are at risk to flooding (identified as low-medium risk – i.e. the yellow areas on the map). This is therefore the threshold for which the two locations are likely to be flooded.

While every effort was made to obtain the flow rates for various return periods for the Crocodile River (East), this was not possible. The discharge could therefore not be compared to the return periods (e.g. 50-, 100-, or 200-year). This meant that a comparison of which (if any) return periods have been exceeded could not be performed.

However, based on the data downloaded from the DWS HIS, an analysis of the daily discharge readings could be made. This enabled an analysis of how often the 241.75 m^3/s discharge was exceeded in the Crocodile catchment. As provided in Figure 8.3, the 241.75 m^3/s discharge was exceeded at gauging stations X2H006 (one time), X2H016 (twenty-five times) and X2H046 (three times). This means that the over one decade (2004 to 2014), 241.75 m^3/s was exceeded 0.03%, 0.70% and 0.08% times at stations X2H006, X2H016 and X2H046, respectively. In total, the observed trends indicate that 241.75 m^3/s was exceeded 0.14% times at various stations across the Crocodile catchment.

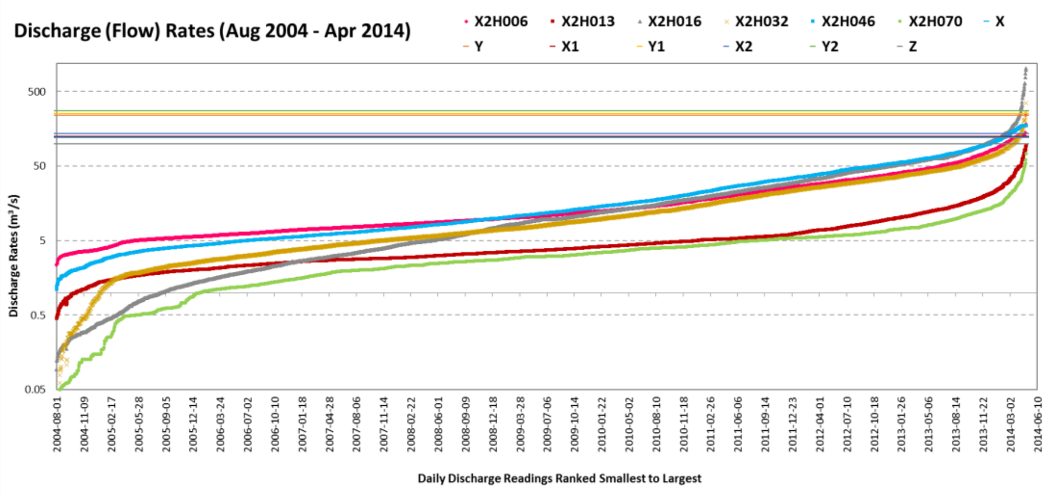


Figure 8.3*:* Daily discharge readings for all 6 gauging stations (shown as points) and the 7 flood scenarios (shown as straight lines)

Based on previous trends, there is therefore a less than 1% likelihood that the segment analysed in this dissertation will be flooded will be flooded over a 10-year period. However, as discussed in Chapter 2, a key indication from climate projections is that the likelihood of extreme flood events for the north-eastern provinces of South Africa (where the Crocodile catchment is located) will increase. This implies that the likelihood of the Crocodile river segment flooding will increase, and the magnitude of these flood events will increase. For the Crocodile river segment that was analysed, this will translate to an increase in the area that will be flooded. A spatial assessment of the areas that are at risk during flood events of varying magnitudes was conducted for this dissertation.

8.4 Conclusions

This chapter provided a spatial flood risk assessment of two locations along the Crocodile River Basin. The spatial risk assessment enabled the comparison the flood risk for seven different discharge rates, using the methodology provided in Chapter 4 and Appendix B. As discussed in Appendix B, high risk areas (identified in red) have a higher probability of being flooded, medium risk areas (identified in orange) have a lower probability than the high risk areas, while the low risk areas (identified in green) have the lowest probability of being flooded.

However, flood risk is a function of the sensitivity to flood events, as well as the ability of a system to cope with floods (i.e. its adaptive capacity). Therefore, it is important to determine the individual sensitivity, as well as adaptive capacity of all systems within a basin. This would enable the determination of the risk of the individual systems within this basin. This assessment is however beyond the scope of this study. In addition, assessment of interventions which would decrease the risk to flood are also outside of the scope of this study.

This study aimed to identify areas that are at high risk to flood events (i.e. spatial risk assessment), and not identify systems that are at high risk. Therefore, the intended outcome was achieved in this chapter.

CHAPTER 9 - CONCLUSIONS

9. CONCLUSIONS

In the recent past, the Crocodile River East in Mpumalanga Province has seen three major floods in a twenty-four-month period, in January 2011, January 2012 and in January 2013. Alarmingly, the frequency of floods is increasing around the world (Alho *et al.*, 2008) and in South Africa (Halloway *et al.,* 2010). Added to this, the Southern Africa Risk and Vulnerability Atlas (2011) indicates that climate change is likely to alter the magnitude, timing, and distribution of storms that produce flood events in the region. This is particularly the case in the Mpumalanga Province, where the likelihood of flood events is projected to increase in coming decades. Therefore, proper planning is required for effective flood risk management.

The principal state organisation, the Department of Water and Sanitation (DWS), is responsible for, among others, water resource management, planning and guidance for water related events including flooding. However, flood mapping is currently limited to historical maps created from previous flood events.

In this light, the main objective of this research was to assess the extent of previous flood events along the Crocodile River Basin, to predict future flood events and estimate how future floods are likely to be distributed, as well as to provide a spatial representation of flood prone areas along the river basin. Therefore, a key outcome of this research was flood risk maps for two locations along a segment of the Crocodile Basin. The flood risk maps provided an indication of the areas along the segment that are at a risk of being inundated during flood events.

However, flood risk is a complex process that combines human and natural factors. It is characterized by the conjunction of the probability of floods to take place and the potential consequences associated to them. Floods only cause damage when flood zones are occupied by vulnerable human systems (Eleutério, 2012). Turner *et al.* (2003) recognised that holistic studies on vulnerability that are meant to have an input in decision making should include a study of all the hazards affecting the system, as an assessment of how the system gets exposed to the hazard, as well as the coping capacity of the system. Variations in these indicators will invariably result in variations in vulnerability. This research, however, does not conduct a detailed overview of the vulnerability of the systems along the basin, but merely identifies the areas that are at high risk. It acknowledges the fact that within a ‘high risk area’, for example, the vulnerability of different households will vary. This is due to the fact that the adaptive capacity and resilience of different households will vary. An assessment at this level is not in the scope of this project.

Therefore, although this research acknowledges the fact that it is essential to identify high flood risk areas (which was achieved and outlined in Chapter 8), it also acknowledge that within high flood risk areas, the risk of individual systems can vary.

9.1 Limitations of Research

There were various challenges that were experienced during this research, which limited and influenced the outcome of this dissertation. Limitations were experienced in the following areas:

- **Water level and discharge data**: Although numerous stations exist along the Crocodile River, data accuracy and data completeness presented challenges in conducting an accurate assessment. Peak discharge values for flood events are integral for modelling previous flood events. For one of the flood events, peak discharge values were not available. This data gap was filled with data acquired from a different source. This approach is often not desirable as different organisation utilise different data monitoring and measuring techniques. Therefore, data monitoring and measuring needs to be a priority for water management institutions.

  In addition, as the analysis used data for only 10 years of data, it prevented any rigorous statistical analysis which is typical of flood risk assessment.

- **Topographical data**: The availability of high resolution topographical data to accurately represent the river channel and surrounding terrain is one of the main impediments for flood modelling. Topographic data are fundamental to flood modelling as they are used throughout the process (Els, 2011). Although either a raster or tin format can be used for topographic representation, a tin format is often recommended for modelling processes. For this dissertation, the vertical resolution offered by the tin and the raster was not at the required scale (i.e. approximately 0.5 m). There is, therefore, a need for South Africa to invest in developing and/or acquiring high resolution DEMs.

- **Orthophotos and Satellite Imagery**: Several challenges were experienced with the available satellite imagery. This was mainly due to the fact that daily images for South Africa are not captured. Firstly, although several Landsat 7 ETM+ (30 m resolution) satellite images could be found, there were no images available for the flood events or any day immediately after. The cloud cover on the days after the flood resulted in the Landsat 7 ETM+ satellite images being unclear and unusable. The high resolution images that were available were when the flood had already receded, and could therefore not be used to compare the flood distribution. Secondly, the MODIS images that were available for the flood events were of a poor resolution, and could thus not be used to compare the flood distribution. Lastly, the limitations in the recording of flood events in South Africa meant that there were no official archive of historical images capturing flood events. There is therefore a need for South Africa to invest in daily satellite imagery and in proving historical images capturing flood events.

Data limitations determine the flood modelling methodology that is used. Higher quality data availability will enable more detailed analysis and the use of sophisticated hydraulic modelling applications. With higher quality data, more accurate and larger scale flood modelling assessments can be conducted. This would enable the application of effective flood planning and the implementation of appropriate flood management approaches.

9.2 Revisiting the Research Aims

This section revisits each of the research aims, and discusses whether these were achieved;

Aim 1: To evaluate the extent of previous flood events and identify the characteristics of the rainfall periods that caused them. *(Achieved - see Chapters 5 and 7)*

Aim 2: To determine how these previous flood events have affected the Crocodile River Basin. *(Partly achieved - see Chapters 5 and 7)*

Aim 3: To develop discharge and water level scenarios for possible future flood events for the Crocodile River, based on these historical events. *(Achieved - see Chapter 6)*

Aim 4: To develop flood maps for these future scenarios that identify flood-prone areas along the Crocodile River Basin. *(Partly achieved - see Chapters 7 and 8)*

Aim 5: To determine how future flood events are likely to affect the settlement patterns, human and physical characteristics of the Crocodile River Basin. *(Partly achieved - see Chapters 7 and 8)*

Although various challenges were experienced regarding data availability, and the accuracy of the available data, the data that was available enabled the research to be completed. A challenge was, however, experienced in terms of obtaining high-resolution daily satellite imagery. This meant that the extent of modelled historic flood events could not be compared with observed flood events. This meant that Aim 2 could only be partially completed.

This research showed that flood modelling is possible with the use of data that is currently available in South Africa. Applications such as ArcGIS, HEC-RAS and MIKE FLOOD enable good quality hydrological analysis, spatial assessment and flood mapping. This research will be instrumental in increasing knowledge of flood risk assessment, projecting future flood events under climate variability, predicting flood prone areas, and therefore guiding planning and decision making.

If South Africa can enhance the existing data sources required for hydraulic modelling, the methodology can be improved and better flood hazard maps can be created. Some African countries already have better quality historic satellite imagery and topographic data. This should encourage South Africa to improve its in-house data if it would like to become the leader in spatial information in Africa (Els, 2011).

9.3 Recommendations for Further Research

The recommendations presented in this section are based on the research findings drawn from the previous sections. In addition, while conducting this research, there were several components that were identified where opportunities for further research exist. These will increase the richness of the outcomes of flood risk assessments.

The data limitations, particularly the lack of high resolution DEMs, creates challenges in obtaining accurate flood maps. This could have a catastrophic impact for planning processes such as land-use and settlement planning. Communities that are considered as socially vulnerable, and thus have a low adaptive capacity, could be located in areas that would have been other-wise been considered as high risk. High quality DEMs enables an accurate representation of the elevation. There is therefore a need for a project, funded by government, which undertakes for high-quality DEMs to be captured across the country.

Lastly, this research conducted a spatial vulnerability assessment. It did not conduct a detailed overview of the vulnerability of the systems along the basin, but merely identified the areas that are at high risk. An identification of each of the individual components of the systems along the basin would require extensive resources, which were beyond the scope of this project. Further research in this area would increase the validity of the flood risk and vulnerability assessment of this basin.

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APPENDIX A: SUPPORTING INFORMATION

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A.1 Estimating Future Floods – The Rainfall-Runoff Relationship

The overall feature of the distribution of Mean Annual Precipitation (MAP) is that it decreases fairly uniformly westwards from the escarpment across the interior plateau of South Africa (as illustrated in Figure 3.11 in Section 3.3.1). Between the escarpment and the Indian Ocean in both the southern and the eastern coastal margins, there is the expected complexity of rainfall patterns induced by irregularities of terrain (*S*chulze, 2011). According to Lynch (2004), approximately 20% of South Africa's land surface area receives less than 200 mm MAP, and 47% receives less than 400 mm MAP. Only about 9% of South Africa receives a MAP in excess of 800 mm (Lynch, 2004).

In hydrology, a fundamental truism is that the runoff response to rainfall is nonlinear, with a larger proportion of rainfall being converted to runoff when a catchment is wetter, either because a region is inherently in a high rainfall zone or because the soil water content just prior to a rainfall event may have been high as a result of previous rainfall. As the runoff-rainfall relationship is a nonlinear one, any changes in rainfall may be amplified in its runoff responses (*S*chulze, 2011). The nonlinearity of implies that there is low predictability of the behaviour of the system.

Another factor affecting the rainfall-runoff relationship is the size of the catchment. Small homogeneous catchments give simple rainfall-runoff relationships but the case is different with large catchments (of national or international scale), or with catchment of complex or variable shapes. In the intermediate scale, of both area and time, rainfall-runoff relationships are complicated due to physical factors (such as geology) and hydrological factors (such as evaporation, infiltration and groundwater flow) (Nicandrou, 2010). In addition, human activity such as engineering developments, land-use types and urbanisation also have an impact on the rainfall-runoff relationships.

Runoff patterns reflect a combination of rainfall characteristics (e.g. the amount of rainfall, its intensity, the concentration of the rainfall season and the persistence of rain days, i.e. whether rain falls on consecutive days causing high runoff responses, or as isolated events) and soil characteristics (e.g. water holding capacity, drainage rates) (Lynch, 2004). In addition, runoff patterns also depend on other catchment characteristics. These include the land cover, the terrain, the drainage pattern and density.

The heterogeneous spatial and temporal distributions of rainfall result in a low overall conversion rate of rainfall to runoff; an average of ~ 9% of rainfall is converted to runoff for South Africa as a whole (Schulze, 2011). Figure A.1 shows that over much of the interior of South Africa the ratio of Mean Annual Runoff (MAR) to MAP is less than 10%, with significant tracts in the west at less than 5% and only small parts exceeding 20%. The eastern region of the country has the highest number of areas where the MAR to MAP ratio is greater than 20%. This low conversion rate is the consequence as much of an overall paucity of rainfall as it is of very high evaporative demand (Schulze, 2011). In addition, the land surface and rainfall properties also have an impact on the conversion rate. The ratio of MAR to MAP is also known as the runoff coefficient.

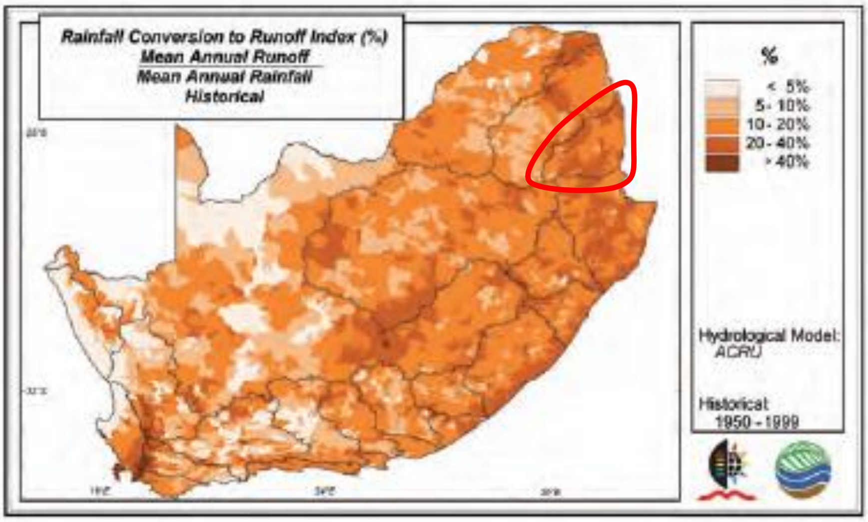


Figure A.1: Ratios of MAR to MAP over South Africa, Illustrating the Low Conversion Rate of Rainfall to Runoff (Schulze, 2011). The Inkomati catchment is circled in red.

As shown in Figure A.1, the runoff coefficient in the Inkomati catchment (circled in red) varies between 10% and 20%, while a smaller portion of a catchment has a runoff coefficient between 20% and 40%. This implies that a minimum of 10% and a maximum of 40% of rainfall in the catchment is converted to runoff. Therefore, in some areas, where 40% of rainfall is converted to runoff, high rainfall events are likely to increase the risk of flooding. However, it is important to note that the MAR shown above is an average, and will therefore vary spatially within the catchment. In addition, the MAR will also vary between rainfall events, as rainfall characteristics such as duration and intensity also impact the conversion of MAP to MAR.

A.2 Data for Flood Scenarios

The runoff (m^3/s) for the two base runoff scenarios is shown in Table A.1, where X represents the February 2009 flood event, and Y represents the January 2012 flood event. The two runoff scenarios identified in Chapter 6 (i.e. a 5% and 15% increase in runoff) were applied to each of the base scenarios (i.e. columns 3 and 4), resulting in a total of four scenarios - where X1 and Y1 represent a 5% increase in runoff for base scenario X and Y respectively, and X2 and Y2 represent a 15% increase in runoff for base scenario X and Y respectively. In addition, as indicated in Chapter 6, the 99.419 m^3/s discharge recorded at the X2H013 gauging station will also be used for the hydraulic modelling (and is shown as Scenario Z). The resulting runoff for the seven identified flood events is provided in Table A.1. Four values. As multiple readings are captured each day, only four time periods are shown in Table A.1, which were taken at equal time spacing throughout the day.

Table A.1: Two Base and Four Flood Scenarios for Hydraulic Modelling (Values for Flood X (Feb 2009) and Flood Y (Jan 2012) are given as m^3/s)

DAY	TIME	X	Y	X1	Y1	X2	Y2	Z
1	1	23.447	20.992	24.619	22.042	26.964	24.141	2.820
	2	19.576	23.734	20.554	24.920	22.512	27.294	2.935
	3	23.822	24.788	25.013	26.027	27.395	28.506	2.763
	4	33.632	23.963	35.314	25.161	38.677	27.557	2.722
2	1	30.907	23.743	32.452	24.930	35.543	27.304	2.681
	2	28.347	23.523	29.765	24.699	32.599	27.051	2.655
	3	26.660	22.612	27.992	23.742	30.658	26.003	2.629
	4	23.579	21.700	24.758	22.785	27.116	24.955	2.533
3	1	21.168	20.690	22.226	21.724	24.343	23.793	2.533
	2	20.448	19.679	21.470	20.663	23.515	22.631	2.533
	3	21.293	18.684	22.358	19.618	24.487	21.487	2.533

	4	21.157	17.689	22.215	18.573	24.331	20.342	2.533
4	1	21.899	17.129	22.994	17.985	25.184	19.698	2.436
	2	25.091	17.535	26.346	18.412	28.855	20.165	2.443
	3	26.413	17.129	27.734	17.985	30.375	19.698	2.449
	4	28.654	17.975	30.086	18.873	32.952	20.671	2.526
5	1	32.507	21.443	34.132	22.515	37.383	24.659	2.862
	2	50.442	30.053	52.964	31.555	58.009	34.561	3.009
	3	42.865	24.324	45.008	25.540	49.294	27.972	2.827
	4	74.885	23.837	78.629	25.029	86.117	27.413	2.735
6	1	88.131	23.211	92.538	24.372	101.351	26.693	2.669
	2	89.022	22.240	93.473	23.352	102.375	25.576	2.603
	3	88.349	21.231	92.766	22.292	101.601	24.415	2.577
	4	82.875	20.528	87.019	21.554	95.307	23.607	2.500
7	1	87.039	19.350	91.391	20.318	100.095	22.253	2.475
	2	73.998	19.075	77.698	20.029	85.098	21.936	2.449
	3	68.542	18.800	71.969	19.740	78.823	21.620	2.449
	4	68.152	17.947	71.560	18.844	78.375	20.639	2.449
8	1	61.178	19.314	64.237	20.280	70.355	22.211	2.577
	2	54.012	20.876	56.713	21.920	62.114	24.007	2.883
	3	50.740	20.470	53.277	21.494	58.351	23.541	3.873
	4	49.374	27.431	51.843	28.803	56.780	31.546	3.553
9	1	47.417	72.770	49.788	76.408	54.530	83.685	3.336
	2	51.629	63.684	54.211	66.868	59.374	73.237	3.118
	3	67.459	36.923	70.832	38.769	77.578	42.461	2.918
	4	56.338	32.610	59.155	34.241	64.789	37.502	2.776
10	1	50.334	28.541	52.850	29.968	57.884	32.822	2.603
	2	67.720	25.109	71.106	26.364	77.878	28.875	2.590
	3	92.379	23.125	96.998	24.281	106.235	26.594	2.577
	4	119.967	21.581	125.965	22.660	137.962	24.818	2.513
11	1	115.051	24.316	120.804	25.532	132.309	27.964	2.612
	2	102.596	65.719	107.725	69.005	117.985	75.576	2.992
	3	98.313	90.133	103.229	94.640	113.060	103.653	3.688
	4	95.592	113.067	100.371	118.720	109.930	130.027	5.655
12	1	95.639	136.000	100.421	142.800	109.985	156.400	12.190
	2	95.682	166.057	100.466	174.360	110.034	190.966	36.695
	3	92.506	183.783	97.131	192.973	106.382	211.351	39.270
	4	90.128	241.750	94.634	253.838	103.647	278.013	50.706
13	1	88.939	234.848	93.386	246.590	102.280	270.075	72.565
	2	87.750	219.333	92.138	230.300	100.913	252.233	99.419
	3	84.282	207.267	88.496	217.630	96.924	238.357	98.888
	4	80.814	194.500	84.855	204.225	92.936	223.675	93.972
14	1	75.924	174.667	79.720	183.400	87.312	200.867	84.649
	2	71.033	159.467	74.585	167.440	81.688	183.387	78.111
	3	64.276	154.667	67.490	162.400	73.917	177.867	76.202
	4	61.256	148.533	64.319	155.960	70.444	170.813	67.308
15	1	59.703	141.067	62.688	148.120	68.658	162.227	61.972
	2	58.150	135.800	61.058	142.590	66.873	156.170	56.011
	3	54.019	132.533	56.720	139.160	62.122	152.413	51.732
	4	50.368	125.667	52.886	131.950	57.923	144.517	48.012
16	1	47.217	121.267	49.578	127.330	54.300	139.457	39.632
	2	51.499	119.658	54.073	125.641	59.223	137.607	34.678
	3	59.163	118.853	62.121	124.796	68.037	136.681	33.338
	4	61.165	118.049	64.224	123.951	70.340	135.756	31.655
17	1	54.223	115.699	56.934	121.484	62.356	133.054	31.379
	2	50.490	115.850	53.015	121.643	58.064	133.228	30.376
	3	45.712	114.799	47.998	120.539	52.569	132.019	29.925
	4	43.127	112.850	45.283	118.493	49.596	129.778	28.683
18	1	42.486	104.449	44.610	109.671	48.859	120.116	26.291
	2	44.852	100.091	47.095	105.096	51.580	115.105	25.144
	3	66.930	95.391	70.277	100.161	76.970	109.700	25.144
	4	64.177	94.139	67.385	98.846	73.803	108.260	27.246

19	1	57.267	102.416	60.130	107.537	65.857	117.778	50.766
	2	50.184	118.605	52.693	124.535	57.712	136.395	43.363
	3	47.217	128.357	49.578	134.775	54.300	147.611	41.489
	4	45.712	131.893	47.998	138.488	52.569	151.677	41.030
20	1	45.413	123.786	47.684	129.975	52.225	142.354	39.114
	2	43.126	126.479	45.282	132.803	49.594	145.451	36.255
	3	42.427	119.100	44.548	125.055	48.791	136.965	35.458
	4	40.919	111.270	42.965	116.833	47.057	127.960	32.212

APPENDIX B: FLOOD HAZARD AND SPATIAL RISK MAPPING

APPENDIX B: FLOOD HAZARD AND SPATIAL RISK MAPPING

To enable the development of flood hazard maps and spatial flood risk mapping, two broad processes were conducted, namely hydraulic modelling and spatial flood risk assessment. This appendix lays out the steps that were taken for the hydraulic modelling, and the spatial flood risk assessment. Largely, this can be summarised as follows:

A. Hydraulic modelling, involving three broad phases:
   1. Preparing data for HEC-RAS 4.1.0 hydraulic modelling using ArcGIS 10.3.1 and the HEC-GeoRAS extension
   2. Conducting the hydraulic analysis in HEC-RAS 4.1.0
   3. Processing the HEC-RAS 4.1.0 results in ArcGIS 10.3.1 and the HEC-GeoRAS extension

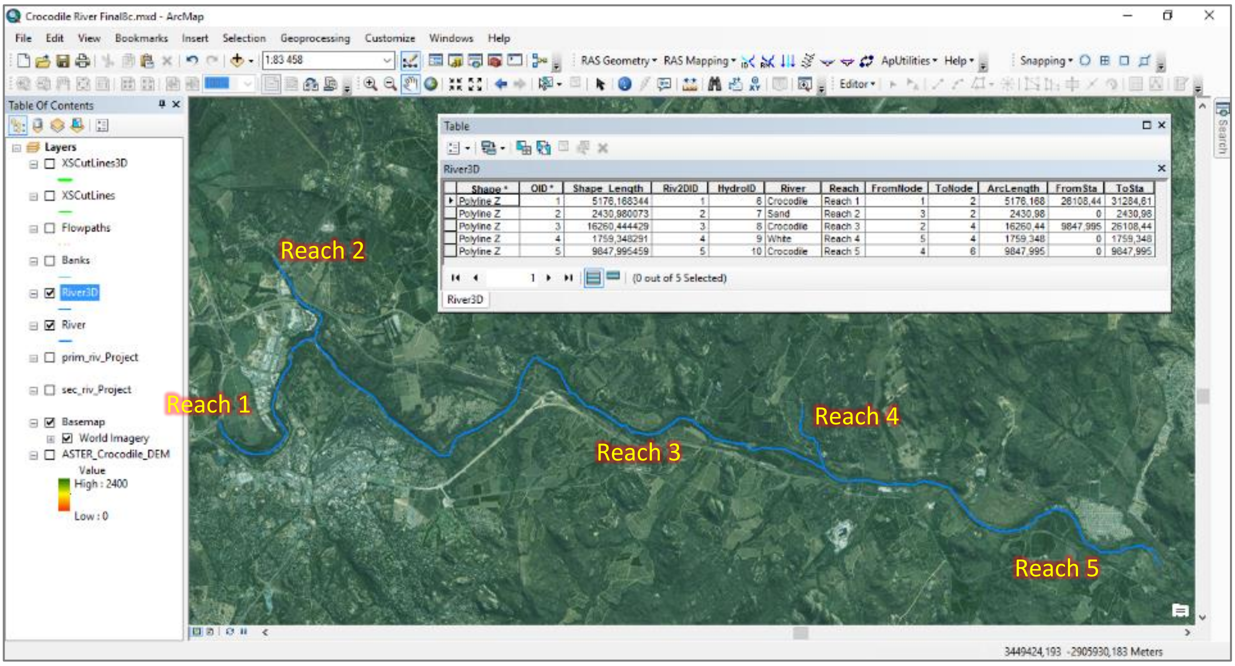
B. Spatial risk assessment in ArcGIS 10.3.1

This appendix does not contain a detailed description of the steps that were taken, but merely provides a brief step-by-step process description. A detailed description can be obtained from US Army Corps of Engineers (2009, 2010), and Leon (2013).

B.1 Hydraulic Modelling

STEP 1: HEC-GeoRAS Pre-Processing

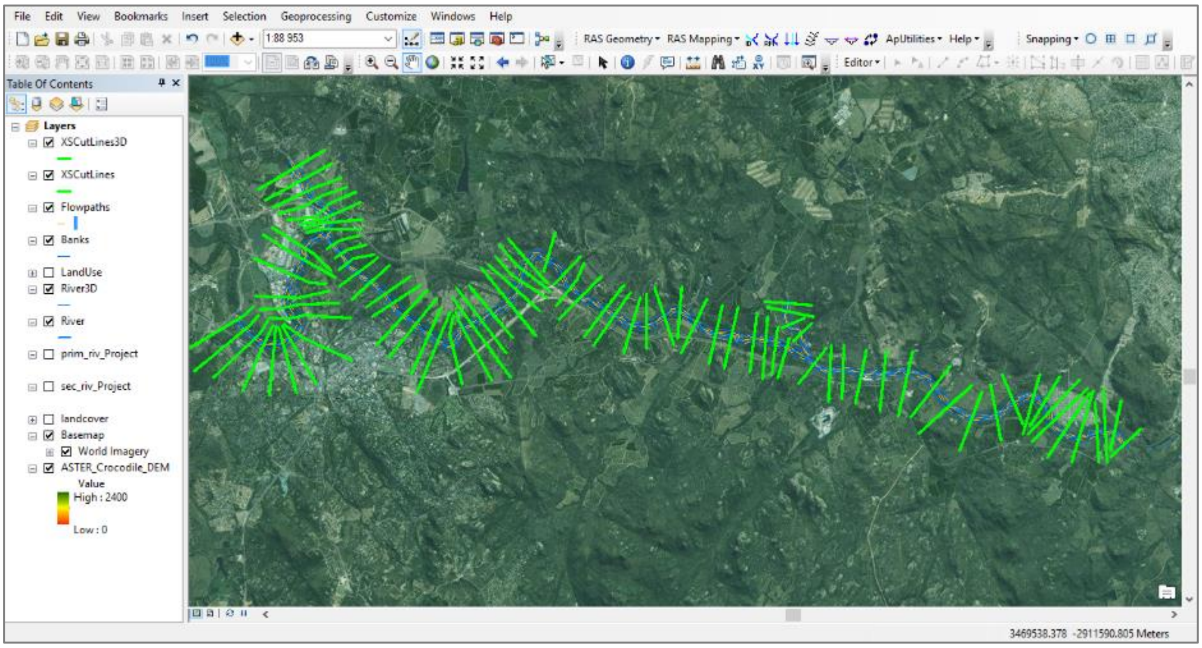
1. Preparation of the Raster DEM in ArcGIS
   a. The two ASTER DEMs (as per Chapter 4.2.2) were merged to form one DEM
   b. The coordinate system was changed from WGS 1984 to WGS 1984 World Mercator (i.e. degrees to metres)
2. HEC-GeoRAS Pre-processing was conducted
   a. Setting up Layer and analysis environment in RAS Geometry
   b. Creating RAS Layers:
      i. river center line and 3D center line – the river consisted of 5 reaches



ii. river banks (left and right)

iii. flow paths (channel, left and right)

iv. cross sections and 3D layer for XS cutlines



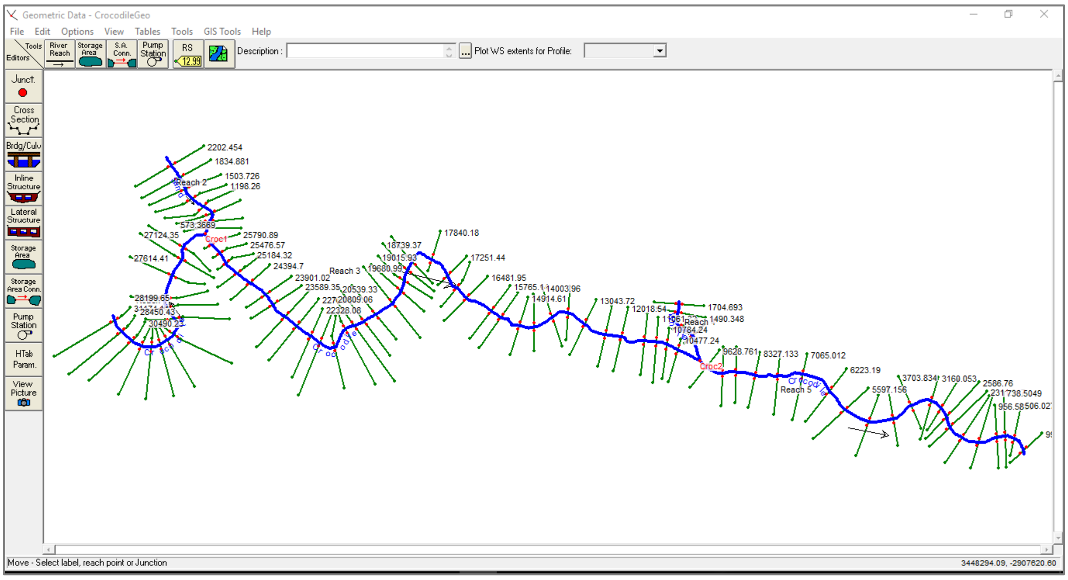
c. Assigning Manning's n values (US Army Corps of Engineers, 2010) to cross-sections based on land use types, as per the table.

Land-use Type	Natural	Waterbodies	Cultivation	Degraded	Urban (Built-up)
Manning's n Value	0.055	0.035	0.055	0.030	0.050

3. Generate HEC-RAS Import file using HEC-GeoRAS

STEP 2: HEC-RAS Modelling

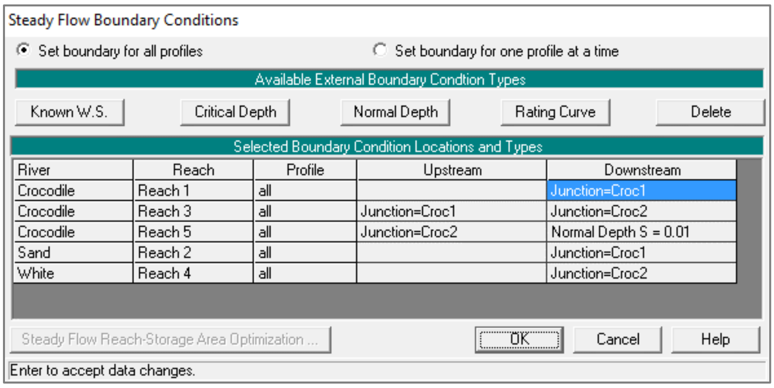
1. Importing import file into HEC-RAS



2. Running HEC-RAS
   a. The flow data were entered (in m^3/s), and a steady analysis was prepared for the 7 profiles (i.e. flood events identified in Section 6.3).

PF1	PF2	PF3	PF4	PF5	PF6	PF7
119.9669	241.7500	125.9652	253.8375	137.9619	278.0125	99.4190

   b. Boundary conditions were defined as normal depth

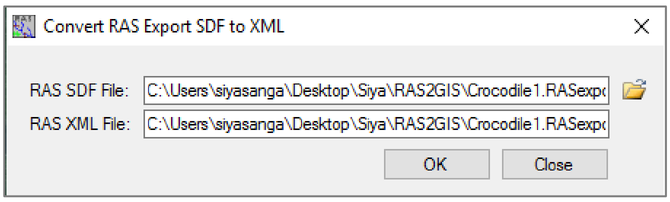


   c. 7 water surface profiles were computed

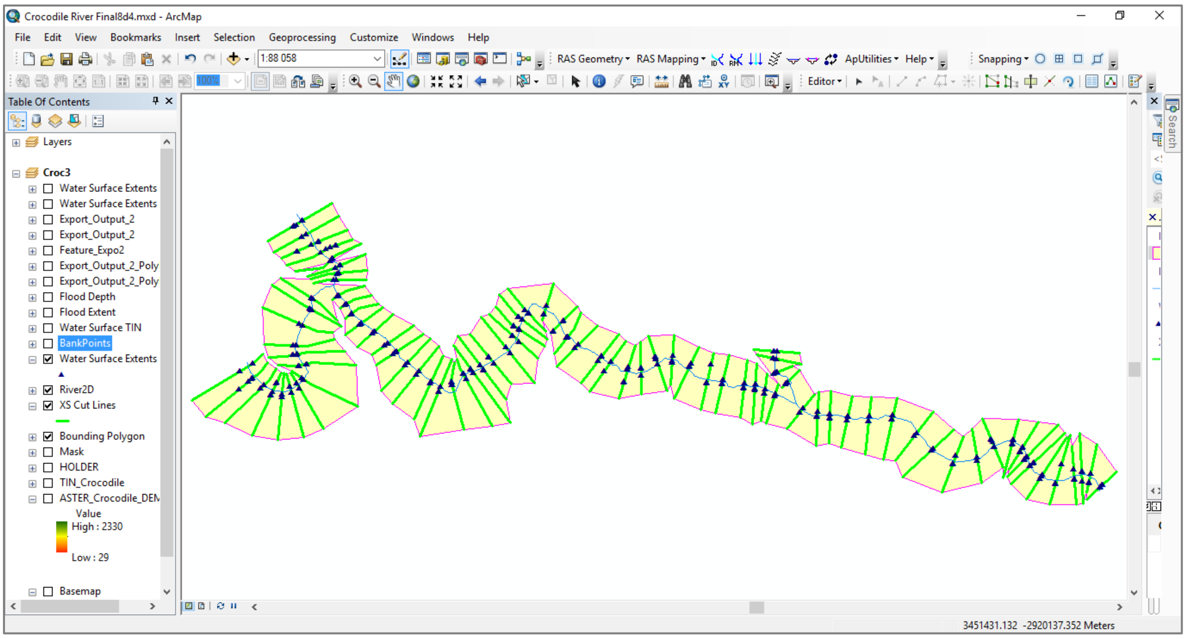
3. The HEC-RAS export file was developed.

STEP 3: HEC-GeoRAS Post-Processing

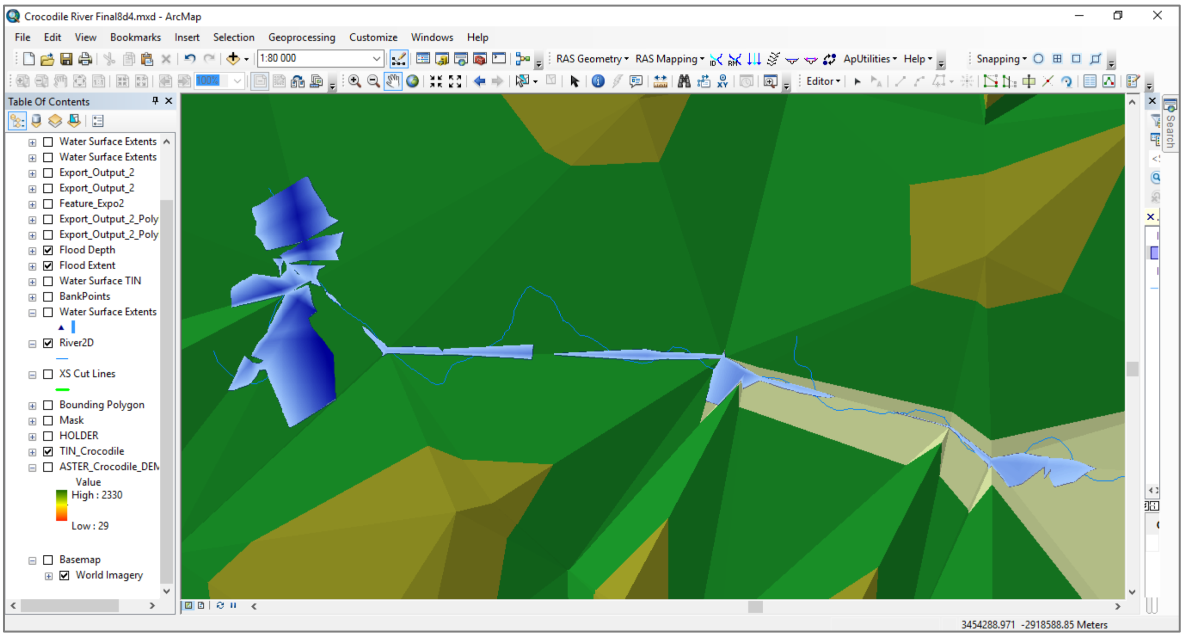
1. Converting the RAS SDF to XML using HEC-GeoRAS
2. Setup up GeoRAS to import the converted RAS data



3. Import the converted RAS data
4. Post-processing of RAS results and floodplain mapping using HEC-GeoRAS
    a. Developing Stream Network, Cross Section and Bounding Polygon

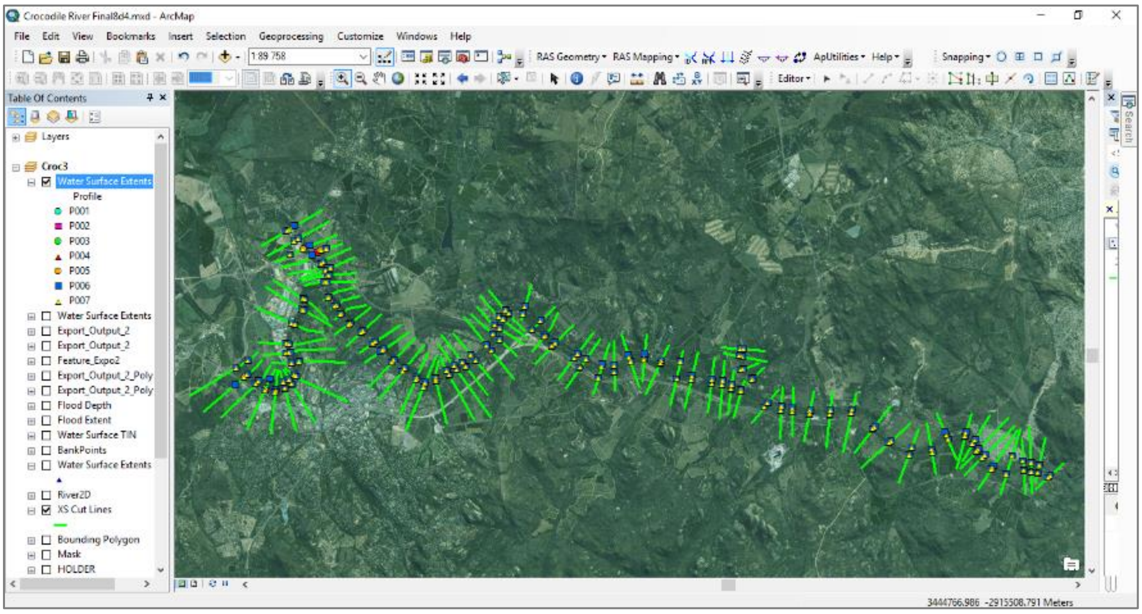


    b. Developing water surface and flood inundation polygons. The standard method (i.e. developing a water surface TIN and floodplain inundation polygon for each water surface profiles using HEC-GeoRAS) could not be used due to the resolution of the TIN (as discussed in Section 4.2.).

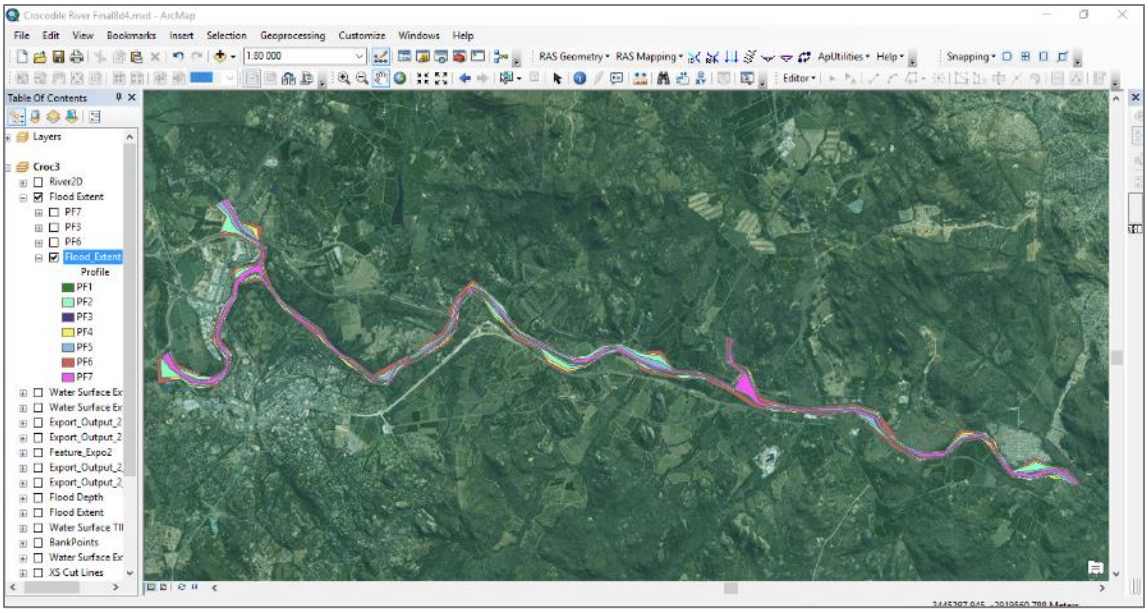


Using raster instead of TIN was not possible, as several challenges were experienced which could not be solved. Therefore, the water extent polygons (which are relevant for this dissertation) were created in ArcGIS manually by using following method:

i. Extract data from the water surface extent for all 7 water profiles



ii. Create polygons for each of the 7 profiles, joining the relevant water surface extent points



B.2 Spatial Risk Assessment

This process that was undertaken for the spatial flood risk assessment is provided in Section 4.5. Briefly, this involved:

1. Flood extent mapping – consisting of identifying the land use areas under the potential influence of a flood of a particular discharge. For this, vulnerability maps are prepared by clipping the land use themes of the floodplains with the flood area polygons for each of the flood events.
2. Identifying flood prone areas - For this, the flood risk maps are prepared by overlaying all the flood extent polygons with the land use map.
3. Spatial Risk Analysis - This involved the analysis of the likelihood of an area to be flooded - i.e. the likelihood of an area to be flooded by a particular discharge (shown by polygons). This was enabled by a risk rating exercise. ArcGIS enables the identification of different risk classes by shading polygons red for a high risk area, orange for medium risk, and green for low risk. As there were 7 profiles modelled, the risk categories were determined as follows.

Risk Categories		**Description**
Minimal		Intersected by 1 polygon
Low		Intersected by 2 polygons
Low-Medium		Intersected by 3 polygons
Medium		Intersected by 4 polygons
Medium-High		Intersected by 5 polygons
High		Intersected by 6 polygons
Very High		Intersected by 7 polygons

4. A flood risk assessment, which uses the risk categories above, as well as the discharge rates associated with the polygons, and describes the areas along the Crocodile River that are at risk. This is provided in Chapter 8.