DATA AVAILABILITY AND REQUIREMENTS FOR FLOOD HAZARD MAPPING IN SOUTH AFRICA

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Thesis presented for the degree of Master of Natural Sciences
at
Stellenbosch University

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December 2011

DECLARATION

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SUMMARY

Floods have been identified as one of the major natural hazards occurring in South Africa. A disaster risk assessment forms the first phase in planning for effective disaster risk management through identifying and assessing all hazards that occur within a geographical area, as required by the Disaster Management Act (Act No. 57 of 2002). The National Water Act (Act No. 36 of 1998) requires that flood lines be determined for areas where high risk dams exist and where new town developments occur. However, very few flood hazard maps exist in South Africa for rural areas. The data required for flood modelling analysis is very limited, particularly in rural areas. This study investigated whether flood hazard maps can be created using the existing data sources. A literature review of flood modelling methodologies, data requirements and flood hazard mapping was carried out and an assessment of all available flood-related data sources in South Africa was made. The most appropriate data sources were identified and used to assess an evaluation site. Through combining GIS and hydraulic modelling, results were obtained that indicate the likely extent, frequency and depth of predicted flood events. The results indicate that hydraulic modelling can be performed using the existing data sources but that not enough data is available for calibrating and validating the model. The limitations of the available data are discussed and recommendations for the collection of better data are provided.

KEYWORDS

Flood hazard mapping, data availability, geographic information system, hydraulic modelling

OPSOMMING

Vloede is van die vernaamste natuurlike gevare wat in Suid-Afrika voorkom. ‘n Ramprisiko-analise is die eerste stap in die proses van suksesvolle ramprisiko-beplanning deur middel van die identifisering en analise van alle gevare wat voorkom in ‘n geografiese gebied, soos vereis deur die Rampbestuurwet (Wet 57 van 2002). Die Nasionale Waterwet (Wet 36 van 1998) bepaal dat vloedlyne slegs vir gebiede waar hoë-risiko damme voorkom en vir nuwe uitbreidingsplanne in dorpe vasgestel moet word. Egter is die data wat vir vloedmodelleringsanalises benodig word baie skaars in Suid-Afrikaanse landelike gebiede. Hierdie studie het ondersoek of vloedgevaar-kartering met die beskikbare data moontlik is. ‘n Literatuurstudie oor vloedmodelleringsmetodologieë, data-vereistes en vloedgevaarkartering is voltooi en alle beskikbare vloed-verwante data in Suid-Afrika is geëvalueer. Geskikte data-bronne is gekies en gebruik om ‘n toetsgebied te assesseer. Deur GIS en hidrouliese modellering te kombineer, is die omvang, waarskynlikheid en diepte van die voorspelde vloedgebeurtenisse gemodelleer. Die studie het bevind dat, alhoewel vloedgevaarkartering met die beskikbare data moontlik is, daar nie genoeg data beskikbaar is om die model te kalibreer en te valideer nie. Tekortkominge van die bestaande data word bespreek en aanbevelings oor die verbetering van die bestaande data vir toepassings in vloedgevaarkartering word gemaak.

TREFWOORDE

Vloedgevaarkartering, data beskikbaarheid, geografiese inligtingstelsel, hidrouliese modellering

ACKNOWLEDGEMENTS

I would like to acknowledge and thank the following:

- My husband, Fritz Els, for always supporting and believing in me, and for making coffee. My two cats, Bob and Bugly, for keeping me company during the late hours.
- Elretha Louw, technical director and mentor at Aurecon, for her support, guidance and encouragement.
- Freeternity Rusinga, civil engineer at Aurecon, for all his time, patience and assistance with the technical aspects of this study.
- My parents for always supporting and believing in me, in their unique way.
- God, for giving me this opportunity.

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ACRONYMS AND ABBREVIATIONS

ADWR	Arizona Department of Water Resources
AMI	Active Microwave Instrument
ASCII	American Standard Code for Information Interchange
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BHS	British Hydrological Society
CAD	Computer-aided design
CBERS	China-Brazil Earth Resources Satellite
CCD	Charged-coupled device
CD: NGI	Chief Directorate: National Geo-spatial Information
CD: SM	Chief Directorate: Surveys and Mapping
CRED	Centre for Research on the Epidemiology of Disasters
CSA	Canadian Space Agency
CSAG	Climate Systems Analysis Group
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DEM	Digital elevation model
DIMP	Disaster Mitigation for Sustainable Livelihoods Programme
DTM	Digital terrain model
DWA	Department of Water Affairs
EC	European Community / Environment Canada
EMA	Emergency Management Australia
ENPAT	Environmental Potential Atlas
ENVISAT	European Space Agency Environmental Satellite
ERS	European Remote-sensing Satellite
ERSDAC	Earth Remote Sensing Data Analysis Center
ESRI	Environmental Systems Research Institute
ETM	Enhanced Thematic Mapper
FAO	Food and Agricultural Organisations (United Nations)
FEI	Finnish Environment Institute
FEMA	Federal Emergency Management Agency

GDEM	Global digital elevation model
GIS	Geographic information system
GLC	Global Land Cover
GLCF	Global Land Cover Facility
GMES	Global Monitoring for Environment and Security
GTOPO 30	Global 30 Arc-Second Elevation data set
HEC	Hydrologic Engineering Centre
HEC-RAS	Hydrologic Engineering Centre-River Analysis System
HEC-SAM	Hydrologic Engineering Centre-Spatial Analysis Methodology
HIS	Hydrological information system
HRSC	High Resolution Stereo Camera
IFSAR	Interferometric Synthetic Aperture Radar
ISDR	International Strategy for Disaster Reduction
ISRO	Indian Space Research Organisation
JRC	Joint Research Centre
LANDSAT	Land Remote-Sensing Satellite (System)
LIDAR	Light Detection and Ranging
MERIS	Medium Resolution Imaging Spectrometer Instrument
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multispectral scanner
NASA	National Aeronautics and Space Agency
NCWE	National Committee on Water Engineering
NGI	National Geo-spatial Information
NLC	National land cover
NOAA	National Oceanic and Atmospheric Administration
NRCAN	Natural Resources Canada
OGC	Open Geospatial Consortium
PEP	Provincial Emergency Program
RADAR	Radio Detection and Ranging
RAS	River Analysis System
RDBMS	relational database management system
S	South
SA	South Africa
SAC	Satellite Application Centre

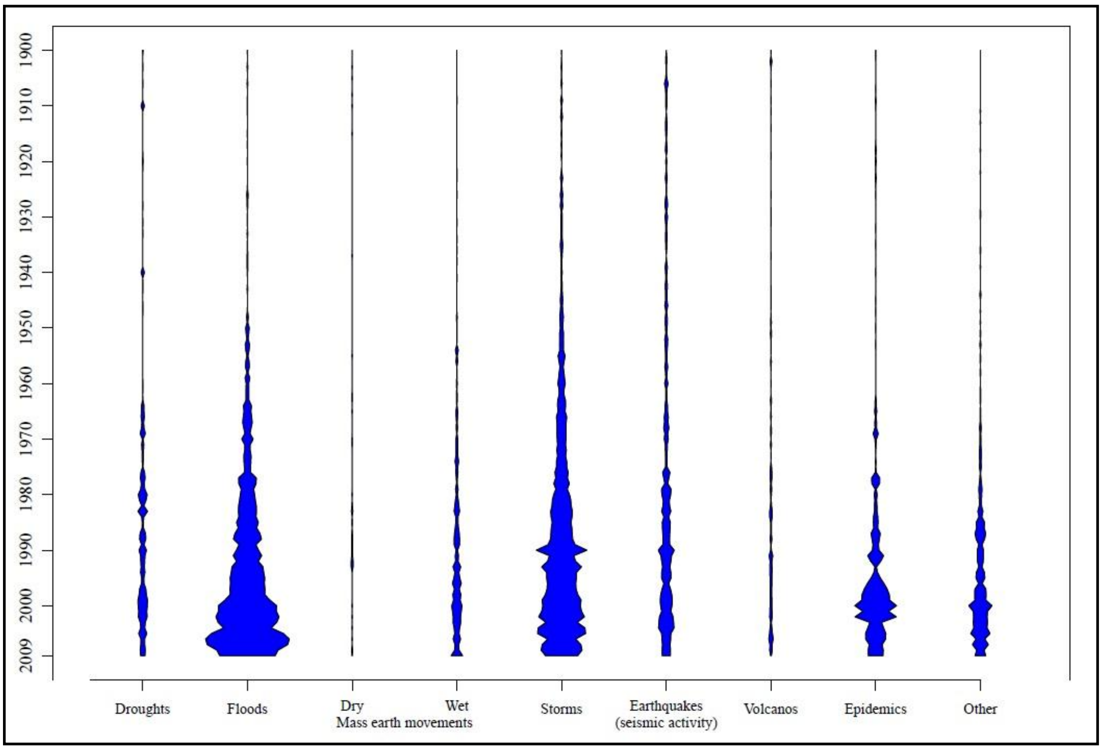
SANBI	South African National Biodiversity Institute
SANSA	South African National Space Agency
SAR	Synthetic aperture radar
SAWS	South African Weather Services
SDF	Spatial data format
SPOT	Satellite Probatoire d'Observation de la Terre
SRTM	Shuttle Radar Topography Mission Data
TIN	Triangular irregular network
TM	Thematic mapper
UCAR	University Corporation for Atmospheric Research
UN	United Nations
UNEP	United Nations Environment Programme
UNOOSA	United Nations Office for Outer Space Affairs
UN-SPIDER	United Nations Platform for Space-based Information for Disaster Management and Emergency Response
USA	United States of America
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal transverse Mercator
XML	Extensible mark-up language

CHAPTER 1: SETTING THE SCENE

1.1 INTRODUCTION

In recent years there has been a significant increase in floods around the world, both in developed and developing countries. Not only the frequency, but the severity of floods have increased to such an extent, specifically in developing countries, that 100-year floods are becoming annual occurrences (Alho et al. 2008; ISDR 2004; Klijn 2009; Shamaoma, Kerle & Alkema 2006; Wisner et al. 2004).

To date, floods are the most frequently occurring natural disaster (see Figure 1.1) with the greatest loss of life. Fatality during a flood hazard event is largely due to drowning and severe injury. The long term secondary effect is, however, more rigorous where affected communities are hampered by impacts such as disease and starvation (Pilon 2004; Watts 2007; Wisner et al. 2004).



Source: CRED (2010)

Figure 1.1 Number of natural disasters reported from 1900 to 2009

Economic losses due to floods are higher than for any other hazard (Pilon 2004; Wisner et al. 2004). Poor communities are more at risk due to the vulnerability of their livelihoods, especially in rural areas where access to services and infrastructure is limited (Garatwa & Bollin 2002; ISDR 2009b; Pilon 2004; Wisner et al. 2004).

It is becoming critical for governments to be proactive in reducing flood risk rather than reactive by providing post-disaster response and recovery (ISDR 2007; Pilon 2004). The first step towards a proactive model is to perform a flood risk assessment to identify the necessary disaster reduction policies required to reduce the risk (ISDR 2004; ISDR 2007).

A 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. The vulnerability is influenced by certain processes or factors (social, economic, environmental and physical) that make the community more susceptible to the impact of the hazard. Resilience refers to the capacity of an exposed community to adapt, resist or change in order to return to their normal functioning and structure. However, the resilience of a community is determined by its ability to reorganise its social systems according to lessons learnt from past experience, in order to reduce the risk of future flood events. At the same time, this capacity of a community is influenced by its available resources, including physical, institutional and economic means, and its ability to reduce the levels of risk (ISDR 2010a).

The first step in performing a flood risk assessment is to complete a hazard assessment that defines the flood hazard in terms of its frequency, magnitude, speed, onset, affected area and duration. This forms the foundation for any further assessments of flood risk parameters (ISDR 2004).

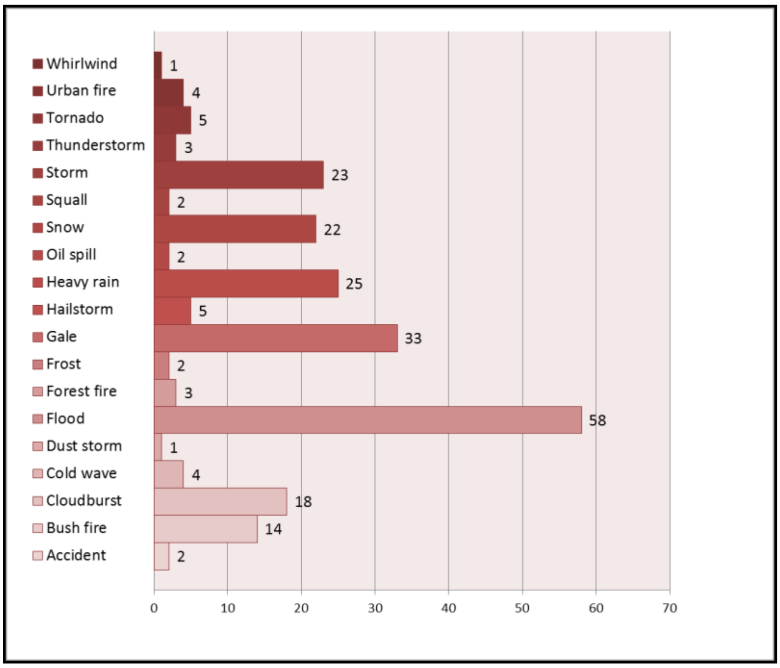
It is imperative for governments to ensure that flood risk assessments are performed for flood prone areas to enable them to implement risk reduction measures. This process must happen in consultation with the community and stakeholders, in order for them to better understand the implications of their actions in aggravating their risk (ISDR 2004; Pilon 2004).

Geographic information system (GIS) is a tool that can be used in every step of the flood risk assessments for visualisation, data management and modelling (Goodchild 2006; Robayo & Maidment 2005). Modelling is used to represent processes that occur within the real world. These processes can be natural (e.g. erosion, avalanche formation, floods) or social (e.g. traffic congestion, retail store location) (Heywood, Cornelius & Carver 2002; Longley et al. 2005). 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 (Klijn 2009; Pilon 2004).

1.2 PROBLEM FORMULATION

Floods have been identified as one of the major natural hazards in South Africa. This is due to the country’s semi-arid to arid climate (Van Oosterom, Zlatanova & Fendel 2005). In 2000 it was estimated that between 50 000 and 100 000 people in South Africa lived within flood-prone areas, most of them in, informal settlements. This statistic excludes people living within formal developments that were built below the 50 year flood line (Alexander 2000).

In the Western Cape, flooding is a common occurrence during winter (Halloway, Fortune & Chasi 2010; Halloway & Roomaney 2008). During the period 2003 to 2008, the province was hampered by ten significant flood disasters that varied between R4.9 million and R996 million in damages. The losses included destruction of infrastructure and loss of human life (Halloway, Fortune & Chasi 2010). Sakulski (2007) determined the number of hazardous events for each province for the period 1800 to 1995. The main data source for this study was the publication, *Caelum – A History of Notable Weather Events*, that was compiled by the South African Weather Services (SAWS) by recording all notable flood events per district. Fifty-eight flood events were recorded in the Western Cape during this period (see Figure 1.2). The Western Cape experience more floods than any of the other eight provinces in South Africa (Sakulski 2007).



Source: Sakulski (2007: 17)

Figure 1.2 Number of hazardous events for the Western Cape

The Western Cape is characterised by a Mediterranean climate with warm, dry summers and cool, wet winters. It is predicted that climate change could cause floods to increase due to fewer but more severe rainfall events (Midgley et al. 2005). Consequently, a flood hazard assessment is essential in any disaster risk assessment for regions in the Western Cape. Flood hazard mapping in the rural areas is limited to historical maps of floods, where available. These historical maps often consist of lines on 1:250 000 topographic map sheets showing the extent of a flood, drawn by the relevant Department of Water Affairs (DWA) officer for the region.

The DWA is responsible for guidance in water related disasters, such as floods, as it is the principal state organisation responsible for water resource management within South Africa (South Africa 1998). Hundred-year flood line maps are, however, only required for high risk dams and for new developments in towns (National Water Act 36 sections 121 and 144).

The data required for flood modelling is often not available, or is of inadequate quality. This is specifically a problem in developing countries such as South Africa (Osti 2008; Shamaoma, Kerle & Alkema 2006; Zimmermann 2008). Data limitations determine the flood modelling methodology to be used, as higher quality data allows for the application of more sophisticated modelling techniques. With better data, more accurate and larger scale flood modelling results can be obtained. This will permit the application of risk reduction measures at a very detailed level.

There is a need to determine if flood modelling can be completed with the existing data sources in South Africa. This can be done through considering the different flood modelling methodologies available and their specific data requirements. A thorough evaluation of the available data in South Africa needs to be completed and the most appropriate data should be selected based on the most appropriate flood modelling approach. The resulting flood hazard maps should be evaluated to identify any shortcomings and, if needed, additional data requirements should be recommended.

1.3 AIMS

The aim of this study is to evaluate the existing data sources that are available for flood hazard mapping in South Africa and to demonstrate how flood modelling can be carried out using this data.

1.4 OBJECTIVES

The research objectives are to:

1. Review the literature on disaster risk management, floods, flood hazard mapping, and different types of existing flood modelling methodologies.
2. Determine the minimum data requirements for flood modelling and carry out an assessment of available data in South Africa.
3. Carry out flood modelling for a test site using available data.
4. Evaluate the flood mapping results and make recommendations about alternative data sources and methods.

1.5 RESEARCH DESIGN

This research is investigative and experimental in nature, with the intended outcome being an evaluation of existing data sources for flood modelling in South Africa. A combination of primary and secondary data will be collected and used to implement an existing hydraulic model for a test site. Due to a lack of suitable reference data, the evaluation is based on qualitative methods only.

The research design is shown in Figure 1.3. Literature regarding disaster risk management, floods, GIS and flood modelling is overviewed in Chapters 2 and 3. Focus is placed on flood hazard mapping requirements and the different flood modelling approaches for identifying the best flood modelling methodology.

Chapter 4 assesses the available data in South Africa for flood modelling. The most appropriate data are identified, based on resolution/scale and coverage.

In Chapter 5, the data sources identified in Chapter 4 will be used to select an appropriate test site in the Western Cape. This is followed by the implementation of the most appropriate flood modelling methodology, given the available data.

Chapter 6 evaluates the resulting flood hazard maps and identifies possible shortcomings and limitations of the available data. The chapter concludes with recommendations for additional data sources.

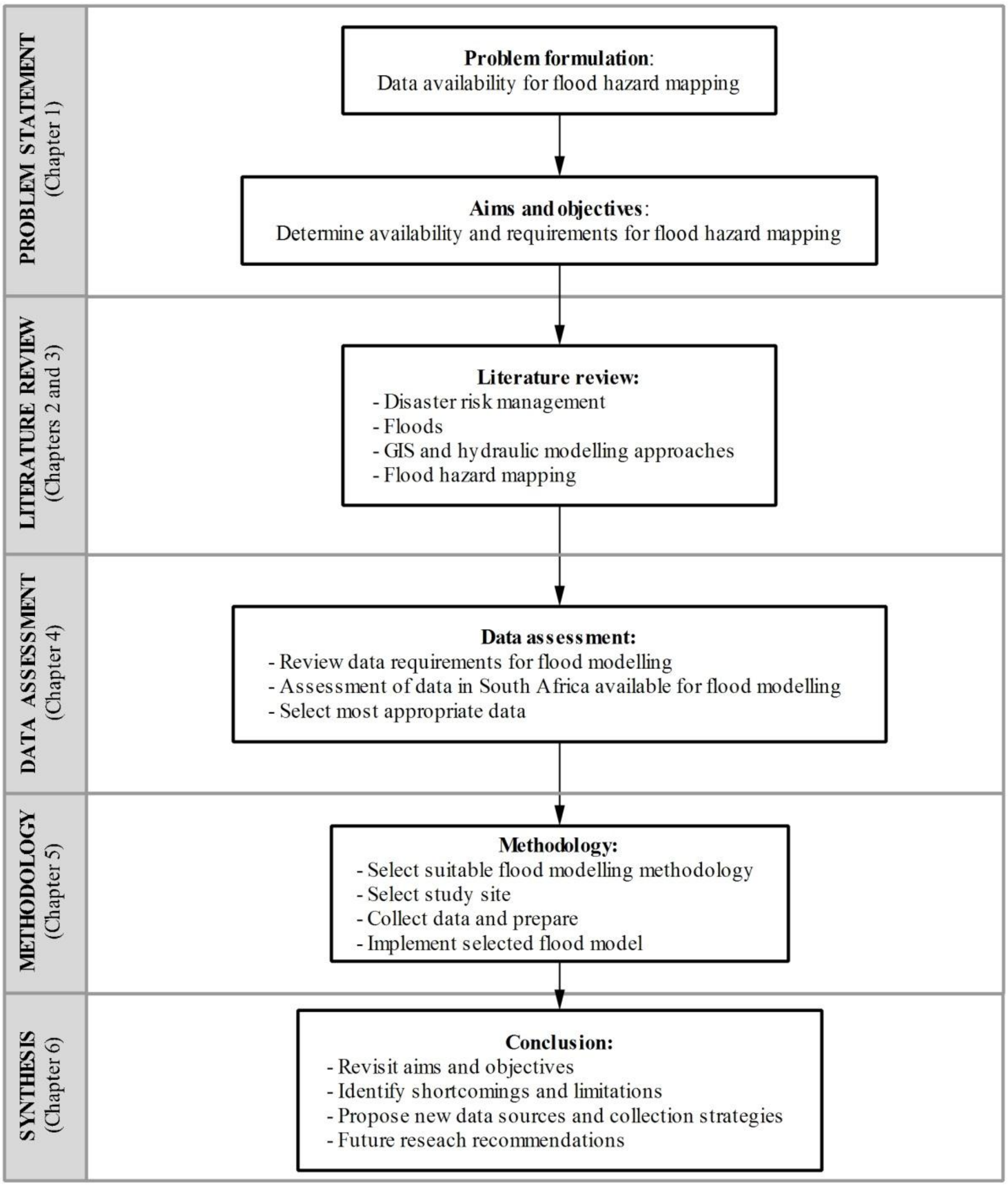


Figure 1.3 Research design

The relevant literature about floods and disaster risk management are reviewed in the next chapter. The literature review focuses on basic definitions and concepts in the disaster management environment and flood as a natural hazard. Further aspects with regards to flood risk mapping are discussed by considering the types and requirements for disaster management purposes.

CHAPTER 2: FLOODS AND DISASTER RISK MANAGEMENT

This chapter explores the parameters of flood hazard mapping by reviewing various definitions and terminology used within the disaster management environment. This is followed by an overview of flood hazards by considering the causes of floods, the factors that increase their severity and impact.

2.1 DISASTER RISK MANAGEMENT

2.1.1 Definitions and terminology

It is important to be familiar with and understand the terms and terminology used in disaster risk management in view of the fact that this study forms part of a succession of processes towards the reduction of risk. The definitions and terminology provided by the International Strategy for Disaster Reduction (ISDR) are the most widely used, but other definitions and terminologies are also included for a more comprehensive overview. Particular emphasis will be placed on natural hazards, as floods fall within this category.

2.1.1.1 Hazards

A hazard is defined by the ISDR (2009a:17) as: “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.” Furthermore, hazards are restricted to natural events that contain a probability of having negative consequences. Only a few hazards, for example earthquakes, are truly natural hazards (ISDR 2009a; Vos et al. 2010). Other hazards such as floods, veld fires and landslides are categorised as a socio-natural or unnatural hazards where human behaviour aggravates the original natural disaster (ISDR 2009a; EMA 2006).

The onset of a hazard can be sudden or slow and it can be classified according to its origin (ISDR 2009a). The classification includes:

- natural hazards, referring to natural processes that occur within the biosphere (e.g. floods and volcanoes);

- technological (anthropogenic) hazards, which originate from technological or industrial conditions, including accidents, infrastructure failure or specific human activities (e.g. industrial pollution, nuclear radiation and dam failures); and
- environmental hazards, which involve processes started by human activities and behaviours that alter or damage natural processes or ecosystems negatively (e.g. land degradation, deforestation and climate change).

Natural hazards are discussed in more detail in the following section.

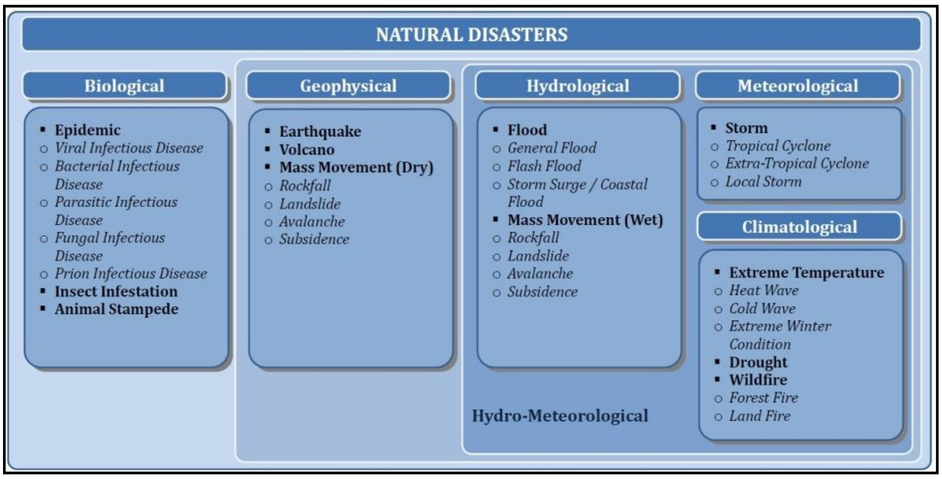
2.1.1.2 Natural hazards

Natural hazards refer to hazards that are natural processes or phenomena, such as climatological, hydrological or geological processes within the biosphere (South Africa 2005) that can cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental degradation (ISDR 2009a). The extent of these natural hazards is influenced by the anthropogenic activities that include environmental degradation and urbanisation (The World Bank 2010).

Natural hazards can be further divided into three categories, namely (ISDR 2010b):

- geological hazards, which refer to processes of endogenous, tectonic or exogenous origins, such as mass earth movements;
- hydro-meteorological hazards, referring to processes of atmospheric, hydrological or oceanographic nature; and
- biological hazards, which are processes of organic origin or those conveyed by biological vectors, including exposure to pathogenic micro-organisms, toxins and bioactive substances.

Vos et al. (2010) subdivides hydro-meteorological hazards into three separate sub-categories, namely meteorological, hydrological, and climatological hazards. A classification of natural hazards is shown in Figure 2.1.



Source: Vos et al. (2010: 7)

Figure 2.1 Natural hazard classification

Meteorological events are defined as short/small to meso scale atmospheric processes (for example a storm) where hydrological hazards include all events caused by the deviation in the normal water cycle and/or overflow of bodies of water due to severe wind (for example flood). Climatological hazards refer to meso to macro scale processes that include climate changes between seasons and decades, for example drought and extreme temperature (Vos et al. 2010).

2.1.1.3 Disaster

A disaster is 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 (ISDR 2009a).

The Disaster Management Act (2002:6) (South Africa 2003) states that a disaster is “a progressive or sudden, widespread or localised, natural or human-caused occurrence which:

- causes or threatens to cause
    - loss of life;
    - disease;
    - damage to property, infrastructure or the environment; or
    - disruption of the life of a community; and
- of magnitude that exceeds the ability of those affected by the disaster to cope with its effects using only their own resources.”

Disasters are often mistaken for a occurrences that are sudden and without warning (e.g. floods) but disasters can develop over a long period of time, like drought and environmental degradation (Amin & Goldstein 2008; ISDR 2009a).

Attention must be given to the interaction between disasters and hazards. Not all hazards result in a disaster. If a hazard damages the lives and livelihoods of a community to such an extent that they are unable to cope, then the hazard has become a disaster (Amin & Goldstein 2008; Hossini 2008; Venton & Hansford 2006).

2.1.1.4 Vulnerability

Vulnerability refers to the level at which an individual, community, environment, property, infrastructure, industry and resource can be negatively affected by a hazard (PEP 2004; South Africa 2003). The conditions that increase the vulnerability of a community are determined by environmental, social, economic and physical processes (ISDR 2010a; Venton & Hansford 2006). Venton & Hansford (2006) define vulnerability as the inability to adequately anticipate, withstand and recover from the effects of a hazard.

2.1.1.5 Capacity to cope

Capacity to cope refers to the ability of communities to use the resources available to them to reduce the negative effects of a hazard (ISDR 2010a). Wisner et al. (2004) define coping capacity as the way that communities act within the available resources and expectations to reduce the adverse effects of a hazard. Resources can include physical and social means that provide access to livelihood and safety (Wisner et al. 2004). Managing of these resources is a continuous process that takes place before, during and after a hazard (ISDR 2010a).

2.1.1.6 Risk

A risk is the probability that harmful consequences or loss can occur due to interactions between natural and anthropogenically induced hazards (ISDR 2010a). The expected loss due to risk includes death, injuries, damage to property and livelihoods, disruption in economic activity and environmental damage (ISDR 2004; PEP 2004). Risk can be defined as a function of hazard, vulnerability and coping capacity (Baas et al. 2008; Botha & Louw 2004; Boudreau 2009; Hossini 2008):

$$R = \frac{H \times V}{C}$$ Equation 2.1

where R is the risk;
H is the hazard;
V is the vulnerability; and
C is the coping capacity.

Previously, risk was determined by a simple formula referring to the product of hazard and vulnerability. However, since communities have the capacity to respond and protect themselves from the effects of hazards, the coping capacity parameter had to be integrated into the existing function (Baas et al. 2008; Botha & Louw 2004; Boudreau 2009).

2.1.1.7 Disaster Management

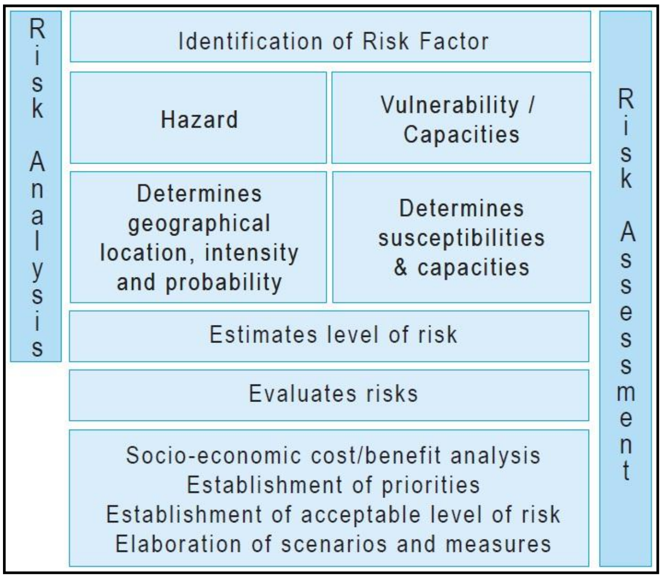
The Disaster Management Act of South Africa (2002: 6) (South Africa 2003) defines disaster management as: "a continuous and integrated multi-sectoral, multi-disciplinary process of planning and implementation of measures aimed at:

- preventing or reducing the risk of disasters;
- mitigating the severity or consequences of disasters;
- emergency preparedness;
- a rapid and effective response to disasters; and
- post-disaster recovery and rehabilitation."

The prevention and reduction of the risk of disasters is one of the objectives that need to be obtained through disaster management (South Africa 2003). Disaster risk management is a structured process where a series of measures are put in place to reduce the impacts of hazards and related disasters. These measures either aim to avoid hazards though prevention or to limit the hazard impact through mitigation and preparedness (ISDR 2010a). Measures can include implementation policies, strategies and the development of the coping capacities of the society and community (ISDR 2010a) through programmes, projects and/or measures and instruments (Garatwa & Bollin 2002).

2.1.1.8 Disaster risk assessment

A risk assessment aims to quantify all the parameters of a risk, namely hazard, vulnerability and coping capacity, for each potential hazard in a region, in order to determine the extent and nature of that risk (ISDR 2010a). The risk assessment forms the first phase in planning an effective disaster risk reduction plan (ISDR 2004; South Africa 2005). Quantitative and qualitative analyses of all possible risks are done in order to understand its physical, social, economic and environmental factors and consequences (ISDR 2004), and thus to prioritise the risk (Baas et al. 2008; South Africa 2005). The implementation of a risk assessment consists primarily of three individual assessments (see Figure 2.2) (ISDR 2010a; South Africa 2005; Venton & Hansford 2006).



Source: ISDR (2004: 63)

Figure 2.2 The risk assessment process

A hazard assessment identifies and analyses potential hazards for a region (Bründl et al. 2009; Garatwa & Bollin 2002; South Africa 2005). It is a thorough and technical study of the nature and behaviour of the hazard by reviewing the location, severity, frequency, probability (Bründl et al. 2009; ISDR 2010a; South Africa 2005), speed of onset and duration (Venton & Hansford 2006) of the potential hazard. The vulnerability assessment is completed next. It analyses the processes (e.g. the physical, social, economic and environmental processes) that increase the conditions of vulnerability. This is followed by a capacity assessment where the various resources available to the community to reduce the effect of the hazard are assessed. The results obtained from the individual assessments are combined to determine the level of risk for different situations and thus to set priorities for action (ISDR 2010a; South Africa 2005).

2.2 FLOODS

2.2.1 Definitions and terminology

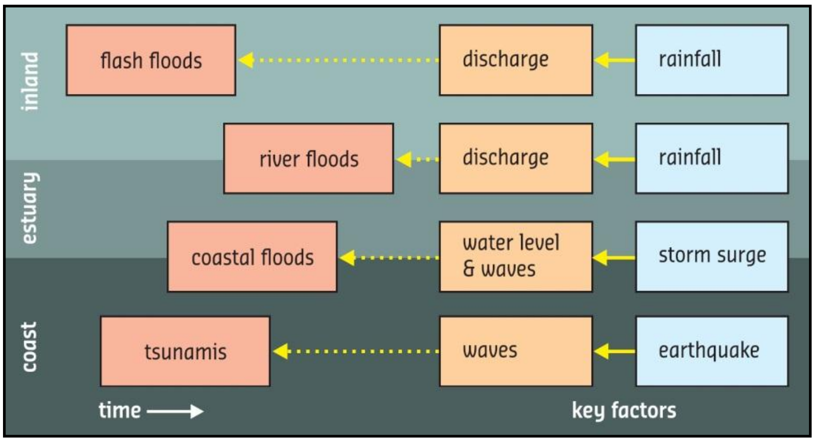
2.2.1.1 Floods

A flood is a natural hazard that can be categorized as hydro-meteorological (Section 2.1.1.2). Floods are defined as the temporary inundation of normally dry land areas resulting from the overflowing of the natural or artificial confines of a river or other body of water, including groundwater (EC 2009a; Klijn 2009; Martini & Loat 2007; Wisner et al. 2004). Hydrologists define floods as a sudden peak in the water level due to a sudden increase in discharge. The water level will drop back to near-constant base flow (or no flow) once the flood has passed (Alexander 2000). Martini and Loat (2007) summarise flooding as the existence of water and/or sediments at unwanted places outside the watercourse.

2.2.1.2 Types of floods

Floods can be described according to the water source (origin), geography of receiving area, 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). These major floods types will each be described in terms of its geography, cause and onset speed (see Figure 2.3).

Coastal or marine floods (see Figure 2.3) are caused by severe coastal storms with large waves that flood coastal areas and estuaries with sea water (EC 2009b; Halloway & Roomaney 2008; Klijn 2009; Martini & Loat 2007; Wright 2008). Large areas are usually affected and huge losses in human life and livelihoods can be experienced. The onset of coastal storms can usually be forecast between days to a few hours ahead (Klijn 2009) while possible sea level rise can occur within four to eight hours after the storm surge has started (Wright 2008). Coastal flooding is accompanied by large, battering waves and floating debris that result in beach erosion and extensive damage to infrastructure along the coast (Wright 2008).



Source: Klijn (2009: 16)

Figure 2.3 Types of floods described according to origin, geography, cause and onset

Riverine (fluvial) floods (see Figure 2.3) are caused by long periods of rain in the catchment area that result in an increase of the water level of the river and the overflow of river banks (EC 2009b; Halloway & Roomaney 2008; Martini & Loat 2007; Wright 2008). It is a slow-onset flood restricted to flood plains (Wisner et al. 2004; Wright 2008) that is characterised by slow velocities and large inundated areas that can cause huge damage but few fatalities (Klijn 2009).

Flash floods (see Figure 2.3) occur at hilly, upper reaches of river basins during intense rainstorms (Klijn 2009; Wright 2008). Although flash floods are a subtype of riverine flooding (Wisner et al. 2004; Wright 2008), they are often considered separately due to the high fatalities and severe damages they can cause. Klijn (2009) refers to flash floods as “small-scale killers” as they are small floods that can occur frequently. The high velocity and debris load of flash floods (Martini & Loat 2007; Wright 2008) and the difficulty in forecasting them (Klijn 2009) make early warning and evacuation very difficult.

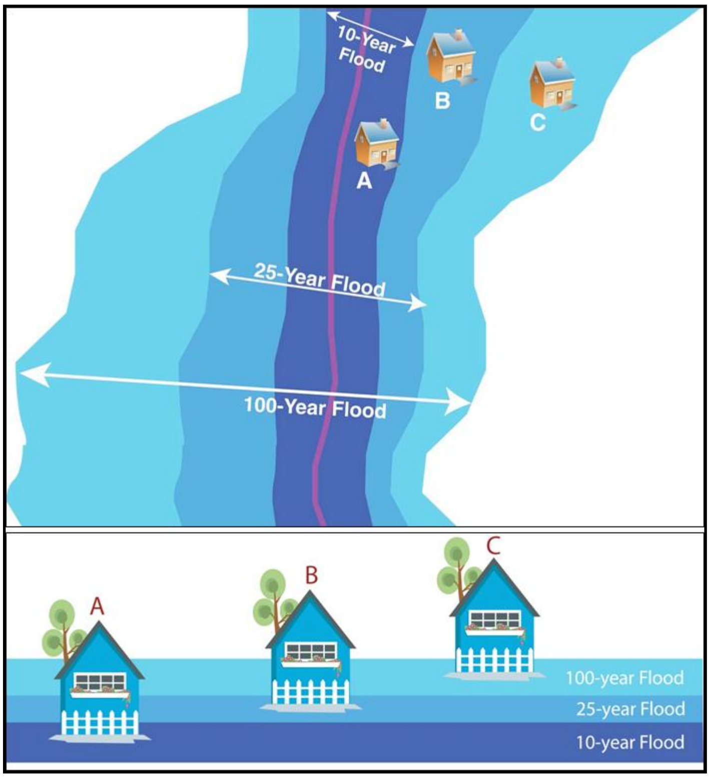
Ponding (pluvial) floods are caused by the accumulation of rain water in low-lying areas with clay type soils (EC 2009b; Halloway & Roomaney 2008; Hankin et al. 2008; Klijn 2009). These floods have a slow onset and can be forecast days ahead, although they can cause major damage, especially in urban areas, but rarely with fatalities (Klijn 2009).

Urban flooding occurs mainly due to limited drainage for rain water in urban areas although flash floods, coastal floods or river floods, can also cause urban flooding (EC 2009b; Klijn 2009; Wright 2008). These floods can occur suddenly and are characterised by rapid runoffs and high velocities (Klijn 2009).

Groundwater floods (seepage) are caused by water rising to the ground surface due to a high water table (Halloway & Roomaney 2008; Hankin et al. 2008; Klijn 2009).

2.2.1.3 Probability (1/100, 1/50 or 1/5)

Frequency analysis is used to determine the probability of the occurrence of a given flood event. The recurrence interval (or return period) is based on the inverse of the probability that the given flood event will occur once or more in any given year (Baer 2008; Haarhoff & Cassa 2009; USGS 2009; Wright 2008), or the average interval between flood events that equal or exceed a given magnitude or severity (Görgens 2003). The recurrence interval is a statistical average for annual recurrence and not the number of years between flood occurrences of the same magnitude (Haarhoff & Cassa 2009; NOAA 2009; Wright 2008). Figure 2.4 indicates the probability for a 100-, 25- and 10-year flood line for a river.



Source: Wright (2008: 33)

Figure 2.4 Floodplains for different probabilities (10-, 25-, and 100-year)

Hydrologists select the flood event with the largest peak discharge for each year. The remaining high flood peaks for one year are ignored even if they are higher than the maximum peaks in the previous years. An analysis is then performed on the peak discharge per year for a given period (e.g. 30 years). The result, the Annual Exceedance Probability, is expressed as the relationship between the peak discharge and the probability that this discharge will be exceeded in any one year (Alexander 2000; Görgens 2003). This interval is specified as the number of years, T, and expressed as "1 in T-year event". Thus, the probability that the 1:T year event will be equalled or exceeded in any particular year is 1/T (Görgens 2003; Haarhoff & Cassa 2009; Wright 2008). The most often used recurrence intervals and probabilities of occurrences are shown in Table 2.1.

Table 2.1 Recurrence intervals and probabilities of occurrences

Recurrence interval, in years (t)	**Probability of occurrence each year (1 in t years)**	**Percent chance of occurrence each year (1/t *100)**
500	1 in 500	0.2%
100	1 in 100	1%
50	1 in 50	2%
25	1 in 25	4%
10	1 in 10	10%
5	1 in 5	20%
2	1 in 2	50%

Source: NOAA (2009) and USGS (2009)

If a 500 year recurrence interval is considered (see Table 2.1), the probability of occurrence is "1 in 500 years" and the percentage chance of occurrence is 0.2 percent.

2.2.1.4 Flood-prone areas

The areas along a river prone to flooding can be divided into different zones, namely the floodplain and floodway. The floodway can be identified by high flow velocities, deep water levels and the presence of debris flow with possible erosion. No development should take place in the floodway and only critical infrastructure such as bridges should be allowed within (ISDR 2004; Wright 2008).

A floodplain represents all areas surrounding the river channel (or floodway) that can be inundated during the occurrence of a flood (FEMA 2008; Wright 2008). There exists no definable boundary for a floodplain as there is no limit to the magnitude of a flood. The probability of inundation decreases as the elevation of a point on the floodplain increases (Alexander 2000). Figure 2.4 indicates a floodplain (also called flood hazard zone) and flood lines for various probabilities for a watercourse.

A flood line is only a line that defines an area in which no development should take place as it is an indication of the water level of a flood with a specified annual exeedance probability (Alexander 2000).

2.2.2 Primary and secondary impacts of flooding

Pelling et al. (2004) estimates that 196 million people in more than 90 countries are exposed to catastrophic flooding every year. Floods have a negative influence on communities and their surrounding environment and can be severe and disruptive to their daily functioning. The following negative effects can arise due to flooding (EC 2009b; Halloway & Roomaney 2008; Klijn 2009; Shulze 2003):

- health problems (increase in the spreading of diseases, e.g. diarrhoea or leptospirosis);
- injuries and death;
- damages and loss to infrastructure such as roads, bridges and telephone lines;
- damages and loss to settlements;
- temporary or permanent closure of businesses and industries;
- financial services cost for insurance and reinsurance;
- isolation of communities due to damaged roads and bridges;
- disruption of water supply;
- damage to agricultural land and crops; and
- damage to ecosystems.

An increase in the occurrence and severity of floods can be ascribed to the contribution of climate change and the tendency by humans to live in flood prone areas (Halloway & Roomaney 2008; Klijn 2009; Wisner et al. 2004). Despite all the negative effects that can occur due to flooding, communities still relocate back to flood prone areas as rivers are vital to their livelihoods. People relocate to floodplain areas to (Schulze 2003; Wisner et al. 2004; Wright 2008):

- utilise the rich soil for agricultural purposes;
- use the river for transport;
- safely access water for household purposes; and

- use the flat plains to establish settlements.

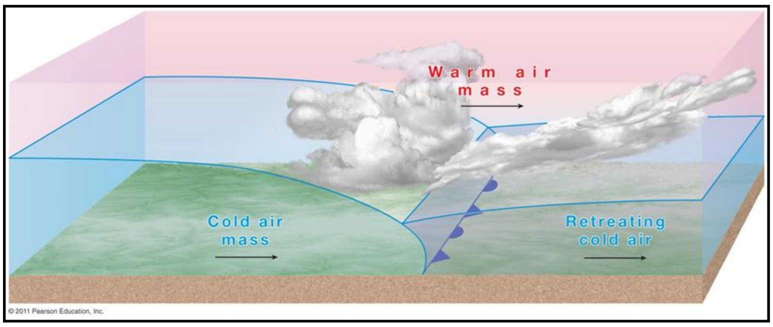
More proactive approaches are now embraced where a “living with flood” approach has been adopted. The aim is to understand the river systems and their processes, and why floods occur (Wisner et al. 2004; Wright 2008).

2.2.3 Causes of floods

Floods can occur due to meteorological, partly meteorological or other causes. Meteorological causes include snowmelt, rain, combined rain and melt, and ice melt. Coastal storm surges and estuarine interactions between stream flow and tidal conditions entail the partly meteorological causes (Alexander 2000; EC 2009b; Smithson, Addison & Atkinson 2002). The remaining causes of floods can be attributed to other natural hazards (e.g. earthquakes, landslides) or human-caused (technological) hazards (e.g. dam breaks, failing levees, etc.) (EC 2009b; Wisner et al. 2004). Weather systems that are mainly responsible for flooding in South Africa are discussed in more detail in the following sections.

2.2.3.1 Intense mid-latitude cyclone systems

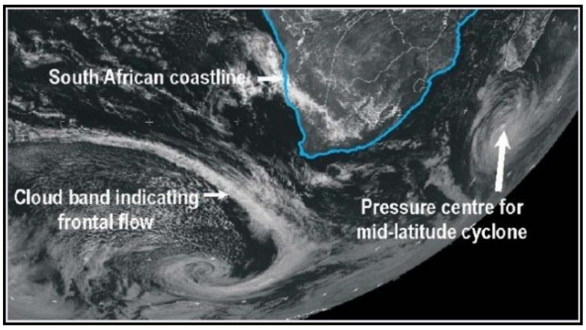
A mid-latitude cyclone is a low pressure system that develops in the mid-latitudes and moves in an easterly direction. They occur together with cold fronts that create a cold mass of air in front of warmer air (see Figure 2.5) (Alexander 2000; CSAG 2011; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000).



Source: McKnight &Hess (2007: 179)

Figure 2.5 The formation of a cold front

This moving mass of warm air forces cold air to rise, causing a very unstable atmosphere, resulting in rain (Alexander 2000; CSAG 2011; Haarhoff & Cassa 2009; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000). Cyclones are mostly responsible for the winter rainfall in the Western Cape and are associated with gale force winds and snow on high lying areas (see Figure 2.6) (Alexander 2000; CSAG 2011; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000).



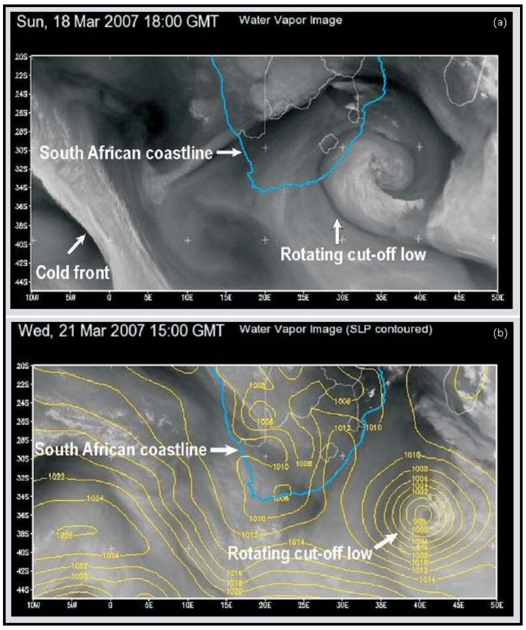
Source: Halloway, Fortune & Chasi (2010: 19)

Figure 2.6 Mid-latitude cyclone and cold front (frontal low)

Figure 2.6 shows the low pressure system moving to the east, followed by the cold front that represents the area between the cold mass behind it and the warmer air in front (Halloway, Fortune & Chasi 2010; McKnight & Hess 2007).

2.2.3.2 Cut-off low and ridging high pressure systems

Historically, most of the major floods in South Africa have been 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; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000). Figure 2.7a shows the occurrence of a cut-off low on 18 March 2007.



Source: Halloway, Fortune & Chasi (2010: 18)

Figure 2.7 Water vapour images of cut-off lows across South Africa: (a) 18 March 2007, (b) 21 March 2007

A cut-off low can remain stationary for days as it loses all momentum during the detachment from the westerly flow as seen in Figure 2.7b, where the system is still present three days after it occurred. 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; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000). The Laingsburg floods are an example of a major flood event that occurred in 1981 due to a cut-off low pressure system, among other causes (CSAG 2011; Tyson & Preston-Whyte 2000).

2.2.3.3 Tropical cyclones

Tropical cyclones (called cyclones in the Indian Ocean, typhoons in the Pacific Ocean, and hurricanes in the Atlantic Ocean) have a closed low pressure circulation with a pressure gradient that increases from the centre to the periphery of the system (CSAG 2011; McKnight & Hess 2007; Tyson & Preston-Whyte 2000). They are also considered as the opposite of mid-latitude cyclones (CSAG 2011). Tropical cyclones are formed from small clusters of convection clouds over the tropics and energy from high sea surface water temperatures (Alexander 2000; Haarhoff & Cassa 2009; Tyson & Preston-Whyte 2000). This causes extremely strong winds, huge waves and abnormal high tides along the coastlines (CSAG 2011; McKnight & Hess 2007; Tyson & Preston-Whyte 2000).

Tropical cyclones begin over the eastern Indian Ocean, east of Madagascar, and then move into a westerly direction (Alexander 2000; Tyson & Preston-Whyte 2000). Figure 2.8 shows the tropical cyclone Cela that travelled down the Mozambique Channel from Madagascar during 15 December 2003 (NOAA 2010).

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 & Preston-Whyte 2000). Tropical cyclones usually occur in the summer months and influences the KwaZulu-Natal and Mpumalanga regions (CSAG 2011).

Source: NOAA (2010)

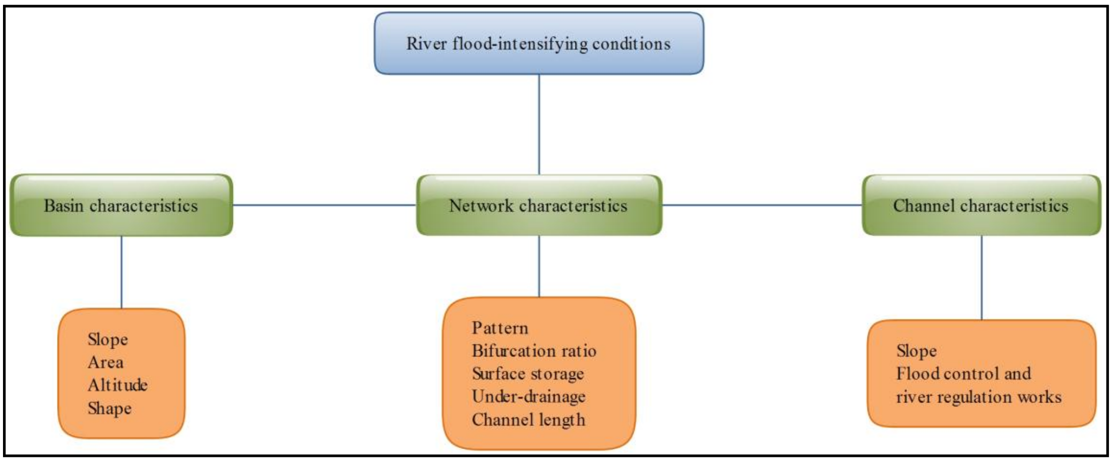
Figure 2.8 Tropical cyclone Cela (15 December 2003)

2.2.3.4 Convective storms

A convective storm is formed when air moves upward due to the heating of the earth surface and the lower atmosphere. Cumulonimbus clouds are formed when the rising air cools down, resulting in a thunderstorm. 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 (Alexander 2000; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000). It seldom causes major floods but these can occur (Alexander 2000; Halloway, Fortune & Chasi 2010; Tyson & Preston-Whyte 2000). Convective storms often occur with other severe weather conditions (e.g. lightning, hailstorms, and tornadoes) (Halloway, Fortune & Chasi 2010; McKnight & Hess 2007).

2.2.4 Factors that influence the severity of riverine floods

The severity of riverine floods is determined by the characteristics of the catchment area, the drainage network and the river channel (Görgens 2003; NCWE 2010; Smithson, Addison & Atkinson 2002). These characteristics exist within a closed system within which there exist relationships and interactions (NCWE 2010; Smithson, Addison & Atkinson 2002). Figure 2.9 depicts these and other characteristics schematically. These characteristics are discussed in more detail in the following sections.



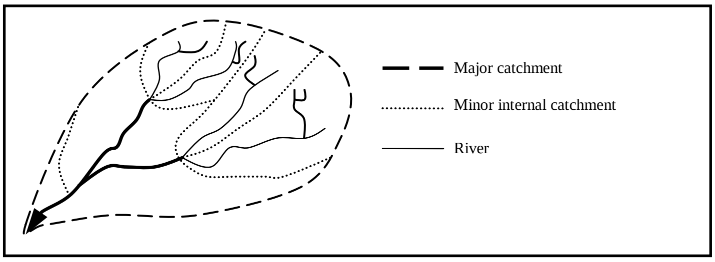
Adapted from: Smithson, Addison & Atkinson (2002: 88)

Figure 2.9 Conditions influencing the severity of riverine flooding

2.2.4.1 Catchment characteristics

A catchment (basin) is defined as an area of any size that drains into a river, stream, lake or any other water body (Goudie & Viles 2005; Hill & Verjee 2010; International Rivers 2009). A catchment starts 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 & Verjee 2010; International Rivers 2009).

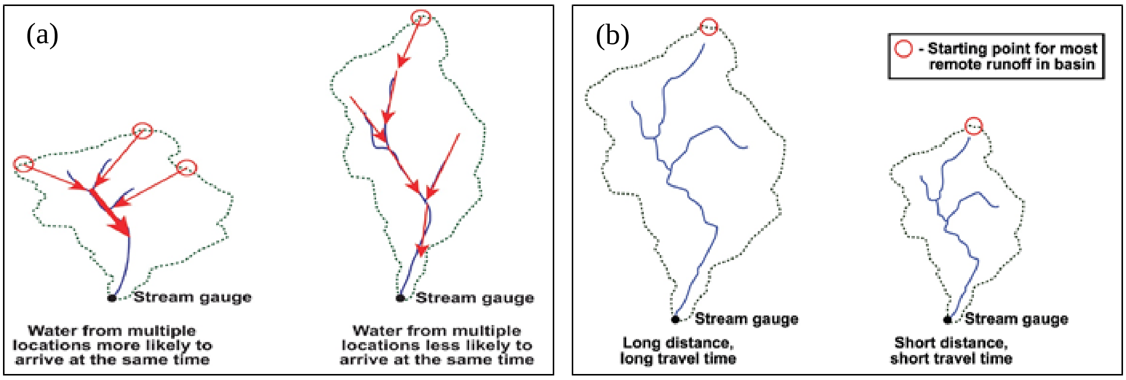
A hierarchy exists between the catchments nested within the major catchment. The catchments are categorised by area, from large to small, as primary, secondary, tertiary and quaternary, as depicted in Figure 2.10 (ENPAT 2001a; Haarhoff & Cassa 2009; McKnight & Hess 2007).



Source: White, Mottershead & Harrison (1992: 237)

Figure 2.10 Delimitation of catchments

Water flow within basins is determined by the characteristics of the basin, such as area, shape and slope (Hill & Verjee 2010; Smithson, Addison & Atkinson 2002). The shape (see Figure 2.11a) of the basin will also influence the surface runoff. When two basins with different shapes but equal areas are considered, the 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 & Verjee 2010; Smithson, Addison & Atkinson 2002).



Adapted from: Hill & Verjee (2010: 15)

Figure 2.11 Influences on runoff: (a) shape and (b) area

The larger the area (see Figure 2.11b) of a basin, the more surface runoff can be expected during a rainfall event. If two differently sized basins with similar shapes are considered, the travel time for the surface runoff from the furthest point would be less for the smaller basin than for the larger one. Thus, the smaller the basin, the more susceptible to floods it becomes (Hill & Verjee 2010; Smithson, Addison & Atkinson 2002).

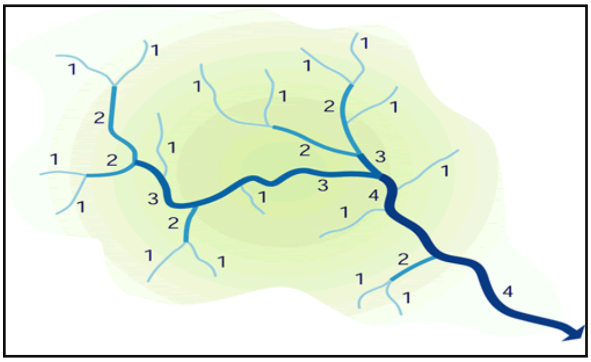
The speed of the surface runoff and the infiltration is determined by the basin slope. Increasing slopes cause the infiltration rate to decrease while the speed of surface runoff increases (Hill & Verjee 2010; Smithson, Addison & Atkinson 2002).

Storage capacity, infiltration and transmissibility are additional catchment characteristics that are influenced by the climate, geology, soil type and vegetation cover (Hill & Verjee 2010; Smithson, Addison & Atkinson 2002).

2.2.4.2 Network characteristics

The amount of water absorption is influenced by the network characteristics, such as pattern, surface storage, under-drainage, channel length and bifurcation ratio (Smithson, Addison & Atkinson 2002).

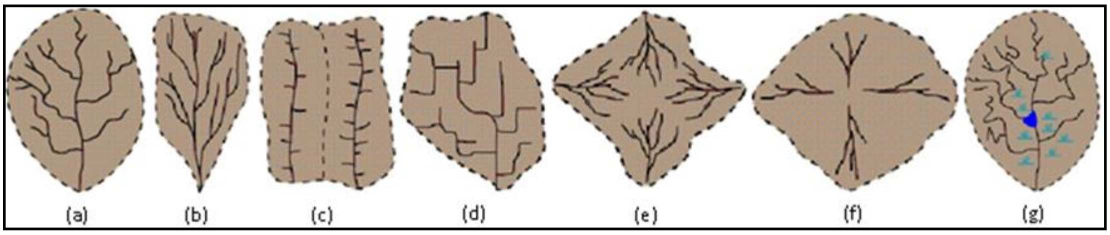
Streams come together to form a large network of streams (see Figure 2.12). Within this network exists a stream order where the first order refers to the smallest streams without any tributaries (McKnight & Hess 2007; Ritter 2010).



Source: UCAR (2010)

Figure 2.12 Stream orders

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 (see Figure 2.13). Complex drainage patterns can hinder the absorption of water and could cause flooding to occur (McKnight & Hess 2007; Ritter 2010).



Source: Ritter (2010)

Figure 2.13 Drainage patters: (a) dendritic, (b) parallel, (c) trellis, (d) rectangular, (e) radial, (f) centripetal and (g) deranged

The surface storage refers to the surface of the network. 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 can increase the likelihood for flooding (Alexander 2000; Wohl 2010; Waugh 2009).

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 (Waugh 2009).

The bifurcation ratio refers to the ratio between the numbers of streams in two sequential hierarchies of basins 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 (Bagyaraj & Curugnanam 2011; Waugh 2009).

2.2.4.3 Channel characteristics

Channel characteristics (slope, flood control and river regulation works) influence the direction and speed of water flow. An increase in channel slope combined with the presence of control measures and river regulation networks, result in an increase in the velocity and energy of the floodwaters (Smithson, Addison & Atkinson 2002; Wohl 2010).

2.3 CONCLUSION

This chapter reviewed basic disaster risk definitions and terminology. The review provides a background to understand floods as natural hazards within the disaster management environment. The causes, impacts, and factors that increase the severity of floods were also considered.

CHAPTER 3: GIS AND HYDRAULIC MODELLING

In this chapter, flood modelling methodologies are studied with regard to modelling types, hydraulic principles, GIS and data requirements. Focus is placed on the types, data requirements and international trends in flood hazard mapping. This provides a foundation for considering various software packages available and to make an informed selection for flood modelling.

3.1 DIFFERENCES BETWEEN HYDRAULICS AND HYDROLOGY

Hydraulics and/or hydrologic modelling is used to determine the susceptibility of a floodplain to different probabilities. Hydrology determines the discharge and speed of water flowing on or below the land surface by considering the interaction of all processes within the hydrological cycle (e.g. evaporation, precipitation, and abstraction) and the physical characteristics of the catchment (BHS 2005; Brutsaert 2005; Haarhoff & Cassa 2009; Hardmeyer & Spencer 2007; McKnight & Hess 2007). Hydraulics study the behaviour of flowing water within a controlled environment such as a river. Thus the focus is only on forces and other processes acting on the water flow within the river channel (Brutsaert 2005; Haarhoff & Cassa 2009; Hardmeyer & Spencer 2007). Discharge values required as data input for hydraulic modelling are obtained from river gauge stations. Hydrologic modelling is completed where gauge data is insufficient or non-existent (Rusinga 2010b, pers com).

Data collection and management is important to both hydrology and hydraulics, and GIS has been used as a tool to assist in data management and the analysis procedure (De Roo, Wesseling & Van Deursen 2000; Maidment & Djokic 2000; Robayo & Maidment 2005). GIS and hydraulic software developed in parallel to each other for almost twenty years without any interaction (Sui & Maggio 1999). In 1975 the first attempt was made by the Hydrologic Engineering Centre (HEC) to link GIS and hydraulic models (Correia et al. 1998), since hydraulic engineers required better quality terrain representation for modelling (Clarke 1998; Singh & Florentino 1996) and GIS professionals needed more specialised analytical and modelling capabilities (Goodchild, Haining & Wise 1992, in Sui & Maggio 1999). It was called Hydrologic Engineering Centre-Spatial Analysis Methodology (HEC-SAM), and was based on a raster model linked to their HEC-1 modelling software (Correia et al. 1998). In this integration, GIS was used to capture and manage a database that was linked to the hydraulic model (Males and Grayman 1992; Stangel 2009). These earlier models were often text based files and occurred in a Computer-Aided Design (CAD) environment (Stangel 2009).

3.2 GIS FUNCTIONALITIES WITHIN HYDRAULIC MODELLING

Intensive research and development to integrate hydraulic modelling and GIS continued into the late 1990s. GIS provided various functions that motivated the integration of GIS and hydraulic models (Goodchild in Clark 1998; Maidment & Djokic 2000) that included:

- pre-processing of spatial depth before importing it into the hydraulic model (Correia et al 1998; Stangel 2009);
- creation of digital terrain models (DTMs) (Correia et al. 1998);
- calculation of watershed characteristics (Correia et al. 1998);
- image overlaying (Correia et al. 1998);
- network analysis (Correia et al. 1998);
- database management (Sui & Maggio 1999); and
- visualisation of results (Sui & Maggio 1999).

These functions are discussed in more detail in the following sub-sections.

3.2.1 Pre-processing

Pre-processing refers to the data preparation that is done before any hydraulic modelling can commence. GIS is used to convert data into a suitable format (e.g. projection system, data structure, scale and data model) for hydraulic analysis (Heywood, Cornelius & Carver 2002; Maidment & Djokic 2000; Robayo & Maidment 2005; Zerger & Wealands 2004). Other tasks performed in GIS during pre-processing include the creation of the terrain or bathymetric surfaces, the integration of various data sources to obtain surface roughness, automated catchment and stream network analysis, as well as metadata management (Bates & De Roo 2000; Maidment & Djokic 2000; Robayo & Maidment 2005).

3.2.2 Direct support

GIS provides direct support in hydraulic modelling by providing a platform for model calibration and prediction (Bates & De Roo 2000; Maidment & Djokic 2000; Zerger & Wealands 2004). This functionality is mostly used by one-dimensional hydraulic models (Werner 2001). The application of direct support is very constrained since most GIS software has copyrighted formats and algorithms which restrict the free use and integration with other environmental analysis software such as hydraulics (OGC 2009; Stangel 2009).

3.2.3 Post-processing

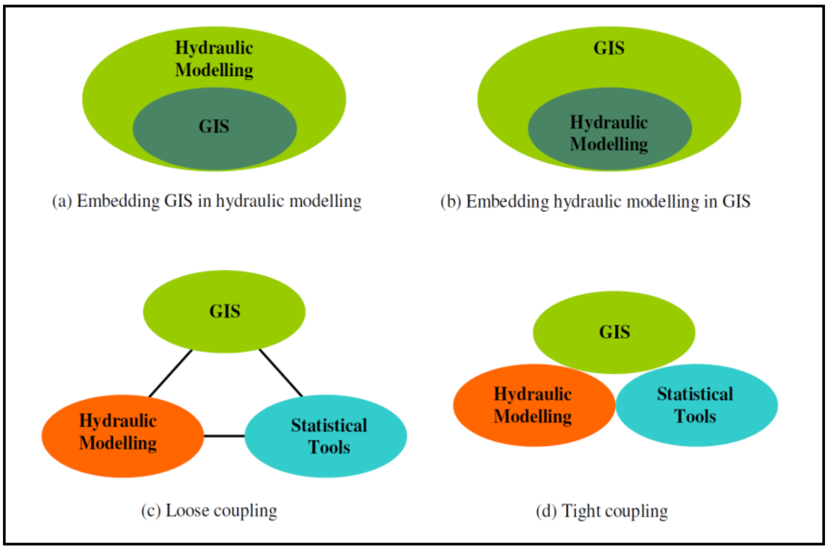
Post-processing is the reformatting, tabulation, mapping and report generation after the modelling has been completed by the hydraulic software (Robayo & Maidment 2005; Zerger & Wealands 2004). This approach is common with two-dimensional hydraulic models, where the complexity of the model prevents the integration with GIS (Dutta, Herath & Musiake 2000; Zerger & Wealands 2004).

3.3 MAIN APPROACHES OF GIS AND HYDRAULIC MODEL INTEGRATION

During their experimentation and research, GIS scientists and hydraulic engineers found that it is more difficult to integrate the two disciplines than originally thought. None of the other integrations with environmental modelling had experienced such difficulties. This could be ascribed to the established standards and practices that already existed within hydraulics. Hydraulic model results were used for legislation purposes and a high level of trust and accuracy has always been required (Sui & Maggio 1999).

There are four approaches to the integration of hydraulic modelling and GIS. These approaches range from tight coupling, where all the integration is done in GIS, to loose coupling, where GIS is merely used for data pre-processing, direct support and post processing (where data formats permit) (De Roo, Wesseling & Van Deursen 2000; Maidment & Djokic 2000; Zerger & Wealands 2004; Stangel 2009). Four approaches evolved during the integration period (Robayo & Maidment 2005; Sui &

Maggio 1999) and are depicted in Figure 3.1. Each of these approaches will be discussed in more detail in the following sections.



Source: Sui & Maggio (1999: 35)

Figure 3.1 Integrating GIS with hydraulic modelling

3.3.1 GIS embedded in hydraulic modelling

In this approach, GIS functionality is embedded within hydraulic models (see Figure 3.1a). GIS is merely seen as a mapping tool that could not handle the complexity of hydraulic principles (Robayo & Maidment 2005; Stangel 2009; Sui & Maggio 1999). Because the combined systems are usually developed by hydraulic engineers, they often do not adhere to GIS data formats. Consequently, this only allows for the implementation of the latest hydraulic development. The GIS functionalities, such as data management and visualisation capabilities, of these software packages are very limited (Heywood, Cornelius & Carver 2002; Stangel 2009; Sui & Maggio 1999).

3.3.2 Hydraulic modelling embedded in GIS

Integrating hydraulic modelling in GIS is accomplished by embedding a module or extension with hydraulic analysis and modelling capabilities in the GIS software package (see Figure 3.1b). Unfortunately, these hydraulic functionalities have been very basic and of inadequate standard for accurate hydraulic analysis (De Roo, Wesseling & Van Deursen 2000; Robayo & Maidment 2005; Stangel 2009; Sui & Maggio 1999).

3.3.3 Loose coupling

Loose coupling (see Figure 3.1c) is the preferred approach where GIS and hydraulic software packages are integrated. Data is exchanged between the two packages by using a data exchange format. Although this requires less software development, the conversion of the data provides problems and errors. However, this seems to be the preferred approach (Robayo & Maidment 2005; Stangel 2009; Sui & Maggio 1999). Another form of the loose coupling approach is where GIS forms a connection between GIS and the hydraulic software. Data exchange is not a problem and the hydraulic modelling is processed within the hydraulic software, which is more accurate than a similar analysis in GIS software (De Roo, Wesseling & Van Deursen 2000; Heywood, Cornelius & Carver 2002; Zerger & Wealands 2004).

3.3.4 Tight coupling

The tight coupling approach (see Figure 3.1d) consists of a GIS software package that has a hydraulic component embedded within the GIS software via macro or conventional software programming. It provides the GIS user with some capability to change or modify the hydraulic modelling but the user requires intensive programming skills. However, this approach provides limited, complex hydraulic modelling options and requires a well-defined interface with the GIS data structure (Robayo & Maidment 2005; Sui & Maggio 1999).

3.4 INTEGRATION PROBLEMS

Both disciplines, GIS and hydraulic modelling, have benefited from the integration, but problems and shortcomings have been identified. These limitations include the normal technical problems as well as conceptual problems. Although various papers have been written on the technical problems, very little research has been completed to address the conceptual questions (Stangel 2009; Sui & Maggio 1999). Enhanced integration cannot take place before certain key concepts have been addressed in further research (Robayo & Maidment 2005; Sui & Maggio 1999).

3.4.1 Complex hydraulic models

Hydraulic modelling is very complex and limits the integration within or coupling with GIS. The average GIS user does not have sufficient skills to utilise these hydraulic extensions within the GIS software to their fullest capacity. Consequently, hydraulic models, that can be added to a GIS environment or coupled with a GIS program, are developed separately (De Roo, Wesseling & Van Deursen 2000; Heywood, Cornelius & Carver 2002; Maidment & Djokic 2000; Robayo & Maidment 2005). Furthermore, the integration is limited by the limited availability of the large scale spatial data required by these complex hydraulic models (Heywood, Cornelius & Carver 2002).

The decision on the type of hydraulic model depends on the type of user and on the quality of the available data. Although complex hydraulic models exist, these do not necessarily provide the best solutions. Less complex models require less detailed data input. This is an important consideration when limited data sources are available. However, complex models provide a wider range of scenarios in their hydraulic modelling (Correia et al. 1998; Robayo & Maidment 2005).

3.4.2 Time variable

A major problem identified in the integration of hydraulic models and GIS is the manner in which GIS handles space, time (Bates & De Roo 2000; Correia et al 1998; De Roo, Wesseling & Van Deursen 2000; Heywood, Cornelius & Carver 2002; Zerger & Wealands 2004) and motion (De Roo, Wesseling & Van Deursen 2000; Sui & Maggio 1999; Zerger & Wealands 2004). All prediction and forecasting models, such as hydraulic modelling, make use of the time dimension that has forced these models to be developed in a non-GIS environment (De Roo, Wesseling & Van Deursen 2000; Heywood, Cornelius & Carver 2002; Robayo & Maidment 2005). The conversion of the hydraulic results into a raster format for visualisation in GIS can only represent one 1 in 100 year event and cannot provide time-series data for different storm scenarios (Bates & De Roo 2000). GIS cannot handle the large quantity of raster images generated for time-series simulation of a storm due to computational and analysis problems that are time dependent (Zerger & Wealands 2004). This limitation is the main reason why GIS is only used for data preparation and visualization, while hydraulic modelling is handled by a hydraulic software package (Correia et al. 1998; Robayo & Maidment 2005). Zerger and Wealands (2004) completed a study that tried to resolve the time-variable problem in GIS. A time-series of flooded areas for all possible storms scenarios were simulated.

Complex data were captured into a relational database management system (RDBMS) that had a spatial object storing capability that was coupled to GIS through a unique identifier (primary key). Maps were generated for all these scenarios and called “Digital Look-up Maps”. This would enable a disaster manager to access a map in GIS for a specific storm scenario. In addition, the relational database provides access to other spatial and non-spatial data (e.g. buildings, road network, inundation statistics and graphs) (Zerger & Wealands 2004).

3.4.3 Data formats

The interoperability between various software products have increased due to improvements in exchanging various data formats. This has provided the opportunity to couple CAD and remote sensing software to GIS and thus enhance the environmental modelling capabilities and the integration with hydraulic models (Correia et al. 1998).

The integration of GIS and hydraulic modelling was often debated during the late 90s. Despite this, very few research papers addressing these shortcomings and problems have emerged in the last 10 years. The integration of GIS and hydraulics has however continued, irrespective of the conceptual problems that still need to be resolved. Some GIS scientists might be concerned that changes in some of these concepts would result in major changes to current GIS spatial models. Because GIS is primarily a toolbox used to assist various disciplines in data management and visualisation, it does not have the ability to perform complex environmental modelling. Complex modelling should be performed in its own discipline environment. However, GIS provides a platform to collect and manage these different model results for visualisation and to understand the interaction and influences involved in different spatial entities.

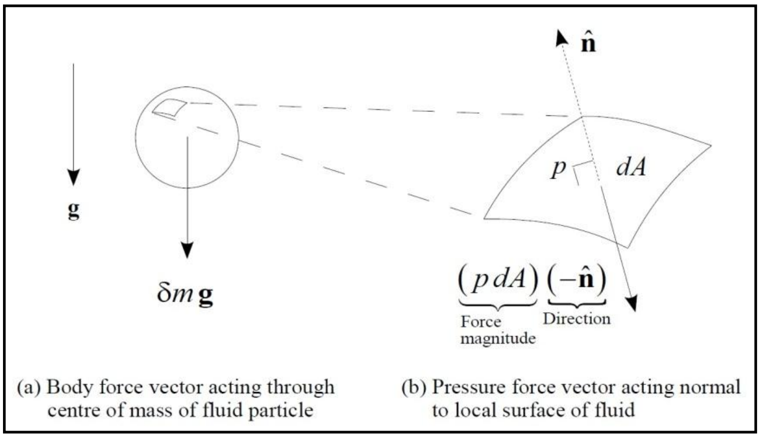
3.5 HYDRAULIC MODELLING

Data and information about historic flood events have been poorly documented in the past and it was difficult to delineate areas prone to flooding. Advances in computer processing power and satellite technology have made numerical analysis the preferred method to determine floodplains (Hunter et al. 2007; Wright 2008).

Complex hydraulic models can be simulated with data input derived from satellite images. The obtained results can then be compared and verified with archived satellite imagery of historic flood events. This section will focus on the fundamental concepts of hydraulics that need to be considered when using hydraulic models for river floodplain analysis.

3.5.1 Types of open-channel flow

Liquid can either flow in a pipe or an open channel. Open-channel flow has a free surface that is exposed to atmospheric pressure or a constant pressure (e.g. rivers, irrigation canals, roadside drainages). Two types of forces (see Figure 3.2) act on the free surface of an open channel flow, namely gravity forces and pressure forces (Janna 2009; Munson et al. 2010).



Source: Fenton (2010: 12)

Figure 3.2 Two types of forces acting on a fluid particle

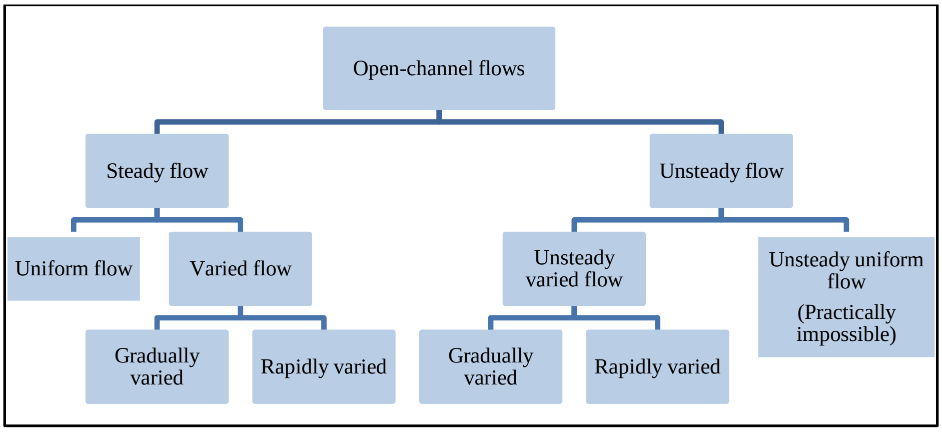
Gravity (body force) (see Figure 3.2a) is the main driving force that allows the flow to move downhill. During this movement, energy is lost due to various drag forces (Munson et al. 2010; Wright 2008).

Open-channel flow can be categorised (see Figure 3.3) depending on the flow depth changes with respect to time and location (Janna 2009; Munson et al. 2010). Each of these categories is discussed in more detail in the following sections.

3.5.1.1 Steady flow vs. unsteady flow (time as the criterion)

A flow is categorised as steady if the depth stays constant at a specific point with respect to time (ADWR 2002; Franzini & Finnemore 2001; Janna 2009; Munson et al. 2010; Sleigh 2006), although conditions may differ from point to point (Franzini &

Finnemore 2001). The friction force between the fluid and channel surface is equal to the gravity force of the fluid but they work in opposite directions, thus the opposite forces are balanced and the depth remains constant (Munson et al. 2010; Wright 2008).



Source: Janna (2009: 353)

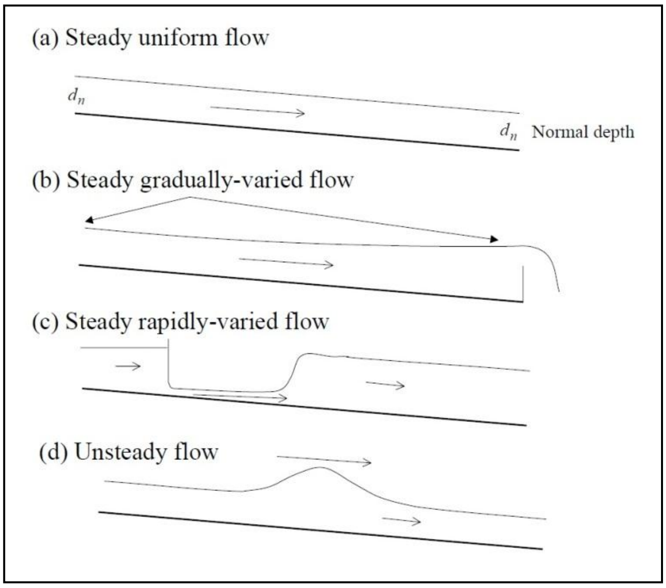
Figure 3.3 Categories of open-channel flow

Unsteady flow is the opposite of steady flow, thus the depth of the flow changes with respect to time (ADWR 2002; Franzini & Finnemore 2001; Janna 2009; Munson et al. 2010). The opposing forces, due to gravity and friction, are unequal, causing the depth to change (Munson et al. 2010; Wright 2008). Floods and surges are examples of unsteady flow in an open-channel flow (Janna 2009).

3.5.1.2 Uniform vs. varied flow (space as the criterion)

Uniform flow occurs where the depth is constant along the length of the channel (Franzini & Finnemore 2001) or the depth of the fluid is the same at every cross-section of the channel (Janna 2009; Munson et al. 2010). Varied flow (also called non-uniform flow) occurs where the depth varies with distance (Munson et al. 2010) or flow enters or leaves along the length of the channel under consideration (Janna 2009). Figure 3.4 explains the difference between steady/unsteady and uniform/varied flow.

Steady, uniform flow (see Figure 3.4a) has no change in the depth with respect to time along the length of the channel (Janna 2009; Sleigh 2006). Unsteady uniform flow is practically impossible since the depth cannot remain constant along the length of the channel as time changes (Janna 2009).



Source: Fenton (2007: 4)

Figure 3.4 Steady/unsteady vs. uniform/varied flow

Varied flow can be further subdivided into gradually and rapidly varying flow. During gradually varying flow (see Figure 3.4b) the depth changes slowly over the length of the channels, while in rapidly varying flow (see Figure 3.4c), the changes in depth are abrupt (Janna 2009; Munson et al. 2010).

3.5.1.3 Critical vs. supercritical flow

The free surface of flow within open channels can change from relatively flat to having large waves. Channel characteristics (depth and flow velocity) and the size (height and length) of the waves influence the wave speed (Janna 2009; Munson et al. 2010). The Froude number is an important parameter in open channel flow that describes the velocity of the channel flow relative to the velocity of the wave (Munson et al. 2010; Sleigh 2006). It describes the relative importance of inertia forces to gravity forces as a ratio (Fenton 2007; Janna 2009) and is expressed as follows (Fenton 2009; Janna 2009; Munson et al. 2010; Sleigh 2006):

$$\mathrm{Fr} = \frac{V^2}{gl} \qquad \text{Equation 3.1}$$

where Fr is the ratio of inertia to gravity forces;
V is the average velocity of the flow (m/s);
g is the acceleration due to gravity (9.81 m^2); and

l is the hydraulic depth (m).

The value of the Froude number, Fr, can be used to further classify the flow. Where Fr is smaller than one (Fr< 1), the flow is sub-critical, meaning that the water velocity is larger than wave velocity, and the flow can be described as tranquil (velocity less than 0.01m/s) and streaming. If F is equal to one (Fr = 1), then the flow is critical, and the velocity of the flow and of the wave are equal. Supercritical flow occurs when F is greater than one (Fr>1), and the flow can be described as rapid and torrential with a high velocity. Water discharge greater than 10 000 m^3/s is associated with supercritical flow (Fenton 2009; Janna 2009; Munson et al. 2010; Sleigh 2006).

3.5.2 Modelling equations

Hydraulic modelling software is based on three basic equations (ADWR 2002; Dyhouse, Hatchett & Benn 2003) from the physical laws regarding the conservation of mass, energy and momentum in fluid dynamics (ADWR 2002; Dyhouse, Hatchett & Benn 2003; Sleigh 2006). The type of flow, the dimensions and other conditions determine which of these three equations are used in the hydraulic modelling of a particular event (ADWR 2002; Fenton 2007; Sleigh 2006).

These three equations will be defined and explained within the context of a closed system with a certain amount of particles and a control volume with a control surface. Based on the conservation of the particles, the total amount of particles in the system will always be equal to the sum of the particles within the volume and the particles leaving the system (Janna 2009).

3.5.2.1 Continuity equation

The continuity (mass) equation is also known as the conservation of mass equation and was developed by Leonardo da Vinci in the year 1500. This equation is formulated as (Dyhouse, Hatchett & Benn 2003; Fenton 2007):

$$Q = A_1 V_1 = A_2 V_2 \qquad \text{Equation 3.2}$$

where Q is the flow rate (m^3/s);

A is the cross-sectional area (m^2); and

V is the average velocity for the cross section (m/s).

This equation is based on the physical law that mass is constant and cannot be changed or destroyed. Thus, if a mass enters a closed system, it cannot be altered, and will equal the mass leaving the system (Janna 2009).

3.5.2.2 Energy equation

The energy equation is also known as the law of conservation of energy or the Bernoulli equation. This equation is based on many experiments that have determined that although energy can change form, the total energy in a closed system remains the same. The equation is formulated as (Dyhouse, Hatchett & Benn 2003):

$$z_2 + \frac{p_2}{\gamma} + \frac{V_2^2}{2g} = z_1 + \frac{p_1}{\gamma} + \frac{V_1^2}{2g} + h_{L_{1-2}} \qquad \text{Equation 3.3}$$

where z is the elevation of the channel centre line (m);
p is the pressure in the open channel (N/m^2);
g is the specific weight of the fluid (n/m^3);
V is the flow velocity of the fluid (m/s); and
h_L is the energy loss between downstream Point 1 and upstream Point 2 (m).

This equation implies that the energy of flow at any cross-section in the channel is equal to the sum of the energy at the cross-section downstream and any intervening energy loss.

3.5.2.3 Momentum equation

The momentum equation is based on Newton's second law of motion which states that linear momentum is conserved. The equation is formulated as (Dyhouse, Hatchett & Benn 2003):

$$\sum F = ma \qquad \text{Equation 3.4}$$

where $\sum F$ is the sum of all external forces acting on the closed system;

m is the total mass of the system; and

a is the acceleration of the centre of mass of the isolated system (m/s^2).

Thus, the sum of all the external forces acting on the closed system is the product of the system's total mass and the acceleration of the centre of mass of the system (ADWR 2002; Dyhouse, Hatchett & Benn 2003; Janna 2009).

3.5.2.4 Manning's equation

Manning's equation was derived from experimental observations to determine the friction loss due to surface roughness (Dyhouse, Hatchett & Benn 2003; Janna 2009). The equation is formulated as follows (Dyhouse, Hatchett & Benn 2003; Janna 2009):

$$V = \frac{R^{2/3}S^{1/2}}{n} \qquad \text{Equation 3.5}$$

where V is the average velocity (m/s);

R is the hydraulic radius (m);

S is the slope of the channel invert (m/m); and

n is Manning's roughness coefficient.

Surface roughness refers to the friction loss due to the roughness of the channel wall, the vegetation, channel irregularities (e.g. depressions, ridges, sand bars and holes) and the curvature of the channel (Janna 2009). Typical values of the Manning coefficient are shown in Table 3.1.

Table 3.1 Manning's roughness coefficient for natural streams

Type of Channel and Descriptions	Normal	Type of Channel and Descriptions	Normal
A. Natural Channels		**D. Artificially lined channels**	
Clean and straight	0.030	Glass	0.010
Sluggish with deep pools	0.040	Brass	0.011
Major rivers	0.035	Steel, smooth	0.012
B. Floodplains		Steel, painted	0.014
Pasture, farmlands	0.035	Steel, riveted	0.015
Light brush	0.050	Cast iron	0.013
Heavy brush	0.075	Concrete, finished	0.012
Trees	0.15	Concrete, unfinished	0.014
C. Excavated earth channels		Planed wood	0.012
Clean	0.022	Clay tile	0.014
Gravely	0.025	Brickwork	0.015
Weedy	0.030	Asphalt	0.016
Stony, cobbles	0.035	Corrugated metal	0.022
		Rubble masonry	0.025

Source: Munson et al. (1998: 656)

The roughness of a floodplain surface increases as it moves from pasture to trees. Manning's coefficient will reflect this by showing a corresponding increase (Munson et al. 2010).

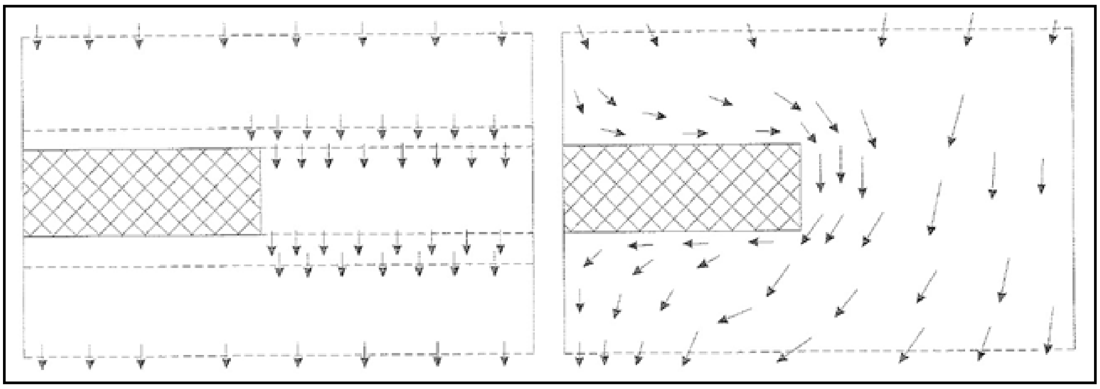
3.5.3 Modelling dimensions

The modelling of fluids 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-, two- and three-dimensional models (ADWR 2002; Dyhouse, Hatchett & Benn 2003; Hunter et al. 2007).

3.5.3.1 One-dimensional 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 & Finnemore 2001), where streamlines intersect the cross sections at right angles and are parallel to each other (Dyhouse, Hatchett & Benn 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 (see Figure 3.5a) in the fluid has the same velocity and direction at a specific time, t (Franzini & Finnemore 2001; Munson et al. 2010). This is a simplified flow analysis where the assumption is made that the velocity components in the other two directions are negligible (ADWR 2002; Dyhouse, Hatchett & Benn 2003; Franzini & Finnemore 2001; Munson et al. 2010). This analysis is suitable for most open channel hydraulic flow occurrences (ADWR 2002; Dyhouse, Hatchett & Benn 2003).

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 (ADWR 2002; Pappenberg et al. 2005). Furthermore, these models require fewer data inputs and minimum computational power to perform the analysis (Pappenberg et al. 2005).



Source: Dyhouse, Hatchett & Benn (2003: 89)

Figure 3.5 Velocity vectors in (a) one-dimensional and (b) two-dimensional flow

3.5.3.2 Two-dimensional 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 (see Figure 3.5b) exist in two dimensions of the horizontal plane (Franzini & 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, Van Alphen & Aerts 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).

3.5.3.3 Three-dimensional modelling

Three dimensional modelling considers the velocity changes in all three dimensions of the channel (Dyhouse, Hatchett & Benn 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, Hatchett & Benn 2003).

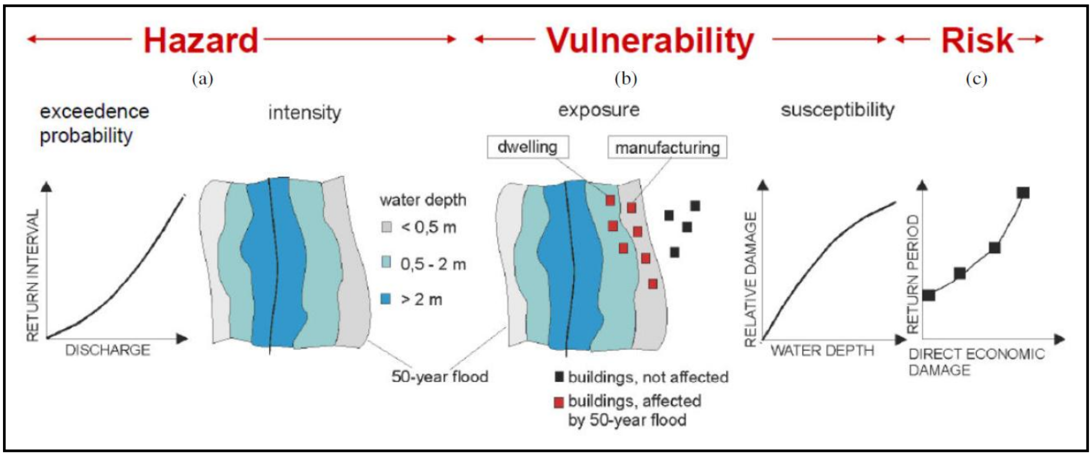
One-dimensional models cannot represent the true river basin and limits the modelling of the complex conditions of extreme flood events (ADWR 2002; Merwade, Cook & Coonrod 2008; Pappenberg et al. 2005), especially the simulation of flood waves (Hunter et al. 2007) and the spreading flows on alluvial fans or unstable alluvial channels (ADWR 2002). The river terrain and the surrounding areas are represented by cross-sections that do not provide a continuous representation of the entire area (Hunter et al. 2007; Merwade, Cook & Coonrod 2008). Merwade, Cook & Coonrod (2008) states that, although high quality data is available, it would have no effect on the quality of the flood lines generated, as cross-sections are used.

Data quality and computational requirements need to be considered when using two- or three-dimensional models for more complex flow conditions (Dyhouse, Hatchett & Benn 2003; Hunter et al. 2007). The availability of high-resolution data and more computational power has increased the use of complex models (Hunter et al. 2007). 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, Hatchett & Benn 2003; Hunter et al. 2007) and appropriate data for the verification of these complex models is very limited (Hunter et al. 2007). Complex models are also more expensive (Dyhouse, Hatchett & Benn 2003).

3.6 FLOOD HAZARD MAPPING

A flood risk assessment is the application of a risk assessment methodology to determine the nature of flood hazards. A flood hazard assessment is the first step towards a flood risk assessment (ISDR 2004; Martini & Loat 2007), and forms an important foundation for flood risk management plans (Martini & Loat 2007; Tyagi 2008). Flood hazard maps can play an integral part in all the phases of the flood risk assessment as they communicate the extent of the flood and other flood parameters to the 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 & Spencer 2007; Pender & Néelz 2007; Schneider, Verdin & Bales 2007; Viljoen & Booysen 2006). Flood hazard mapping can be further integrated to analyse and map the vulnerabilities and the resulting risk to a community (ISDR 2004; Lechtenbörger 2006; Martini & Loat 2007).

Figure 3.6 explains the mapping of the risk parameters in a flood risk assessment. The probability, extent and flood depth of the flood hazard are modelled and mapped in Figure 3.6a. Through overlaying the results from the flood hazard map with the locations of all buildings in the area, the exposure can be calculated to determine the vulnerability of any buildings (see Figure 3.6b). Both these maps are used to calculate the risk (see Figure 3.6c) in terms of economic damage for the different probabilities (Merz & Thieken 2004).



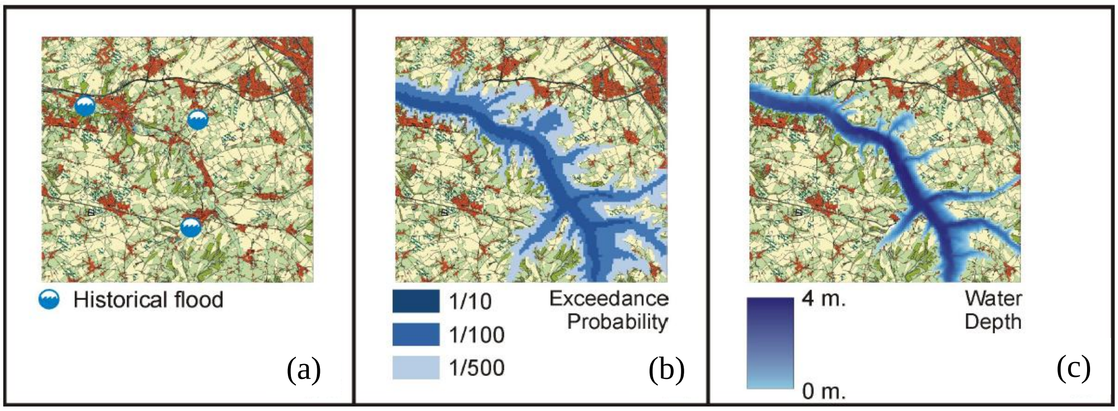
Source: Merz & Thieken (2004: 3)

Figure 3.6 Flood risk mapping: (a) hazard, (b) vulnerability, and (c) risk mapping

The purpose of flood hazard mapping is to determine the (ISDR 2004; Kleeberg, Röttcher & Spanknebel 2006; Martini & Loat 2007):

- frequency, i.e. the probability of an occurrence in a specific time period;
- extent, i.e. the geographical area of impact;
- severity (intensity), i.e. the water level or water depths; and
- flow velocity and/or direction of flow.

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; De Moel, Van Alphen & Aerts 2009; Klijn 2009; Zimmermann 2008). Bründl et al. (2009) summarise flood hazard maps as results from a hazard analysis that indicate the locations of flood events for certain return periods. The requirements or needs of the stakeholders will determine the flood parameters to be mapped in the flood hazard map (De Moel, Van Alphen & Aerts 2009; Hardemeyer & Spencer 2007; Martini & Loat 2007). For example, a flood propagation map will be required in the event of an emergency, to determine how, when and where people need to be evacuated while water levels are rising (De Moel, Van Alphen & Aerts 2009; FEI 2007; Van Manen & Brinkhuis 2005). The basic types of flood hazard maps are indicated in Figure 3.7.



Adapted from: De Moel, Van Alphen & Aerts (2009: 293)

Figure 3.7 Basic types of flood hazard maps: (a) historical maps, (b) extent maps for different probabilities, and (c) depth maps

The basic types of flood hazard maps are:

- historical (event) maps (Figure 3.7a), indicating the locations of historical events with point symbols on a map (De Moel, Van Alphen & Aerts 2009; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010);
- extent maps (Figure 3.7b), the most common type, displaying 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 (Alho et al. 2008; De Moel, Van Alphen & Aerts 2009; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010), namely 10 and 50 years for high, 100 years or greater for a medium, and 1000 years for low probabilities (Büchele et al. 2006; Martini & Loat 2007; Schneider, Verdin & Bales 2007);
- flood depth maps (Figure 3.7c), displaying the water depths (levels) derived from one- and two-dimensional models for river flooding (Büchele et al. 2006; De Moel, Van Alphen & Aerts 2009; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010; Schneider, Verdin & Bales 2007);
- 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; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010; Reich 2005; Schneider, Verdin & Bales 2007);

- flood wave maps, displaying the movement of the waves, as determined by two-dimensional models (Büchele et al. 2006; De Moel, Van Alphen & Aerts 2009; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010); and
- duration of inundation maps, indicating the period that an area was or may be under water (De Moel, Van Alphen & Aerts 2009).

The stakeholders' requirements will determine the type of flood hazard maps required.

3.6.1 Stakeholders in flood mapping

Stakeholders play an important role in flood hazard mapping. Their needs or requirements will determine the type of flood parameter to be mapped (De Moel, Van Alphen & Aerts 2009; Kleeberg, Röttcher & Spanknebel 2006) and the scale or level thereof (Martini & Loat 2007).

Stakeholders can include disaster managers, emergency workers, town planners, the public or community and insurance companies (De Moel, Van Alphen & Aerts 2009; Kleeberg, Röttcher & Spanknebel 2006; Martini & Loat 2007; Pender & Néelz 2007). Currently, governments are responsible for developing flood hazard maps for emergency and disaster management planning, town planning (land use or rezoning), and public awareness. In some European countries, insurance companies have started to generate flood hazard maps to determine insurability, differentiation of premiums and to assess long term financial solvency (De Moel, Van Alphen & Aerts 2009; Kleeberg, Röttcher & Spanknebel 2006). Flood hazard maps allow insurance companies to prioritise their investments, and governments and communities to prepare for flood disasters (Takeuchi 2001). International river commissions have started to show an interest in flood hazard mapping for their requirements (De Moel, Van Alphen & Aerts 2009).

3.6.2 Requirements and scale

The required flood parameters to be mapped for each stakeholder's requirements or needs are shown in Table 3.2.

Table 3.2 Flood parameters and scale according to requirements

REQUIREMENT	**SCALE/LEVEL**		**FLOOD PARAMETER** (**BOLD** indicates minimal parameters to be mapped)
Disaster management planning	National/regional	1:100 000-1:1 000 000	**Extent**
	Local	1:5 000-1:50 000	**Extent, depth** and other parameters where appropriate
Town planning (land use)	National/regional	1:100 000-1:500 000	**Extent**
	Local	1:5 000-1:25 000	**Extent for different probabilities**, depth, velocity and duration
Emergency planning and management	National/regional	1:100 000-1:500 000	**Extent**
	Local	1:5 000-1:25 000	**Extent and depth for different return periods, and other parameters where appropriate**
Public awareness	Local	1:10 000-1:25 000	**Extent for different probabilities and depth**
Insurance	Local	1:10 000-1:25 000	**Extent for different probabilities**, depth, and velocity (if significant)

Adapted from: Martini & Loat (2007: 13-16)

Each requirement has different levels/scales at which the specific flood parameters can be mapped. For disaster management, the mapping of the flood extent at national and regional levels are required at a scale between 1:100 000 and 1:1 000 000 (Martini & Loat 2007). In Germany, mapping of floods for disaster and emergency response are done at a scale of greater than or equal to 1:5 000 for urban areas. Catchments of areas greater than 10km² require the flood extent for different probabilities (10-, 50- and 100 year events), extreme events of 1000 years, and historical events. Depth mapping is done for 100 year events for different probabilities. At local level, a 1:5 000 scale is used, but for simplified approaches, a 1:50 000 scale is applied (Büchele et al. 2006). In Europe, the guidelines by the European Flood Risk Directive stipulates a 1:2 000 to 1:25 000 scale for urban areas, and a 1:100 000 to 1:1 000 000 scale for rural areas for both extent and depth mapping (Mavrova-Guirginova, Pencheva & Belyashka 2010). The United States of America (USA) performs a 100- and 500 year probability for insurance purposes at different scales of mapping that are mainly determined by the density of the population and infrastructure. A scale of 1:6 000 is considered for urban areas and 1:24 000 for rural areas (Schneider, Verdin & Bales 2007).

In South Africa, the National Water Act (sections 121 and 144), only requires the 100 year flood line for new developments on town layout plans (South Africa 1998). No further guidelines are available for the mapping of the probability or the scale of a flood hazard in either rural or urban areas.

3.6.3 Flood hazard mapping procedures

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, Van Alphen & Aerts 2009). The modelling of the flood hazard consists of three main steps, namely (Büchele et al. 2006; De Moel, Van Alphen & Aerts 2009):

1. the collection of historical data of water levels or inundation zones and calculating the discharge for specific return periods;
2. the modelling of water levels using hydraulic models, either one- or two-dimensional; and
3. the water levels are combined with the DTM using one- or two-dimensional models.

In both one-dimensional and two-dimensional models the DTM is used to calculate the water levels by subtracting the DTM elevations from the modelled water level data (FEI 2007; Pender & Néelz 2007).

3.7 FLOOD MODELLING SOFTWARE

Various software packages are available for the modelling of flood hazards. Differentiation between these software packages can be made based on modelling type, dimension (one, two or three dimensions), data requirements and the applications for which it was originally developed. Pender & Néelz (2007) have compiled a table (see Table 3.3) that lists the various flood modelling software available for flood hazard modelling and their applications.

Basic GIS software, for example ArcGIS and Delta Mapper, are considered modelling software that analyse in zero dimensions and do not adhere to the basic physical laws involved in hydraulics (Maidment 2002; Pender & Néelz 2007).

Table 3.3 Flood modelling software and applications

Dimension	**Distinguishing Features**	**Available Software**	**Potential Application**
0D	No physical laws included in simulation	ArcGIS, Delta Mapper, etc.	Broad scale assessment of flood extents and flood depths
1D	Solution of one-dimensional St. Venant equations	Infoworks RS (ISIS), Mike 11, HEC-RAS	Design scale modelling which can be of the order of 10-100s of km, depending on catchment size
$1D^{+}$	1D plus flood storage, cell approach to the simulation of floodplain flow	Infoworks RS (ISIS), Mike 11, HEC-RAS	Design scale modelling which can be of the order of 10-100s of km, depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data
$2D^{-}$	2D minus the law of conservation of momentum for the floodplain flow	LISFLOOD-FP	Broad scale modelling of urban inundation depending on cell dimensions
2D	Solution of the two-dimensional shallow wave equation	TUFLOW, Mike 21, TELEMAC	Design scale modelling of the order of 10s of km. May have the potential for use in broad scale modelling if applied with very course grids
$2D^{+}$	2D plus a solution for vertical velocities using continuity only	TELEMAC 3D	Predominately coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.
3D	Solution of the three-dimensional Reynolds averaged Navior Stokes equations	CFX, FLUENT, PHEONIX	Local prediction of three-dimensional velocity fields in main channels and floodplains

Source: Pender & Néelz (2007:108)

One-dimensional software is used to perform very basic hydraulic analysis of, for example, water level and extent. The water level is then combined with a DTM to determine the water depth or inundation zones (Büchele et al. 2006; De Moel, Van Alphen & Aerts 2009; FEMA 2009). Infoworks RS, Mike 11 and HEC-RAS are examples of software packages that carry out one-dimensional modelling. Both HEC-RAS and Mike 11 are accepted by the Federal Emergency Management Agency (FEMA) for hydraulic modelling of one-dimensional flow (FEMA 2009). According to Pender & Néelz (2007), one-dimensional models are sufficient for flood defence and planning in risk reduction measures, while two-dimensional models are appropriate for risk mitigation through increasing resilience and disaster management planning. Thus, one-dimensional models are sufficient to identify areas that are located within flood prone areas, but not for the development of disaster managements plans where various stakeholders would be involved (Martini & Loat 2007; Pender & Néelz 2007).

From Table 3.3 it is evident that very few pure GIS software programs exist that can carry out flood modelling processes independently. They are considered inferior as they do not adhere to basic hydraulic principles. GIS is primarily used for data preparation, calibration, validation, and visualisation (Goodchild in Clarke 1998; Heywood, Cornelius & Carver 2002; Sui & Maggio 1999).

This chapter described GIS and hydraulics, provided an overview of the current flood modelling methodologies, and explained basic hydraulic concepts. The types of flood modelling software were also examined while taking the noted concepts of hydraulics and flood hazard mapping into consideration. This lays a foundation for the examination of flood hazard mapping by considering its purpose, types, stakeholders and data requirements. An inventory of available data for flood modelling is provided in the next chapter.

CHAPTER 4: DATA REQUIREMENT ANALYSIS

The availability of data determines the methodology and the flood parameters to be modelled in flood hazard mapping (Zimmermann 2008). Developing countries have limited data sources available for flood modelling, and where data does exist; it is of poor quality, expensive or has distribution limitations due to security classification (ISDR 2009b; Zimmermann 2008). The data requirements for flood modelling need to be determined in order to provide the foundation for performing a thorough assessment of data sources in South Africa by evaluating their coverage, quality, and accessibility.

4.1 DATA SOURCES

An assessment of data sources for flood hazard mapping in South Africa has been completed as part of this study. Both international and national data sets have been assessed. The data source assessment is based on resolution/scale and coverage.

The following data input is required for the hydraulic modelling of the most basic flood parameters, such as extent and depth, in flood hazard mapping:

1. Topographical data that describes the topography of the study area (Büchele et al. 2006; De Moel, Van Alphen & Aerts 2009; Maidment 2002; Sane & Huokuna 2008; Wright 2008; Zimmermann 2008).
2. Land cover (land use) data to calculate Manning’s roughness coefficient (Büchele et al. 2006; Mavrova-Guirginova, Pencheva & Belyashka 2010; Wright 2008; Zimmermann 2008).
3. Historical data for the calibration and validation of the flood modelling (Büchele et al. 2006; Martini & Loat 2007; Mavrova-Guirginova, Pencheva & Belyashka 2010; Wright 2008; Zimmermann 2008).

The accuracy of these data sources is important as it influences the reliability of the final flood hazard map (De Moel, Van Alphen & Aerts 2009; FEI 2007; Maidment 2002; Martini & Loat 2007; Uhrich in Büchele et al. 2006).

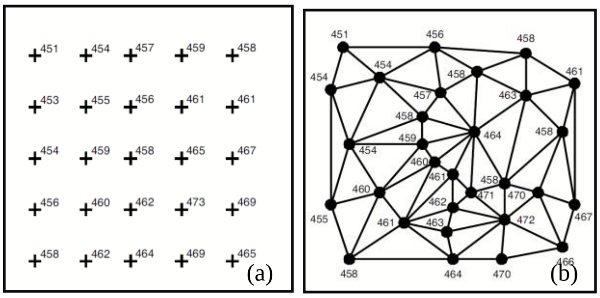
Flood hazard mapping can be prepared at a national and local level with the scale ranging from 1:100 000 to 1:1 000 000 and 1:5 000 to 1:50 000, respectively. The flood extent, as one of the parameters, is mapped at national and local levels, while depth, velocity and duration are all mapped at a local level (Martini & Loat 2007).

4.1.1 Topographical data

Topographical data is required to describe a river and its surrounding area (Maidment 2002; Martini & Loat 2007). Contours, DTMs, satellite imagery and orthophotos, are examples of data sources that can be used for topographical data (Martini & Loat 2007; Zimmermann 2008).

DTMs are the most frequently used data sources for topographic data (Heywood, Cornelius & Carver 2002; Maidment 2002). A DTM is a digital model that represents a topographic surface based on height and other topographic features (Heywood, Cornelius & Carver 2002).

The preferred data sources for constructing DTMs are observation points combined with additional structural features describing the phenomena to be modelled. The structural features can include drainage channels, ridges and surface continuities. The observation points can represent height either as regularly or irregularly spaced points and can include contours and spot heights, as well as data from stereoscopic aerial photos, satellite images and field surveys. When the points are regularly spaced, the data structure is called a digital elevation model (DEM), otherwise it is referred to as a triangular irregular network (TIN) for irregularly spaced points (Ackerman 2005; Casas et al. 2006; DeMers 2002; FEI 2007; Heywood, Cornelius & Carver 2002; Maidment & Djokic 2000; Mizukoshi & Aniya 2002; Pender & Néelz 2007). The frequency of these observation points is called the resolution of the DTM (Heywood, Cornelius & Carver 2002). These two data structures are shown in Figure 4.1.



Source: Zeiler (1999: 163)

Figure 4.1 Data structures: (a) DEM and (b) TIN

Both data structures have positive and negative characteristics and the choice between them, will be based on the analysis that needs to be done (Wise 2007). The different characteristics of these data structures are summarised in Table 4.1.

Table 4.1 Comparison of DTM data structure characteristics

Characteristics	**DEM**	**TIN**
Capturing of topological relationships	completely	additional capturing required
Computer processing	simple	difficult
Complexity of algorithms	simple	complex, and not always available
Display of structural features	not possible	easily
Display of variable point density	not possible	possible
Amount of points required for accuracy	large quantity	few

🟩 positive 🟥 negative

The DEM data structure requires less computer processing, defines topology rules better and have less complex algorithms, but cannot display structural features and variable point density. On the other hand, TIN requires additional capturing of topology relationships and more computer processing. It also has complex algorithms that do not always exist for the DEM counterpart. The advantage of a TIN is its ability to display structural features and variable point density. A TIN also requires fewer points for accuracy, compared to DEM data (Wise 2007).

Three main data sources are used for creating DTMs. The first, ground surveys, provide high accuracy DTMs but are time consuming, expensive and limited to small study areas. Photogrammetric data capturing involves the stereoscopic interpretation of imagery (aerial photos or satellite imagery), which reduces the effort to collect data while maintaining a high level of accuracy. Digitised contours from topographic maps are used, mainly for projects with large study areas. The accuracy is limited because a visualisation feature is used as input to a numerical interpolation calculation, but it remains the best option when working at medium to small scales (Maidment & Djokic 2000).

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, Cornelius & Carver 2002). With the arrival of remote sensing, especially airborne laser altimetry (Marks & Bates 2000) and interferometric synthetic aperture radar (Maidment & 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).

The horizontal and vertical accuracy of the DTM is important as it will influence the reliability of the extent and depth of the modelled flood hazard map (Casas et al. 2006; DeMers 2002; De Moel, Van Alphen & Aerts 2009; FEI 2007; Maidment 2002; Martini & Loat 2007; Sane & Huokuna 2008; Uhrich in Büchele et al. 2006; Zerger & Wealands 2004). Martini & 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 & Loat 2007).

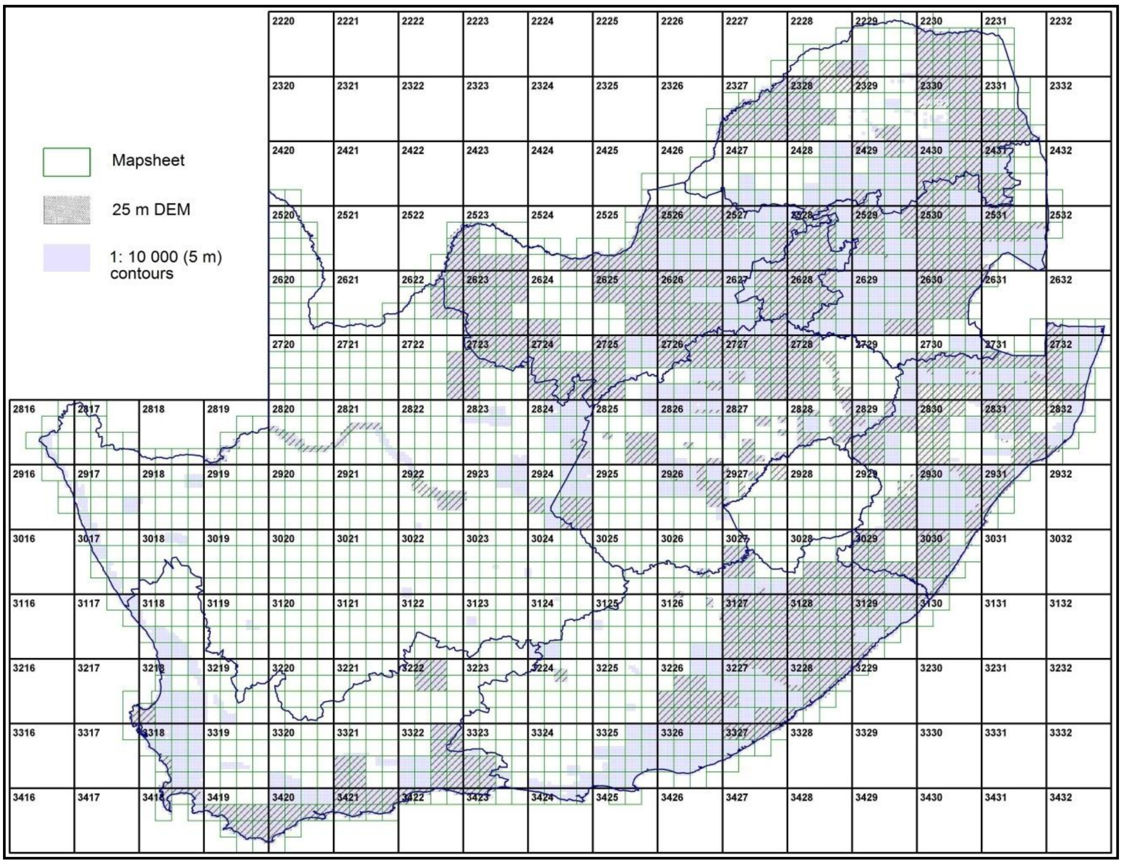
Various topographical data sources exist (see Table 4.2) in South Africa in the form of contours or DEMs. The quality of the topographical data source is an important factor in the accuracy and reliability of the final flood hazard map (De Moel, Van Alphen & Aerts 2009; Martini & Loat 2007; Sane & Huokuna 2008; Uhrich in Büchele et al. 2006), thus it is important to select the most suitable topographic data source.

Table 4.2 Topographical data sources in South Africa

Type	**Data Set**	**Resolution/ Interval**	**Coverage**	**Source**
Contour	CD: NGI 1: 10 000 contours	5-20 m*	South Africa (SA) (partial coverage)	CD: NGI (2011a)
	CD: NGI 1: 50 000 contours	20 m*	SA	CD: NGI (2011a)
DEM	CD: NGI 25 m DEM	25 m	SA (partial coverage)	CD: NGI (2011a)
	ASTER GDEM	30 m	Global	ERSDAC (2009)
	CD: NGI 50 m DEM	50 m	SA (partial coverage)	CD: NGI (2011a)
	SRTM 90 m DEM	90 m	Global	ERSDAC (2009)
	GTOPO 30	1 km	Global	ERSDAC (2009)

* Vertical interval

Chief Directorate: National Geo-spatial Information (CD: NGI) (previously Chief Directorate: Surveys and Mapping) 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 intervals with partial coverage of South Africa and a vertical accuracy of 2.5 (CD: NGI 2011a). The coverage of the 1:10 000 scale contours and the 25m DEM from CD: NGI is shown in Figure 4.2.



Source: CD: NGI (2009a, pers com)

Figure 4.2 Coverage of the 1:10 000 contours and 25 m DEM from CD: NGI

The remaining DEM data sources are from international custodians. The oldest and most coarse DEM is the Global 30 Arc-Second Elevation data set (GTOPO 30) with a 1 km resolution and vertical accuracy of 30 m. The Shuttle Radar Topography Mission (SRTM) DEM was released in 2003 by National Aeronautics and Space Agency (NASA) free of charge and covers almost the whole earth. It has a 90 m resolution and 10 m vertical accuracy (Hunter et al. 2007; ERSDAC 2009). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global digital elevation model (GDEM) was released in August 2009 and has a resolution of 30 m and a vertical accuracy of 7 m to 14 m (ERSDAC 2009).

From this data source assessment it is evident that, for topographical purposes, very limited data is available for South Africa. According to Martini & Loat (2007), a DEM of a resolution of between 10x10 m and 5x5 m is required for flood modelling. In addition, hydraulic modelling requires an accurate representation of the stream channel and surrounding area. Low resolution (>10 m) DEMs are insufficient for hydraulic modelling of river channels as it cannot represent sharp changes in the topography of the terrain. DEMs are sufficient for extracting watershed characteristics in hydrological analysis and TINs for stream channel description in hydraulic analysis. Although a TIN can be created from a DEM, the stream channel detail is still not sufficient for hydraulic analysis (Anderson 2000; Andrysiak & Maidment 2000; Maidment & Djokic 2000; Rusinga 2009, pers com). Generally, TINs are recommended as they can potentially provide a better representation of the river channel and surrounding area (Casas et al. 2006; Maidment & Djokic 2000; Rusinga 2009, pers com). The available DEMs have resolutions that vary between 30 m and 1 km, and do not adhere to the required guidelines. The best topographical data that is available is the 5 m contours (scale 1:10 000). The application of this data for flood modelling is evaluated in Chapter 5.

4.1.2 Land cover (land use) data

Land use refers to the human activity (e.g. grazing, conservation) 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 man-made features (e.g. buildings, roads) on the surface of the earth (Thompson 1996). Often, these two terms are considered the same, but in this study land cover will be the preferred term as it has a more direct bearing on the data required for hydraulic modelling.

Land cover data is required to determine the Manning's roughness coefficient needed in hydraulic modelling (Ackerman 2005; Hernandes & Zhang 2007). The available land cover data sets (see Table 4.3) for South Africa include both national and international data sources.

Table 4.3 Land use (cover) data sources in South Africa

Type	**Name**	**Resolution/Scale**	**Coverage**	**Source**
Vector	NLC 1994	1:250 000	SA, Lesotho & Swaziland	Fairbanks et al. (2000)
Vector	NLC 2000	1:50 000	SA	Schoeman et al. (2010)
Vector	ENPAT	1:250 000	SA	ENPAT (2001b)
Raster	NLC 2009	30 m	SA	SANBI (2010)
Raster	Globcover	300 m	Global	Bicheron et al. (2008)
Raster	GLC 2000	1 km	Global	Mayaux et al. (2006)

It is evident from Table 4.3 that South Africa has four land cover data sets available. The first and oldest, National Land Cover (NLC) 1994, was released in 1996 by the

Council for Scientific and Industrial Research (CSIR). This vector data set was manually digitised from the Land Remote-Sensing Satellite (Landsat) Thematic Mapper (TM) satellite imagery (hardcopy) collected from 1994 to 1996 and contained 31 land cover classes (Fairbanks et al. 2000; Schoeman et al. 2010).

NLC 2000 was the second land cover data set, and was completed in 2002, based on the Landsat 7 Enhanced Thematic Mapper (ETM) satellite imagery for the period 2000 to 2002. This raster data set contains 45 land cover classes (Schoeman et al. 2010).

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

NLC 2009 land cover data set was developed by the South African National Biodiversity Institute (SANBI) and released during 2010. This data set was based on the merging of the NLC 2000 as base layer with other more recent national land cover data sets that were developed by other state organisations or parastatal institutions (SANBI 2010). NLC 2009 is in a raster format and has a final classification of eight classes (SANBI 2009).

The Globcover project was started in April 2005 by a consortium consisting of international institutions such as the Food and Agricultural Organisations (FAO), the United Nations Environment Programme (UNEP), and the Joint Research Centre (JRC). The aim was to provide a global land cover data set based on the 300 m Medium Resolution Imaging Spectrometer Instrument (MERIS) spectrometer on board the European Space Agency Environmental Satellite (ENVISAT) launched in 2002. This land cover data set was derived from an automatic classification for the period December 2004 to June 2006 and contains 22 land cover classes (Bicheron et al. 2008).

The Global Land Cover (GLC) 2000 project’s objective was to provide a global land cover data set for the year 2000 that could provide information to the members of the

Kyoto Protocol, the Ramsar Convention, the Convention to Combat Desertification, and the International Convention on Climate Change. The data set was based on the VEGETATION VEGA2000 sensor on board the Satellite Probatoire d'Observation de la Terre (SPOT) 4 satellite (Fritz et al. 2003; JRC 2009).

The land cover data set needs to be at a scale of 1:50 000 since the hydraulic analysis is performed at this scale. Both the international land cover data sources, Globcover and GLC 2000, would be insufficient for this study due to their coarse resolutions, 300 m and 1 km respectively. Thus the NLC 2000 is the most suitable of the remaining four data sets as it was carried out at a scale of 1:50 000 and contains 45 land cover classes. Though the NLC 2009 could be considered, it has significantly fewer classes (8) compared to the 45 of the NLC 2000.

4.1.3 Historical data

Historical data is required for hydrological data input and for the calibration and validation of the flood modelling (Büchele et al. 2006; Martini & Loat 2007; Zimmermann 2008). Sources of historical data can include (FEI 2007; Martini & Loat 2007):

- dated flood maps;
- water level records of rivers;
- gauge station records (for velocity);
- flood marks;
- pictures, paintings and drawings;
- newspaper articles about past flood events, with dated photographs;
- historical reports or books about flood events; and
- aerial and satellite photos.

The capturing of data on hazard events, both spatially and non-spatially, is very limited in South Africa (Halloway, Fortune & Chasi 2010). Details of historical events are mainly obtained from newspaper articles and South African Weather Services (SAWS) reports (Sakulski 2007).

4.1.3.1 Water level and velocity data

DWA is the government organisation responsible for the monitoring, recording, assessing and dissemination of information about water resources in South Africa.

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; South Africa 1998). This information system should include the following information (De La Harpe 1998; South Africa 1998):

- hydrological data (flow and rainfall in rivers);
- water quality;
- groundwater; and
- water use licenses and other water use.

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; South Africa 1998).

The Hydrological Services at DWA are responsible for providing hydrological data and information. Their Hydrological Information System (HIS) consists of various databases which include data on river stations (see Figure 4.3), 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).

Figure 4.3 River stations in the Western Cape

4.1.3.2 Aerial and satellite imagery

Imagery is used to capture required data layers for hydraulic analysis (Rusinga 2009) and for the calibration and validation of the flood model (Büchele et al. 2006; Martini & Loat 2007; Zimmermann 2008). Table 4.4 depicts a list of relevant imagery sources available in South Africa.

The CD: NGI has a large archive of ortho- and aerial photography. Some of the aerial photos date from 1926. Their data set consists of panchromatic and colour images at different scales from across South Africa. Orthophotos are available at a scale of 1:10 000. Most of the images are from analogue photography, but since 2008 only digital imagery has been captured (CD: NGI 2011b).

Unfortunately, no aerial photography is available that specifically captures flood events, though CD: NGI will verify whether or not the area and date of the flood event coincides with any of the archived ortho- and aerial photos (CD: NGI 2009b, pers com).

There is a wide range of satellite imagery (see Table 4.4) available for South Africa that is distributed by local and international custodians. Two types of satellite imagery can be considered for capturing a flood event. The first approach is to use optical images that are captured through the detection of radiation wavelengths in the visible (0.04 µm to 0.7 µm) and infrared (0.7 µm to 100 µm) range on the electromagnetic spectrum. The absorption of radiation by these so-called passive satellite sensors can be hindered by clouds. This reduces the area suitable for further analysis and creates cloud shadows that can cause errors in the classification. Thus, imagery can only be captured during day time with limited to non-existent cloud cover (Altan et al. 2010; GMES 2010; NRCAN 2008).

Table 4.4 Aerial and satellite imagery available for flood model calibration and validation in South Africa

Type	**Name**	**Resolution/Scale**	**Coverage**	**Source**
Aerial photo	CD: NGI Panchromatic (Pan)	1: 20 000	SA	CD: SM (2006)
		1: 30 000	SA	CD: NGI (2011b)
		1: 40 000	SA	CD: SM (2006)
		1: 50 000 – 1: 60 000	SA	CD: SM (2006)
		1: 80 000	SA	CD: SM (2006)
		1: 150 000	SA	CD: NGI (2011b)
	CD: NGI Colour	1: 10 000	SA	CD: NGI (2011b)
		1: 20 000	SA	CD: SM (2006)
		1: 30 000	SA	CD: SM (2006)
Orthophotos	CD: NGI Colour	1: 10 000	SA	CD: NGI (2011b)
Satellite imagery (optical)	GeoEye-1 Pan	0.41 m	Global	GeoEye (2011)
	Worldview-1 Pan	0.5 m	Global	DigitalGlobe (2011b)
	Worldview-1 MS	0.55 m	Global	DigitalGlobe (2011b)
	WorldView-2 Pan	0.46 m	Global	DigitalGlobe (2011c)
	WorldView-2 MS	0.52 m	Global	DigitalGlobe (2011c)
	Quickbird Pan	0.65 m	Global	DigitalGlobe (2011a)
	IKONOS Pan	0.82 m	Global	GeoEye (2010)
	GeoEye-1 MS	1.65 m	Global	GeoEye (2011)
	SPOT 5 Pan	2.5 m	Global	SPOT Image (2008)
	Quickbird MS	2.62 m	Global	DigitalGlobe (2011a)
	IKONOS MS	3.2 m	Global	GeoEye (2010)
	RapidEye (Level 1B)	5 m	Global	RapidEye (2011)
	RESOURCESAT-1 (IRS-P6) Liss 4 MS	5.8 m	Global	ISRO (2011)
	Sumbandilasat MSS	6.25m	SA (partial coverage)	Koekemoer, Govender & Smit (2011)
	SPOT 1, 2, 3 Pan	10 m	Global	SPOT Image (2010)
	SPOT 4 Pan	10 m	Global	SPOT Image (2010)
	SPOT 5 MSS	10 m	Global	SPOT Image (2008)
	Landsat 7 Pan	15 m	Global	GLCF (2009)
	SPOT 1, 2, 3 MS	20 m	Global	SPOT Image (2010)
	SPOT 4 MS	20 m	Global	SPOT Image (2010)
	CBERS CCD	20 m	Global	CBERS (2011)
	RESOURCESAT-1 (IRS-P6) Liss 3 MS	23.5 m	Global	ISRO (2011)
	Landsat 4, 5 MSS	30 m	SA	GLCF (2009)
	Landsat 7 MSS	30 m	SA	GLCF (2009)
	Landsat 1-4 MSS	60 m	SA	GLCF (2009)
	Modis MS(band 1-2)	250 m	Global	NASA (2011)
	Modis MS(band 3-7)	500 m	Global	NASA (2011)
	Modis MS(band 8-36)	1 km	Global	NASA (2011)
	NOAA AVHRR	1 km	Global	NOAA (2011)
Satellite imagery (RADAR)	TerraSAR-X High Resolution Spotlight	1 m	Global	Infoterra (2009)
	TerraSAR-X Spotlight	2 m	Global	Infoterra (2009)
	Radarsat-2	3 m	Global	CSA (2011)
	TerraSAR-X StripMap	3 m	Global	Infoterra (2009)
	Radarsat-1	8 m	Global	CSA (2011)
	ERS AMI SAR 2	30 m	Global	Eurimage (2011)
	TerraSAR-X ScanSAR	100 km	Global	Infoterra (2009)

The second type of satellite imagery that can be used for flood event monitoring are captured by active sensors. Radio Detection and Ranging (RADAR) sensors can, for example, generate electromagnetic radiation (in the microwave region of the spectrum) that penetrates clouds. This type of imagery is consequently not influenced by weather events (e.g. mist, rain, lightning) and has an all-weather capturing capability which is extremely valuable since flood events are associated with clouds. Furthermore, RADAR can capture images during the night. RADAR is, however, often less accurate than its optical counterpart due to geometric distortions (e.g. layover, radar shadows and foreshortening) (Altan et al. 2010; GMES 2010; NRCAN 2008; Streicher 2011).

Satellite imagery can be classified into three categories according to their geometric resolution (Altan et al. 2010):

- low/medium (30 m – 1 000 m);
- medium (10 m – 30 m); and
- high (0.1 m – 10 m).

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) (see Section 3.6.2). Table 4.4 lists the range of satellite imagery that is available in South Africa.

When historical flood data is used, images captured before and during the disaster are required to allow for proper identification of previously existing water bodies for calibration and validation purposes (Altan et al. 2010). Separate data sets are needed to perform calibration and validation (Longley et al. 2005). During the calibration process, the flood model results are compared with the historic imagery of a similar event. The error margin is calculated and the parameters in the flood modelling analysis are adjusted until a result is obtained that corresponds with the historic imagery (Dyhouse, Hatchett & Benn 2003). Validation can only commence after the calibration has been completed. The same historic imagery used in the calibration cannot be used in the validation and different imagery of a historic flood event is required. The second set of historical imagery is used to perform further flood modelling analysis that can be used for validation purposes. If the flood modelling result corresponds to the event as captured by the historic imagery, it can be concluded that the result has been validated and that it is accurate within the limits of uncertainty (Dyhouse, Hatchett & Benn 2003; Longley et al. 2005).

The flood extent image should preferably be captured within 8 to 24 hours after the flood event has occurred (GMES 2010). Temporal resolution (return cycle) refers to the frequency with which images are captured by a satellite for the same area or to the time period that it takes a satellite to complete one orbit (Longley et al. 2005; NRCAN 2008). Areas located in the high latitudes will have a higher temporal resolution (NRCAN 2008). The temporal resolution is only of importance when the flood extent must be monitored over a period of time (GMES 2010), thus seeing the flood extent retreating over a period of 1 to 3 days. The selection of imagery for the verification and calibration of the flood model depends on the selected study area and the availability of imagery for when historical flood events occurred. Images listed in Table 4.4 with resolutions of 30 m or better (e.g. GeoEye, SPOT, Landsat, CBERS CCD, RESOURCESAT-1, ERS AMI SAR 2 (RADAR)) can be considered for calibration and validation purposes. Higher resolution imagery (e.g. GeoEye, WorldView) enables the identification of flooding remnants (e.g. erosion terraces, debris, alluvial deposits) and can consequently reduce the temporal resolution requirements by several days.

This chapter assessed the data sources available in South Africa for flood hazard mapping. Suitable data sources were selected based on their scale and coverage. This allowed the identification of a suitable area to demonstrate whether this data can be used to perform flood modelling. This demonstration will be described in more detail in the next chapter.

CHAPTER 5: FLOOD MODELLING DEMONSTRATION

This chapter will demonstrate how flood modelling can be performed using the data sources identified in Chapter 4. The methodology applied in this chapter is, however, restricted by the available data. Complex analyses were not possible since the required detailed data for both the topographic representation and flow are not available in South Africa. Only one-dimensional, steady flow hydraulic modelling could be carried out to determine primary flood parameters (e.g. extent and depth). Flood hazard maps were created at a scale of 1:50 000, but could not be validated due to the unavailability of archived satellite imagery. The aim of this chapter is to provide an overview of the flood modelling process and to qualitatively evaluate the suitability of available data for flood hazard mapping.

5.1 DEMONSTRATION AREA IDENTIFICATION

Only a few suitable data sources in South Africa are available for flood hazard modelling (see Chapter 4). The data sources that could potentially be used for flood hazard mapping are summarised in Table 5.1.

Table 5.1 Data sources suitable for flood hazard mapping

Data Input	**Name**
Topographic	CD: NGI 1: 10 000 (5 m) contours
Land cover	NLC 2000
Water level	DWA’s Hydrological Information System

The identification of a suitable area for demonstrating how flood modelling can be performed using the data listed in Table 5.1 was challenging. This was mainly due to the limited coverage of 1:10 000 scale contours (see Figure 4.2) and river gauge stations (Figure 4.3). In the Western Cape, 1:10 000 contour availability is mainly restricted to the West Coast, Overberg and Eden District Municipalities. Although gauge stations exist for both major and minor rivers, flow data is often absent, inconsistent or incomplete for many stations. This aspect was a major restriction for selecting an appropriate demonstration area. Notwithstanding, a suitable river gauge station located along the *Great Berg River* between Piketberg and Riebeeck West was identified (see Figure 5.1). The demonstration area was chosen to include an area 5 km upstream and downstream of the station, which is located on Drieheuvels farm.

Figure 5.1 Drieheuvels demonstration area

The total length of river segment within the *Great Berg River* is about 12 km. Farming communities live in close proximity to the river and are vulnerable to severe flooding events that may occur. Possible impacts due to flooding can include death, injury, damages to agricultural land or disrupted water supply, as discussed in Section 2.2.2.

Dates of major flood events that occurred at Drieheuvels were compiled from the list of peak discharge values. Two major floods, occurring between 6 and 11 June 2007 and from 25 to 28 June 2007, were identified. The dates of these floods were confirmed by a report on the consequences of flood disasters that occurred in the West Coast district during this period (DIMP 2007). Archives of high and medium resolution satellite imagery (Table 4.4) were searched for imagery of these two flood events. Only one Landsat 7 ETM+ (30 m resolution) satellite image for 17 June 2007 could be found. The six day delay was too long to identify the flood extent with any certainty and thus the calibration and validation of the model could not be done. This limits the level of uncertainty calculation. The resulting model should consequently only be considered as a prediction of the flood parameters for large scale purposes as discussed in Section 3.6.2.

5.2 SOFTWARE SELECTION

Software packages that perform one-dimensional modelling include HEC-RAS, Infoworks RS and Mike 11. HEC-RAS is the most widely used computer program for floodplain analysis (Dyhouse, Hatchett & Benn 2003) and has been approved by FEMA (FEMA 2009). HEC-RAS 4.0 was consequently selected for the demonstration. ArcGIS 9.3 and the HEC-GeoRAS 4.1 extension were chosen for data pre-processing, direct support and post-processing as HEC-GeoRAS provides a bridge between the hydraulic- and GIS software and enables data exchange between the two disciplines.

5.2.1 HEC-RAS

HEC-RAS was first developed by the United States Army's Engineering Corps in 1995, and was the successor to the HEC-2 river hydraulics software. As discussed in Section 3.5.3, HEC-RAS is a one-dimensional software modelling program that allows the modelling of floodplains in steady and unsteady open-channel flows that are either natural or man-made (Brunner 2008a; Dyhouse, Hatchett & Benn 2003).

The software's basic computational procedure includes the solution of the one-dimensional energy equation (using Manning's equation). Where the water surface profile varies rapidly, the momentum equation is incorporated. The effects of obstructions, bridges, culverts, dams, weirs and other structures in the floodplain are taken into consideration during the computation (Brunner 2008a).

HEC-RAS can handle a full network of constructed channels or a natural network such as a dendritic system (see Section 2.2.4.2) or a single river reach (Ackerman, Evans & Brunner 1999; Brunner 2008a; Brunner 2008b). This software recognises reaches as river segments that are divided by junctions. All reaches are orientated downstream (Ackerman, Evans & Brunner 1999).

HEC-RAS handles input and output data as flat files (American Standard Code for Information Interchange (ASCII) and binary), that can be exported to other formats. Various formats of geometric data can be imported from other HEC-related software packages into an existing or a newly created geometry file. Multiple geometry data can be imported per reach (Brunner 2008a).

5.2.2 HEC-GeoRAS

HEC-GeoRAS was developed in a joint effort between the HEC and the Environmental Systems Research Institute (ESRI) as an extension to ArcGIS 9.x (and the previous ArcGIS 8.x and ArcView 3.x) (Ackerman 2005). The functionality of Hec-GeoRAS is based on the Spatial Analyst and 3D Analyst ArcGIS extensions (Ackerman 2005; Warner et al. 2008). Without these two extensions, the free downloadable HEC-GeoRAS would not be functional.

HEC-GeoRAS is a loose coupled integration (see Figure 5.2) and forms a bridge between ArcMap, and HEC-RAS, as discussed in Section 3.3.3 (Heywood, Cornelius & Carver 2002; Robayo & Maidment 2005; Zerger & Wealands 2004). Data is exchanged between the two software packages using a data exchange format (Robayo & Maidment 2005; Stangel 2009; Sui & Maggio 1999).

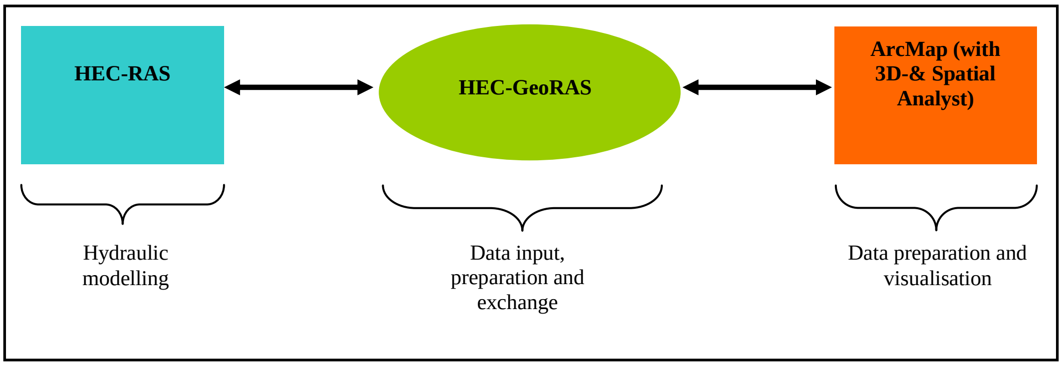


Figure 5.2 Loose coupling integration between HEC-RAS and ArcMap

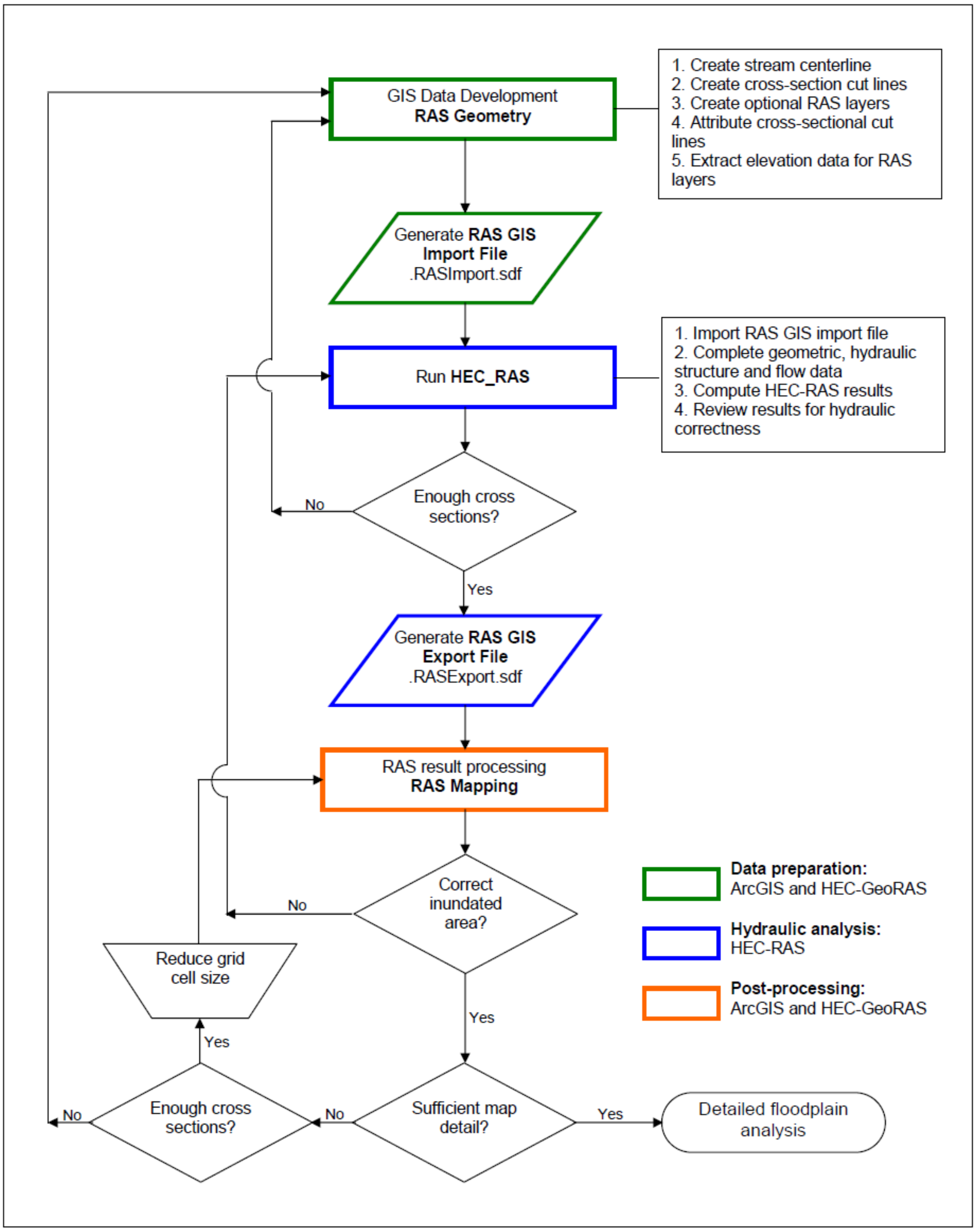
HEC-GeoRAS assists ArcMap in providing pre-processing, direct support and post-processing functionality before and after the hydraulic analysis. For pre-processing, data preparation is done by both software packages, but HEC-GeoRAS provides the extra capability to capture the geometric data according to the HEC-RAS format required for the hydraulic modelling. HEC-GeoRAS exports and imports the spatial data to different formats between ArcMap and HEC-RAS by using a data exchange format called a RAS GIS File (Ackerman 2005; Ackerman, Evans & Brunner 1999; Merwade 2009).

For direct support functions, ArcMap and HEC-GeoRAS are used to calibrate and validate the hydraulic results obtained through HEC-RAS. The modelled water level profile is imported from HEC-RAS via HEC-GeoRAS into ArcMap, where the flood hazard mapping is performed (Ackerman 2005; Merwade 2009).

Post-processing functionalities allow ArcMap and HEC-GeoRAS to prepare and style the final flood hazard map results for visualisation and presentation purposes (Ackerman 2005; Ackerman, Evans & Brunner 1999; Merwade 2009).

5.3 MODELLING OVERVIEW

There are three main phases in flood modelling analysis using HEC-RAS, namely data preparation, hydraulic analysis, and post-processing. Data preparation and post-processing are performed in ArcMap with the extension HEC-GeoRAS, and all hydraulic analysis is performed within HEC-RAS. An overview of the process flow is given in Figure 5.3. These phases are discussed in more detail in the following sections. A step-by-step account of the modelling process is provided in Appendix A.



Adapted from: Ackerman (2005: 18)

Figure 5.3 Process flow diagram for flood modelling

5.4 DATA PREPARATION

The data preparation phase included all the procedures for the creation, preparation and exchange of the spatial data required for the hydraulic analysis. All of these procedures were carried out in ArcMap and HEC-GeoRAS.

Two main data types, namely topographic data and RAS layers, were prepared for the hydraulic analysis. Topographic data represents the surface of the river and the surrounding terrain to be modelled, whereas RAS layers include the river network, cross-sections and other relevant river analysis system parameters. The geometric data required by HEC-RAS is developed based on the intersection of the RAS layers with the topographic data (Ackerman 2005).

The creation and preparation of the topographic data and RAS layers are discussed in more detail in the following sections.

5.4.1 Topographic data

Topographic data provides the elevation for the stream channel and the surrounding area. The 5 m contours were selected as the most appropriate data source to create a TIN of the demonstration area (Section 4.1.1). Figure 5.4 shows the steps workflow for creating the TIN.

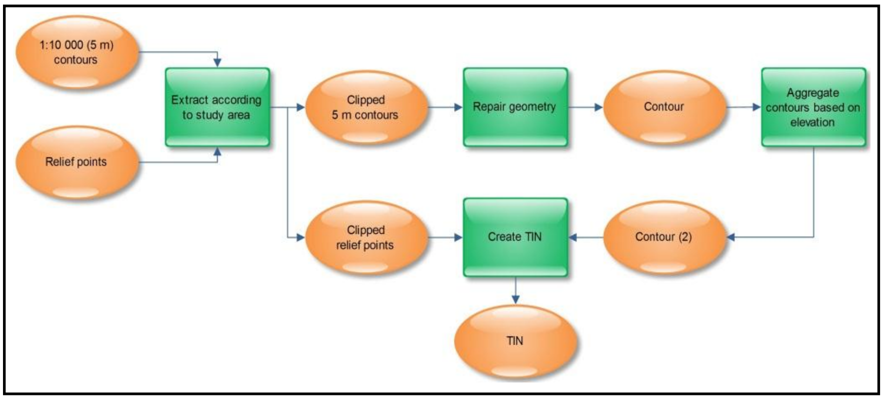


Figure 5.4 TIN creation workflow

The contours must be clipped to an area larger than the demonstration area to ensure better topographic representation at the boundaries. The Repair Geometry tool in ArcGIS was used to identify and correct any geometric problems in the *Contours* shapefile. The contours were then aggregated based on the *Height* field, using the Dissolve tool, which reduced the number of features from 5577 to 191. Relief points were used as an additional data set in the 3D Analyst Create TIN, from the Features tool, to create the TIN.

Triangulation was set to *hard line* to indicate a significant break in elevation (Andrysiak & Maidment 2000; Rusinga 2009, pers com). The resulting TIN (see

Figure 5.5) was examined and it was found that it contained insufficient detail of the stream channel.

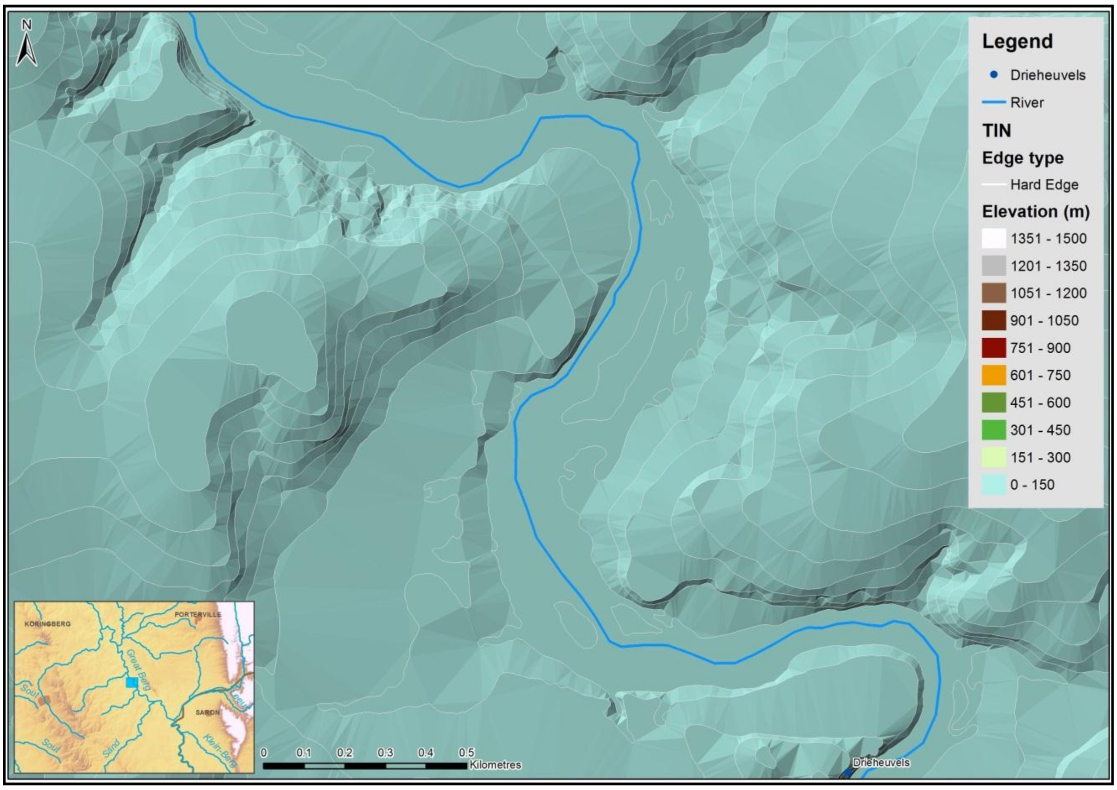


Figure 5.5 TIN representing the stream channel

The river channel was represented as a large flat area with a stepped river bed. This topographic representation of the river channel was inaccurate and caused discontinuous flood lines that were characterised by unreal islands in the middle of the river channel (Rusinga 2010c, pers com).

According to Rusinga (2009, pers com) the flat areas in the resulting river channel are regular occurrences in TINs that where created from contours with large vertical intervals. The size of these flat areas increases as the terrain becomes flatter.

To overcome this problem, a GIS tool was developed by the Hydrology Section of Aurecon (previously Ninham Shand Consulting Engineers). The so-called Upgrade River Centre Line tool uses a digitised 3D river centre line that snaps to the contour and creates a TIN without flat areas (Rusinga 2009, pers com).

Figure 5.6 shows the workflow of the Upgrade River Centre Line tool. The river centre line is intersected by the contours, and the elevation of the specific contour is assigned to the river centre line. The Upgrade River Centre Line tool linearly interpolates elevations between the intersection points on the river centre line and assigns these interpolated values to vertices between the intersected contours (Rusinga 2010c, pers com). This approach of 3D interpolation is an accepted approach in the creation of river channel representations for hydraulic analysis (Djokic 2010, pers com).

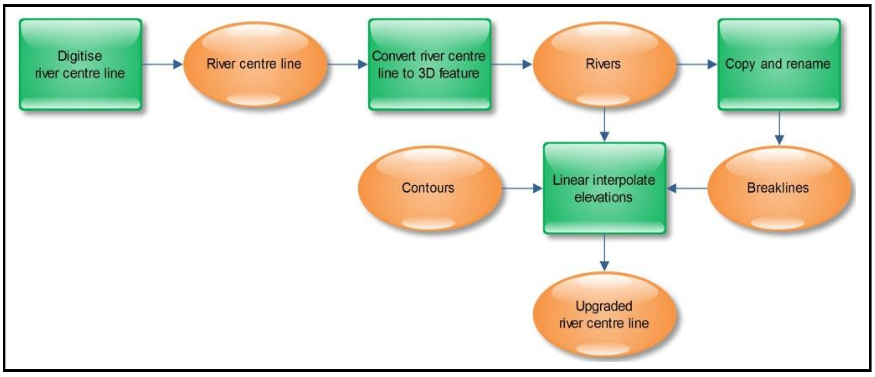


Figure 5.6 Upgrade River Centre Line tool workflow

The Profile Graph tool in the 3D Analyst extension of ArcGIS was used to verify the success of the process. The profile of the graph (see Figure 5.7) is stepped and not flat, indicating that the upgrade of the river centre line was successful. The profile graph shows that the elevation values were interpolated between the contours and added to the river centre line. The river centre line starts at a height of 45 m and decreases steadily over its length of 45 km to a height of 20 m.

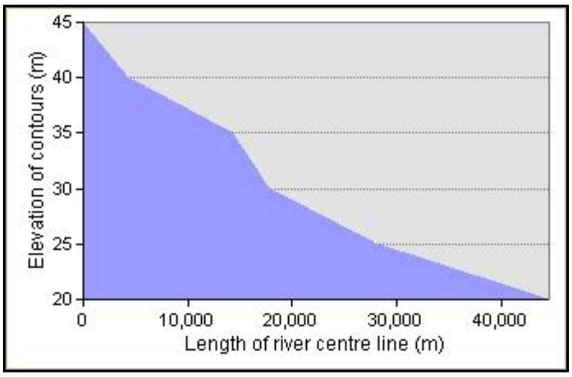


Figure 5.7 Profile graph of the upgraded river centre line

The upgraded river centre line and contours were used to create a second TIN (see Figure 5.8). It is evident that the river channel is more defined compared to the first TIN (see Figure 5.5). The large flat areas have been removed and there is a better indication of the slopes within the river channel. The second TIN was consequently used in the demonstration.

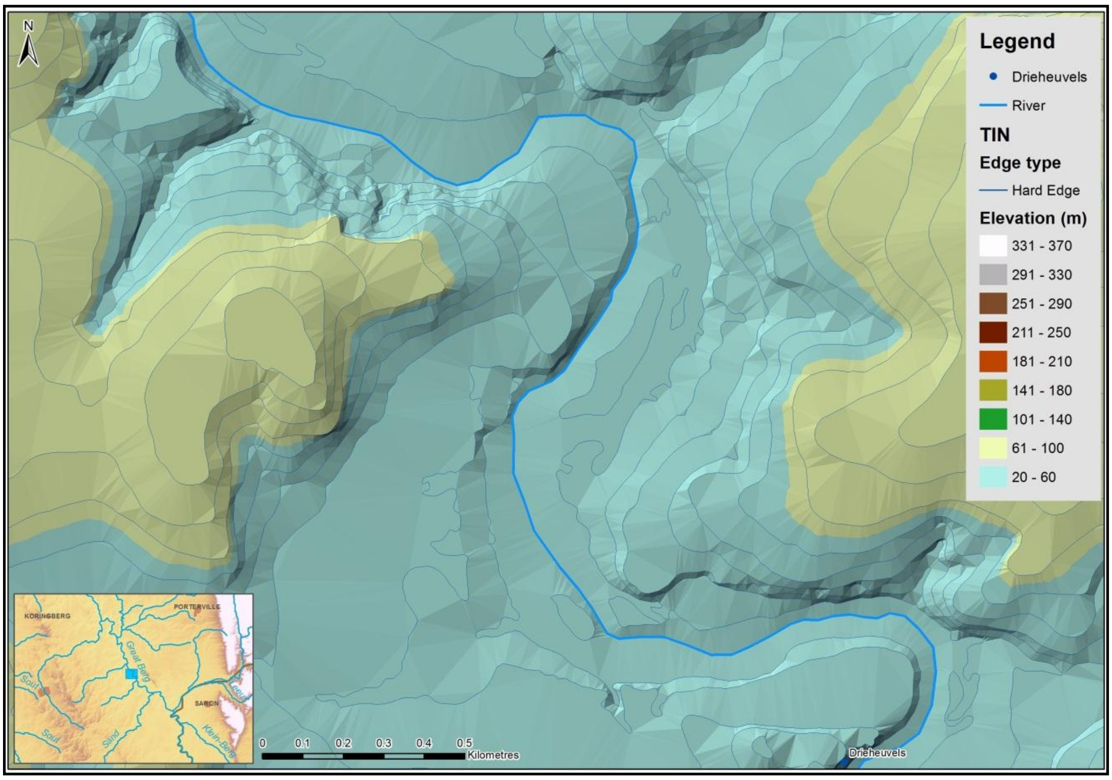
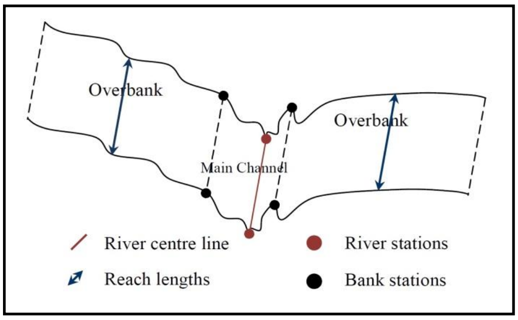


Figure 5.8 TIN built with the upgraded river centre line

5.4.2 RAS layers

The RAS layers represent cross-sections and other data that describe the river and its surrounding terrain. Each of these layers will be described in the following sections. The RAS layers that were created for this demonstration are *Stream Centerline* (river centre line), *Bank Lines*, *Flow Path Centerlines*, *Cross-sectional Cut Lines* and *Land Use Areas* (see Figure 5.9).



Adapted from: Ackerman, Evans & Brunner (1999: 2)

Figure 5.9 Cross-sectional cut lines intersecting with river centre line and bank lines

The cross-sections are taken perpendicular to the direction of the flow in the main channel and the overbanks. Data abstracted from the cross-sections include (Ackerman, Evans & Brunner 1999):

- station elevation data containing the actual physical ground elevation for the reaches measured at specific locations;
- reach lengths indicating the distances between cross-sections and used to calculate the energy losses and flow carrying capacity;
- main channel bank stations indicating the actual division of the cross-sections between the main channel and the bordering overbank flows (also called adjacent flood plain areas);
- roughness coefficients required to indicate relative channel roughness, using Manning's values, which are required for calculating the frictional energy loss between cross-sections; and
- contraction/expansion coefficients used to indicate rapid flow changes, depending on the type of flow.

HEC-GeoRAS automatically creates a geodatabase containing the empty RAS layers within the same folder and with the same name as the ArcMap document.

5.4.2.1 Stream centre line

The stream centre line layer describes the river network and connectivity, starting upstream and going downstream following the direction of the river flow (Ackerman 2005; FEI 2007). It considers each reach in the network separately. The stream centre line layer is required to create the river stations for the cross-sections and to indicate the flow path of the main channel. River stations are created at the points of intersection between the cross-sectional cut lines and the river centre line layer (Ackerman 2005; Merwade 2009). The river centre line digitised for creating the TIN (see Section 5.4.1) was imported into the geodatabase for this purpose.

5.4.2.2 Bank lines

The bank lines layer indicates the boundary between the flow in the main stream channel and the overbank floodplain area (see Figure 5.9). Banks stations are created where each bank line intersects with a cross-sectional cut line. Furthermore, the bank lines indicate changes in the characteristics of the cross-sections, for example, higher Manning's coefficient values are assigned to overbank areas to compensate for the rougher vegetation (Ackerman 2005; Merwade 2009). The bank lines layer (see Figure 5.10) was digitised from a SPOT 5 image captured during 2010. Alternatively, any of the high resolution images discussed in Section 4.1.3.2 can be used. These images clearly indicate areas prone to main channel flow and overbank flood plain areas by observing the differences in vegetation and land cover.

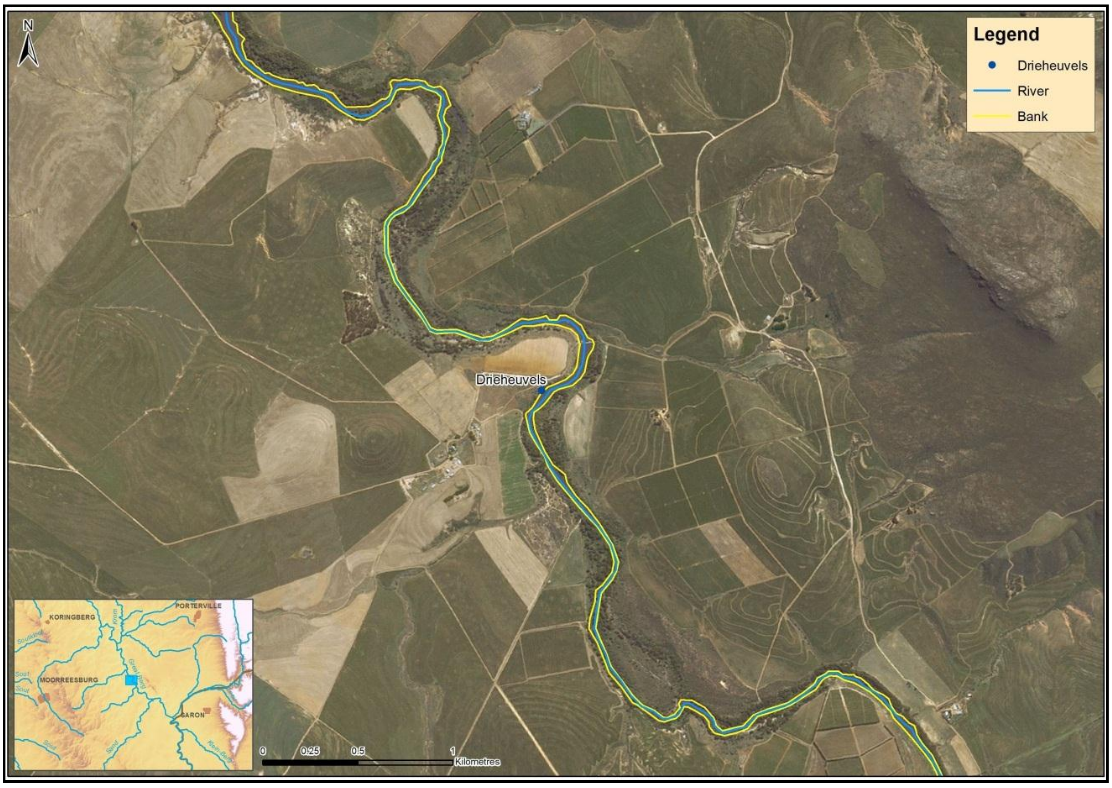
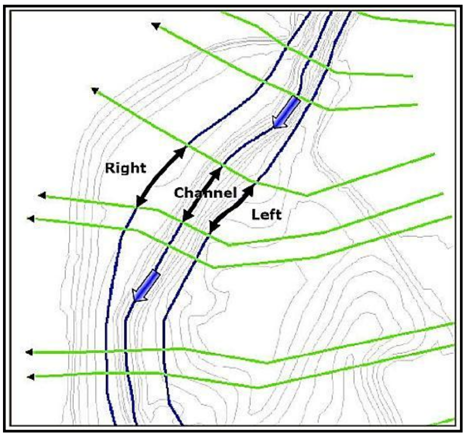


Figure 5.10 *Banks* layer

5.4.2.3 Flow path centre line

The flow path centre line layer describes the downstream reach lengths (hydraulic flow path) (see Figure 5.11) between the cross-sectional cut lines for the main stream channel as well as the left and right overbanks (Ackerman 2005; Merwade 2009).



Source: Ackerman (2005: 54)

Figure 5.11 Calculation of downstream reach lengths from flow paths and cut lines

The captured flow path centre line layer is shown in Figure 5.12.

Figure 5.12 *Flow Path Centreline* layer

5.4.2.4 Cross-sectional cut lines

The captured cross-sectional cut lines layer is shown in Figure 5.13.

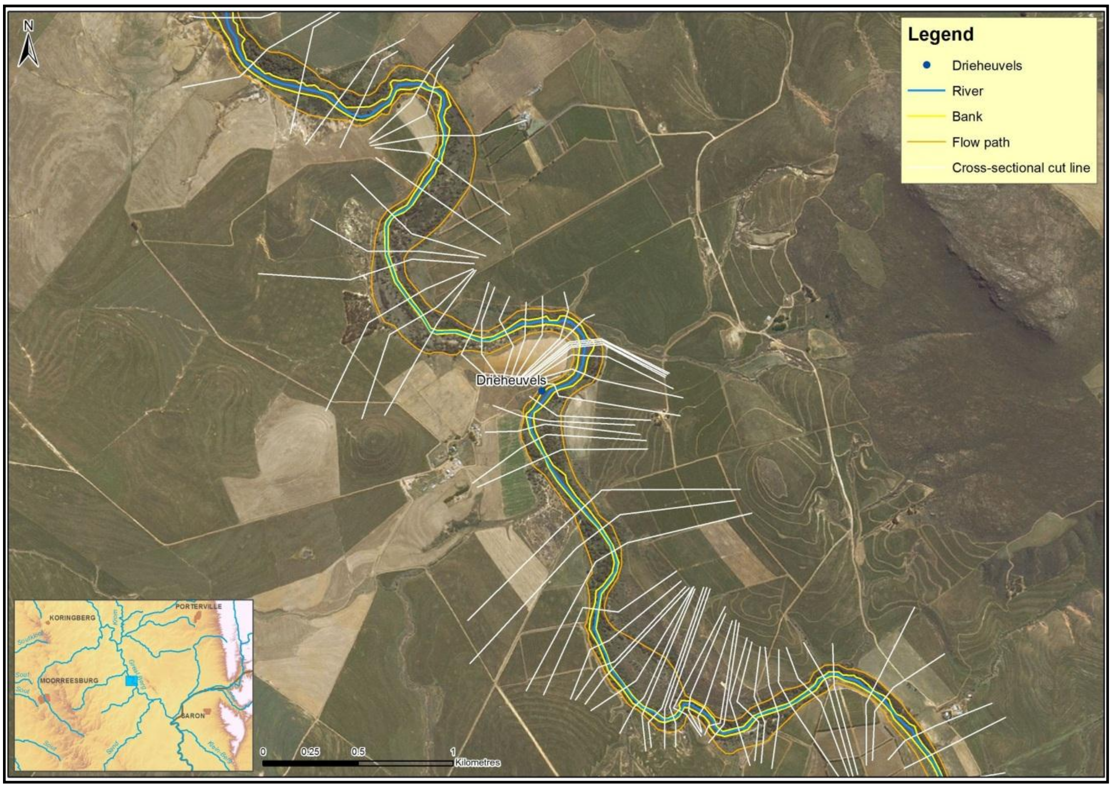


Figure 5.13 *Cross-sectional Cut Lines* layer

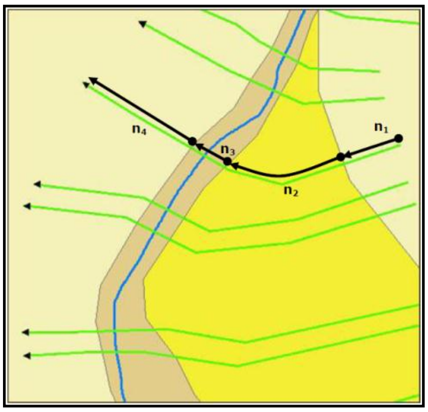
Cross-sectional data is required to display the river geometry (ground surface profile) (Correia et al. 1998) and to determine the flow carrying capacity of the river and the adjacent floodplains (Brunner 2008b). The cross-sections (see Figure 5.9) are captured perpendicular to the direction of the flow. The locations of cross-sectional cut lines are determined by three factors, namely (Rusinga 2010b, pers com):

- change in contours;
- directly before and after bridges; and
- changes in land cover.

An elevation value is assigned to each river station based on the elevation where that cross-sectional cut line intersects with the TIN (Ackerman 2005; Merwade 2009).

5.4.2.5 Land cover

The land cover layer is needed to calculate the Manning's coefficient values (also called n values) along each cross-sectional cut line. This data set must be a polygon layer with an attribute named *N-Value*, which contains the Manning's coefficient value for each land cover type (Ackerman 2005; Hernandes & Zhang 2007; Merwade 2009). Figure 5.14 indicates the calculation of Manning's coefficient values. The Manning's coefficient values are calculated for each intersection between the cross sectional cut lines and the land use polygon layer.



Source: Ackerman (2005: 66)

Figure 5.14 Calculation of Manning's coefficient values

The NLC 2000 data set was selected (see Section 4.1.2) to determine the Manning's coefficient value for roughness and the resulting *Land Use* (land cover) shapefile is shown in Figure 5.15.

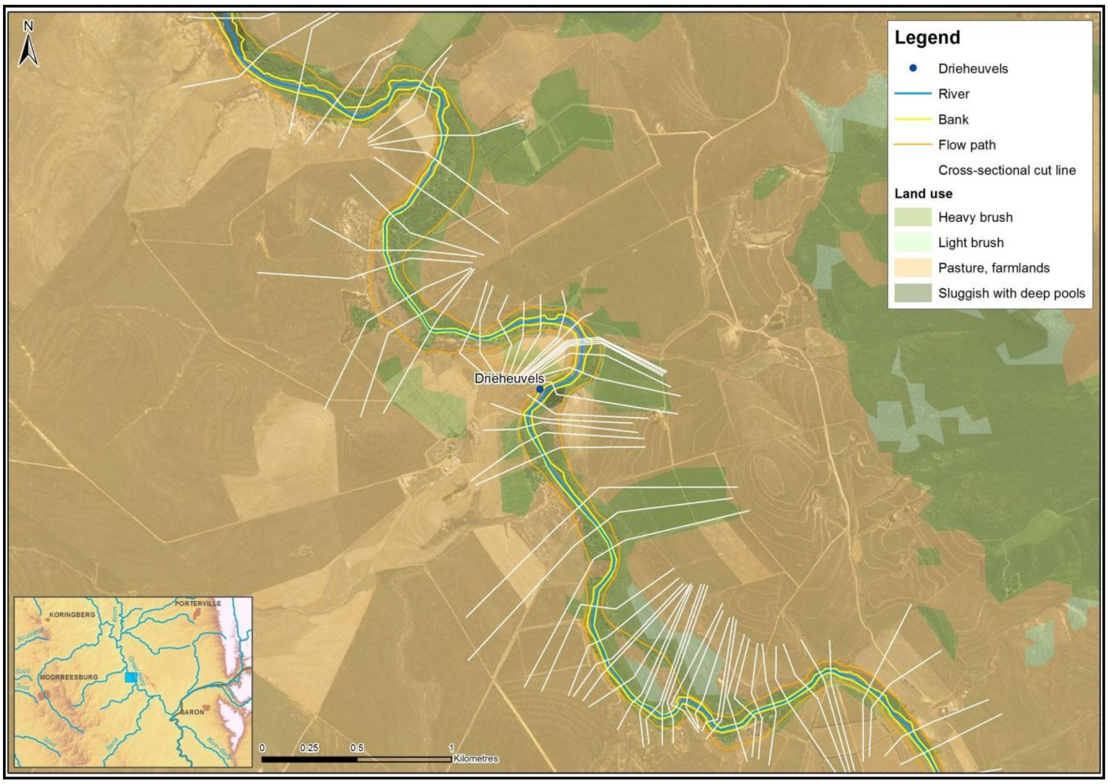


Figure 5.15 *Land use* layer

The corresponding Manning’s roughness coefficient for each land use type (see Table 5.2) was added to the attribute table of the *LandUse* shapefile.

Table 5.2 Manning’s roughness coefficients for the demonstration area

Land Cover Type	**Manning’s Categories**	**Manning’sValue (n)**
Cultivated, temporary, commercial, dryland	Floodplains/Pasture, Farmlands	0.035
Shrubland and Low Fynbos	Floodplains/Light brush	0.050
Thicket, Bushland, Bush Clumps, High Fynbos	Floodplains/Heavy Brush	0.075
Water bodies	Natural Channels/Sluggish with deep pools	0.040

The Manning’s coefficient value was extracted at each intersection of the *Cross-sectional Cut Lines* and *Land Use* boundaries. (Ackerman 2005; Merwade 2009). The resulting table, *Manning*, contains the relative station number and the resulting Manning’s coefficient value extracted at the intersection of every *Cross-Sectional Cut Line* and *Land Use* boundary.

5.4.2.6 Optional layers

The following optional layers can be added to the RAS layers (Ackerman 2005; Merwade 2009):

- ineffective flow areas: specifies areas where water flow is stagnant and not part of an existing flow, including areas of zero velocity, for example dead water zones upstream and downstream of bridges or culverts;
- bridges and culverts: identifies river crossings which are indicated in the same way as the cross-sectional cut lines. A river station will be created where a cross-sectional cut line intersects the stream centre line;
- blocked obstructions: delineates areas that do not permit flooding or that are permanently removed from the flow area of the cross–sections;
- levee alignment: indicates linear features like levee systems and high ground that channel lateral water flow in the floodplain;
- inline structure: defines any dams that stretch across a river and are handled the same as bridges and culverts;
- lateral structure: identifies any structures like dams and gated structures that are located next to the main river channel where possible spill over is expected; and
- storage area: models any detention storage in the floodplain and is connected with a lateral structure to the main channel.

Once the RAS layers have been created, HEC-GeoRAS extracts the elevation values at every intersection of the RAS layers with the TIN to create the geometric data for HEC-RAS. This elevation data together with all the captured RAS layers were exported to an exchange file which was imported into HEC-RAS in the hydraulic analysis phase (Casas et al. 2006).

5.5 HYDRAULIC ANALYSIS

The hydraulic analysis phase entails the application of the hydraulic software, HEC-RAS, and consists of four steps, namely (Ackerman 2005):

1. importing and defining the geometric data;
2. completing the geometric and flow data;
3. computing HEC-RAS; and
4. reviewing the results.

Each of these steps is discussed in the following sections.

5.5.1 Importing and defining the geometric data

The exchange file created in ArcMap and HEC-GeoRAS contains all the geometric data required by HEC-RAS for the hydraulic analysis (Ackerman 2005; Casas et al. 2006). The river network was imported first, as it describes the connectivity of the river reaches. It also determines the naming convention within HEC-RAS that will be used for referencing additional data (Ackerman 2005; Merwade 2009). The cross-sectional data was added next and tests were performed to ensure that the cross-sections captured in ArcMap are sufficient for the hydraulic analysis. Edits and adjustments can be made to inaccurate cross-sections by using the Graphical Cross-Section Editor tool in HEC-RAS (Ackerman 2005; Merwade 2009). This tool was used to view all the imported cross-sections for this demonstration and was found to be in order. Cross-sections were intersecting with the stream centre line, bank lines and land cover layers.

5.5.2 Completing the geometric and flow data

5.5.2.1 Geometric data

All the geometric data was successfully imported into HEC-RAS. Various tools are available in HEC-RAS to validate this data. For instance, the Graphical Cross-section Edit tool (Tools menu) can be used to change the locations of bank stations, Manning’s n-values, ground points and structures.

Each cross-section can have up to 500 elevation points. Many of these can be redundant, particularly in relatively homogenous terrain (Merwade 2009). The Cross-Section Points Filter tool (Tool menu) can be used to remove these redundant elevation points. Owing to the low resolution of the terrain data used in this demonstration, the number of elevation points per cross-section was never more than 74 and thus no filtering of the points was required.

5.5.2.2 Flow data

Flow data represents hydraulic events that have taken place (Ackerman, Evans & Brunner 1999; Brunner 2008b; Correia et al. 1998; FEI 2007) and includes the following (Brunner 2008b):

- flow regime: differentiates between subcritical, supercritical, and mixed flow regimes for steady flow conditions;
- boundary conditions: describes the starting water level at the opposite ends of the river (i.e. upstream and downstream). The hydraulic analysis starts at a cross-section with a known water surface level (downstream section if the flow is subcritical, and upstream section if the flow is supercritical);and
- peak discharge value: calculates the water surface profile at each cross-section. A minimum of one value is required per reach and is captured from upstream to downstream. The flow is assumed constant from the first upstream cross-section with a value continuing downstream until another value is added lower down in the reach.

These parameters are required to perform the hydraulic analysis within HEC-RAS. The first two parameters will depend on the type of flow to be modelled (see Section 3.5.1).

The first parameter, flow regime, can be described as either steady or unsteady. A steady flow system was selected for this demonstration because it is used to determine floodway encroachments for floodplain management and flood insurance studies (USACE 2011). The main characteristic of steady flow is that depth stays constant at a specific point with respect to time (see Section 3.5.1.1.).

The second parameter, boundary conditions, is required to determine a starting water surface to allow HEC-RAS to begin with the calculations (Brunner 2008a; Merwade 2009). If the flow is subcritical then boundary conditions are required at the downstream ends of the river system, or if the flow is supercritical (see Section 3.5.1.3) then boundary conditions are required at the upstream ends of the river system. Otherwise, if a mixed flow is considered, then boundary conditions are required for both ends (upstream and downstream) of the river system (Brunner 2008a).

HEC-RAS offers four types of boundary conditions from which to choose when entering the data, namely (Brunner 2008a):

- known water surface elevations: a known water surface is added for each profile;
- critical depth: requires no input from the user as HEC-RAS automatically calculates the critical depth for each profile;
- normal depth: requires the input of the energy slope that will be used in calculating normal depth (Manning's equation) at that location (the slope of the channel is often used where the energy slope is unknown); and
- rating curve: requires that the user adds elevations against a flow rating curve in order for HEC-RAS to interpolate the elevation from the rating curve, given the flow.

For this demonstration, a subcritical flow with a normal depth was used, as the energy slope is not available. However, an approximation based on the slope of the channel bottom can be used (Brunner 2008a). Boundary conditions were consequently required for downstream ends, while the channel slope was needed to represent the energy slope for normal depth.

The third parameter, the peak discharge value, needed to be calculated for different probabilities or recurrences (Section 2.2.1.3). There are three main methods for the calculation of peak discharge values, namely (Görgens 2003; Van Der Spuy, Rademeyer & Linström 2004):

- probabilistic (statistical): statistical calculations based on observed flood peaks (historical data);
- deterministic: hydrological analysis of physical factors such as catchment and climate characteristics are performed; and
- empirical: mathematical models are developed to fit available data (for example catchment characteristics and flood region).

A basic probabilistic methodology was followed to calculate the peak discharge values for the demonstration as it only requires data from gauge stations where the other two methods require input on the catchment characteristics. This method consists of two steps (Baer 2008; Görgens 2003):

- analytical calculation based on the probability characteristics of the observed flood peaks (historic data); and

- checking the goodness-of-fit of the data to a particular distribution by means of either graphical or statistical methods, or both.

The peak discharge values for Drieheuvels gauge station (G1H013) were obtained from the DWA’s hydrological information system (HIS) for the analytical calculation of the probability. This station has a complete list of verified data for peak discharge values and peak level from 1965, covering a period of 45 years. A list of monthly maximum discharge peaks (in m³/s) for station G1H013 was downloaded and investigated. The annual maximum peak discharge value was identified for each year, and ranked by assigning a rank of one to the largest and forty-five to the smallest. From these rankings the recurrence intervals were calculated using Equation 5.1 (Baer 2008; Görgens 2003):

$$T = \frac{(n+1)}{m} \qquad \text{Equation 5.1}$$

where T is the recurrence interval (in years) for each flood;
n the number of years of record; and
m the rank or order of the annual flood discharges from the greatest (1) to the smallest for the number of years of record.

The recurrence value and annual peak discharge are plotted on a flood frequency graph with a log-normal distribution where the horizontal (x) axis represents the recurrence interval as logarithmic (see Figure 5.16). A log-normal distribution is a special form of the Log-Pearson Type III distribution that provides an acceptable range to represent Southern African conditions (Görgens 2003).

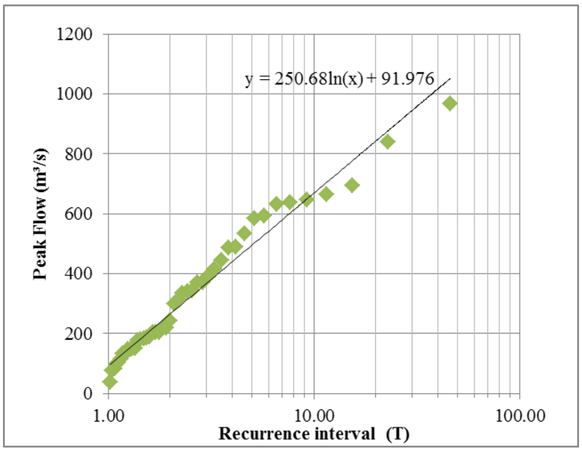


Figure 5.16 Flood frequency graph

Next, a logarithmic equation (see Figure 5.16) was derived that best represents the distribution of the peak discharge values in the flood frequency graph. The derived logarithmic equation for the demonstration area was:

$$y = 250.68\ln(x) + 91.976 \qquad \text{Equation 5.2}$$

where y is the peak discharge (m^3/s); and
x is the recurrence interval (in years) for each flood.

This logarithmic equation was used to calculate the peak discharge values for different recurrence intervals (Table 5.3).

Table 5.3 Peak discharge calculation

Recurrence Interval(years)(x)	**Calculated Peak Discharge(m³/s)(y)**
1	91.98
2	265.73
3	367.38
4	439.49
5	495.43
6	541.13
7	579.78
8	613.25
9	642.78
10	669.19
15	770.83
20	**842.95**
25	898.88
50	**1072.64**
100	**1246.40**
500	1649.85
1000	1823.61

HEC-RAS simulates a profile for each flow discharge input. The number of profiles required can be set by the user and three profiles were selected for this demonstration, namely the 20-, 50- and 100-year recurrence intervals as recorded in Table 5.3 and indicated in bold.

The calculated flood peak values, 842.95 m³/s, 1072.64 m³/s, and 1246.40 m³/s, were used to model three different hypothetical profiles, for 20-, 50- and 100-year recurrence intervals respectively.

5.5.3 HEC-RAS analysis

The hydraulic analysis can commence once the geometric and flow data have been entered into HEC-RAS. A surface profile for steady subcritical flow was modelled for each selected peak discharge value (20-, 50- and 100-year recurrence). The following parameters of flood hazard mapping were modelled for this demonstration (Correia et al. 1998; Merwade 2009):

- flood extent; and
- cumulative water depth (taken from the first cross-section).

The results were exported to HEC-GeoRAS and ArcMap to create the flood hazard maps.

5.6 POST-PROCESSING

The post-processing phase entails importing the hydraulic analysis results from HEC-RAS into ArcMap for creating the flood hazard maps. The aim of visualising the results is to determine the floodplain area (for flood hazard mapping) and for calibrating and validating the model.

For this demonstration, the extent analysis and the water surface parameters were imported for each profile. The profiles of the water surface and the original TIN of the demonstration area were converted to a grid to allow the use of map algebra to calculate the flood depth. The floodplain area was determined for each water surface profile by subtracting the rasterised TIN from the relevant water surface grid. Areas with positive values will not be flooded, while the opposite is true for areas with negative values (Ackerman 2005; Merwade 2009). Figure 5.17 shows the resulting flood extent, water surface grid and flood depth.

In the previous section, flood modelling analysis was carried out for three different recurrence intervals (probabilities), namely the 20-, 50-, and 100-year intervals. These results were used to create the different flood hazard maps that describe the magnitude and/or probability of a flood.

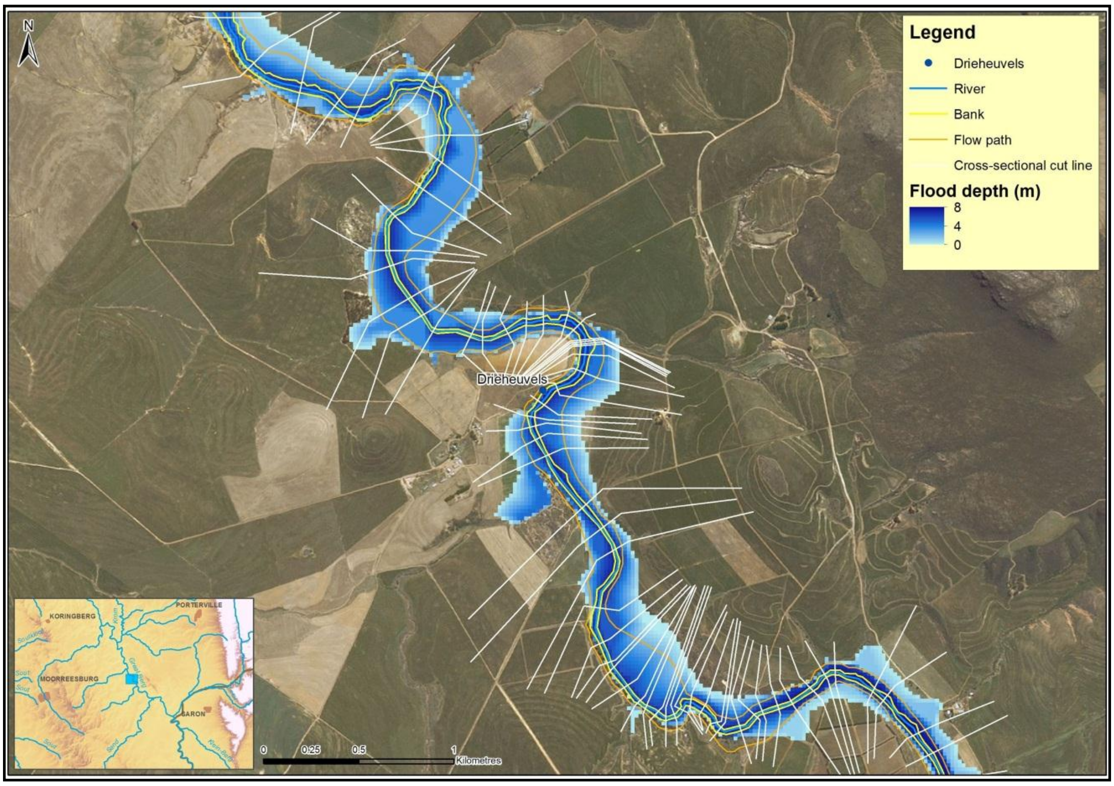


Figure 5.17 Inundation polygon for 1: 100 year recurrence interval

The hydraulic results represent two parameters for flood hazard mapping as discussed in Section 3.6.2. The first parameter, extent, indicates the inundated areas for each hypothetical profile for the different recurrence intervals. This extent parameter is the most common modelled parameter. The second parameter, depth, displays the water depth (levels) for the different profiles.

These two parameters were imported into ArcMap using HEC-GeoRAS and then overlaid with SPOT 5 images to indicate areas of inundation and the associated depth. These flood hazard maps are discussed in more detail in the following sections.

5.6.1 Extent map

The extent map was the first flood hazard map to be created. Figure 5.18 indicates the geographical area of impact for different probabilities of occurrence in a specific time period. The scale of this map is 1:30 000, which is a requirement for maps used by stakeholders in disaster management on a local scale, as defined in Section 3.6.2. The difference in the extent of the 50- and 100-year flood is not that significant, as indicated by the small difference in the calculated peak discharge values, namely 1073.64 m³/s and 1246.40 m³/s, respectively.

Figure 5.18 Extent map for different probabilities of occurrence

After performing a visual inspection along the boundary of the flood extent, it was found that none of the homesteads located along the river will be affected by a 100-year event. Although the clearance is estimated at 50 m for some homesteads, it should raise concern for a 500- or 1000-year event. Several small areas of cultivated agricultural land will be flooded by all three selected occurrence interval events.

5.6.2 Flood depth map

The flood depth map indicates, to a certain extent, the severity (intensity) of a flood event by indicating the water depths (levels). The flood depth maps for the 20-, 50-, and 100-year floods are indicated in Figure 5.19, Figure 5.20 and Figure 5.21.

Figure 5.19 Flood depth map for 20-year flood

Figure 5.20 Flood depth map for 50-year flood

The depth along the channel centre line increases as the extent of the inundation increases. In the 20-year event for example, the depth varies between shallow water of 0.02 cm along the boundaries of the inundation to a depth of 7.4 m at the stream channel. The depth at the stream channel increases to over 8 m for the 50- and 100-year events.

Figure 5.21 Flood depth map for 100-year flood

In this chapter, the flood modelling was carried out for a demonstration area. Data was collected from the sources identified in Chapter 4 and was prepared and applied to map flood hazards. Suitable imagery of the selected flood event was not available and prevented empirical calibration and validation of the resulting maps. Nevertheless, the demonstration showed that flood hazard maps can be created by using the limited data sources available in South Africa.

CHAPTER 6: CONCLUSION

6.1 REVISITING THE RESEARCH PROBLEM

The frequency of floods is increasing around the world (Alho et al. 2008) and in South Africa (Halloway, Fortune & Chasi 2010). Rural communities are becoming more vulnerable to the consequences of floods and governments need to be more proactive. The use of disaster risk assessments is therefore becoming more important to mitigate or prevent the impacts of floods and to implement adaptive measures. A flood hazard assessment is the first step in a flood risk evaluation and aims to describe the physical characteristics of a flood, such as the location, severity, frequency, and distribution.

Many developing countries, like South Africa, have limited access to data sources for hazard mapping. The aim of this study was to assess whether the available data sources are adequate to perform hydraulic modelling for flood hazard mapping. Existing hydraulic modelling methodologies and their required data were investigated and data requirements were determined by consulting international guidelines for flood hazard mapping. It was found that a scale of 1:5 000 to 1:50 000 is required to map the extent and depth of a flood for disaster management purposes (see Section 3.6.2). HEC-RAS was identified as a hydraulic software package that can perform hydraulic modelling to calculate fundamental flood parameters (extent and depth) with minimal data inputs.

An evaluation of available data in South Africa was completed and the most suitable datasets were identified. The data needed are:

- topographic data of the river channel and the surrounding terrain;
- land cover data to determine the Manning’s coefficient values due to friction; and
- historical data for hydrological data input, and for the calibration and validation of the hydraulic model.

A demonstration site for which suitable data was available was identified to illustrate how flood modelling can be performed with limited data sources. Flood hazard maps for the extent and depth of the 20-, 50- and 100-year events were simulated. The results showed that flood hazard maps can be created with available data sources. However, topography and river gauge data are limited to a few areas in South Africa. In addition, historical data for calibrating and verifying such maps are often unavailable.

6.2 DATA LIMITATIONS AND RECOMMENDATIONS

There is a need for more accurate and recent data sets in South Africa as flooding is becoming a more frequently occurring phenomenon. Without appropriate data, flood assessments will be limited, increasing the vulnerability of poor rural communities that are often without the means to cope with an extreme flood event. The availability of adequate data sets for hydraulic modelling has restricted the scale of flood hazard mapping and the selection of a demonstration area. These limitations and possible solutions will be discussed in more detail in the following sections.

6.2.1 Topographical data

The availability of topographical data to accurately represent the river channel and surrounding terrain is one of the main impediments for flood modelling. Topographic data is fundamental to flood modelling and is used throughout the process. Either a DEM or TIN can be used for topographic representation but a TIN is recommended when a high resolution DEM is unavailable (see Section 4.1.1).

In this study, 5 m (1:10 000 scale) contours were used to create a TIN. A larger scale data source would have produced better results. Better topographical data would also enable the creation of larger scale locality maps for more detailed disaster management planning. For such detailed analyses, DEMs of 5 m to 10 m resolution or 1 m vertical interval contours are required (Martini & Loat 2007). Presently, such topographical data is only available for small areas within South Africa. This indicates that there is a need to invest in a high resolution DEM. Possible options will be discussed in the following paragraphs.

The CD: NGI develops DEMs from contours or from stereoscopic pairs of photogrammetric images. The latter is the preferred method as it is more accurate (CD: NGI 2011a). Current DEMs available from CD: NGI have a 25 m or a 50 m resolution, while contours are only available in 5 m to 20 m vertical intervals (see Section 4.1.1). High resolution DEMs of 0.04 m is possible with photogrammetry but the accuracy of the elevation points are often lost during the automated data extraction techniques used to reduce the time of manual extraction. This approach is also more expensive when elevation extraction for larger areas is attempted. Alternatively, the use of a High Resolution Stereo Camera (HRSC) can be considered. This camera, together with photogrammetric processing software, allows the capturing of DEMs with a vertical accuracy of between 0.15 m to 0.25 m at a flight height of 3 000 m (Sanders et al. 2005).

South African National Space Agency (SANSA) is investigating the inclusion of the Indian P5 (Cartosat-1) satellite data to its current portfolio by 2012. This will enable the development of 5 m DEMs that can be applied in hydraulic modelling (Nieckau 2011).

Light Detection and Ranging (LIDAR) can be used to generate high resolution (up to 0.1 m) DEMs, but this technology is still very expensive (Combrink 2011; Joyce 2011), especially for large areas (Sanders et al. 2005). A more cost-effective technology is Interferometric Synthetic Aperture Radar (IFSAR) wich is available on a number of satellite systems (e.g. ERS, RADARSAT, TerraSAR-X). IFSAR can produce DEMs with up to 0.5 m vertical accuracy and can be used for elevation data collection at regional or even national scales (Sanders et al. 2005).

6.2.2 Land cover data

Land cover data is needed by the hydraulic model to determine Manning’s coefficient values along each cross-sectional cut line. Most of the current land cover data sets in South Africa are very dated and at a small scale. The CD: NGI appointed Satellite Application Centre (SAC), now SANSA, to facilitate workshops with all users of land cover data during January and February 2008, to determine a methodology for creating a new land cover data set. Over 180 land cover classes were defined during this process and it was decided to condense this classification into eight super classes and 32 sub-classes. These classes will be derived from a combination of satellite imagery that includes Landsat 7 ETM+, SPOT 5, SAR and Light Detection and Ranging (LIDAR) technologies (Lück et al. 2010). CD: NGI is currently compiling bid specifications to test the methodology at five different district municipalities across South Africa using an automated classification (Parker 2011, pers com). Such land cover data will significantly enhance hydraulic modelling as more detailed allocations of Manning's coefficient values would be possible. The larger scale of the data will allow more detailed modelling.

6.2.3 Historical data

6.2.3.1 Water level and velocity data

Day-to-day river basin management is vital for the effective management and forecasting of floods. Real-time and historical databases are integral to such an information system (Terakawa 2003). Peak discharge values are required to calculate the flow for different occurrence intervals. Many river gauge stations do not capture discharge values. In such cases, a hydrological analysis needs to be carried out for the specific river catchment before the hydraulic modelling can commence (Rusinga 2010a, pers com). In addition, very few of these gauge stations contain verified data sets.

There is a need for the data recorded at gauge stations to be more complete by also capturing water depth and discharge values. Firstly, attention should be given to updating existing gauge stations to record comprehensive hydrological databases. Thereafter, flood prone areas along the river should be identified where additional gauge stations could be positioned (Clarke & Ratcliffe 2007). In addition, these gauge stations can be equipped to act as early warning systems for flood events, thus serving a dual purpose.

Alternatively, various government organisations, from national to municipality level, can have their own water monitoring programmes that capture detailed data with regard to water level, velocity and pollution. Possible planning and coordination between these organisations can allow stakeholders access to these water monitoring databases to resolve the gauge station data shortage.

6.2.3.2 Aerial photography and satellite imagery

Historic aerial photography or satellite images are required for calibration and validation purposes where the extent and depth of a particular flood event are determined from an image and compared with the result of the hydraulic model. Although a wide selection of satellite images was available for the study site, none of these correlated with the date on which a historic flood event occurred. Thus, neither calibration nor validation of the hydraulic model demonstration could be completed. There is no official archive of historical images capturing flood events, or any other hazards, in South Africa.

Pre-disaster images are available in South Africa but access to real-time satellite imagery during disasters is needed. Real-time satellite imagery is expensive and will restrict the development of a database of historic images. Alternative approaches to collecting real-time images are to utilise the South African Sumbandilasat images or the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER).

Sumbandilasat can, at no cost, capture frequent high resolution images of specific areas during natural disasters such as floods. Although this satellite's altitude stabilisation system failed to function properly during the early phases of the mission, alternative settings have been made that allow the satellite to tumble "head-over-heals" and capture images from south to north when orbiting in a north to south direction (Koekemoer, Govender & Smit 2011). Simultaneously, large scale (1:5 000 to 1:25 000) hydraulic modelling can be attempted as the Sumbandilasat images have a pixel resolution of 6.25 m. Flood parameters can therefore be mapped for other applications (e.g. emergency response and town planning) (see Table 3.2), provided that better topographical data and land cover data also become available.

The SPIDER programme was established on 14 December 2006 by the United Nations Office for Outer Space Affairs (UNOOSA) with the objective to provide access and develop the capacity of all countries and organisations (international and regional) in the use of all space-based information during the whole disaster management cycle. One of the frameworks used by the UN-SPIDER, is the use of SpaceAid that facilitates fast and efficient access to satellite imagery during a disaster on a 24 hours per day/7 days a week basis. Such a request for support can be activated either by a United Nations (UN) agency or by an authorised government agency by using a fax, e-mail or telephone hotline. During this activation process, users liaise with UN-SPIDER experts to determine the satellite image requirements. These requests are forwarded to all satellite providers that have a standardised agreement with UN-SPIDER. Any of these providers can decide to provide the selected images on a voluntary basis and, if possible, free of charge. To prevent duplication, the provider will inform all the other providers of any intended contributions (Altan et al. 2010).

6.3 CONCLUDING REMARKS

This study has shown that flood modelling is possible with the use of available data in South Africa. HEC-RAS was identified as a suitable software package as it requires minimal data input to perform hydraulic analysis. Although the implemented model could not be empirically calibrated or validated (due to the unavailability of suitable historic satellite images of flood events) the resulting flood hazard maps hold much potential for supporting disaster mitigation decisions.

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. The limited availability of flood hazard maps can have a disastrous impact, especially on already vulnerable communities. 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.

REFERENCES

Ackerman CT 2005. *HEC-GeoRAS, GIS tools for support of HEC-RAS using ArcGIS.* Davis: United States Army Corps of Engineers.

Ackerman CT, Evans TA & Brunner GW 1999. Hec-GeoRAS: Linking GIS to hydraulic analysis using ARC/INFO and HEC-RAS. Paper delivered at the 19th Annual ESRI User Conference, San Diego.

ADWR (Arizona Department of Water Resources) 2002. Floodplain hydraulic modelling [online]. Phoenix: Arizona Department of Water Resources. Available from: http://www.adwr.state.az.us/azdwr/SurfaceWater/FloodManagement/documents/SS9-02FloodplainHydraulicModeling1.pdf [Accessed 18 October 2009].

Alexander WJR 2000. *Flood risk reduction measures*. Pretoria: Department of Civil Engineering, University of Pretoria.

Alho P, Sane M, Huokuna M, Käyhkö J, Lotsari E & Lehtiö L 2008. Mapping of floods. *Environmental Administration Guidelines* 2: 59-101.

Altan O, Backhaus R, Boccardo P & Zlatanova S (eds) 2010. *Geoinformation for disaster and risk management: Examples and best practices*. Copenhagen: Joint Board of Geospatial Information Societies.

Amin S & Goldstein G (eds) 2008. *Data against natural disasters: Establishing effective systems for relief, recovery, and reconstruction*. Washington: The World Bank.

Anderson DJ 2000. GIS-based hydrologic and hydraulic modelling for floodplain delineation at highway river crossings. Master's thesis. Austin: University of Texas, Faculty of Graduate School.

Andrysiak PB & Maidment D 2000. *Visual floodplain modelling with geographic information systems (GIS)*. Publication No 00-4. Austin: Bureau of Engineering Research, University of Texas.

Baas S, Ramasamy S, DePryck JD & Battista F 2008. *Disaster risk management system analysis*. Rome: Food and Agriculture Organisation.

Baer EM 2008. Recurrence interval [online]. Northfield: Carlton College. Available from http://serc.carleton.edu/quantskills/methods/quantlit/RInt.html#calculations [Accessed 6 October 2010].

Bagyaraj M & Gurugnanam B 2011.Significance of morphometry studies, soil characteristics, erosion phenomena and landform processes using remote sensing and GIS. *Research Journal of Environmental and Earth Sciences* 3: 221-233.

Bates PD & De Roo APJ 2000. A simple raster-based model for flood inundation simulation. *Journal of Hydrology* 236: 54-77.

BHS (British Hydrological Society) 2005. Hydrological Gateway [online]. London: Institution of Civil Engineers. Available from: http://www.hydrology.org.uk/contact.htm [Accessed 30 April 2011].

Bicheron P, Defourny P, Brockmann C, Schouten L, Vancutsem C, Huc M, Bontemps S, Leroy M, Archard F, Herold M, Ramera F & Arino O 2008. GLOBCOVER: Products description and validation report [online]. Toulouse: Medias France. Available from: http://globcover.s3.amazonaws.com/LandCover_V2.2/GLOBCOVER_Products_Description_Validation_Report_I2.1.pdf [Accessed 18 May 2011].

Botha JJ & Louw EJM 2004. *Step by step guidelines to prepare a disaster management plan - Guidelines 2: How to prepare disaster risk reduction plans.* Cape Town: Business and Information Solutions Division, Africon.

Boudreau T 2009. *Solving the risk equation: People-centered disaster risk assessment in Ethiopia*. London: Humanitarian Policy Group.

Bründl M, Romang HE, Bischof N & Rheinberger CM 2009. The risk concept and its application in natural hazard risk management in Switzerland. *Natural Science and Earth System Sciences* 9: 801-803.

Brunner GW 2008a. *HEC-RAS, River Analysis System user's manual.* Davis: United States Army Corps of Engineers.

Brunner GW 2008b. *HEC-RAS, River Analysis System hydraulic reference manual.* Davis: United States Army Corps of Engineers.

Brutsaert W 2005. *Hydrology: An introduction*. Cambridge: Cambridge University Press.

Büchele B, Kreibich H, Kron A, Thieken A, Ihringer J, Oberle P, Merz B & Nestmann F 2006. Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks. *Natural Science and Earth System Sciences* 6: 485-503.

Casas A, Benito G, Thorndycraft VR & Rico M 2006. The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. *Earth Surface Processes and Landforms* 31: 444-456.

CD: NGI (National Geo-spatial Information) 2011a. Maps and geo-spatial information [online]. Cape Town: CD: NGI. Available from: http://www.ngi.gov.za/ index.php/Image-tabs-home/maps-and-geo-spatial-information.html [Accessed 15 May 2011].

CD: NGI (National Geo-spatial Information) 2011b. National aerial photography and imagery programme [online]. Cape Town: CD: NGI. Available from: http://www.ngi.gov.za/index.php/Image-tabs-home/ national-aerial-photography-and-imagery-programme.html [Accessed 21 May 2011].

CD: SM (Chief Directorate: Surveys and Mapping) 2006. *Mapping South Africa*. Cape Town: CD: SM.

CBERS (China-Brazil Earth Resources Satellite) 2011. CBERS 1, 2 and 2B cameras [online]. São José dos Campos: National Institute of Space Research. Available from: http://www.cbers.inpe.br/?hl=en&content=cameras 1e2e2b [Accessed 4 June 2011].

Clark MJ 1998. Putting water in its place: A perspective on GIS in hydrology and water management. *Hydrological Processes* 12: 823-834.

Clarke B & Ratcliffe G (eds) 2007. *Berg River Baseline Monitoring Programme: Final Report–Volume 5: Synthesis*. Publication No P WMA 19/G10/00/2107. Pretoria: Department of Water Affairs.

Combrink A 2011. Introduction to lidar-based aerial surveys (Part 2). *PositionIT*. June 2011.

Correia FN, Rego FC, Da Graca Saraiva M & Ramos I 1998. Coupling GIS with hydrologic and hydraulic modelling. *Water Resource Management* 12: 229-249.

CRED (Centre for Research on the Epidemiology of Disasters) 2010. Emergency Events Database (EM-DAT): The international disaster database [online]. Brussels: CRED. Available from: http://www.emdat.be/disaster-profiles [Accessed 22 August 2010].

CSA (Canadian Space Agency) 2011. RADARSAT systems: Satellite characteristics [online]. Quebec: CSA. Available from: http://www.asc-csa.gc.ca/ eng/satellites/radarsat/radarsat-tableau.asp [Accessed 2 August 2011].

CSAG (Climate Systems Analysis Group) 2011. South African weather [online]. Cape Town: University of Cape Town. Available from: http://www.myweather.co.za/ weatherinfo/SAWeather.html [Accessed 6 March 2011].

De La Harpe 1998. *Guide to the National Water Act*. Pretoria: Department of Water Affairs and Forestry.

DeMers MN 2002. *GIS modelling in raster*. New York: John Wiley & Sons, Inc.

De Moel H, Van Alphen J & Aerts JCJH 2009. Flood maps in Europe — methods, availability and use. *Natural Hazards and Earth System Sciences* 9: 289-301.

De Roo APJ, Wesseling CG & Van Deursen, PA 2000. Physically based river basin modelling within a GIS: the LISFLOOD model. *Hydrological Processes* 14: 1981-1992.

DigitalGlobe 2011a. Quickbird [online]. Longmont: DigitalGlobe. Available from: http://www.digitalglobe.com/index.php/85/QuickBird [Accessed 2 August 2011].

DigitalGlobe 2011b.WorldView-1 [online]. Longmont: DigitalGlobe. Available from: http://www.digitalglobe.com/index.php/86/WorldView-1 [Accessed 2 August 2011].

DigitalGlobe 2011c. WorldView-2 [online]. Longmont: DigitalGlobe. Available from: http://www.digitalglobe.com/index.php/88/WorldView-2 [Accessed 2 August 2011].

DIMP (Disaster Mitigation for Sustainable Livelihoods Programme) 2007. *Severe weather compound disaster: June 2007 cut-off lows and their consequences in the West Coast, South Africa.* Cape Town: University of Cape Town.

Dutta D, Herath S & Musiake K 2000. Flood inundation simulation in a river basin using a physically based distributed hydrologic model. *Hydrological Processes* 14: 497-519.

DWA (Department of Water Affairs) 2009. Hydrological Services [online]. Pretoria: DWA. Available from http://www.dwaf.gov.za/Hydrology/about.htm [Accessed 18 October 2009].

Dyhouse G, Hatchett J & Benn J 2003. *Floodplain modelling using HEC-RAS.* Michigan: Haestad Press.

EC (Environment Canada) 2009a. Glossary [online]. Quebec: Environment Canada. Available from: http://www.ec.gc.ca/Water [Accessed 16 March 2009].

EC (European Community) 2009b. *Project Floodsite* [online]. Oxfordshire: Samui Design & Management Ltd. Available from: http://www.floodsite.net [Accessed 20 March 2009].

EMA (Emergency Management Australia) 2006. *Hazards, disasters and your community*. 7th ed. Barton: EMA.

ENPAT (Environmental Potential Atlas) 2001a. Catchments [online]. Pretoria: Department of Environmental Affairs (DEA). Available from http://www.environment.gov.za/ enviro-info/intro.htm [Accessed 2 July 2009].

ENPAT (Environmental Potential Atlas) 2001b. Environmental Potential Atlas for South Africa [online]. Pretoria: Department of Environmental Affairs (DEA). Available from: http://www.environment.gov.za/enviro-info/enpat.htm [Accessed 24 September 2009].

ERSDAC (Earth Remote Sensing Data Analysis Center) 2009. Aster [online]. Tokyo: ERSDAC. Available from http://www.ersdac.or.jp/GDEM/E/2.html [Accessed 25 September 2009].

Eurimage 2011. ERS [online]. Rome: Eurimage. Available from: http://www.eurimage.com/products/ers.html [Accessed 2 June 2011].

Fairbanks DHK, Thompson MW, Vink DE, Newby TS, van den Berg HM & Everard DA 2000. The South African Land-cover Characteristics Database: A synopsis of the landscape. *South African Journal of Science* 96: 69-82.

FEI 2007. Flood mapping [online]. Helsinki: Finland's Environmental Administration. Available from: http://www.ymparisto.fi [Accessed 2 November 2007].

FEMA (Federal Emergency Management Agency) 2008. Guide to emergency management and related terms, definitions, concepts, acronyms, organisations, programs, guidance, executive orders and legislation [online]. Washington: FEMA. Available from: http://www.training.fema.gov/emiweb/edu/docs/ terms%20and%20definitions/Terms%20and%20Definitions.pdf [Accessed 15 September 2010].

FEMA (Federal Emergency Management Agency) 2009. Numerical models meeting the minimum requirement of NFIP [online]. Washington: FEMA. Available from http://www.fema.gov/plan/prevent/fhm/en_hydra.shtm [Accessed 10 August 2009].

Fenton J 2007. *Open channel hydraulics.* Karlsruhe: Institute for Hydromechanics, University of Karlsruhe.

Fenton J 2010. *A first course in hydraulics.* Karlsruhe: Institute for Hydromechanics, University of Karlsruhe.

Franzini JB & Finnemore EJ 2001. *Fluid mechanics with engineering applications*.10th ed. New York: The McGraw-Hill Companies Inc.

Fritz S, Bartholomé E, Belward A, Hartley A, Stibig H, Eva H, Mayaux P, Bartalev S, Latifovic R, Kolmert S, Roy PS, Agrawal S, Bingfang W, Wenting X, Ledwith M, Pekel J, Giri C, Mücher S, Badts E, Tateishi R, Champeaux J & Defourny P 2003. Harmonising, mosaicing and production of the Global Land Cover 2000 database [online]. Brussels: European Commission. Available from: http://bioval.jrc.ec.europa.eu/products/glc2000/products/GLC2000_EUR_20849EN.pdf [Accessed 15 May 2011].

Garatwa W & Bollin C 2002. *Disaster risk management: Working concept*. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ).

GeoEye 2010. *GeoEye constellation*. Virginia: GeoEye.

GeoEye 2011. *GeoEye-1 fact sheet*. Herndon: GeoEye.

GLCF (Global Land Cover Facility) 2009. Landsat [online]. Maryland: GLFC. Available from http://www.landcover.org/data/landsat/ [Accessed 20 October 2009].

GMES (Global Monitoring for Environment and Security) 2010. Floods [online]. Frascati: European Space Agency. Available from: http://www.emergencyresponse.eu/gmes/docs_wsw/RUB_119/ssp_gmes_datasheet_01_floods_vi.pdf [Accessed 9 June 2011].

Goodchild MF 2006. GIS and disasters: Planning for catastrophe. *Computers, Environment and Urban Systems* 30: 227-229.

Görgens A 2003. *Floods and stormwater, Vol 1: Design flood hydrology*. Stellenbosch: Institute for Water and Environmental Engineering, University of Stellenbosch.

Goudie A & Viles H 2005. *The earth transformed: An introduction to human impacts on the environment*. Victoria: Blackwell Publishing.

Haarhoff J. & Cassa AM 2009. *Introduction to flood hydrology*. Cape Town: Juta and Company Ltd.

Halloway A, Fortune G & Chasi V 2010. *Risk and development annual review: Western Cape 2010*. Cape Town: Peri-Peri Publications, Disaster Mitigation for Sustainable Livelihoods Programme.

Halloway A & Roomaney R 2008. *Weathering the storm: Participatory risk assessment for informal settlements*. Cape Town: Peri-Peri Publications, Disaster Mitigation for Sustainable Livelihoods Programme.

Hankin B, Waller S, Astle G & Kellagher R 2008. Mapping space for water: screening for urban flash flooding. *Journal for Flood Risk Management* 1: 13-22.

Hardmeyer K & Spencer MA 2007. Using risk-based analysis and geographic information systems to assess flooding problems in an urban watershed in Rhode Island. *Environmental Management* 39: 563-574.

Hernandes T & Zhang PE 2007. Floodplain analysis using computational tools. Paper presented at the World Environmental and Water Resources Congress of the Environmental and Water Resources Institute, Tampa.

Heywood I, Cornelius S & Carver S 2002. *An introduction to Geographic Information Systems*. 3rd ed. Harlow: Pearson Education Limited.

Hill CD & Verjee F 2010. *Flash flood early warning system reference guide 2010*. Boulder: University Corporation for Atmospheric Research (UCAR).

Hossini V 2008. *The role of vulnerability in risk management*. Working paper series 8. Bonn: Institute for Environment and Human Security, United Nations University.

Hunter NM, Bates PD, Horrit MS & Wilson MD 2007. Simple spatially-distributed models for predicting flood inundation: A review. *Geomorphology* 90: 208-225.

Infoterra 2009. TerraSAR-X basic image products [online]. Friedrichshafen: Infoterra GmbH. Available from: http://www.infoterra.de/basic-imagery [Accessed 2 August 2011].

International Rivers 2009. Catchment basics [online]. Berkley: International Rivers. Available from: http://internationalrivers.org [Accessed 02 July 2009].

ISDR (International Strategy for Disaster Reduction) 2004. *Living with risk: A global review of disaster reduction initiatives*. Geneva: ISDR.

ISDR (International Strategy for Disaster Reduction) 2007. *Disaster risk reduction: A global review 2007*. Geneva: ISDR.

ISDR (International Strategy for Disaster Reduction) 2009a. *2009 UNISDR terminology on disaster risk reduction*. Geneva: ISDR.

ISDR (International Strategy for Disaster Reduction) 2009b. *Global assessment report on disaster risk reduction*. Geneva: ISDR.

ISDR (International Strategy for Disaster Reduction) 2010a. Terminology: Basic terms and disaster risk reduction [online]. Geneva: ISDR. Available from: http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm [Accessed 21 August 2010].

ISDR (International Strategy for Disaster Reduction) 2010b. Hazard classification [online]. Geneva: ISDR. Available from http://www.unisdr.org/eng/mediaroom/ facts-sheets/fs-hazard-clasification.htm [Accessed 21 August 2010].

ISRO (Indian Space Research Organisation) 2011. IRS-P6 [online]. Andhra Pradesh: ISRO. Available from: http://www.nrsc.gov.in/irs-p6.html [Accessed 2 August 2011].

Janna WS 2009. *Introduction to fluid mechanics*. 4th ed. Boca Raton: CRC Press.

Joyce K 2011. Remote sensing and geological hazard assessment. Paper delivered at the Earth Observation and Geological Hazard Assessment Workshop, Pretoria.

JRC (Joint Research Centre) 2009. Global environment monitoring: GLC 2000 [online]. Brussels: European Commission. Available from: http://bioval.jrc.ec.europa.eu/ products/glc2000/glc2000.php [Accessed 04 October 2009].

Kleeberg H, Röttcher K & Spanknebel H (eds) 2006. Flood hazard map guidelines [online]. Heft: German Working Group of the Federal States on Water Issues. Available from: http://www.lawa.de/documents/Flood-Hazard-Map-Guidelines_ea8.pdf [Accessed 19 July 2010].

Klijn F (ed) 2009. *Flood risk assessment and flood risk management: An introduction and guidance based on experience and findings of FLOODsite (an EU-funded Integrated Project).* Delft: Deltares, Delft Hydaulics.

Koekemoer J, Govender N & Smit I 2011. SumbandilaSat provides valuable imagery. *PositionIT*. April/May.

Lechtenbörger C 2006. CEDIM-Risk Map Germany: First results. In Ammann WJ, Dannenmann S & Vulliet L (eds) *Risk 21 – Coping with risks due to natural hazards in the 21*st *century*, 139-146. London: Taylor & Francis Group.

Longley PA, Goodchild MF, Maguire DJ & Rhind DW (eds) 2005. *Geographic Information Systems and Science*. 2nd ed. New York: John Wiley & Sons Ltd.

Lück W, Mhangara P, Kleyn L, & Remas H 2010. Land cover field guide. Pretoria: CSIR Satellite Application Centre (SAC). Available from: http://www.ngi.gov.za/images/stories/technical_info/publication/CDNGI_Land_Cover_Methodology_and_Field_Guide_v2.pdf [Accessed 3 February 2011].

Maidment D 2002. *ArcHydro: GIS for water resources*. Redlands: ESRI Press.

Maidment D & Djokic D 2000. *Hydrologic and hydraulic modelling support with Geographic Information Systems*. Redlands: ESRI Press.

Males RM & Grayman WM 1992. Past, present and future of Geographic Information Systems in water resources. *Geographic Information Systems Issue* 87: 5-11.

Marks K & Bates P 2000. Integration of high-resolution topographic data with floodplain flow models. *Hydrological Processes* 14: 2109-2122.

Martini F & Loat R (eds) 2007. *Handbook on good practices for flood mapping in Europe*. Emmeloord: Drukkerij Feiko Stevens.

Mavrova-Guirginova M, Pencheva D & Belyashka M 2010. Maps in the context of the European Flood Risk Directive. Paper presented at 3rd International Conference on Cartography and GIS, Nessebar.

Mayaux P, Eva H, Gallego J, Strahler AH, Herold M, Agrawal S, Naumov S, De Miranda EE, Di Bella CM, Ordoyne C, Kopin Y & Roy PS 2006. Validation of the global land cover 2000 map. *Geoscience and Remote Sensing* 44: 1728-1739.

McKnight TL & Hess D 2007. *Physical geography: A Landscape appreciation*. 9th ed. New Jersey: Prentice-Hall.

Merwade V 2009. Tutorial on using Hec-GeoRAS with ArcGIS 9.3 [online]. West Lafayette: University of Purdue. Available from: http://web.ics.purdue.edu/~vmerwade/education/georastutorial.pdf [Accessed 3 May 2010].

Merwade V, Cook A & Coonrod J 2008. GIS techniques for creating river terrain models for hydrodynamic modelling and flood inundation mapping. *Environmental Modelling and Software* 23: 1300-1311.

Merz B & Thieken A 2004. Flood risk analysis: Concepts and challenges. *Austrian Water and Waste Management* (*Österreichische Wasser- und Abfallwirtschaft)* 56: 3-4.

Midgley GF, Chapman RA, Hewitson B, Johnston P, De Wit M, Ziervogel G, Mukheibir P, Van Niekerk L, Tadross M, Van Wilgen BW, Kgope B, Morant PD, Theron A, Scholes RJ & Forsyth GG 2005. *A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape*. Publication No ENV-S-C 2005-073. Stellenbosch: CSIR.

Mizukoshi H & Aniya M 2002. Use of contour-based DEMs for deriving and mapping topographic attributes. *Photogrammetric Engineering & Remote Sensing* 68: 83-93.

Munson BR, Young DF, Orkiishi TH & Huebsch WW 2010. *Fundamentals of fluid mechanics*. 6th ed. Toronto: John Wiley and Sons Inc.

NASA (National Aeronautics and Space Administration) 2011. MODIS [online]. Washington: NASA. Available from: http://modis.gsfc.nasa.gov/about/ specifications.php [Accessed 2 August 2011].

NCWE (National Committee on Water Engineering) 2010. Understanding and managing flood risk [online]. Barton: NCWE. Available from:http://www.ncwe.org.au/ pos_papers/flood_man.html [Accessed 21 March 2011].

Nieckau N 2011. Providing access to cutting edge satellite imagery [online]. Johannesburg: EE Publishers (Pty) Ltd. Available from: http://www.eepublishers.co.za/article/providing-access-to-cutting-edge-satellite-imagery.html [Accessed 1 June 2011].

NOAA (National Oceanic and Atmospheric Administration) 2009. Understanding flood recurrence intervals [online]. Davenport: National Weather Service. Available from: http://test.crh.noaa.gov/dvn/?n=Understandingfloodrecurrenceintervals. [Accessed 3 July 2009].

NOAA (National Oceanic and Atmospheric Administration) 2010. Tropical Events [online]. Camp Springs: National Environmental Satellite, Data and Information Service. Available from: http://www.osei.noaa.gov/Events/ Tropical/IndOcean/2003/TRCcela352_N6L.jpg [Accessed 12 March 2011].

NOAA (National Oceanic and Atmospheric Administration) 2011. Advanced Very High Resolution Radiometer - AVHRR [online]. Camp Springs: National Environmental Satellite, Data and Information Service Satellite Services

Division. Available from: http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html [Accessed 4 June 2011].

NRCAN (Natural Resources Canada) 2008. Fundamentals of remote sensing [online]. Quebec: NRCAN. Available from: http://cct.rncan.gc.ca/resource/tutor/ fundam/ index_e.php [Accessed 2 August 2011].

OGC (Open Geospatial Consortium) 2009. Open Geospatial Consortium [online]. Wayland: OGC. Available from: http://www.opengeospatial.org/ [Accessed 16 May 2009].

Osti RP 2008. Flood mapping: A point of departure for flood risk management. Paper delivered at the World Meteorological Organisation's Expert Group Meeting on Flood Mapping, Geneva.

Pappenberg F, Beven K, Horrit M & Blazkova S 2005. Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. *Journal of Hydrology* 302: 46-69.

Pelling M, Maskrey A, Ruiz P & Hall L (eds) 2004. *Reducing disaster risk: A challenge for development – A global report*. New York: United Nations Development Programme.

Pender G & Néelz S 2007. Use of computer models of flood inundation to facilitate communication in flood risk management. *Environmental Hazards* 7: 106-114.

PEP (Provincial Emergency Program) 2004. *Hazard, risk and vulnerability analysis tool kit*. Victoria: British Columbia Ministry of Public Safety and Solicitor General.

Pilon PJ (ed) 2004. *Guidelines for reducing flood losses*. New York: ISDR.

RapidEye 2011. Satellite imagery product specification [online]. Brandenburg an der Havel: RapidEye. Available from: http://www.rapideye.de/upload/ RE_Product_Specifications_ENG.pdf [Accessed 2 August 2011].

Reich J 2005. Flood hazard maps in Baden-Württemberg [online]. Stuttgart: Ministerium für Umwelt und Verkehr Baden-Württemberg. Available from: www.uvm.**baden-wuerttemberg**.de/servlet/is/1253/Floz_Hazard_Maps.pdf [Accessed 21 August 2009].

Ritter ME 2010. The physical environment: An introduction to physical geography [online]. Stevens Point: University of Wisconsin. Available from:

http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/title_page.html [Accessed 03 October 2010].

Robayo O & DR Maidment 2005. Map to map: converting a NEXRAD rainfall map into a flood inundation map [online]. Austin: Center for Research in Water Resources. Available from http://www.crwr.utexas.edu/reports/pdf/2005/rtp05-01.pdf [Accessed 11 April 2011].

Sakulski D 2007. *Spatial and temporal frequency and distribution of hazardous events over South African territory for the period between years 1800 and 1995 based on 'CAELUM' document.* Pretoria: Cooperation Unit for Southern Africa, United Nations University.

SANBI (South African National Biodiversity Institute) 2009. Updating national land cover [online]. Pretoria: SANBI. Available from: http://bgis.sanbi.org/landcover/ Landcover2009.pdf [Accessed 6 October 2010].

SANBI (South African National Biodiversity Institute) 2010. National land cover 2009 [online]. Pretoria: SANBI. Available from: http://bgis.sanbi.org/landcover /project.asp [Accessed 6 October 2010].

Sanders R, Shaw F, MacKay H, Galy H & Foote M 2005. National flood modelling for insurance purposes: Using IFSAR for flood risk estimation in Europe. *Hydrology and Earth System Sciences* 9: 449-456.

Sane M & Huokuna M 2008. Procedure for identifying automatically possible flood risk areas. Paper presented at the Thematic Workshop for Flood Mapping of the World Meteorological Organisation, Dublin.

Schneider V, Verdin J & Bales J 2007. Flood hazard inundation mapping. Paper presented at the Global Facility for Disaster Reduction and Recovery Seminar Series, Washington.

Schoeman F, Newby TS, Thompson MW & Van Den Berg EC 2010. *South African National Land-cover Change Map*. Publication No GW/A/2010/47. Pretoria: Institute for Soil, Climate and Water, Agriculture Research Council.

Schulze RE 2003. *Managing climate variability and climate change in water resources*. Publication No 45. Pietermaritzburg: School of Bioresources Engineering and Environmental Hydrology, University of Natal.

Shamaoma H, Kerle N & Alkema D 2006. Extraction of flood-modelling related base-data from multi-source remote sensing imagery. Paper delivered at ISPRS

Commission VII Mid-term Symposium “Remote Sensing: From Pixel to Processes” conference, Enschede.

Singh VP & Fiorentino M (eds) 1996. *Geograhical information systems in hydrology*. Dordrecht: Kluwer Academic Publishers.

Sleigh A 2006. Fluid mechanics: Open channel hydraulics [online]. Leeds: University of Leeds. Available from: http://www.efm.leeds.ac.uk/CIVE/CIVE2400/OpenChannelHydraulics2.pdf [Accessed 19 September 2010].

Smith LC 2002. Emerging applications of Interferometric Synthetic Aperture Radar (InSAR) in Geomorphology and Hydrology. *Annals of the Association of American Geographers* 92: 385-398.

Smithson P, Addison K & Atkinson K 2002. *Fundamentals of the physical environment*. London: Routledge.

South Africa (Republic of) 1998. Act on national water, Act 36 of1998. *Government Gazette of South Africa* 19182, 26.8.1998.

South Africa (Republic of) 2003. Act on disaster management, Act 57 of 2002. *Government Gazette of South Africa* 26228, 31.3.2004.

South Africa (Republic of) 2005. *National Disaster Management Act: Policy Framework.* Notice 654 of 2005. Pretoria: Government Printer.

SPOT Image 2008. Technical information [online]. Toulouse: SPOT Image. Available from: http://www.spotimage.com/automne_modules_files/standard/public/p234_0916b39e58c710b3bb5788fdcc025f80niveau_anglais_2008.pdf [Accessed 09 October 2010].

SPOT Image 2010. SPOT satellite technical data [online]. Toulouse: SPOT Image. Available from: http://www.spotimage.com/automne_modules_files/standard/public/p229_a48f99c03cb2bc7f6beb7acc41f29fffSpotSatelliteTechnicalData_EN_Sept2010.pdf [Accessed 5 June 2011].

Stangel D 2009. *GIS and hydraulic model integration*. Paper delivered at the Pacific Northwest Section American Water Works Association conference, Salem.

Streicher A 2011. E-Learning for radar image interpreters [online]. New Security Learning. Available from: http://www.newsecuritylearning.com/index.php/feature/105-e-learning-for-radar-image-interpreters [Accessed 21 August 2011].

Sui DZ & Maggio RC 1999. Integrating GIS with hydrological modelling: practices, problems, and prospects. *Computers, Environment and Urban Systems* 23: 33-51.

Takeuchi K 2001. Increasing vulnerability to extreme floods and societal needs for hydrological forecasting. *Hydrological Sciences Journal* 46: 869-881.

Terakawa A 2003. *Hydrological data management: Present state and trends*. Publication No 964. Geneva: World Meteorological Organisation.

The World Bank 2010. *Natural hazards, unnatural disasters: The economics of effective prevention*. Washington: The World Bank.

Thompson M 1996. A standard land-cover classification scheme for remote-sensing applications in South Africa. *South African Journal of Science* 92: 34-42.

Tyagi A 2008. Overview and objectives. Paper delivered at the World Meteorological Organisation's Expert Group Meeting on Flood Mapping, Geneva.

Tyson PD & Preston-Whyte RA 2000. *The weather and climate of Southern Africa*. Cape Town: Oxford University Press.

UCAR (University Corporation for Atmospheric Research) 2010. Hydrology [online]. Boulder: UCAR. Available from: http://www.meted.ucar.edu/ [Accessed 02 October 2010].

USACE (United States Army Corps of Engineers) 2011. Features [online]. Davis: USACE. Available from: http://www.hec.usace.army.mil/software/hec-ras/hecras-features.html [Accessed 11 August 2011].

USGS 2009. Floods: Recurrence intervals and 100-year floods [online]. Virginia: USGS National Center. Available from: http://ga.water.usgs.gov/edu/100yearflood.floods.html [Accessed 2 July 2009].

Van Der Spuy D, Rademeyer PF & Linström CR 2004. *Flood hydrology course: Flood frequency estimation methods as applied in the Department of Water Affairs and Forestry*. Stellenbosch: Institute for Water and Environmental Engineering, University of Stellenbosch.

Van Manen SE & Brinkhuis M 2005. Quantitative flood risk assessments for Polders. *Reliability Engineering & System Safety* 90: 229-237.

Van Oosterom P, Zlatanova S & Fendel EM (eds) 2005. *Geo-Information for disaster management*. Dordrecht: Springer.

Venton P & Hansford B 2006. *Reducing risk of disaster in our communities*. Teddington: Tearfund.

Viljoen MF & Booysen HJ 2006. Planning and management of flood damage control: The South African experience. *Irrigation and Drainage* 55: S83-S91.

Vos F, Rodriguez J, Below R & Guha-Sapir D 2010. *Annual disaster statistical review 2009: The numbers and trends*. Brussels: Centre for Research on the Epidemiology of Disasters.

Warner JC, Brunner GW, Wolfe BC & Piper SS 2008. *HEC-RAS, River Analysis System application guide*. Davis: United States Army Corps of Engineers.

Watts J 2007. North Korea shows signs of openness after flood. *The Lancet*, 370: 1021-1022.

Waugh D 2009. *Geography, an integrated approach*. Cheltenham: Nelson Thornes.

Werner MGF 2001. Impact of grid size in GIS based flood extent mapping using a 1D Flow Model. *Physical Chemical Earth* 26: 517-522.

White ID, Mottershead DN & Harrison SJ 1992. *Environmental systems: An introductory text*. London: Chapman & Hall.

Wise SM 2007. Effect of differing DEM creation methods on the results from a hydrological model. *Computers & Geosciences* 33: 1351-1365.

Wisner B, Blaikie P, Cannon T & Davis I 2004. *At risk: Natural hazards, people's vulnerability and disasters*. New York: Routledge.

Wohl E 2010. Stream channel development [online]. Flossmoor: Advameg, Inc. Available from: http://www.waterencyclopedia.com/Re-St/Stream-Channel-Development.html [Accessed 0 October 2010].

Wright JM 2008. *Floodplain management: Principles and current practices.* Knoxville: University of Tennessee.

Zeiler M 1999. *Modelling our world: The ESRI guide to geodatabase design*. Redlands: Environmetal Systems Research Institute (ESRI), Inc.

Zerger A & Wealands S 2004. Beyond modelling: Linking models with GIS for risk management. *Natural Hazards* 33:191-208.

Zimmerman M 2008. Data mining for flood mapping. Paper delivered at the World Meteorological Organisation's Expert Group Meeting on Flood Mapping, Geneva.

PERSONAL COMMUNICATIONS

CD: NGI (sales@sli.wcape.gov.za) 2009a. RE: DEM coverage. Email to Z Els (zelda.els@af.aurecongroup.com) (11 August 2009).

CD: NGI (sales@ruraldevelopment.gov.za) 2009b. RE: Aerial photos. Email to Z Els (zelda.els@af.aurecongroup.com) (20 October 2009).

Djokic D (ddjokic@esri.com) 2010. RE: ArcHydro customisation. Email to P Wilson (peter.wilson@af.aurecongroup.com) (22 April 2010).

Parker A 2011 (aparker@ruraldevelopment.gov.za) 2011. Re: NGI Land Cover Initiatives. E-mail to A van Niekerk (avn@sun.ac.za) (18 July 2011).

Rusinga F 2009. Interview about HEC-RAS flood modelling and topographic data. Cape Town, Aurecon South Africa (Pty) Ltd (28 October 2009).

Rusinga F 2010a. Interview about calibration and validation of flood modelling results. Cape Town, Aurecon South Africa (Pty) Ltd (12 February 2010).

Rusinga F 2010b. Interview about cross-section and land use in HEC-GeoRAS. Cape Town, Aurecon South Africa (Pty) Ltd (04 May 2010).

Rusinga F (freeternity.rusinga@af.aurecongroup.com) 2010c. RE: 3D river interpolator. E-mail to Z Els (zelda.els@af.aurecongroup.com) (13 May 2010).

[Word Count: 28, 034]

APPENDIX: MANUAL FOR FLOOD MODELLING

This document details the procedures to be followed to carry out flood modelling in the demonstration area. The methodology can be replicated in other areas where similar data is available.

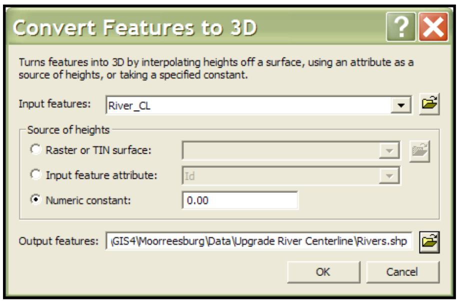
1. DATA PREPARATION PHASE

1.1 Topographical data

The 5 m contours are needed to build a TIN. The Upgrade River Centre Line tool is used to eliminate flat areas in the river channel and the following steps need be completed before the Upgrade River Centre Line tool can be applied (Rusinga 2009, pers com):

- digitise a river centre line that snaps to the contours;
- convert this river centre line to a 3D feature and name it “Rivers”;
- make a copy of the above river centre line and name it “Breaklines”; and
- ensure that the contours data set is named “Contours”.

A polyline shapefile, *River_CL*, is created to digitise the river centre line as one continuous line without any segments. It is important that the river centre line snaps to contours when digitised in a downstream direction and that it never touches the contours except where the river would run (Rusinga 2009, pers com). The river centre line, *River_CL*, should be converted to a three-dimensional feature using the Features to 3D tool (see Figure A.1) in 3D Analyst.



Convert Features to 3D

Turns features into 3D by interpolating heights off a surface, using an attribute as a source of heights, or taking a specified constant.

Input features: River_CL

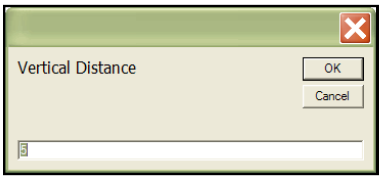
Source of heights
○ Raster or TIN surface:
○ Input feature attribute: Id
● Numeric constant: 0.00

Output features: \GIS4\Moorreesburg\Data\Upgrade River Centerline\Rivers.shp

Figure A.1 Features to 3D tool

It is important to ensure that the numeric constant (see Figure A.1) is selected as the source of height and that the initial z-value is nil. The z-values should then be updated using the Upgrade River Centre Line tool. A copy must be made of the three-dimensional river centre line, *Rivers*, and named *Breaklines*. The contour shapefile must then be renamed to *Contours*. In the creation of the TIN, the *Breaklines* layer must be used as a hard breakline and the *Contours* layer as soft breaklines.

In the final step, the river centre line should be updated with the Upgrade River Centre Line tool. All the required shapefiles, namely *Rivers*, *Breaklines* and *Contours* must be added to an ArcMap project. The vertical distance must be set at 5 m in the Upgrade River Centre Line tool (see Figure A.2).

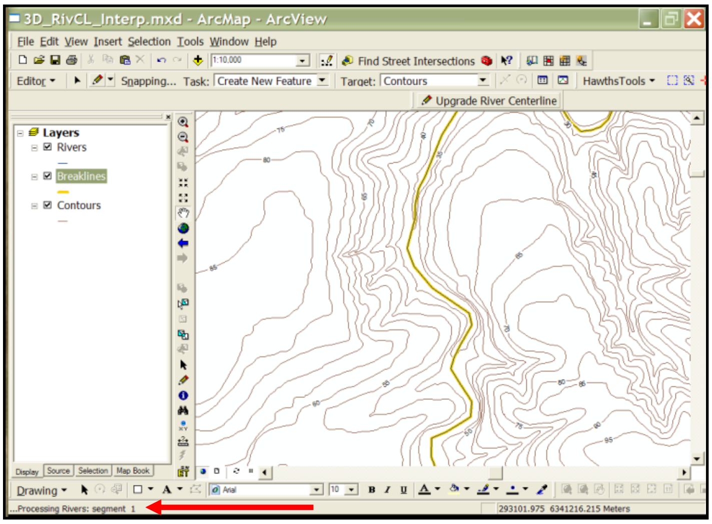


Vertical Distance

5

Figure A.2 Vertical distance set at 5m in the Upgrade River Centre Line tool

The Upgrade River Centre Line tool begins to process after the vertical distance is defined. The processing status (see Figure A.3) is shown in the bottom left corner of the ArcMap project.



3D_RivCL_Interp.mxd - ArcMap - ArcView

...Processing Rivers: segment 1

293101.975 6341216.215 Meters

Figure A.3 Upgrade River Centre Line tool busy with processing

1.2 RAS layers

HEC-GeoRAS needs to be configured before the capturing of the RAS-layers can commence. The HEC-GeoRAS toolbar (see Figure A.4) includes four menus, namely RAS Geometry, RAS Mapping, ApUtilities and Help.

Figure A.4 Menus of the HEC-GeoRAS toolbar

The RAS Geometry menu provides functions for creating and preparing RAS layers. The second menu, RAS Mapping, contains the post-processing phase functions while the ApUtilities menu lists the data management functions. The Help menu provides support guidelines (Ackerman 2005; Merwade 2009). Data preparation and post-processing should be performed in one ArcMap project, but in different data frames in order to prevent confusion. A data frame for the data preparation phase should be created using the Add New Map function (ApUtilities menu). Although this function is also available in ArcMap, the HEC-GeoRAS function is preferred as it ensures consistency regarding data management and naming conventions for hydraulic analysis within HEC-RAS. It is important to ensure that all the RAS layers and the data frame are in the same projection. The projection, Universal Transverse Mercator (UTM) 34 South (S), must be used for this demonstration. Empty RAS layers should then be created using the Create RAS Layers tool (RAS Geometry menu).

Stream centre line layer

In HEC-GeoRAS, the stream centre line layer must be named *River*. The stream centre line shapefile (see Figure A.5) created during the TIN creation should subsequently imported into the geodatabase.

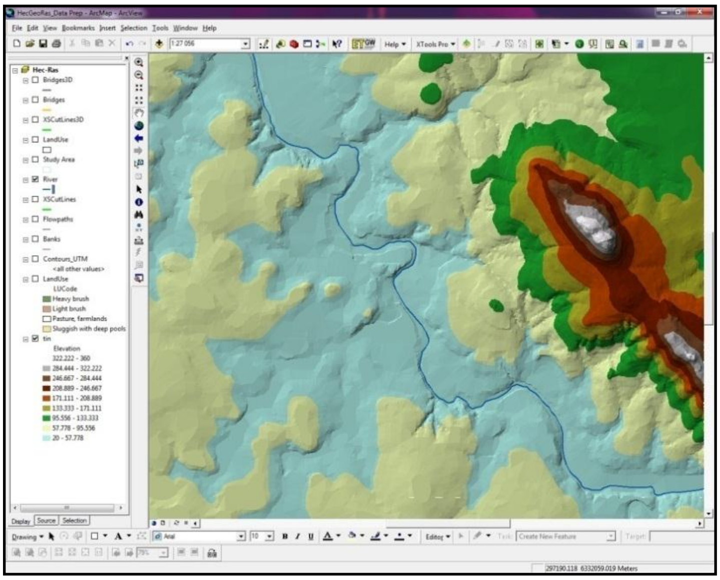


Figure A.5 Stream centre line layer, *River*, and TIN

In HEC-RAS each river and its reaches must have a unique name. The Assign River Code/Reach Code tool (see Figure A.6) should be used to assign names (Ackerman 2005; Merwade 2009).

Figure A.6 Stream Assign River Code/Reach Code tool

The tool first prompts the user to assign a River/Reach ID to the *River* feature, after which the river and reach names are requested. Each river feature must also have a unique ID in the geodatabase. Occasionally this ID field (see Figure A.7) cannot be updated with the Assign River Code/Reach Code tool in which case ArcMap's Editor toolbar should be used to manually update the ID field.

Shape *	OID *	Shape_Length	HydroID	River	Reach	FromNode	ToNode	ArcLength	FromSta	ToSta
Polyline	1	41003.756256	1	Berg	Berg	<Null>	<Null>	<Null>	<Null>	<Null>

Record: 1 Show: All Selected Records (0 out of 1 Selected)

Figure A.7 Updated HydroID, River and Reach fields

For this demonstration, the *River*- and *Reach* fields must be assigned the same name, namely *Berg*, since the river consists of one reach (see Figure A.7).

Topology needs to be defined to ensure that the reaches of the river are all connected to create a river network. The Topology tool (see Figure A.8) for stream centre line features under the RAS Geometry menu can be used to update the topology (Ackerman 2005; Merwade 2009).

Stream Centerline: River
Terrain TIN: tin2

Figure A.8 Topology window

The TIN should be used as input for this tool. An additional table that captures the x-, y- and z-coordinates of the nodes should be created simultaneously. This table is used to create the exchange file, the RAS GIS Import File. The River feature's attribute fields, *FromNode* and *ToNode*, should then be populated with integer data for the respective nodes to define the connectivity between the reaches (see Figure A.9) (Ackerman 2005; Merwade 2009). For this demonstration, there are only two nodes since the river consist of one reach.

Shape *	OID *	Shape_Length	HydroID	River	Reach	FromNode	ToNode	ArcLength	FromSta	ToSta
Polyline	1	41003.756256	1	Berg	Berg	1	2	<Null>	<Null>	<Null>

Figure A.9 Updated *FromNode* and *ToNode* fields

The final step is to calculate the actual length of the reach in map units and to populate the *ShapeLength* field. The Lengths/Stations tool for stream centre line features in the RAS Geometry menu should be used for this purpose. The length is calculated using the river station numbers and to measure the reach distance from downstream to upstream (Ackerman 2005; Merwade 2009). The updated fields, *ArcLength*, *FromSta* and *ToSta*, are shown in Figure A.10.

Shape *	OID *	Shape_Length	HydroID	River	Reach	FromNode	ToNode	ArcLength	FromSta	ToSta
Polyline	1	41003.756256	1	Berg	Berg	1	2	41003.758	0	41003.7

Figure A.10 Updated *ArcLength*, *FromSta* and *ToSta* fields

The calculation is done by assigning a station number, zero, at the downstream end of each river. This reach distance should equal the river length at the upstream end. Since this river has only one reach, the river station at the downstream end is zero, as indicated in the *FromSta* field, and the upstream end, *ToSta* field, indicates the length of the whole river and thus the reach. This also explains why the same measurement is used for the *ArcLength* and *ToSta* fields.

Bank lines layers

The bank layer, Banks, should be digitised in a downstream direction, first the left bank and then the right (Ackerman 2005; Merwade 2009) from a SPOT 5 image.

Flow path centre line layer

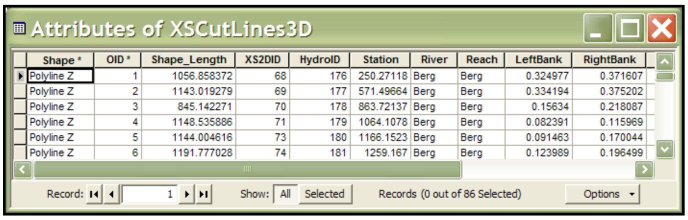
The Create Flow Paths tool (RAS Geometry menu) can be used to create the stream centre line as a *FlowPath* feature in the HEC-GeoRAS geodatabase. The river centre line created during the creation of the TIN can be used to represent the main channel flow line. The remaining left and right flow paths should additionally be digitised. After the digitising of the flow paths is completed, the flow paths can be labelled according to their type, namely *Left*, *Right* or *Channel*, in the attribute table.

Cross-sectional cut lines layer

The Cross-sectional Cut Lines layer is created using the Create RAS Layers tool (RAS Geometry menu). Cross-sectional cut lines must be digitised perpendicular to the direction of flow, from the left to the right bank, looking downstream. The lines must cover the entire flood extent, particularly the stream centre line and overbank flow paths. The Profile tool is used to test whether the cross-sectional cut lines cover the width of the floodplain (Ackerman 2005; Merwade 2009).

The attribute data of the *Cross-sectional Cut Lines* layer is captured after the digitising is completed. The attribute data includes the river name, bank stations, river stations, and downstream reach lengths. The river names should be added by using the River/Reach Names tool for cross-sections under the RAS Geometry menu. Next, the river and bank stations can be assigned to the cross-sectional cut lines by using the Stationing and Bank Stations tool for cross-sectional cut lines under the RAS Geometry menu. Finally, the downstream reach length should be assigned to the cross-sectional cut lines using the Downstream Reach Lengths tool for cross-sectional cut lines under the RAS Geometry menu (Ackerman 2005; Merwade 2009).

Elevation values must be extracted where the cross-sectional cut lines intersect with the TIN to create a three-dimensional cross-sectional cut line layer, named *Cross-sectional Cut Lines 3D* (Ackerman 2005; Merwade 2009). The attribute field should then be opened and the Shape field should indicate the value, Polyline Z (see Figure A.11), to ensure that the conversion has taken place.



Shape *	OID *	Shape_Length	XS2DID	HydroID	Station	River	Reach	LeftBank	RightBank
Polyline Z	1	1056.858372	68	176	250.27118	Berg	Berg	0.324977	0.371607
Polyline Z	2	1143.019279	69	177	571.49664	Berg	Berg	0.334194	0.375202
Polyline Z	3	845.142271	70	178	863.72137	Berg	Berg	0.15634	0.218087
Polyline Z	4	1148.535886	71	179	1064.1078	Berg	Berg	0.082391	0.115969
Polyline Z	5	1144.004616	73	180	1166.1523	Berg	Berg	0.091463	0.170044
Polyline Z	6	1191.777028	74	181	1259.167	Berg	Berg	0.123989	0.196499

Record: 1

Show: All Selected

Records (0 out of 86 Selected)

Figure A.11 Attributes of Cross-sectional cut lines 3D

Land cover layer

For this demonstration, the NLC 2000 land cover data set should be projected from geographical coordinates to UTM 34 S and clipped according to the extent of the demonstration area. Unnecessary fields such as Area and Perimeter must be deleted from the attribute list. It is important not to create a multi-part feature since HEC-GeoRAS cannot function with multiple geometries in one feature (Merwade 2009).

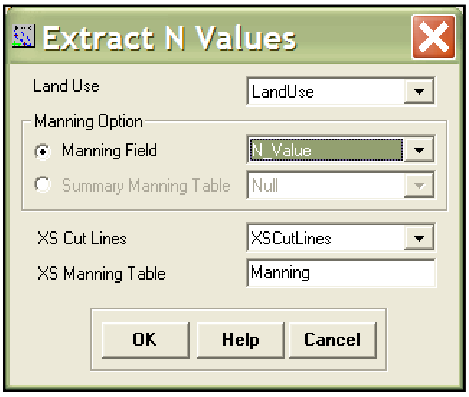
A *Land Use* layer can be created using the Create RAS Layers tool under the RAS Geometry menu. The *Land Use* shapefile that was compiled from the NLC 2000 set should be imported into the HEC-GeoRAS geodatabase's *Land Use* layer.

Two fields must be added to the attribute table of the *LandUse* shapefile, namely *LUCode* and *N_Values*. The *LUCode* contains the description of the land use type and the *N_Value* the corresponding Manning's roughness coefficient (Table A.1).

Table A.1 Manning's roughness coefficients for the demonstration area

Land Cover Type	**Manning's Categories**	**Manning'sValue (n)**
Cultivated, temporary, commercial, dryland	Floodplains/Pasture, Farmlands	0.035
Shrubland and Low Fynbos	Floodplains/Light brush	0.050
Thicket, Bushland, Bush Clumps, High Fynbos	Floodplains/Heavy Brush	0.075
Water bodies	Natural Channels/Sluggish with deep pools	0.040

The Manning's coefficient value can be extracted at each intersection of the *Cross-sectional Cut Lines*- and *Land Use* boundaries using the Extract N-Values tool (RAS Geometry menu) (see Figure A.12) (Ackerman 2005; Merwade 2009).



Extract N Values

Land Use: LandUse

Manning Option

● Manning Field: N_Value

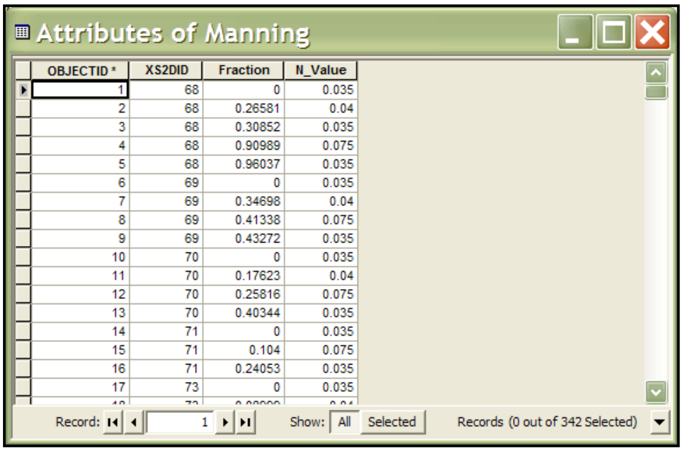
○ Summary Manning Table: Null

XS Cut Lines: XSCutLines

XS Manning Table: Manning

Figure A.12 Extract N-Values window

Two options are available for entering Manning's coefficient values. When selecting the Manning Field option, the values that should be used are those already captured in the attribute field of the *Land Use* layer. If no land use layer is available, the second option, Summary Manning Table, can be used (Ackerman 2005; Merwade 2009). For this demonstration, the first option, Manning Field, is selected. The *Cross-sectional Cut Lines* layer is selected as the input for the cross-sections. The name of the Cross-sectional Manning Table is left at default, namely *Manning*, and the result is shown in Figure A.13.



OBJECTID *	XS2DID	Fraction	N_Value
1	68	0	0.035
2	68	0.26581	0.04
3	68	0.30852	0.035
4	68	0.90989	0.075
5	68	0.96037	0.035
6	69	0	0.035
7	69	0.34698	0.04
8	69	0.41338	0.075
9	69	0.43272	0.035
10	70	0	0.035
11	70	0.17623	0.04
12	70	0.25816	0.075
13	70	0.40344	0.035
14	71	0	0.035
15	71	0.104	0.075
16	71	0.24053	0.035
17	73	0	0.035

Record: 1

Show: All Selected

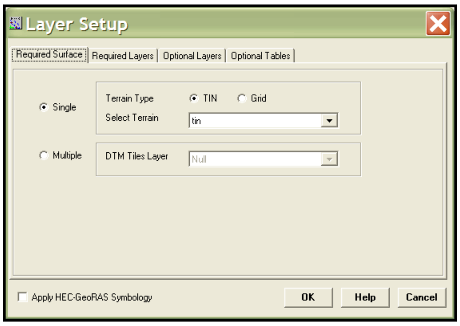
Records (0 out of 342 Selected)

Figure A.13 Attributes of the extracted Manning's values

1.3 GIS import file

The final step in the data preparation phase is the creation of the exchange file, the RAS GIS Import File, from the captured RAS layers in ArcMap and HEC-GeoRAS. All the RAS layers should be verified before exporting to HEC-RAS (Ackerman 2005; Casas et al. 2006; Merwade 2009).

This is done in the Layer Setup window (RAS Geometry menu). The first tab, Required Surface (see Figure A.14), defines the topographical data.



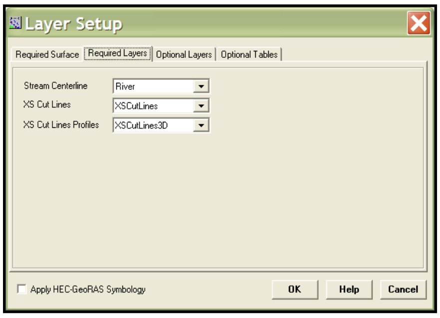
● Single
Terrain Type: ● TIN ○ Grid
Select Terrain: tin

○ Multiple
DTM Tiles Layer: Null

☐ Apply HEC-GeoRAS Symbology

Figure A.14 Required Surface tab

The *terrain type* must be selected as *TIN*, and the TIN created for this demonstration selected (see Figure A.14). The minimal RAS layers required to perform the hydraulic analysis are defined in the Required Layers tab (see Figure A.15).

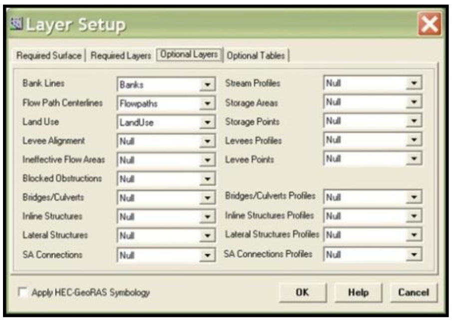


Stream Centerline: River
XS Cut Lines: XSCutLines
XS Cut Lines Profiles: XSCutLines3D
☐ Apply HEC-GeoRAS Symbology

Figure A.15 Required Layers tab

These layers include the *Stream Centerline*, the two-dimensional *Cross-sectional Cut Lines* and the three-dimensional *Cross-sectional Cut Lines 3D*, which must be selected for verification (see Figure A.15).

The layers *Banks*, *Flow Paths* and *Land Use*, should be selected for verification in the Optional Layers tab (see Figure A.16).

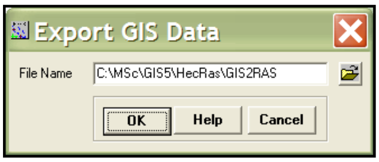


Bank Lines: Banks
Flow Path Centerlines: Flowpaths
Land Use: LandUse
Levee Alignment: Null
Ineffective Flow Areas: Null
Blocked Obstructions: Null
Bridges/Culverts: Null
Inline Structures: Null
Lateral Structures: Null
SA Connections: Null
Stream Profiles: Null
Storage Areas: Null
Storage Points: Null
Levees Profiles: Null
Levee Points: Null
Bridges/Culverts Profiles: Null
Inline Structures Profiles: Null
Lateral Structures Profiles: Null
SA Connections Profiles: Null
☐ Apply HEC-GeoRAS Symbology

Figure A.16 Optional Layers tab

In the last tab, Optional Tables, the *Manning* table should be selected as the input for the Manning’s roughness coefficient values. The OK button must be selected to complete the verification of the layers in each tab.

The Export GIS Data window (RAS Geometry menu) should then be used to export all the verified layers and tables to the RAS GIS Import File for HEC-RAS (see Figure A.17).



File Name C:\MSc\GIS5\HecRas\GIS2RAS

Figure A.17 Export GIS Data window

Two files are created, namely an intermediate Extensible Mark-up Language (XML) file, GIS2RAS.xml, and an ASCII file, GIS2RAS.RASImport.sdf. Spatial Data Format (SDF) is a file format that is recognised and imported by HEC-RAS.

2. HYDRAULIC ANALYSIS

2.1 Import and define the geometric data

The exchange file created in ArcMap and HEC-GeoRAS, GIS2RAS.RASImport.sdf must be imported into HEC-RAS. HEC-RAS should be started and a new project saved. The geometric data must be imported and edited within the Geometric Data window (see Figure A.18) that opens by selecting Geometric Data under the Edit menu in the main HEC-RAS window.

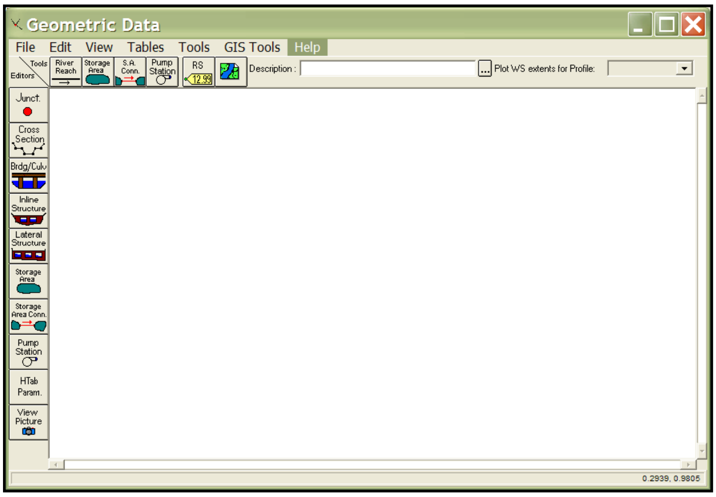
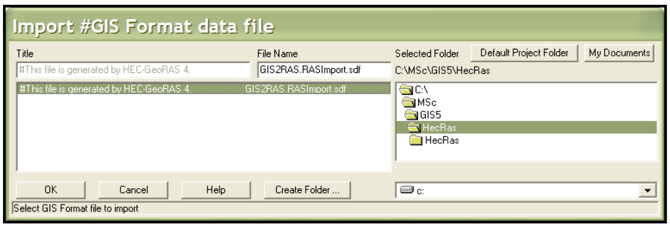


Figure A.18 Geometric Data window (empty)

The Import Geometry Data tool (see Figure A.19), under the File menu in the Geometric Data window, is used to import the geometric data created in ArcMap and HEC-GeoRAS.



Title: #This file is generated by HEC-GeoRAS 4.

File Name: GIS2RAS.RASImport.sdf

Selected Folder: C:\MSc\GIS5\HecRas

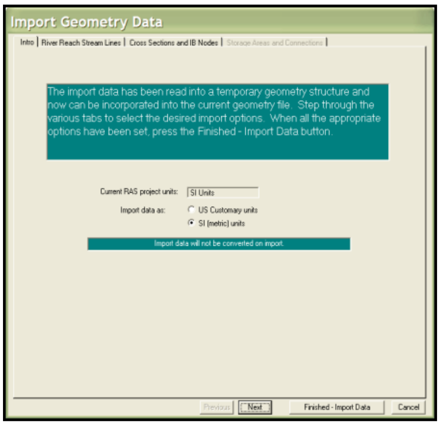
#This file is generated by HEC-GeoRAS 4. GIS2RAS.RASImport.sdf

c:

Select GIS Format file to import

Figure A.19 GIS Import window

The data type to be imported should be specified as GIS Format and the GIS2RAS.RASImport.sdf file must be selected. The initial tab, Intro (see Figure A.20), of the import process must be opened and the projection of the geometric data to be imported defined.



The import data has been read into a temporary geometry structure and now can be incorporated into the current geometry file. Step through the various tabs to select the desired import options. When all the appropriate options have been set, press the Finished - Import Data button.

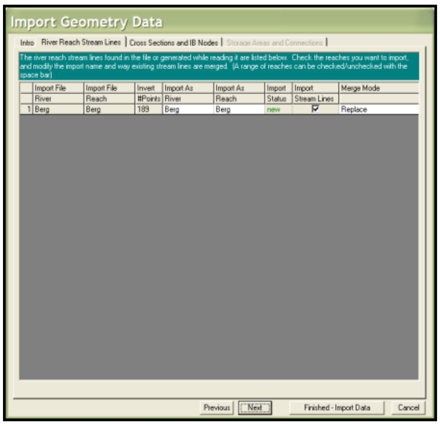
Current RAS project units: SI Units

Import data as:
○ US Customary units
● SI (metric) units

Import data will not be converted on import.

Figure A.20 Import Geometry (Intro tab) window

The *SI (metric) units* option should be selected for the UTM 34S projection. In the River Reach Stream Lines tab (see Figure A.21), the import parameters for the stream centre line must be confirmed.



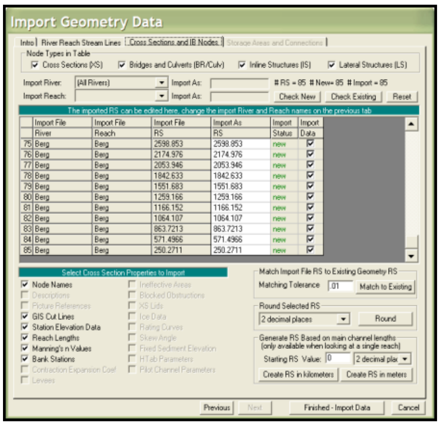
The river reach stream lines found in the file or generated while reading it are listed below. Check the reaches you want to import, and modify the import name and way existing stream lines are merged. (A range of reaches can be checked/unchecked with the space bar)

	Import File River	Import File Reach	Invert #Points	Import As River	Import As Reach	Import Status	Import Stream Lines	Merge Mode
1	Berg	Berg	189	Berg	Berg	new	☑	Replace

Figure A.21 Import Geometry (River Reach Stream Lines tab) window

The checkbox under the Import field should be ticked, to import the single river reach, namely *Berg*. In the Cross-sections and IB Nodes tab (see Figure A.22), the cross-sectional geometric data should be imported. All the checkboxes must then be checked to ensure that all the cross-sectional cut lines are imported and the remaining parameters should be left at default.

Figure A.22 indicates the 85 cross-sectional cut lines that should be imported into HEC-RAS. The importing process is started by selecting the Finished–Import Data button.



Node Types in Table
☑ Cross Sections (XS) ☑ Bridges and Culverts (BR/Culv) ☑ Inline Structures (IS) ☑ Lateral Structures (LS)

Import River: (All Rivers) Import As:
Import Reach: Import As:
RS = 85 # New= 85 # Import = 85

The imported RS can be edited here, change the import River and Reach names on the previous tab

	Import File River	Import File Reach	Import File RS	Import As RS	Import Status	Import Data
75	Berg	Berg	2598.853	2598.853	new	☑
76	Berg	Berg	2174.976	2174.976	new	☑
77	Berg	Berg	2053.946	2053.946	new	☑
78	Berg	Berg	1842.633	1842.633	new	☑
79	Berg	Berg	1551.683	1551.683	new	☑
80	Berg	Berg	1259.166	1259.166	new	☑
81	Berg	Berg	1166.152	1166.152	new	☑
82	Berg	Berg	1064.107	1064.107	new	☑
83	Berg	Berg	863.7213	863.7213	new	☑
84	Berg	Berg	571.4966	571.4966	new	☑
85	Berg	Berg	250.2711	250.2711	new	☑

Select Cross Section Properties to Import

- ☑ Node Names
- ☐ Descriptions
- ☐ Picture References
- ☑ GIS Cut Lines
- ☑ Station Elevation Data
- ☑ Reach Lengths
- ☑ Manning's n Values
- ☑ Bank Stations
- ☐ Contraction Expansion Coef
- ☐ Levees
- ☐ Ineffective Areas
- ☐ Blocked Obstructions
- ☐ XS Lids
- ☐ Ice Data
- ☐ Rating Curves
- ☐ Skew Angle
- ☐ Fixed Sediment Elevation
- ☐ HTab Parameters
- ☐ Pilot Channel Parameters

Match Import File RS to Existing Geometry RS
Matching Tolerance .01

Round Selected RS
2 decimal places

Generate RS Based on main channel lengths (only available when looking at a single reach)
Starting RS Value: 0 2 decimal plac

Figure A.22 Import Geometry (Cross-Sections and IB Nodes tab) window

The imported geometric data is displayed in the Geometric Data window (see Figure A.23) when the import process is complete. The RAS GIS Import File should be successfully imported from ArcMap and HEC-GeoRAS into HEC-RAS.

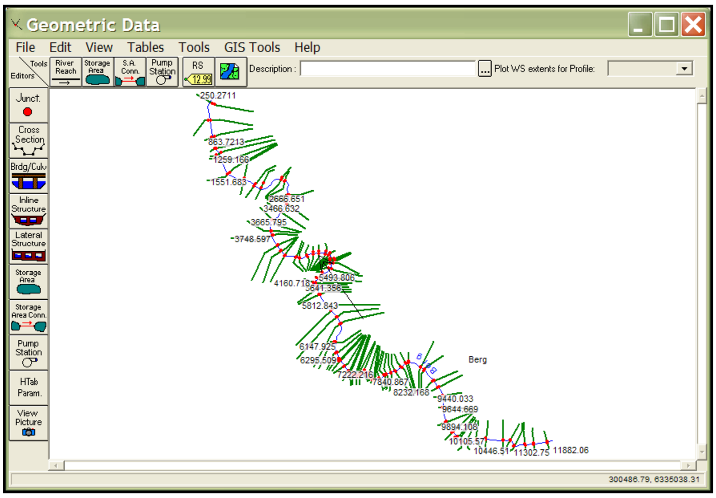
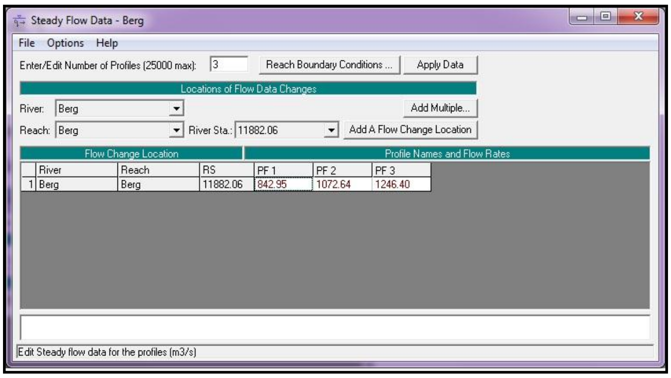


Figure A.22 Geometric data (with imported geometric data)

2.2 Complete flow data

The calculated flood peak values, 842.95 m³/s, 1072.64 m³/s and 1246.40 m³/s, must be added to the Steady Flow Data window (Edit menu) for the generation of the three different hypothetical profiles for the 20-, 50- and 100-year recurrence intervals (see Figure A.23).



Enter/Edit Number of Profiles (25000 max): 3

River: Berg

Reach: Berg

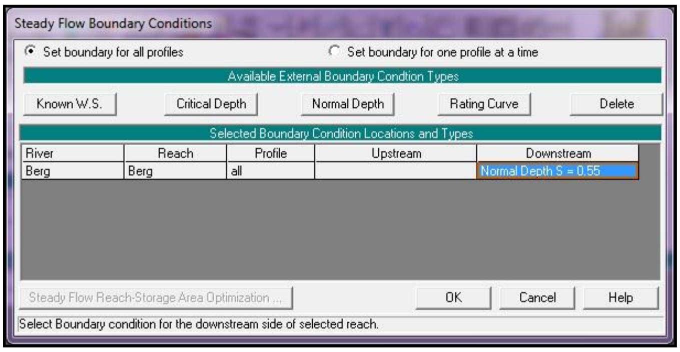
River Sta.: 11882.06

	River	Reach	RS	PF 1	PF 2	PF 3
1	Berg	Berg	11882.06	842.95	1072.64	1246.40

Edit Steady flow data for the profiles (m3/s)

Figure A.23 Steady Flow Data window with defined flow data

The downstream flow conditions should be defined by selecting the Reach Boundary Conditions button and entering the downstream water level in the Steady Flow Boundary Conditions window (see Figure A.24).



● Set boundary for all profiles ○ Set boundary for one profile at a time

River	Reach	Profile	Upstream	Downstream
Berg	Berg	all		Normal Depth S = 0.55

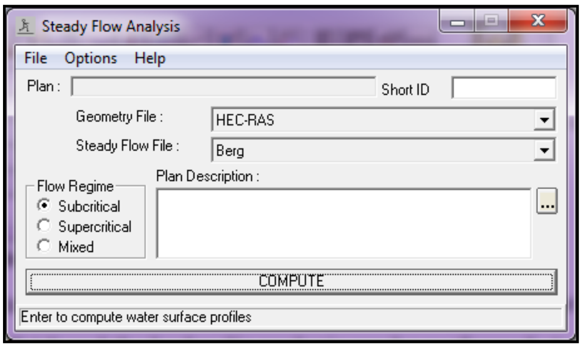
Select Boundary condition for the downstream side of selected reach.

Figure A.24 Steady Flow Boundary Conditions for downstream flow

A channel slope of 0.55 must be calculated to represent the energy slope for a Normal Depth selection. The OK button can then be selected to finish and then save the entered parameters for the flow data.

2.3 HEC-RAS analysis

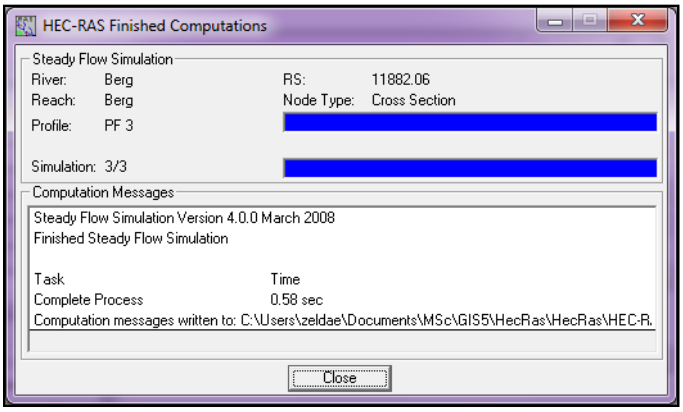
A steady flow analysis is performed using the Steady Flow Analysis window (Run Menu) (see Figure A.25).



Plan :
Short ID
Geometry File : HEC-RAS
Steady Flow File : Berg
Plan Description :
Flow Regime
● Subcritical
○ Supercritical
○ Mixed
Enter to compute water surface profiles

Figure A.25 Steady Flow Analysis window

A subcritical flow regime must be selected. After a successful simulation, a HEC-RAS Finished Computations window (see Figure A.26) appears that indicates the status and time the analysis took to complete. The results, extent and depth, obtained through the hydraulic analysis can then be exported into a format that can be viewed in ArcMap.



Steady Flow Simulation
River: Berg
Reach: Berg
Profile: PF 3
RS: 11882.06
Node Type: Cross Section
Simulation: 3/3

Computation Messages

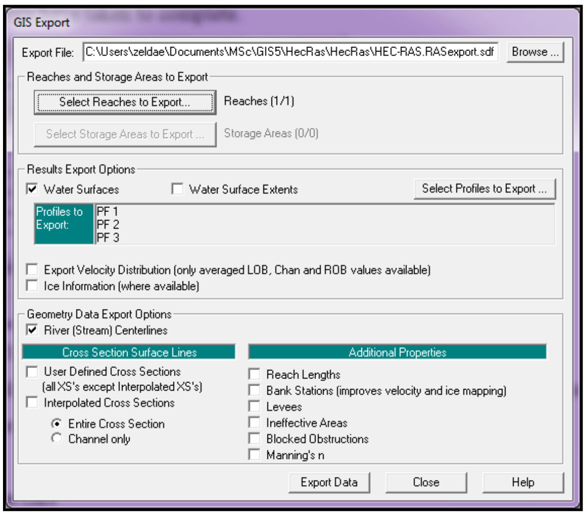
```
Steady Flow Simulation Version 4.0.0 March 2008
Finished Steady Flow Simulation

Task                          Time
Complete Process              0.58 sec
Computation messages written to: C:\Users\zeldae\Documents\MSc\GIS5\HecRas\HecRas\HEC-R.
```

Figure A.26 HEC-RAS Finished Computations window

2.4 Exporting to GIS

The hydraulic analysis results can be exported into an exchange file, the RAS GIS Export File (.RASExport.sdf) that can only be viewed by HEC-RAS. Further file conversion must take place in the post-processing phase to ensure the viewing of the results in ArcMap and HEC-GeoRAS.

The Export GIS Data tool (see Figure A.27) under the File menu is used to export the three profiles generated during the hydraulic analysis.



GIS Export

Export File: C:\Users\zeldae\Documents\MSc\GIS5\HecRas\HecRas\HEC-RAS.RASexport.sdf

Reaches and Storage Areas to Export

Reaches (1/1)

Storage Areas (0/0)

Results Export Options

☑ Water Surfaces
☐ Water Surface Extents

Profiles to Export: PF 1, PF 2, PF 3

☐ Export Velocity Distribution (only averaged LOB, Chan and ROB values available)
☐ Ice Information (where available)

Geometry Data Export Options

☑ River (Stream) Centerlines

Cross Section Surface Lines

☐ User Defined Cross Sections (all XS's except Interpolated XS's)
☐ Interpolated Cross Sections
● Entire Cross Section
○ Channel only

Additional Properties

☐ Reach Lengths
☐ Bank Stations (improves velocity and ice mapping)
☐ Levees
☐ Ineffective Areas
☐ Blocked Obstructions
☐ Manning's n

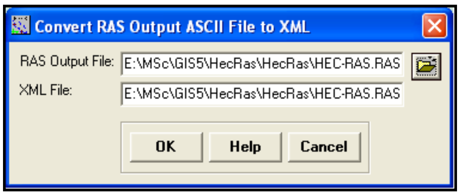
Figure A.27 GIS Export window

All three profiles, for 20-, 50- and 100-year recurrence intervals, must be selected for export and the remaining settings left at default. A window appears which indicates a successful export and that the exchange file, RAS GIS Export File, had been created.

3. POST-PROCESSING PHASE

3.1 Importing the RAS file

HEC-RAS has created an ASCII exchange file, RAS GIS Export File (.RASExport.sdf) that contains all the hydraulic analysis results. This SDF file cannot be recognised by HEC-GeoRAS directly and must be converted into an XML file. During the conversion, HEC-GeoRAS converts the SDF file into an XML file by using the Convert RAS Output ASCII file to XML tool (see Figure A.28). A message will appear to confirm that the import had been successful.



Convert RAS Output ASCII File to XML

RAS Output File: E:\MSc\GIS5\HecRas\HecRas\HEC-RAS.RAS

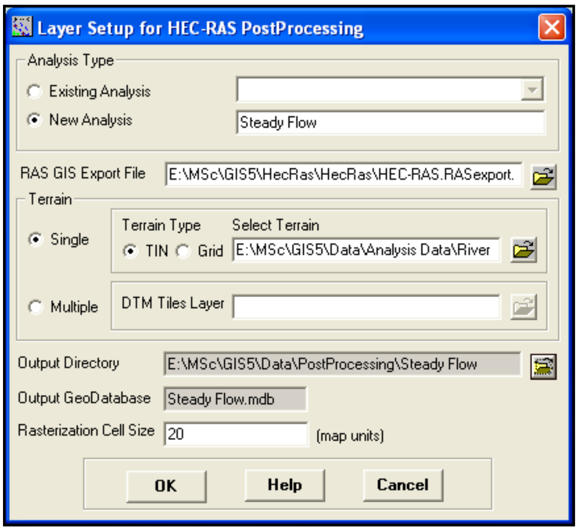
XML File: E:\MSc\GIS5\HecRas\HecRas\HEC-RAS.RAS

Figure A.28 Convert RAS Output ASCII File to XML window

Next, the layer setup has to be configured before any post-processing analysis can commence. The Layer Setup for HEC-RAS Post-Processing window (see Figure A.29) under the RAS Mapping menu should be used for the configuration. The analysis type will determine whether changes can be made to the variable used in the analysis (Ackerman 2005).

For an existing analysis, the variables should remain fixed and should not be changed, but with new analysis, all the variables need to be defined. These include (Ackerman 2005):

- an analysis name to specify a new directory;
- the location of the RAS GIS Export File (newly created XML file);
- the output directory, as the post-processing results (water surface and grids) need to captured;
- the output geodatabase and name thereof to save vector data created during the post-processing; and
- the rasterisation cell size required for the grid calculations.



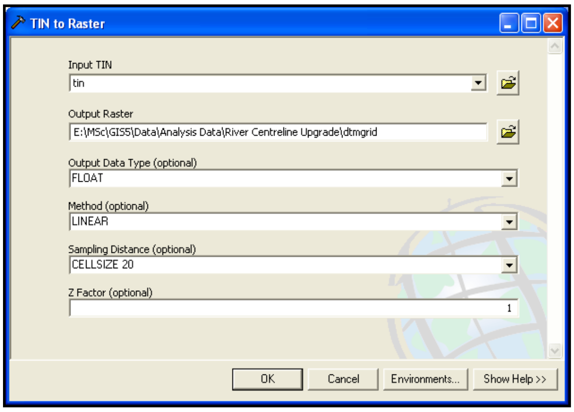
○ Existing Analysis
● New Analysis: Steady Flow
RAS GIS Export File: E:\MSc\GIS5\HecRas\HecRas\HEC-RAS.RASexport.
● Single — Terrain Type: ● TIN ○ Grid — Select Terrain: E:\MSc\GIS5\Data\Analysis Data\River
○ Multiple — DTM Tiles Layer:
Output Directory: E:\MSc\GIS5\Data\PostProcessing\Steady Flow
Output GeoDatabase: Steady Flow.mdb
Rasterization Cell Size: 20 (map units)

Figure A.29 Layer Setup for HEC-RAS Post-Processing window

A new analysis, Steady Flow, must be defined, with the newly created XML file as the RAS GIS Export File. The single terrain option must be selected for the TIN terrain type and the location of TIN defined. Next, the output directory can be defined and the default raster flow size, 20, accepted.

A new data frame, Steady Flow, must be added into the TIN. At the same instance, a grid, labelled *dtmgrid*, should be created from the TIN. Unfortunately, this conversion does not occur automatically and an alternative method must be applied. The Tin to Raster tool (see Figure A.30), under the Conversion menu of the 3D Analyst extension can be used to convert the original TIN to a grid with a cell size 20. This grid should be then added to the data frame, Steady Flow.

Next, the cross-sectional cut lines can be read from the RAS GIS Export File (newly created XML file) using the Read RAS GIS Export File menu item. These cut lines should be saved into the newly created geodatabase.



TIN to Raster

Input TIN: tin

Output Raster: E:\MSc\GIS5\Data\Analysis Data\River Centreline Upgrade\dtmgrid

Output Data Type (optional): FLOAT

Method (optional): LINEAR

Sampling Distance (optional): CELLSIZE 20

Z Factor (optional): 1

Figure A.30 Tin to Raster tool

A bounding polygon (see Figure A.31) should be delineated from the cross-sectional cut lines by connecting the edges to define the analysis extent for the flood hazard mapping (Ackerman 2005; Merwade 2009).

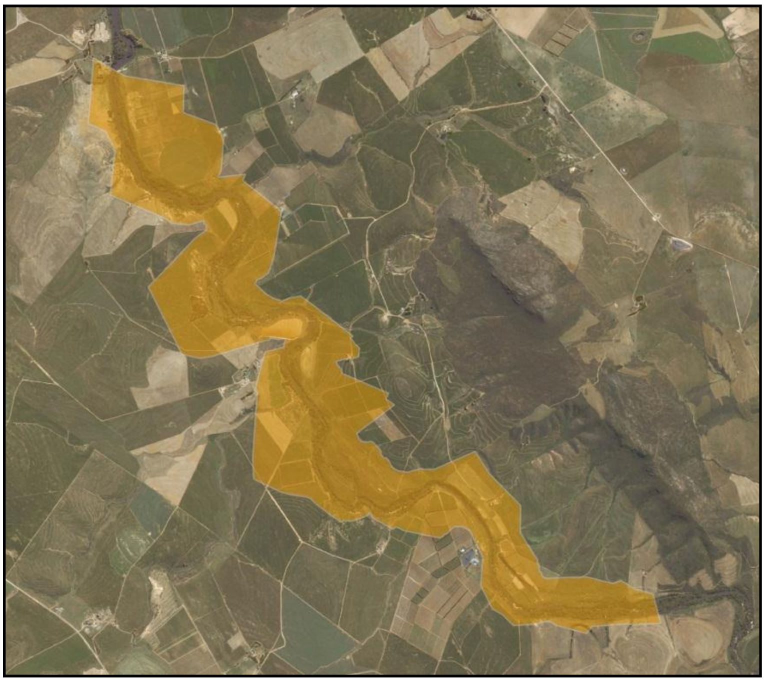


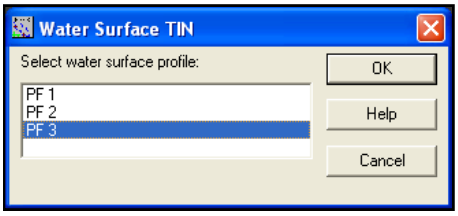
Figure A.31 The extent of the analysis for the inundation mapping

The hydraulic results can now be imported into ArcMap and HEC-GeoRAS, and the flood hazard mapping can commence.

3.2 Flood hazard mapping

Finally, the GIS layers should be created from the hydraulic results obtained from HEC-RAS. The content of the RAS GIS Export File and the original TIN created in the data preparation phase form the foundation of all further analysis in the post-processing phase.

The first step is to create a water surface TIN of each water surface profile by using the Water Surface Generation tool (see Figure A.32) from Inundation Mapping under the RAS Mapping menu.



Water Surface TIN

Select water surface profile:

PF 1
PF 2
PF 3

Figure A.32 Water Surface Generation tool

Profile 3 (1: 100 year) should be selected as the first water surface profile for which a TIN is created to represent the water surface elevation. This water surface TIN (see Figure A.33) covers the whole extent of the bounding polygon to ensure that areas of possible inundation are not excluded from the analysis.

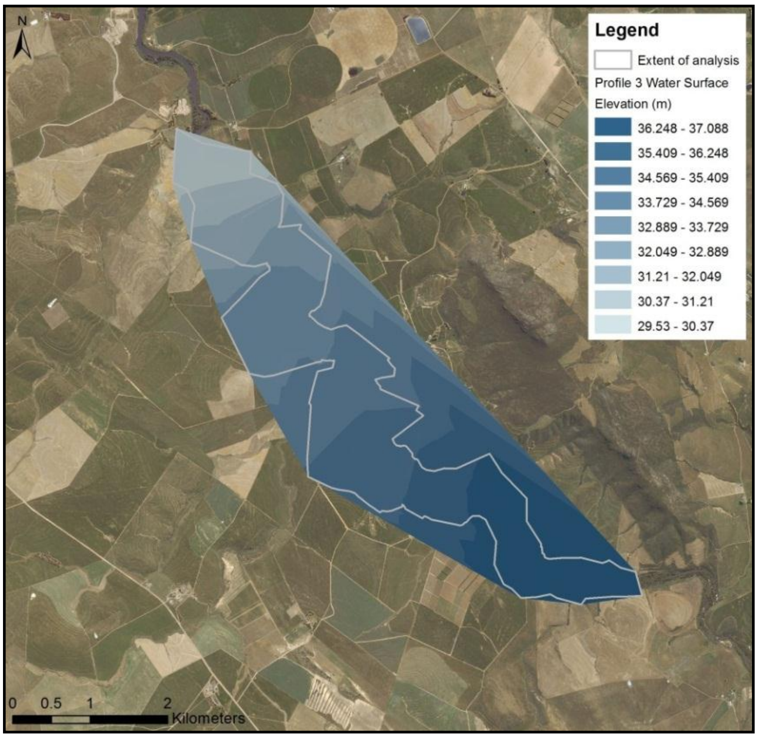


Figure A.33 Water surface extent as determined by the bounding polygon’s edges

The floodplain should be determined for each water surface profile that has a surface TIN by using the Grid Intersection tool from Floodplain Delineation under Inundation Mapping from the RAS Mapping menu.

Both the water surface TIN and the original TIN (created in the data preparation phase) should be converted to grids of the same cell size and origin. A depth grid can then be created that represents areas, also called positive areas, where the water surface is higher than the original TIN and where possible flooding is thus indicated. Lower areas can be indicated as dry.

The depth grid should be overlaid with the bounding polygon to clip only areas relevant to the hydraulic analysis. Thereafter, the depth grid can be converted to a floodplain polygon as shown in Figure A.34. This flood hazard mapping process should be repeated for the other two profiles.

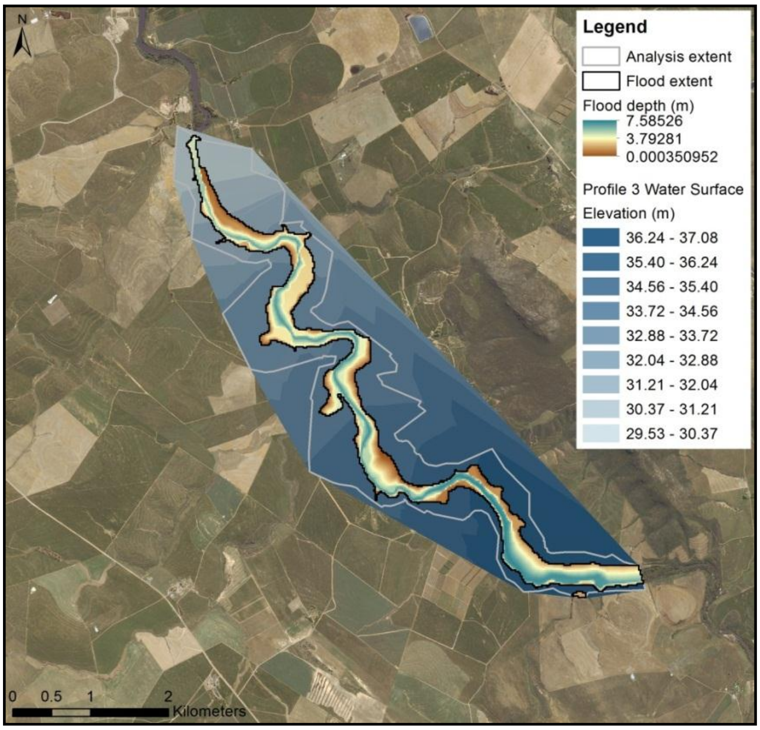


Figure A.34 Inundation polygon for 100-year recurrence interval