UNIVERSITY OF
ZULULAND

FULL DISSERTATION

Submitted in fulfilment of the requirements for the degree of MASTER OF SCIENCE in the field of HYDROLOGY in the Faculty of Science and Agriculture at the University of Zululand

With the title:

SIMULATION OF CATCHMENT RUNOFF, EROSION AND SEDIMENT TRANSPORT USING A TRANSIENT NUMERICAL MODEL FOR MLALAZI CATCHMENT

FACULTY OF SCIENCE AND AGRICULTURE

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February 2019

DEDICATION

This work can only be dedicated to the Lord, He is the Ultimate keeper. His love, generosity and kindness are very fundamental and I thank Him for keeping me in the high place of confidence and faith, hence this work a success.

DECLARATION

I Rasifudi Khathutshelo Joshua of student number 201454749 declare that this research is my own work and is submitted in fulfillment of a Master of Sciences degree in Hydrology. This is my own work and it has not been submitted to this university or any other university for any degree. All the reference materials have been fully acknowledged and the research complies with the University's Plagiarism Policy.

04 March 2019

Signature *Date*

Khathutshelo Joshua Rasifudi

Name in full

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to:

- Mr JJ Le Roux for providing soil erodibility, topography factor and cover factor data which was crucial for this study;
- Prof J.J. Simonis for his supervision and guidance as project leader at the initial stages of the research project;
- Mr. B.K. Rawlins for his supervision and meaningful inputs;
- My co-supervisor and mentor Prof Bruce Kelbe for his powerful mentorship and most importantly his guidance throughout this research project. I am so grateful for the opportunity to be mentored by such a decorated individual within the water sciences fraternity; and
- to all the people in my own life who have been powerful in giving support, may God keep you as you have kept me; I owe you a debt of gratitude.

ABSTRACT

Catchments and estuaries are fragile systems that are prone to serious degradation from many different anthropogenic impacts. Much research has been conducted on developing an understanding of the fluvial processes in river catchments and in estuary dynamics. Many of the anthropogenic impacts on estuarine systems are generally derived from subjective expert opinion in South Africa. The Mlalazi Estuary is one of the best conserved estuaries in KZN. As a result of the changing state of the marine and fluvial conditions there is a possibility that such changes may trigger management interventions. There is therefore a need to derive reliable flows from the Mlalazi Catchment as it is a driver of sediment deposition and erosion processes which may impact on the opening or closing of the Mlalazi Estuary. The latest Reserve Determination study for Mlalazi Estuary was based on rapid assessment with low confidence (<40%) in simulated monthly streamflow. The study illustrated a need for further detailed assessment of catchment hydrology using appropriate and calibrated models. In an ungauged catchment where there is limited observed data, numerical models are useful tools to derive best estimates of flow, erosion and sediment transport. In this study the HEC-HMS hydrological model was developed, calibrated, validated and applied for simulation of runoff, erosion and sediment transport from the Mlalazi Catchment into the estuary. Calibration and validation was done at delineated sub-catchments with observed flow records. An event based calibration approach and a continuous approach were used in the development of the model. For the event model the initial and constant loss method was used for simulating rainfall loss from the catchment surface, while the Soil Moisture Accounting (SMA) Model was employed for the continuous simulations. The event calibration was based on two selected extreme storm events, namely the Domoina (31 Jan 1984) and Imboa (17 Feb 1984) cyclonic events; and the validation was done on two storm events in February 1985 and September 1987. The calibration and validation for continuous simulations of flows were from 1977-1986 and 1986-1999 respectively. The Nash-Sutcliffe Efficiency (NSE) and overall Root Mean Square Error (RMSE) were used to evaluate the model performance. The continuous flows for the catchment were then simulated from 1950 to 2017 incorporating erosion and sediment transport. The erosion was simulated using the Modified Universal Soil Loss Equation (MUSLE), and the Ackers-White method was chosen for sediment transport potential. The erosion and sediment transport models were not calibrated due to limitations of observed data, but parameter values were estimated from other studies available in literature for this region. The simulated sediment yield from the catchment was evaluated by comparison to sediments yield found by other studies in this region.

It was concluded that a physically based, numerical simulation model provides a pragmatic method for the derivation of reliable hydrodynamic data and information in catchments with limited observed data like the Mlalazi Catchment. Furthermore, this study allowed a smooth linkage with the study of the Mlalazi Estuary that employed the HEC-RAS model.

ABBREVIATIONS

ARC-ISCW	Agricultural Research Council Institute for Soil, Climate and Water
CCWR	Computing Centre for Water Research – University of KwaZulu-Natal
DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
DT	Discharge Table
DWS	Department of Water and Sanitation
ET	Evapotranspiration
GIS	Geographical Information Systems
HEC-DSS	Hydrological Engineering Centre – Data Storage System
HEC-HMS	Hydrologic Engineering Centre – Hydrological Modelling System
HEC-RAS	Hydrologic Engineering Centre – River Analysis System
HRU	Hydrological Research Unit – University of Zululand
IDM	Inversed Distance Method
KZN	KwaZulu-Natal
MUSLE	Modified Universal Soil Loss Equation
NGI	National Geo-spatial Information
NLC	National Land Cover
NSE	Nash-Sutcliffe Efficiency
RMSE	Root Mean Square Error
SAPWAT	South African Planning and Water Requirement Tool
SAWS	South African Weather Services
SMA	Soil Moisture Accounting
WRC	Water Research Commission

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CHAPTER 1: INTRODUCTION

Catchments and estuaries are fragile systems that are prone to serious degradation from many different anthropogenic impacts. Much research has been conducted on developing an understanding of the fluvial processes in river catchments and in estuary dynamics (Chow *et al*., 1988). Many of the anthropogenic impacts on estuarine systems are generally derived from subjective expert opinion in South Africa (DWS, 2015). The ever-increasing reports of sedimentation problems in South African estuaries due to increased sediment yields from the catchment, lead to calls for increased flushing of these estuaries and mouth breaching, both natural and mechanical in order to remove the sediment (CSIR, 1999 and 2003, DWS, 2015). There is a need to be more objective in the assessment of these systems by using numerical models to provide reproducible, comparable and consistent catchment and estuary dynamic information to evaluate hydrological concepts and predict impacts and responses to changes in catchment conditions (Beven, 2001). These numerical models can be a possible tool to aid in the decision making process of dredging or artificial breaching (managing) of estuaries, in order to prevent flooding, lower water levels, restore tidal circulation, flushing pollutants, nutrients, and promoting migration patterns in fish and other biological resources into the ocean, rather than to remove accumulated sediment.

Many estuaries in South Africa are only temporarily open to the sea due to the various interactions between the fluvial and marine processes (Beck and Basson, 2008). However, many estuaries are often closed more frequently and for longer periods than in the past due to reduced river flows (Beck and Basson, 2008). The behaviour of these estuary mouths is driven by three main components; river, tidal and wave processes (O’Brian, 1931). Open-mouth conditions at small estuaries are principally maintained by river flow and especially by a strong base flow. A reduction in minimum (base) low flow commonly results in an increase in closed mouth conditions (Beck and Basson, 2008). There is a need to develop relationships (models) that establish the linkages between the estuary state and the controlling environment. In this study one of the three main components driving the state of the estuary is in the form of river and sediment flows through the estuary. A major contributor to the flow and sediment dynamics in the estuary is the discharge of these hydrological components from the catchments.

Overland surface water flows and stream channel flows affects the landscape. Surface flow result in erosion and sediment loads which are carried to stream channels where it is transported to the estuary. Headwater streams with steep slopes have high velocity which leads to stream bed erosion and rapid transport of the sediment load. Sediment load can be carried by stream flow to the lower reaches of the catchment where they are often deposited because of the decrease in flow velocity along a declining channel gradient. Diversion structures and reservoirs in the catchment can also affect the movement of sediments through the catchment where reservoirs will trap some or most sediments which enter with the flow (USACE, 2000; Rossouw *et al.,* 1998). The sediment load from the catchment that is exported into the estuary can affect the estuary bathymetry and tidal prism.

In catchments where there are no records or limited observed data of flow or sediment, suitable rainfall-runoff and erosion models can be used as the most effective tools to derive the best estimates of the flow and sediment loads. The resultant runoff and sediments are routed to downstream sinks, while also modelling the erosion and the deposition of the sediments in reservoirs and river reaches (Pak *et al.,* 2010). Models are useful tools for estimating flow and sedimentation in areas with limited observed data. The Mlalazi Catchment has some flow stations on the Ntuze River tributary and one on the upper reaches of the Mlalazi River. However, there is not a single flow station which measures the outflows from the whole catchment. Therefore, for catchment surface soil erosion and sediment routing studies, information from a well calibrated rainfall-runoff model should be considered as the reliable and pragmatic approach for estimating the discharge from the catchment into the estuary (HEC, 2015). There are no sediment or erosion monitoring stations in the catchment.

The latest Reserve Determination study for the Mlalazi Estuary (DWS, 2015) was based on a rapid assessment technique with low confidence for the simulated monthly flow but produced no sediment yield for assessment. The study was based on an uncalibrated monthly WRSM2000 (Pitman) model that was unable to provide reliable predictions of storm and sediment yields. The study illustrated the need for further and more detailed assessment of the catchment hydrology using appropriate and calibrated models.

While it is possible to measure the flow and sediment entering an estuary, these are seldom measured in small catchments because of the cost and difficulties associated with the measurement techniques. A more pragmatic and cost effective approach for a clear understanding of the reality and enable future predictions is the configuration, calibration, validation and application of a physically based continuous numerical hydrological model (Surur, 2010). The following questions arise in the choice and application of models:

- Whether such a model can be configured and applied to the Mlalazi Catchment to provide the transient flow and sediment yield data at the required temporal and spatial level of accuracy for use in the Mlalazi Estuary hydrodynamic study?
- What data will be required for the application of a numerical hydrological model?
- Which is the most appropriate model to use with the available data?

1.1 Problem Statement

The Mlalazi Estuary is one of the best conserved estuaries in KZN (Mann, *et al.,* 1996). As a result of the changing state of the marine and fluvial conditions (Begg, 1978) there is a possibility that such changes may trigger management interventions (DWS, 2015). There is therefore a need to derive reliable flows from the Mlalazi Catchment as it is a driver of sediment deposition and erosion processes which may impact on the opening or closing of the Mlalazi Estuary. Catchment runoff is directly associated with climatic and geomorphic conditions that may change in response to human induced activities associated with land use and land cover change at the catchment scale (Day, 1981). These changes may alter the total runoff of the catchment and therefore also impact on the resultant opening and the closing of the estuary mouth.

1.2 Aim of Study

The aim of this study is to configure, calibrate, validate and apply a suitable numerical hydrological model for the simulation of runoff, erosion and sediment transport from the Mlalazi Catchment into the Mlalazi Estuary as important drivers of the hydrodynamics of the estuary.

1.3 Specific Objectives

(a) Review literature on catchment hydrological models and select a suitable model for application in the Mlalazi Catchment.
(b) Establish the required temporal resolution of the required model simulations.
(c) Identify data needs, availability and source the data required for the selected model.
(d) Create a Digital Elevation Model (DEM), assess its accuracy for hydrological modelling in the catchment and supplement where necessary.
(e) Calibrate and validate the model.
(f) Compute catchment flows and sediment load series to be incorporated into the estuary model.

1.4 Research Hypothesis

Catchment runoff and sediment loads are one of the main driving variables of the estuary mouth dynamics. An assessment of these hydrological drivers is important in facilitating an understanding of ecological, morphological and hydrodynamic processes in estuarine studies. A physically based, numerical simulation model is the most pragmatic tool for the derivation of hydrodynamic information in catchments with limited observed data.

1.5 Thesis Organisation

This thesis is organised into six chapters. The first chapter gives an introduction for the study. The second chapter contains a literature review of hydrological models to enable the selection of a suitable model for the study. The third chapter gives an overview of the study area including the data available and their analysis. The fourth chapter provides the methodologies used in the model configuration, choices of process models, the calibration and validation of the model. The fifth chapter presents and discusses the model results. The sixth chapter contains the conclusions reached and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Hydrological Modelling

Models are simplified representations of specific features of the real world, predicting effects from causes (Jewitt and Gorgens, 2000). Hydrological models are conceptual and/or mathematical representations of the process(es) involved in the transformation of input variables. The input variable used such as precipitation and evaporation are transformed, through surface and subsurface transfer processes of water and energy into hydrological outputs. The outputs include streamflow, soil moisture and groundwater (Hughes, 2004).

In general terms, numerical models can be classified as empirical or physically-based; deterministic or stochastics; event or continuous and furthermore, a model can be categorised as either distributed or lumped. There is also a distinction between measured-parameter and fitted-parameter models. This is critical for application of hydrological models in catchments where observations of input and output are limited or unavailable. The different categorisation of numerical models is given in Table 2.1.

The selection and configuration of the resources and process that need to be included in the model depend on the purpose of the model application. There is not enough data to develop an empirical model; event and continuous flow records are required; the catchment is too large for a lumped model; so it has been established from the purpose and review of the model and the catchment characteristics and available data that a distributed, physical based parameterised model is the most suitable for this study.

The parameters required as input to physically-based models are generally obtained from field measurements, maps and other sources of information (Hughes, 1991). Physically-based numerical models are created from conceptual models which are built upon the base knowledge of the pertinent physical, chemical and biological processes that act on the input to produce the desired output (USACE, 2000).

Table 2.1: Categorisation of numerical models (from Ford and Hamilton, 1996)

Category	**Description**
Empirical or physically-based (Conceptual)	Empirical models rely on calibration of pseudo-physical parameters representative of selected processes against an observed record. They are built upon observation of input(s) and output(s) without seeking to represent explicitly the process of conversion. Physically-based hydrological models represent a system of resources linked through hydrological processes defined in terms of physical laws parametrised as a linked set of equations.
Deterministic or Stochastic	If all the input parameters and processes in a model are considered free of random variation and known within certainty limits, the model is generally classified as a deterministic model. Whereas, if the model incorporates the random nature of the processes and the description in the predicted of output, the model is a stochastic model.
Event or continuous	An event model will simulate a single storm event for a specified duration varying from hours to days, while a continuous model simulates a longer period for predicting catchment response both during and between precipitation events.
Lumped or distributed	A model can also be lumped (1D) or distributed (2D) in form. In a distributed model, the spatial variations of characteristics and processes are considered explicitly, while they are averaged or ignored in a lumped model. However, distributed models invariably have an inherent level of averaging at smaller scales than lumped models.
Measured parameter or fitted-parameter	In a measured-parameter model, parameters are determined from measurements or by direct methods based on observation, while in a fitted-parameter model, parameters cannot be measured and they are found by fitting the model with observed values of inputs and outputs variables. Fitted-parameter models have limitations for application in catchments without some observed data. Many models can have both determined and fitted parameters.

The major hydrological processes in rainfall-runoff modelling are the volume of runoff, direct flows and base flow. The runoff volume is how much volume remains in excess from rainfall falling on a catchment after accounting for losses from interception, surface and subsurface storage, evaporation and transpiration. The direct runoff is the transformation of excess rainfall into runoff at the outlet of the contributing catchment. This is water that has not infiltrated or been stored on the catchment and moves over or just beneath the catchment surface to a discharge point in the catchment. Base flow is the sustained runoff of prior rainfall that was stored temporarily in the catchment saturated zone, plus the delayed subsurface runoff from the current storm (USACE, 2000).

There are numerous deterministic hydrological models that are available for simulating the runoff and erosion at catchment scales. The following sections outline some of the commonly available model codes that have been identified that may be suitable for this study.

2.2 Different Hydrological Models

2.2.1 MIKE SHE Model

MIKE SHE is described as a deterministic, physically based, distributed modelling system that has its origin in the SHE (System Hydrologique European) model (Abbott *et al.,* 1986). It was developed as a fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models (DHI, 2003). It solves partial differential equations describing mass flow and momentum transfer. It is a parametric model of physical processes, illustrated in Figure 2.1, from which parameters for the physics-based equations can be obtained from measurements and used in the model application (DHI, 2003).

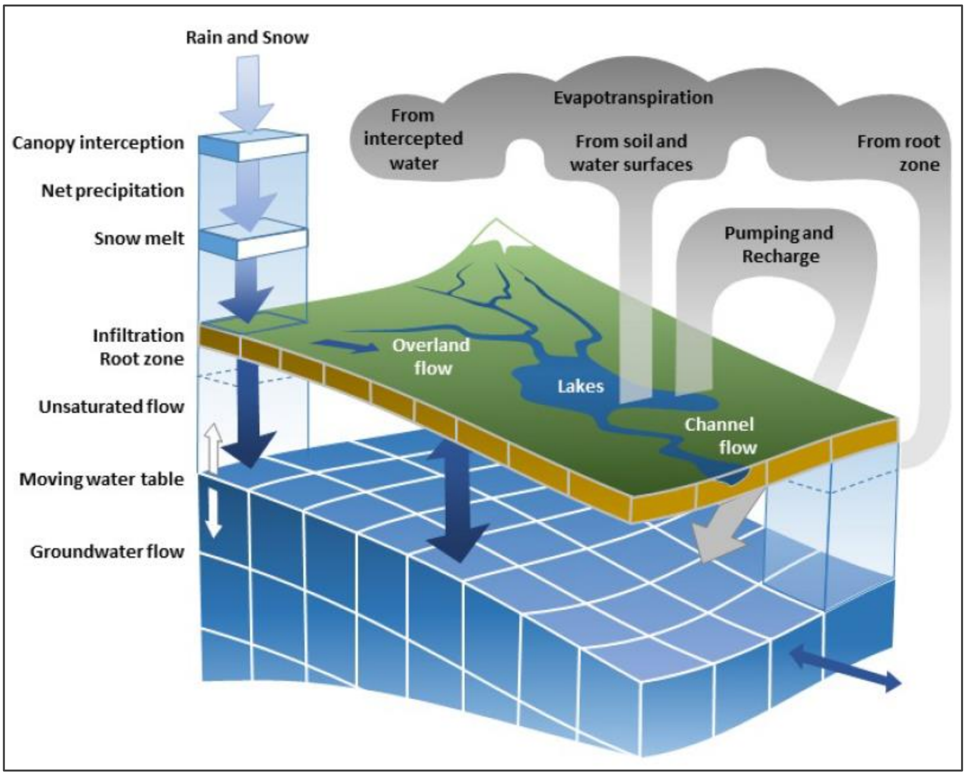


Figure 2.1: MIKE SHE catchment hydrological processes (DHI, 2003)

MIKE SHE simulates major hydrological processes which include evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow and their interactions (Butts *et al.,* 2004). Coupled with MIKE 11 it can also simulate the flow and depth in the rivers.

This model is flexible in input requirement and there is no predefined list of required input data. The required data depends on the hydrological processes which are assumed to dominate the catchment under consideration and the process models selected, which in turn, depend on what problems are to be solved. Basic model parameters required for nearly every MIKE SHE model include the following:

- Model extent – typically a polygon incorporating the topographical catchment boundary
- Topography – as point or gridded surface
- Precipitation – as station data (rain gauge data)

Additional basic data required for runoff simulations are as follows:

- Reference Evapo(transpi)ration) as station data or calculated from meteorological data
- Sub-catchment delineation – for rainfall distribution
- River morphology (Geometry and cross-sections).
- Land use distribution – for vegetation (Leaf Area Index (LAI), interception and evaporation).
- Soil distribution – for distributing infiltration, runoff and sediment processes.

Limitations of the MIKE SHE physical-based model:

- Require significant amount of data and the cost of data acquisition may be high.
- Attempts to represent flow processing at a grid scale with mathematical description that, at best are valid for small scale experimental conditions.
- Relative complexity may lead to over-parameterized descriptions for simple applications (DHI, 2003)

The successful applications of this model are found in surface-water and groundwater hydrology interaction applications (Refsgaard *et al.,* 1999; Feyen *et al.,* 2000; Andersen *et al.,* 2001; Vazquez and Feyen, 2003; Johnson *et al.,* 2003).

The MIKE SHE model does not have any physical limit to the size of the model or model boundary, but the mathematical descriptions applied are best suited for small scale conditions, it is advisable to always apply the model in a distributed system. Practical limits are that little extra detail or slightly smaller grid size will lead to long computer run times. This is a commercial product that is not freely available, severe restrictions apply to the model size if used without a dongle and the model runs in demo mode (DHI, 2003).

2.2.2 The ACRU Model

ACRU is a physical conceptual model. It is conceptual in that it consists of a system in which important hydrological processes and couplings are idealized. In addition its, physical to the degree that physical processes are represented explicitly in the process and the model uses input variables that can be estimated from the physical characteristics of the catchment. ACRU is therefore not a parameter fitting or optimizing model but is critically dependent on reliable estimates of the parameter values for the catchment to be modelled. The acronym ACRU is derived from the Agricultural Catchments Research Unit within the Department of Agricultural Engineering of the University of KwaZulu-Natal (UKZN), South Africa (Schulze, 1995).

Compulsory data inputs into ACRU include the catchment area, daily rainfall, reference evaporation, soil properties and land use information that is common to most of the similar models. Optional data can be inputted into the model based on the suitability of the study (Schulze, 1995).

ACRU revolves around multi-layer soil water budgeting in the unsaturated zone. A flow diagram in which multi-layer soil water budgeting is accounted for in ACRU is depicted in Figure 2.2. In the model total streamflow (channel runoff) is generated as stormflow and base flow depending upon the magnitude of daily rainfall in relation to dynamic soil water budgeting. Stormflow is made up of quick overland flow and delayed stormflow. Base flow is the sum of (unsaturated) groundwater flows and delayed through-flows, and typically recedes much slower than the stormflow (Royappen, 2002).

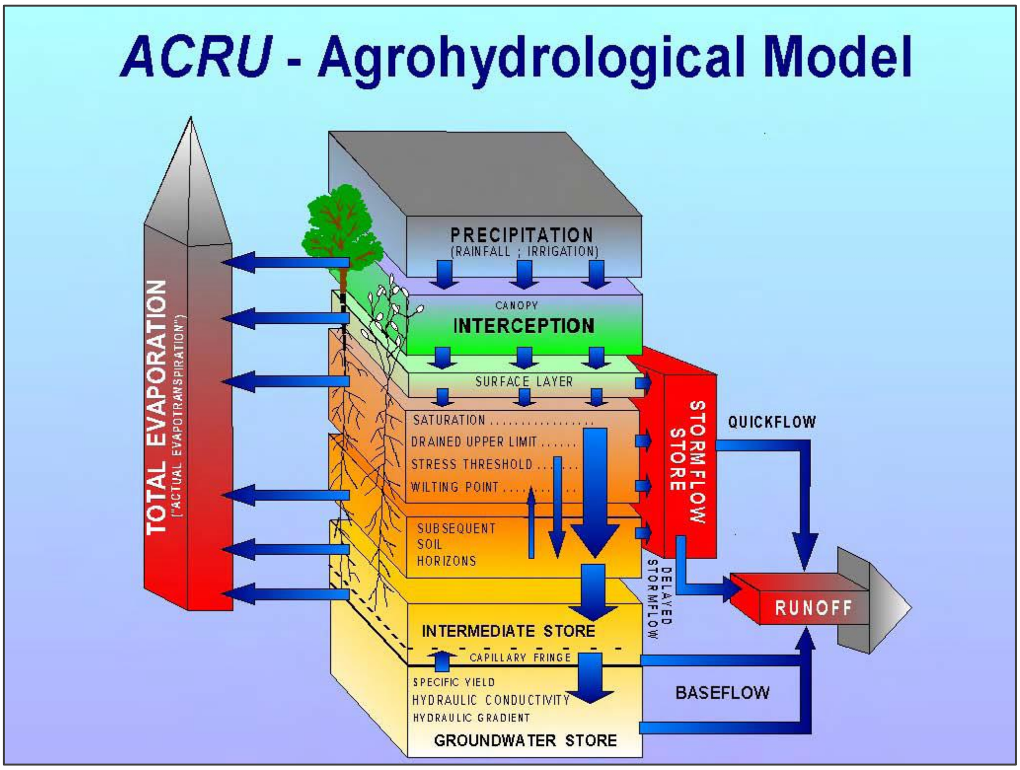


Figure 2.2: ACRU model flow diagram (Schulze, 1995)

A conceptualised illustration of the ACRU model is based on the fact that land use affects hydrological responses to precipitation through canopy interception, changes in infiltration rates of rainfall into the soil and the rates of evapotranspiration. The model has been shown to be highly responsive to these changes (Jewitt and Schulze, 1999).

Components of the soil water budgeting are integrated with modules in the ACRU system to simulate the required catchment components leading to erosion and sediment yield. The model adequately represents hydrological processes and their response to land use changes (Hope *et al.,* 2004).

The model operates at relatively fine temporal and spatial resolution using a daily time step and small sub-catchments delineation. It is recommended that sub-catchments do not exceed 50 km^2 (Smithers and Schulze, 1995). These, sub-catchments may be further divided into pseudo (not genuine expression) sub-catchments representing the various land uses in the catchment (Pike and Schulze, 2001).

A study by Gush *et al.* (2002) revealed that the weakness of the ACRU model was the failure to account for the full storage capacity of soils, and hence their capacity to absorb rainfall following extended drying events. ACRU is based on hillslope hydrological processes and does not incorporate groundwater dynamics. This limits its suitability for applications in groundwater dominated systems such as Maputaland Coastal Plain in KZN (Kelbe, pers. comm.). However, the hydrological processes in the Mlalazi Catchment are mainly hillslope dominated and the model should be suitable for application.

ACRU has been used widely in South Africa to assess the hydrological response of catchments to the impacts of changing land uses and climate in the hydrological system at varying spatial and temporal scale. Warburton, Schulze and Jewitt (2011) have done a study which compares simulated against observed stream flow in climatically diverse South African catchments. The study confirmed that ACRU model can be used with confidence to simulate streamflow and represent hydrological response from a range of climates and diversity of land uses.

2.2.3 SHETRAN Model

SHETRAN is a physically-based, distributed, deterministic, integrated surface and subsurface modelling system that also has its origin in the SHE (Systeme Hydrologique Europeen) model (Abbott *et al.,* 1986). It is designed to simulate water flow, sediment transport and contaminant transport at catchment scale (Ewen *et al.,* 1995). The concept is based on the conceptual model of hydrological processes illustrated in Figure 2.3.

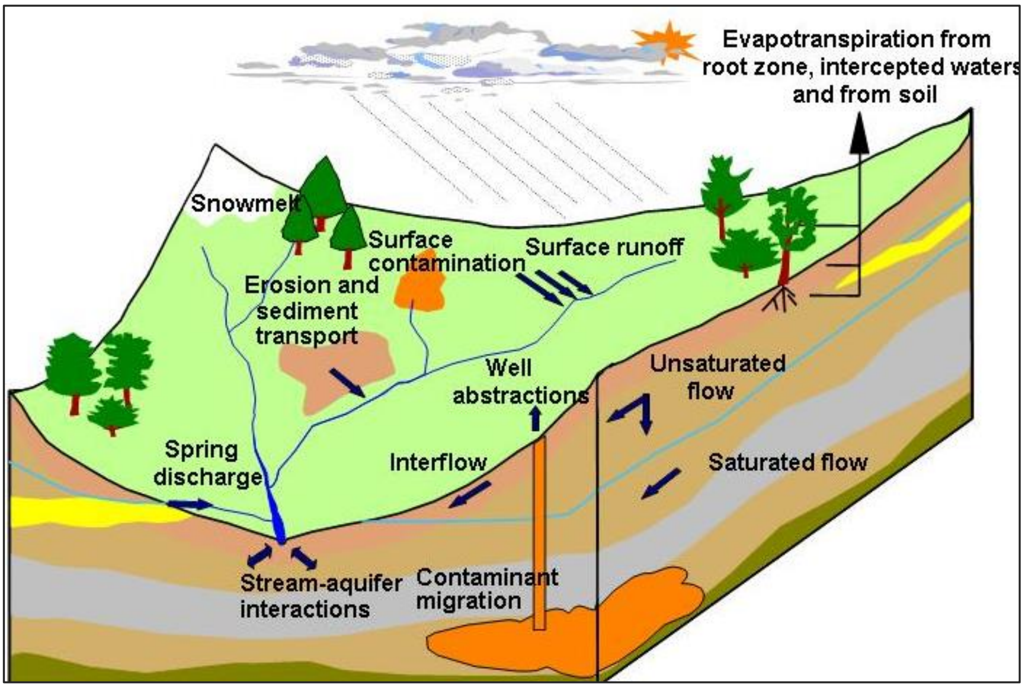


Figure 2.3: SHETRAN model processes (SHETRAN, 2018)

Essential data required for running SHETRAN are a Digital Elevation Model (DEM) with a spatial resolution better than 50 x 50 m and a catchment mask which can be created in GIS. Meteorological inputs include precipitation and potential evapotranspiration. Optional data can be a vegetation map and soil category both with a maximum limit of nine categories. River network data is automatically setup in SHETRAN from the DEM (Ewen *et al.,* 1995).

The time step in SHETRAN can vary throughout the simulation period, during dry periods the time step can be relatively large (basic time step of one or two hours is often used). During a storm event smaller time steps are used because the rates of infiltration into the ground and surface runoff can both vary rapidly. The time step is modified based on user-defined criteria for the rates of rainfall (Ewen *et al.,* 1995). For each simulation, there are three flow modules which are automatically included; namely the variable saturation zone (VSS); evapotranspiration/interception (ET), and overland/channel (OC).

- ET component calculates the net rainfall and evaporation.
- VSS calculates groundwater flows in saturated zone and soil moisture in unsaturated zone.

- Potential evaporation is calculated using Penman's combined energy balance/turbulent transfer equation (Penman, 1948).
- OC module calculates the depth of surface water on the ground surface and in stream channel networks, the flow of surface water across the ground surface, along stream channel networks and into or out of stream channels.
- Both overland and channel phases of the OC module are based on the diffusive wave approximation of the full St. Venant equations, allowing backwater effects to be modelled.
- SHETRANS, like MIKE SHE, is a commercial product with a free version that has limitation on the size and functions available.

The SHETRAN sediment transport component simulates soil erosion by raindrop and leaf drip impacts, detachment of soil by overland flow and channel erosion. Sediment is transported by overland channel flows calculated in the flow component of SHETRAN, and is routed through the sediment continuity equation (Lukey, *et al.,* 1995).

2.2.4 SWAT Model

SWAT (Soil and Water Assessment Tool) is a river basin or catchment model developed by Dr. Jeff Arnold for the United States Department of Agriculture (USDA) Agricultural Research Services (ARC). This is one of the widely used catchment scale simulation tool around the world to address catchment questions. It was developed to predict the impacts of land management practices on water, sediment and agricultural sediment yields in large catchments with varying soils, land use and management conditions over long periods of time (Neitsch *et al.,* 2011).

The SWAT model is a physical based model which requires specific information of weather, soil properties, topography, vegetation and land management practices in a catchment. SWAT can directly model the physical processes associated with water, sediment and nutrient movement in catchments with limited or no monitoring data and has been used to model the relative impact of alternative input data on water quality or other variables. This is a semi-distributed model which allows a catchment to be divided into a number of sub-basins that is similar to other models such as HEC-HMS. The input information for each sub-basin is categorised into: climate; hydrological response unit, ponds or wetlands; groundwater; and the main channel. Hydrological response units are lumped catchment areas within the sub-basin that are comprised of unique land covers, soil and management combinations (Neitsch *et al.,* 2011).

The simulation of the hydrology of the catchment in SWAT is separated into two major divisions: the land phase and the water or routing phase. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticides loading to the main channel in each sub-basin. The water or routing phase controls the movement of water, sediments, etc. through the channel network of the catchment to the outlet (Neitsch *et al.,* 2011). This is an open-source model with algorithms which are readily available and has been used in many scientific studies.

2.2.5 HEC-HMS Model

HEC-HMS is a semi-distributed conceptual hydrological model that has been developed and used extensively by the US Army Corps of Engineers (USACE) for hydrological studies. Like all other models, it requires precipitation, potential evapotranspiration, runoff from the catchment (only required for calibration and validation), geographical (geomorphic) information of the basin (for obtaining simulated runoff as output) and land use (Sintayehu, 2015). HEC-HMS model setup consists of four main components comprising the basin model, meteorological model, control specifications for each simulation run, and storage of input data (time series data) (HEC, 2006).

This is a simplified distributed model, where parameters are allowed to vary in space by dividing the basin into a number of smaller (lumped) sub-basins. The main advantage of using HEC-HMS which is a semi-distributed model is that its structure is more physically-based than the structure of lumped models. It is furthermore, less demanding on input data than fully distributed models (Sintayehu, 2015).

HEC-HMS is based on a Soil Moisture Accounting (SMA) model. The SMA model is patterned after Leavesley’s (1983) rainfall-runoff modelling system and is described in detail in Bennett (1998). This model simulates the movement and storage of water through the vegetation, the soil surface, the soil profile, and in (unsaturated) groundwater layers. Given precipitation and potential evapotranspiration (ET), the model computes basin surface runoff, (unsaturated) groundwater flow, losses due to ET, and deep percolation over the entire basin (USACE, 2000).

In the Soil Moisture Accounting (SMA) module showed in Figure 2.4, water is stored in canopy leaves, in surface depressions, in soil profile, and in two groundwater layers. Canopy interception is considered as initial loss from the incident rainfall. The infiltration rate is subtracted from the precipitation that exceeded canopy storage (effective rainfall). The effective rainfall that is not infiltrated is accounted for in depression storage where it is subsequently re-distributed over time through evaporation, infiltration and runoff. Overflow from the depression storage is considered as surface runoff (direct runoff). Water stored in the soil profile is lost to evapotranspiration and to percolation into the groundwater layers. The two groundwater storage layers serve as a shallow aquifer and deep aquifer. Water in the deep aquifer moves slowly, but eventually some returns to the channels as base flow. Lateral flow from the deep groundwater aquifer contributes to stream base flow (Sintayehu, 2015).

HEC-HMS does not incorporate the full groundwater dynamics that are necessary in studies in some primary aquifers (Kelbe. pers. comm.).

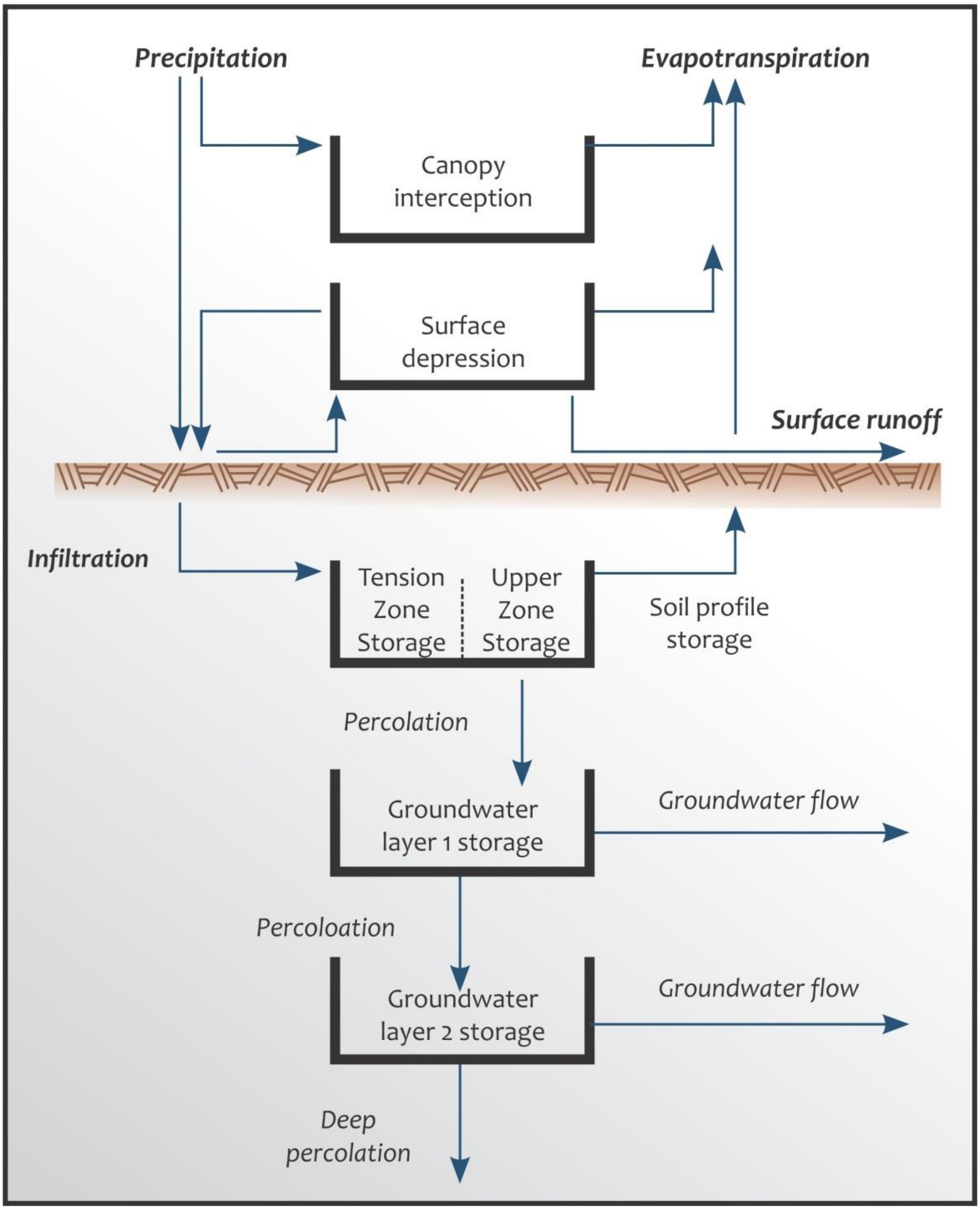


Figure 2.4: Continuous SMA algorithm (Bennett, 1998)

2.2.6 Model Selection

All the models discussed above have the necessary capacity to achieve the required results for the purpose of this study. A general comparative analysis was done to enabled a selection of a suitable model, this is given is Table 2.2.

Table 2.2: Comparative analysis of reviewed models

Parameter	**MIKE SHE**	**ACRU**	**SHETRAN**	**HEC-HMS**	**SWAT**
Rainfall Input	Daily	Uses daily data	Uses hourly data	Uses minutes	Daily
Spatial distribution of data	Grid raster	GIS raster	Grid raster	GIS raster	Grid raster
Flow data output	Hourly and daily	Daily	Both hourly and daily	Minutes, hourly and daily	Daily
Typical maximum catchment size (km^2)	No size limits, depends hardware limits	10000 (km^2)	2500 (km^2)	No size limits, depends on computer memory	No size limits
Erosion and sediment transport method	Erosion and sediment transport is simulated using a conceptual approach	Uses MUSLE which is an empirical model	Uses empirical equations from literature that describes physical characteristics of flow and land interaction that result in erosion, transport and sediment deposition	Uses MUSLE and also based on the sediment transport potential concept of the stream	Uses MUSLE
River sediment routing	In stream sediment transportation and deposition is simulated.	No river sediment is routed	River sediment can be routed including estimation of the proportion of sediment coming from river erosion	River sediment can be routed including deposition of sediments in the stream	Sediments routed as a function of peak channel velocity
Availability	Commercial product	Open source	Commercial product	Open source	Open source

Based on a general comparative analysis of all the models reviewed the MIKE SHE and SHETRAN could not be used because they are commercial products that were not freely available. The ACRU model although being an open source was not selected because it doesn’t allow the routing of sediments. The HEC-HMS and the SWAT models are both semi-distributed models which allows for the simulation of runoff with less data requirements compared to a fully distributed model. For the Mlalazi Catchment with limited observed data, a physical based model such as SWAT would be dependent on observed data which some might either be of bad quality or not available. The HEC-

HMS model was selected as the preferred model because it is a conceptual model which will allow some hydrological processes to be simulated using empirical and parameter fitting process models. This model also presented an attribute of being able as part of river sediment routing to simulate deposition of sediments in the stream.

The model time-step ranges from minutes to daily which could allow for a storm event simulation with ease. HEC-HMS data is spatially distributed as GIS raster which makes it easy for data preparation and hydrological analysis in ArcMap using HEC-GeoHMS. The model also comes with its own database storing system (DSS) which allows a smooth link of all input datasets with the model setup.

The choice of the HEC-HMS model was also based on a careful consideration that the selected model for rainfall-runoff, erosion and sediment transport which are drivers of the estuary dynamics, such a model should derive information which is compatible or allow a smooth linkage with the HEC-RAS model. The HEC-RAS model is selected in the WRC study which this study forms part of, to route flows and sediments in the Mlalazi Estuarty Catchment. The WRC study aims to derive estimates of flow rate, water level and sediment transport to the Mlalazi Estuary that could influence the mouth dynamics that lead to open or closed state. The study will allow for estuary management interventions and application of information derived to other systems such as the Siyaya Estuary.

CHAPTER 3: STUDY AREA AND DATA ANALYSIS

The Mlalazi Catchment is a coastal catchment that lies between the Ngoye Hills and the Indian Ocean in the north-eastern region of South Africa. The Catchment drains into the Mlalazi Estuary near the town of Mtunzini in northern KZN (Figure 3.1). The Mlalazi River flows from the Ngoye Hills and comprises of two main tributaries, namely Mkukuze River flowing in an easterly direction and KwaGugushe River (also known as Ntuze River) which drains of the north-eastern sub-catchments. The confluence of Ntuze River and Mlalazi River coincides with the upper reaches of the Mlalazi Estuary and forms the outlet for this study. The Mlalazi Catchment delineated for the study covers a surface area of 397 km^2.

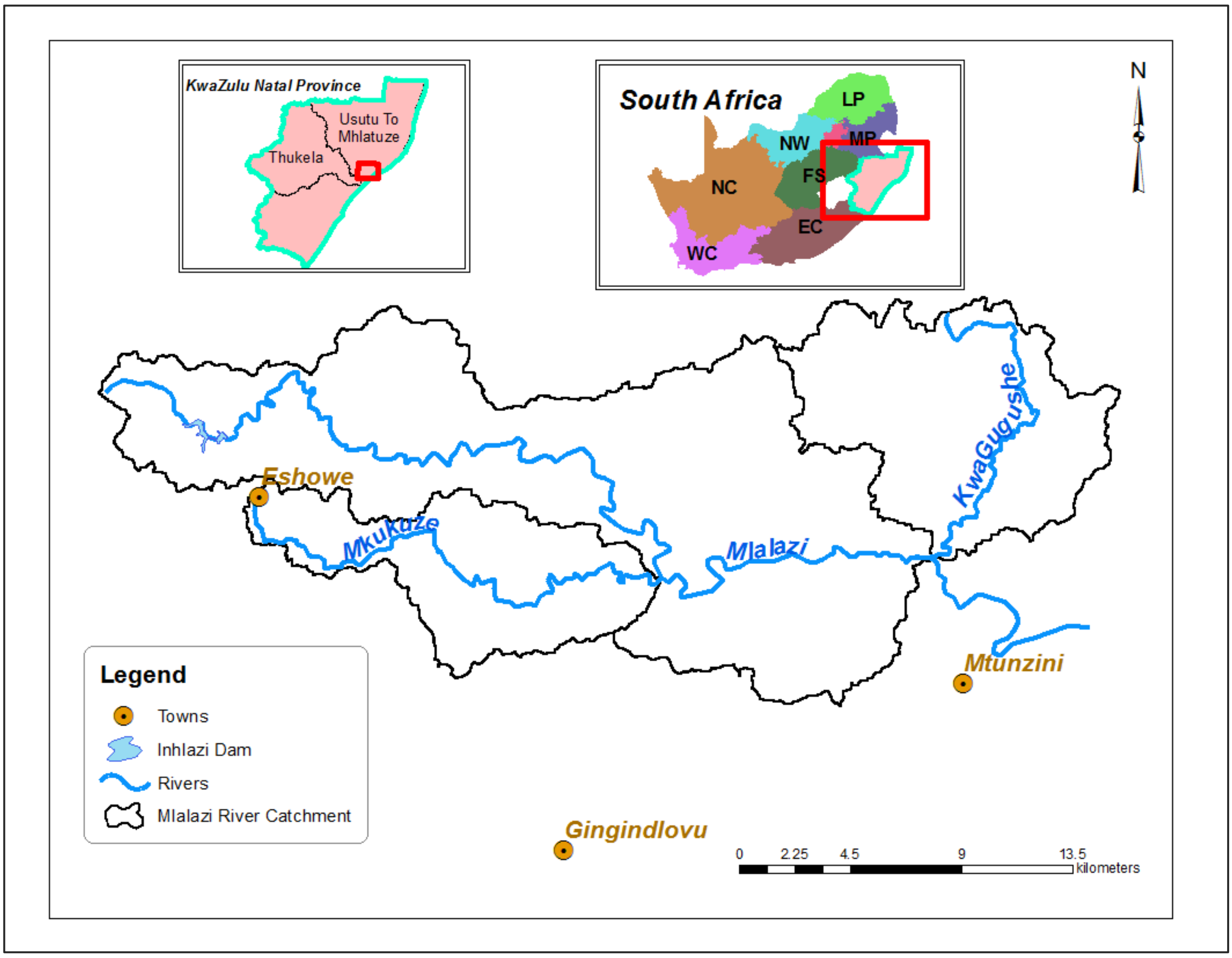


Figure 3.1: Location of the study area showing the Mlalazi Catchment

3.1 Geomorphology Data

The geomorphology of a region reflects the historical processes forming the land and water features within the catchment. Many geomorphic features can be described by the surface elevation and drainage network. Terrain data (topography) is a critical requirement in catchment runoff modelling. An extension tool used on an ArcGIS platform, known as HEC-GeoHMS, uses terrain data to determine drainage paths and some of the physical characteristics of the catchment. As part of the basin processing, HEC-GeoHMS operates on a DEM to derive sub-basin delineation and for preparation of hydrological input parameters. The generation of catchment drainage network in HEC-GeoHMS can cause spurious networks due to imperfection in the DEM. It is therefore necessary to impose the actual river network on the DEM in the processes of delineating sub-catchment boundaries.

Five meter elevation contours and spot heights data for the study area were obtained from the National Geo-spatial Information (NGI) section in the Department of Rural Development and Land Reform. These datasets are much better than the SRTM elevation datasets. The NGI data was used to create a 10 by 10 m resolution DEM which was used for the delineation of the sub-catchments using the derived river networks in the Mlalazi Catchment through the application of the HEC-GeoHMS extension tool in the ArcMap platform. Figure 3.2 shows the derived DEM. The elevation ranges from sea level at the inlet into the Mlalazi Estuary to 638 m AMSL in upper reaches of the Ngoye Hills.

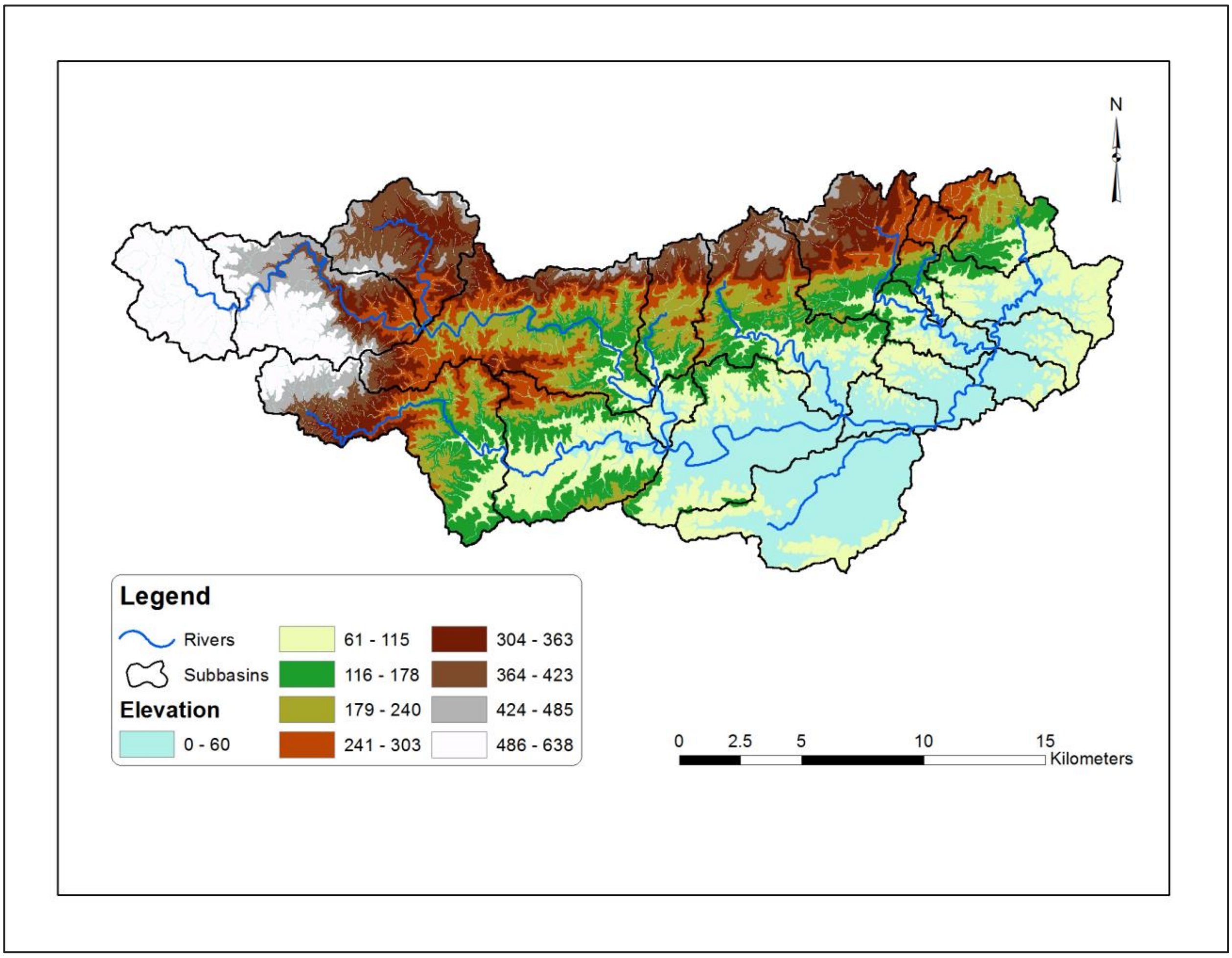


Figure 3.2: DEM derived from 5m contours and elevation points

3.2 Climatic Data

Climatic conditions are the main driving variables affecting the hydrology of the study area in rainfall-runoff modelling. The rainfall and evaporation data are the required driving variables of the model to provide reliable prediction of the runoff and sediment yield for the Mlalazi Catchment for the physical condition. However, there is strong relationship between the main driving variables of rainfall and evaporation and the runoff and sediment yield from the Catchment. Both of these data sets are prone to errors that can have a significant influence on the calibration and validation process. Consequently it is important to evaluate these data sets for systematic and random errors.

3.2.1 Rainfall

Daily rainfall records for several sites in and around the Mlalazi Catchment were provided by the Department of Water and Sanitation (DWS) and the South African Weather Services (SAWS) and HRU (Kelbe). Additional long term daily rainfall and evapotranspiration data was extracted from a SAPWAT4 modelling tool. This tool is used to determine crop irrigation water requirements in South Africa as a result of a WRC project by van Heerden *et al.,* (2016). The tool has incorporated 50 years and more of daily data for about 1925 quaternary catchments. This data originates from the quaternary weather database of South Africa produced by Schulze and Maharaj (2006). In this datasets the centroid of each quaternary was handled as a virtual weather station. Additional rainfall records exist for several gauges deployed in the Ntuze Catchment in previous Water Research Commission (WRC) projects (Hope and Mulder, 1979). Figure 3.3 shows the rain gauges with limited records that have been sourced in and around the Mlalazi Catchment.

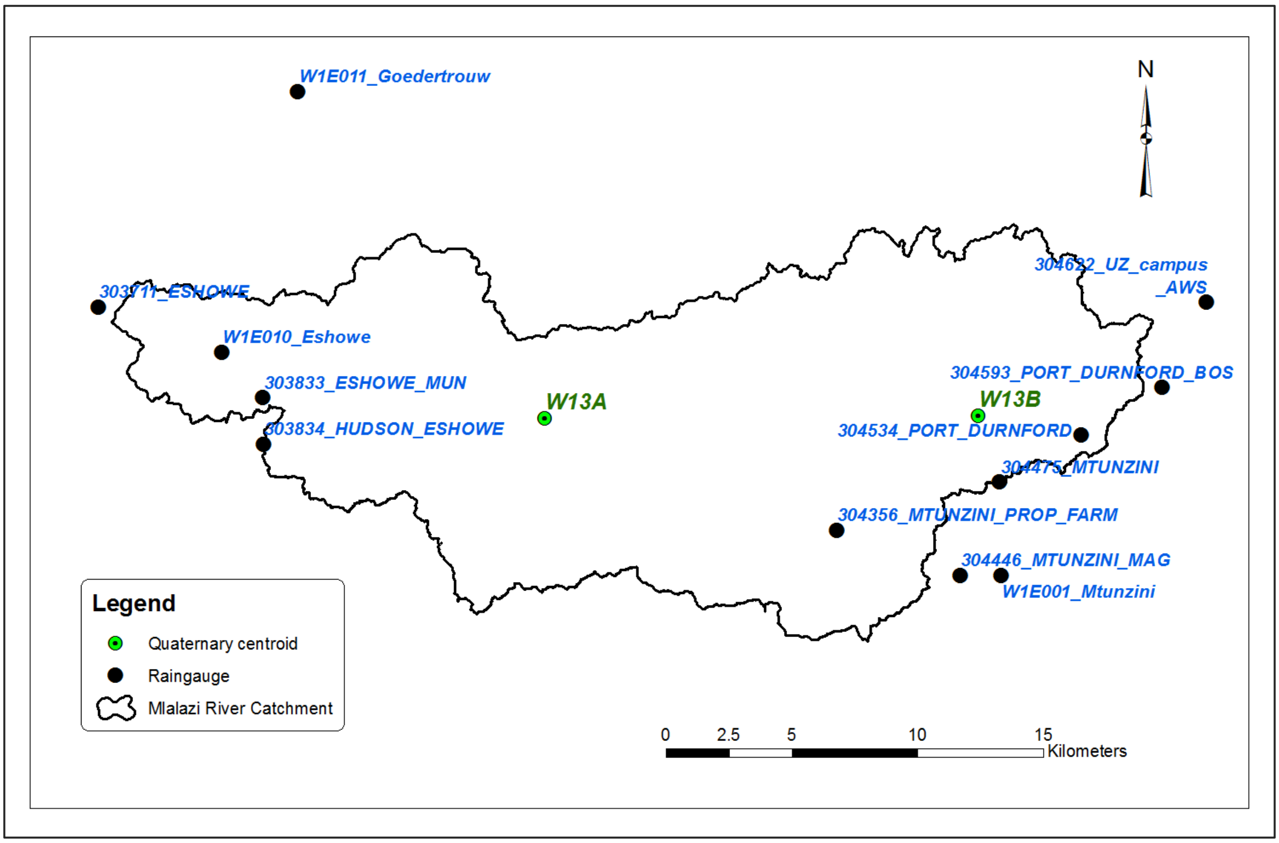


Figure 3.3: Location of rain gauges in the study Catchment

The available rainfall data was captured and stored into HEC-DSSVue database tool which is compatible to HEC-HMS. Table 3.1 shows the available rainfall stations with records that are available for use in the meteorological model using the inverse distance method.

Table 3.1: Rainfall station record length and altitude distribution

Name	Period of observation	Altitude (m)
303711 Eshowe West	06Jan1957 – 01Feb1989	595
303833 Eshowe Municipality	06Jan1957 – 01Feb1989	529
W1E010 Eshowe Dam	06Jan1957 – 28Jan1997	501
303834 Eshowe Hudson	06Jan1957 – 01Feb1989	517
W13A Quaternary covering Mkukuze tributary	01Jan1950 – 31Dec2015	332
304446 Mtunzini Magistrate	11Jan1916 – 21Oct1996	60
W1E001 Mtunzini	01Apr1969 – 30Nov1996	9
304593 Port Durnford	03Jan1949 – 16Mar2018	75
W13B Quaternary covering the Ntuze tributary	01Jan1950 – 31Dec1999	66
W1E011 Godertrouw	08May1983 - 31May2018	224
304356 Sasex Mtunzini	03Jan1966 – 29Apr1993	15
304475 Mtunzini Sugar	31Dec1946 – 29Apr1993	56
304622 UZ Campus	30Aug1975 – 30Dec1977	80

The rainfall records are derived from point source measurements (~$10^{-3}m^2$) of atmospheric processes that are random in nature and variable in space and time. It is not possible for a single point measurement to capture the spatial distribution of rainfall at catchment scales > 50 km^2. In a study of the nature of convective storm in the north eastern region of South Africa, Kelbe (1984) established that the characteristic (average) area of a large convective storm cell was between 50-100 km^2 and lasted for an average of 30 minutes. Although these convective cells generally combined to form a swath across a catchment as they propagated under prevailing wind regimes, the rainfall variability across the swath varies considerably and cannot be measured adequately by a standard rain gauge. These typical storm areas are generally a factor of 2 smaller than the catchment. It is necessary to have several point measurements of rainfall to adequately represent the distribution of rainfall in a catchment in order to provide a reliable estimate of the catchment runoff and sediment yield. This can be a serious limitation in the reliability of rainfall-runoff modelling results.

The rainfall records for most stations could not be trusted since there are particular events which were recorded by one or two stations but missed by other surrounding rain gauges. An example is given in Figure 3.4 where a storm event in December 1980 was recorded as >500mm by rain gauge MTZ Ongoye (Mtunzini Magistrate) and none of the other surrounding gauges. It was subsequently captured on the derived rainfall series for centroid station W13B. A similar problem was encountered on rainfall series for centroid station W13A which had an event in May 1971 which had to be removed as an outlier since it was recorded as the most extreme event ever experienced with rainfall record 509 mm. This was not recorded at surrounding stations and it was replaced with an arithmetic mean of a record at Eshowe Municipality and Eshowe Hudson with a value of 185 mm.

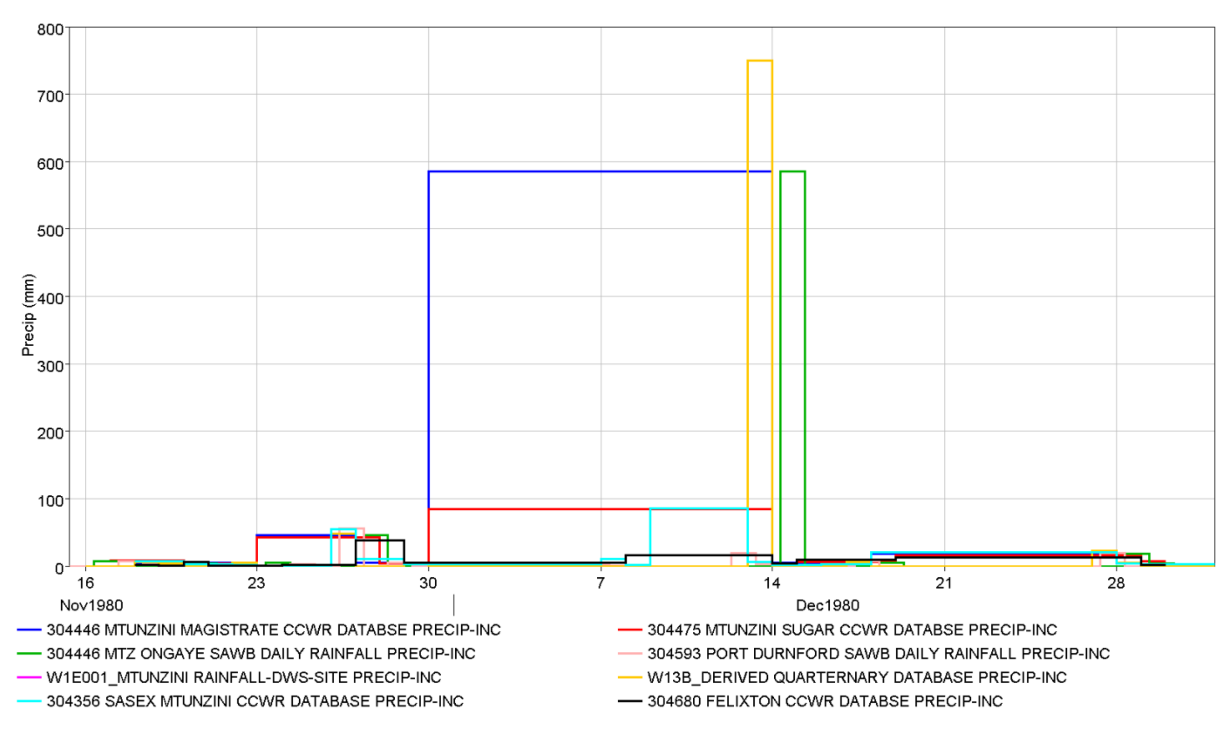


Figure 3.4: Rainfall gauge data analysis

It would be necessary to use all gauge records available for this simulation study. Unfortunately, all these gauges have variable length records with missing data and many of them are no longer operational. The choice of methods and gauge networks for distributing the rainfall are important criteria in the configuration of the runoff model. The Inverse-Distance Method (IDM) used to distribute point rainfall over the Mlalazi Catchment is the preferred method (described in detail in Chapter 4 under Meteorological model) but it requires continuous data with no missing records that has proved elusive to generate in this study. The stations chosen to generate rainfall series for the simulation study was Port Durnford, centroid station W13A and W1E011 at the Goedertrouw Dam was used to extend records from 2015 – 2018. Port Durford station represents the more coastal region and W13A represents the inland area of the Mlalazi Catchment. These stations were chosen after performing a consistency analysis. Since they contain fewer gaps, they are consistent with most stations within the vicinity of the Catchment. A plot of the rainfall series of the three chosen stations is given in Figure 3.5 to illustrate the variability between the various sites across the catchment.

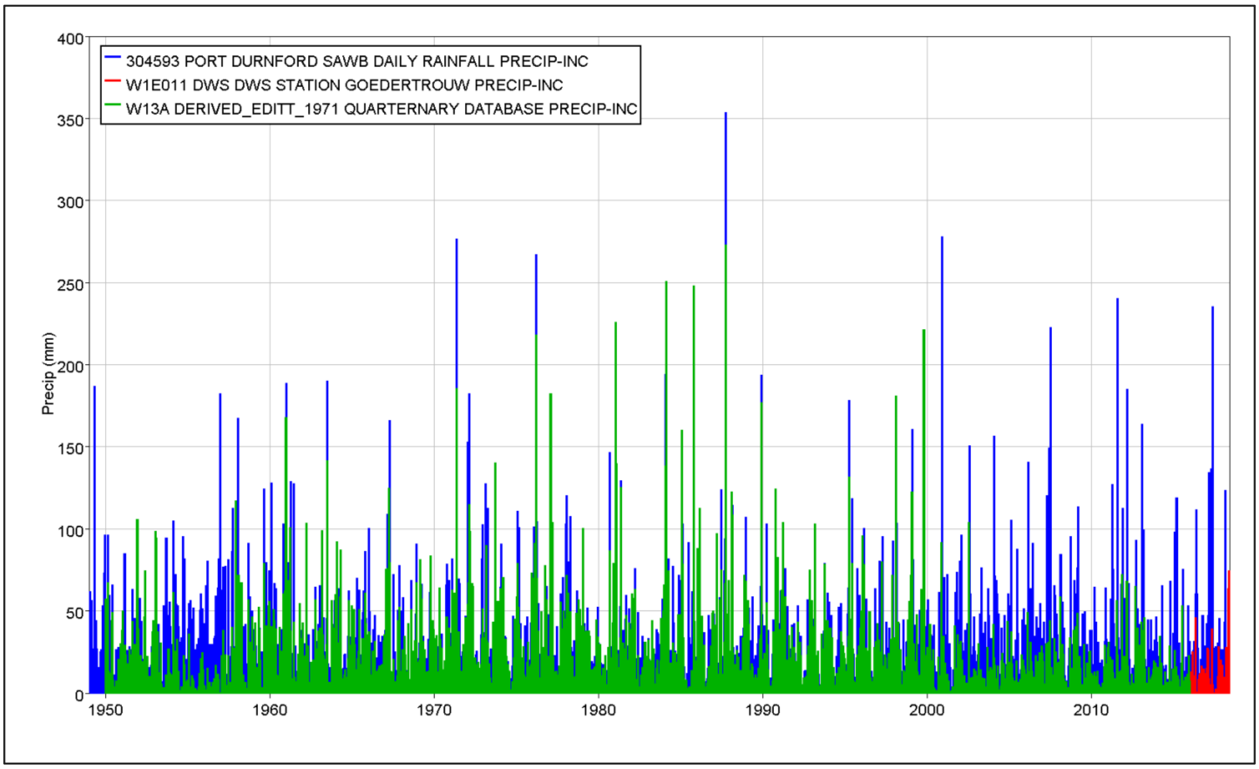


Figure 3.5: Chosen rainfall station data series

W1E011 and W13A are stations which are more inland while Port Durnford is located in the more coastal area towards the east. It is evident from the above plot that from year 2000 to 2017 the derived station W13A and W1HE011 has recorded less rainfall compared to the coastal station records at Port Durnford. The most extreme event experienced in the study area was the flood in September 1987.

3.2.2 Evaporation

Potential evapotranspiration data from the quaternary weather database for W13A (Mkukuze Catchment) and W13B (Ntuze Catchment) were imported and stored into HEC-DSSVue. Both these records were then linked to the meteorological model IDM as specified evapotranspiration for each gauge. This time series was then linked to relevant sub-catchments of the Mlalazi Catchment configuration. The linkage was based on the sub-catchment's location which is either on W13A or W13B as shown in Figure 3.6 and the station’s period of observation is given in Table 3.2.

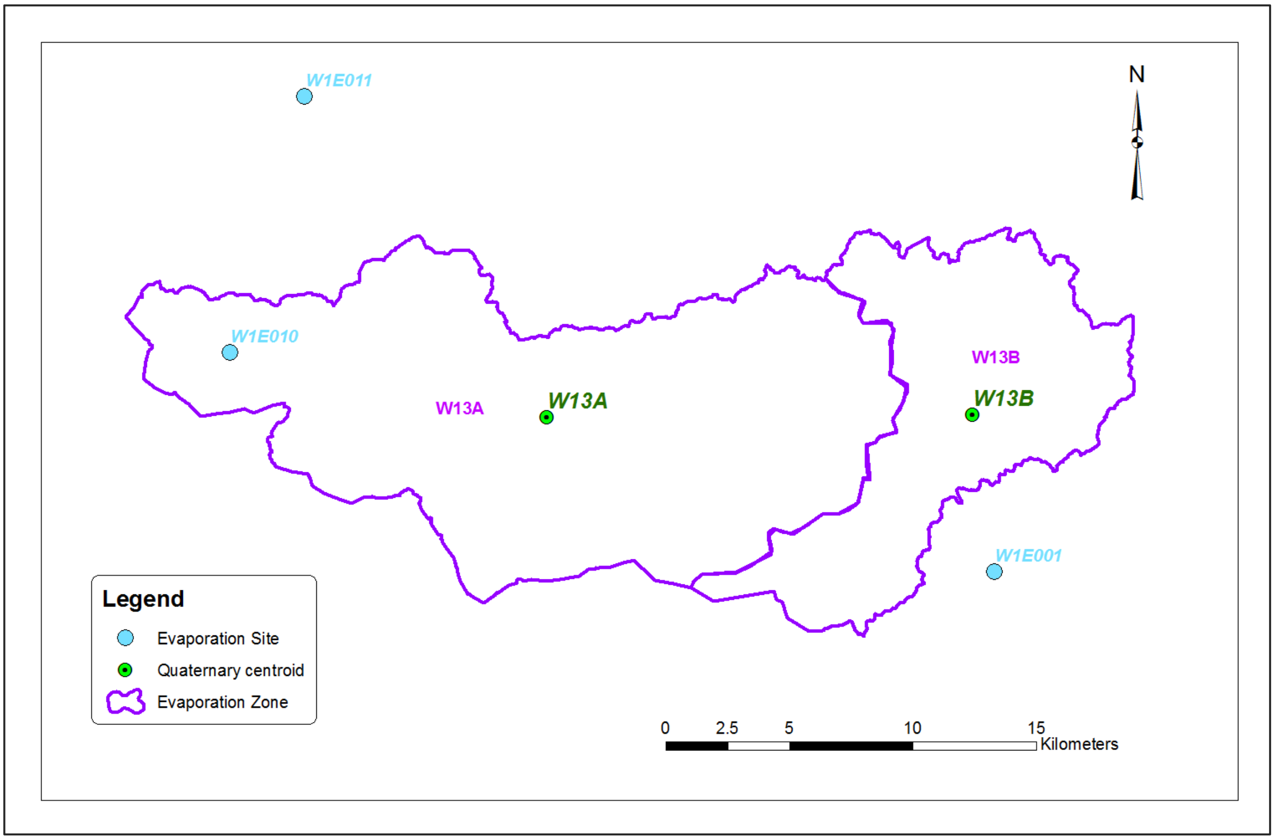


Figure 3.6: Catchments represented by the Quaternary Catchments

Table 3.2: Potential evaporation data captured

Station Name	Period of observation	Data Type	Time Step
W13A QC database	01Jan1949 – 01Jan1999	ET	1Day
W13B QC database	01Jan1949 – 01Jan1999	ET	1Day
W1E011 Goedertrouw Dam	01May1983 – 31May2018	A pan	1Day
W1E010 Eshowe Dam	01Nov1978 – 01Jan1997	A pan	1Day
W1E001 Mtunzini	01Apr1966 – 01Dec1998	A pan	1Day

There was not enough climatic data to calculate EvapoTranspiration (ET) using either the Penman-Monteith or Priestly Taylor method as available options in HEC-HMS, because of this limitation the daily ET equivalent value was derived from 2000 to 2018 by multiplying the A-pan values from station W1E011 by a pan coefficient (0.7) to extend the ET information. The time series of ET information from the Quaternary Catchment databases which has been extended is given in Figure 3.7.

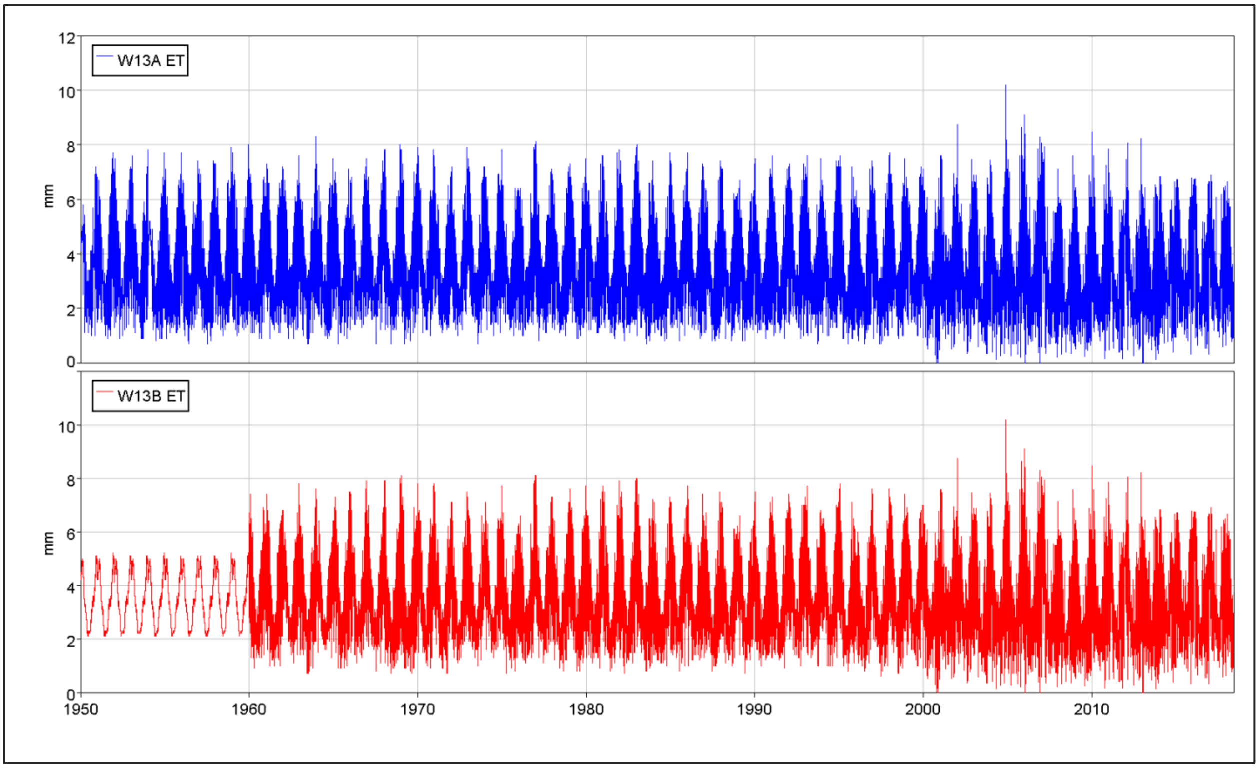


Figure 3.7: ET information derived for W13A and W13B catchments

3.3 River Network Data

The river network was obtained from NGI and compared to the 2016 Google Earth images for verification. The river data did not correspond well with the latest Google Image possibly due to imperfections in digitisation or format conversions. The river network was modified to include all the streams for use in the development of the model. The river network, as modified and used to develop the model is shown in Figure 3.8.

The national DWS established several flow gauging station in the Catchment that have some record of flow measurements that are currently available. However, only one gauge (W1H004) on the small (19 km^2) catchment in the upper reaches of the Mlalazi River (Figure 3.9) is still operational. This flow gauge on the Eshowe Dam has been operational since 31 August 1948 and is monitored on a regular basis by DWAF (now DWS). DWS also built six nested flow gauging station in the Ntuze tributary for the HRU (University of Zululand) in the 1970’s for research purposes. These were operated by the HRU for various research projects from 30 November 1976 to 30 January 2000. The data for all these station is available from DWS –Hydrological Services website (DWS, 2018).

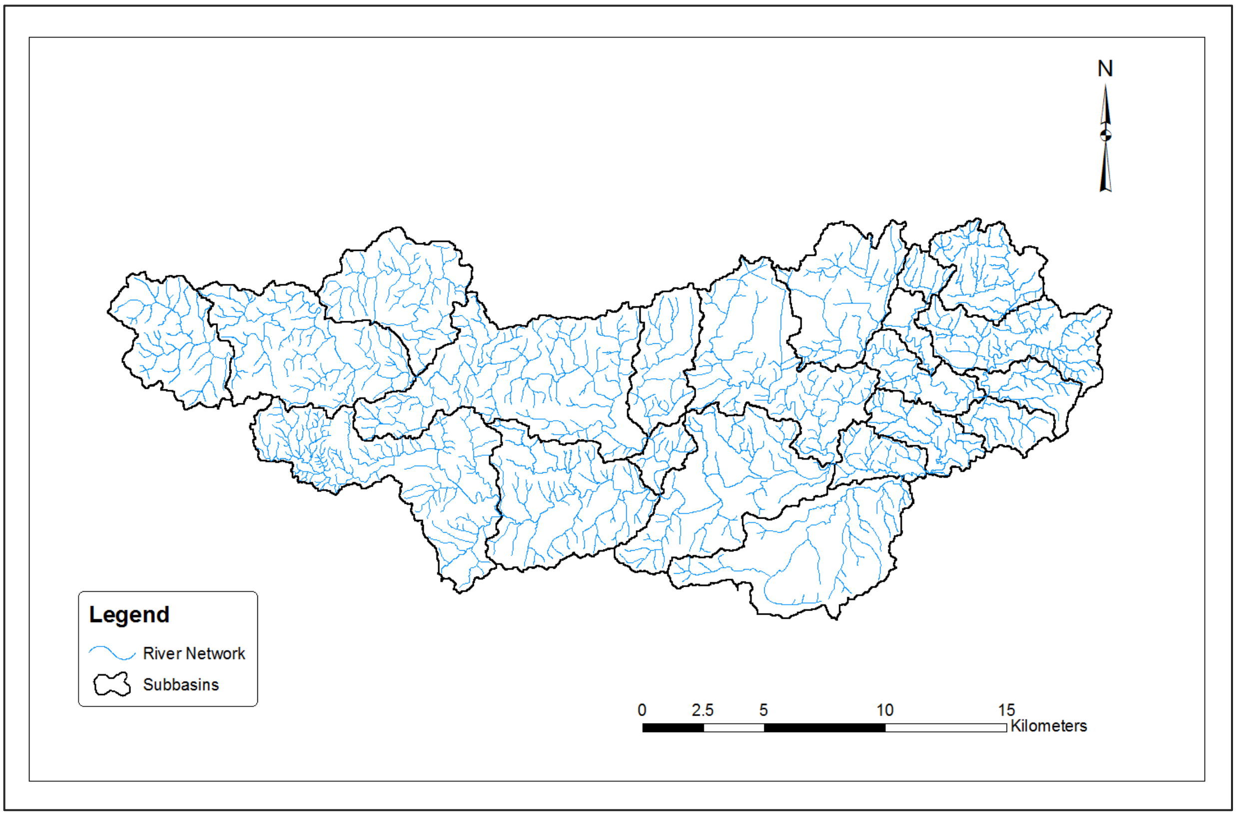


Figure 3.8: Mlalazi River Network

3.3.1 Runoff

Stream flow data is required to calibrate and validate model predictions. Unfortunately there are no flow records for the Mlalazi Catchment as a whole and the records that are available only cover approximately a quarter of the catchment area. There is only one regular monitoring gauge in the Mlalazi Catchment at W1H004 on the Eshowe Dam (Table 3.3). There are also short flow records for six weirs in the Ntuze Catchment taken from DWS database. Some additional data for these sites have been made available from the HRU records. Figure 3.9 shows the location of flow gauging stations in the Mlalazi Catchment and Table 3.3 lists the monitoring period and catchment area for each gauge.

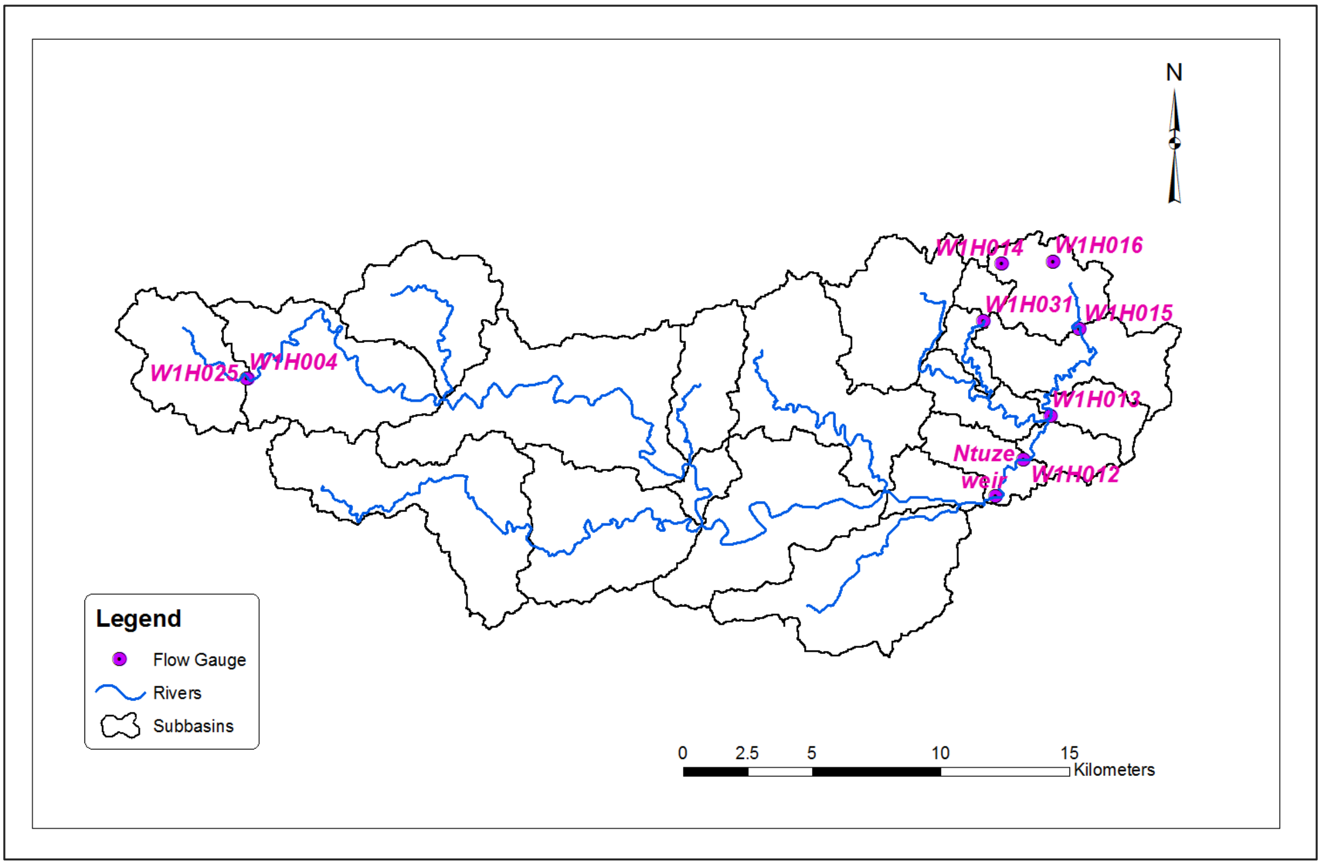


Figure 3.9: Main rivers and the location of the River gauging station in the study Catchment.

Table 3.3: Flow gauging stations in the study Catchment and their period of record

Station Number	**Period of observation**	**Area (km^2)**
W1H004 Eshowe	31Aug1948 – 30Oct2015	19
W1H012	31Jul1977 - 30Jan2000	82
W1H031	30Sep1988 – 29Nov1998	3
W1H025 Eshowe	30Jun1959 – 29Nov1990	
W1H013	30Nov-1976 – 30Dec1999	33
W1H014	13Nov1979 – 04Dec1988	12
W1H015	30Nov1976 – 30Dec1997	23.5
W1H017	30Nov1976 – 30Dec1997	0.65

The runoff measurements are derived from various types of hydraulic structures that have measurement limits and require regular maintenance for a reliable data series. These gauges represent the entire catchment and would provide a more reliable indicator of the effective rainfall than a few point measurements. The gauge data could provide a method of evaluating the rainfall record(s) that have proved to be problematic in this study as discussed earlier in this chapter. Unfortunately, the gauge data only covers the Ntuze Catchment and a small portion of the Mlalazi Catchment at station W1H004 on the Eshowe Dam (Eshlazi Dam). All the other gauges with exception of W1H004 have a short monitoring period from 1977 to 1997 (Table 3.3). However, the Ntuze gauges are nested and provide a method of verifying several storm events that do not reflect the rainfall record at some gauges.

The gauging stations used for calibration are W1H004; W1H031; W1H015 and W1H012. However W1H004 might not at all times show a reliable rainfall-runoff relationship since Eshlazi Dam is located immediately upstream which was built in the early 1980s and is used for water supply for Eshowe Town. The flow gauge which covers the largest part of the catchment on Ntuze River is W1H012. This gauge has been used extensively in this study for most of the calibrations and validations in order to get best estimates of runoff and sediments yield from the Mlalazi Catchment.

Rainfall and flow data for the calibration period were plotted to analyse for consistency and reliability of the driving variable (rainfall) and calibration data (flow). A plot of the data is shown in Figure 3.10 for flow gauge W1H012 from August 1977 to July 1986.

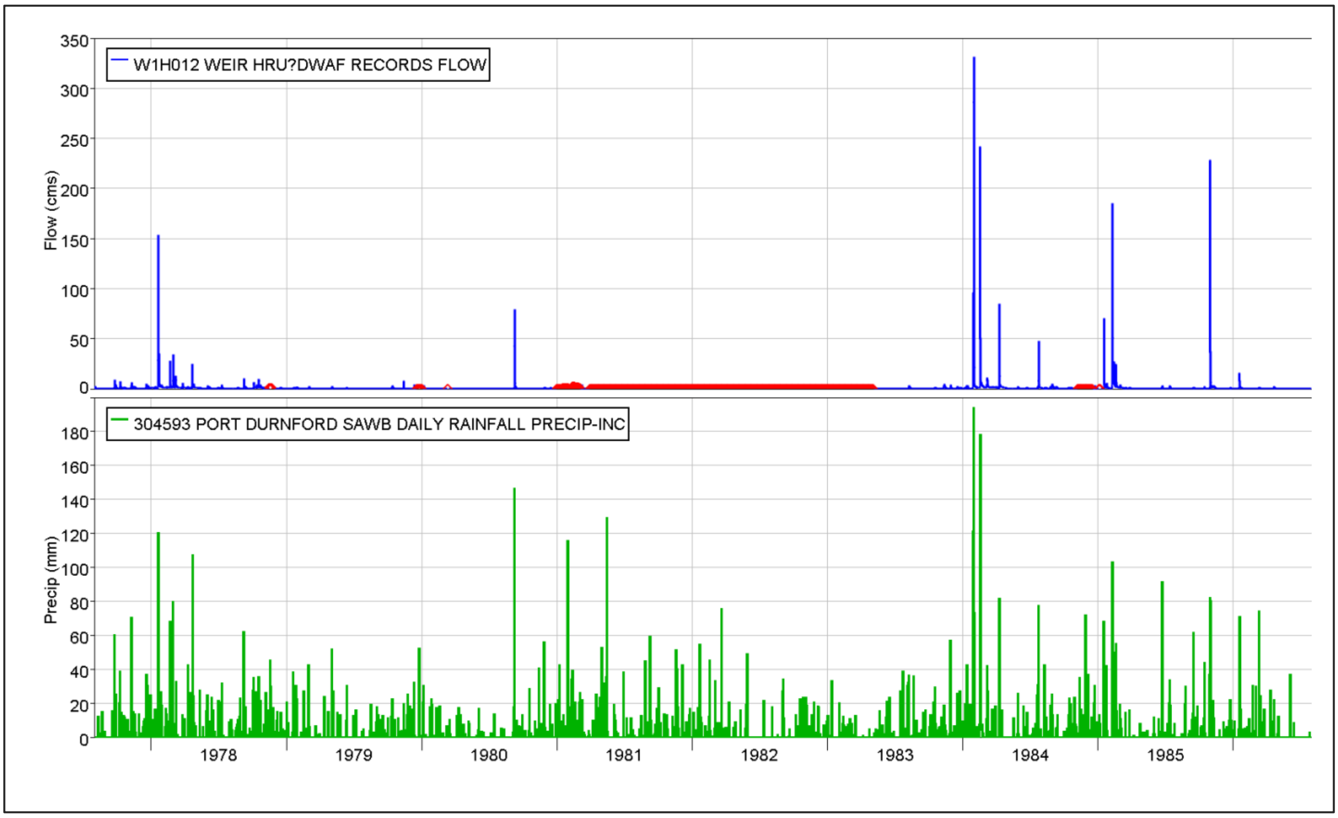


Figure 3.10: Consistency analysis for weir W1H012 (Red points –missing data)

It can be observed that the cyclonic rainfall in January and February 1984 (Domoina and Imboa respectively) was recorded on the rainfall series and also resulted in an extreme event at the flow station. However, in 1978 rainfall peaked to more than 100 mm but there was no flow of such magnitude which resulted. Again in 1980 rainfall peaked to more than 140 mm but the resultant flow did not exceed 100 m^3/s. The largest discrepancy identified was in 1985 when flows of approximately 200 m^3/s were recorded as a resultant of a small rainfall amount of only 80 mm. This analysis shows that rainfall and resultant flows are not corresponding at all times. This could be a problem of the reliability of rainfall data for a point source measurement, or possibly also errors in gauge data. There are gaps of missing observed flow data from 1981 to 1983 in the dataset.

A calculation was done on the possible catchment yield. Assuming that the catchment of W1H012 (82 km^2) had no losses (Impervious), then cyclone Domoina with rainfall of 194 mm/day when converted to mean daily flow rate will yield a flow of 183 m^3/s, substantially less than the recorded flow of 330 m^3/s. Similarly, Imboa (February 1984) with rainfall of 178 mm/day will yield a flow of 169 m^3/s. Looking at Figure 3.10 it is evident that the two analysed events show a large discrepancy between the rainfall and runoff measurements that needs to be analysed further.

The flow gauging station W1H012 is a compound sharp crested V-notch weir (Figure 3.11) with a specified rating table that is available on the DWS portal. The rating table has an upper structural limit for a stage measurement of 4.78 m with a corresponding discharge rate of 482 m^3/s. Flow measurements above this stage limit cannot be accurately determined because the weir becomes hydraulically drowned (submerged). This is illustrated in Figure 3.11 after the peak of the Domoina Floods that reached a maximum stage value of 8.93 m above the lower V-Notch. This could present a limitation on all extreme events recorded which their mean stage is above the structural limit and their flows cannot be determined using the rating table. An event recorded where the mean daily stage exceeded the structural limit was a flood on 28 September 1987 were the mean daily stage reached a height of 6 m. Figure 3.11 shows the station W1H012 which was submerged under water during the 1987 flood and after it was repaired in 2000.

Figure 3.11: W1H012 during 1987 Flood (A) and in 2000 when it was repaired (B) (Photos by B Kelbe)

3.3.2 W1H012 Discharge Table

The runoff data was only used for calibrating and validating the model predictions. After analysis done on the observed flow data at station W1H012 which was used for calibration and validation, it was evident that the flood events of observed runoff has been over estimated and not valid above the structural limits of the rating equation. This necessitated further analysis of the station's stage-discharge relationship or Discharge Table (DT).

The calibration file for the station W1H012 was obtained from the DWS streamflow hydraulics. It was found that the current applicable DT for W1H012 was calculated by H. Steyn on 30 December 1994. It was calibrated using the rating equation of a compound broad crest weir, although it is a sharp crested compound weir. This DT was designed up to a structural limit of 4.78 m and calculated with an estimated error of ±30% at high flows closer to the structural limit. There are only two surveys done for this station which was on 28 April 1988 and 03 May 1988. The DT did not take into account the impact of submergence since the station does not have a downstream monitoring gauge plate and globally in literature there is no submergence correction factor for a broad crest weir.

Submergence of a structure starts when the downstream water level reaches the height of the crest of the low notch and starts to have effect on the discharge assumptions of flow through the structure. If a station is calibrated and submergence is not taken into account, the discharge table will overestimate the flows above the level of submergence which is unknown for this weir.

A V-notch structure is much more accurate at low flows. The error increases when one considers the structure under submerged conditions when the assumptions of critical flow conditions over the sharp crested notches are not valid. The compound weir W1H012 consists of a low V-notch; other notches of sharp crest, but it is not a broad crest as it has been calibrated by H. Steyn (Figure 3.12). The DT by H. Steyn was found to be over-estimating high flows and therefore could not be used for calibration and validation of the model for extreme events.

Figure 3.12: Gauging weir W1H012 on 16 January 1981 (DWS)

In the DWS – Streamflow Hydraulics calibration file it was found that there is a DT calculated based on a fitted equation produced from 35 current gauging's. They were done between 1980 and 1983 and included other points produced using a slope area method based on surveys of flood marks. This fitted equation DT was calculated by Mr GD Jones on 15 October 1981 up to a DT limit of 5.67m. The equation of the DT was:

$$Q = A(H + D)^B \tag{1}$$

Where Q is the discharge and H is the stage; A = 2.27537; D = 0.000 and B = 2.57848. This fitted equation had a R^2 value of 0.989. This DT was considered to be more accurate and suitable for use for this study since it was produced from more direct methods rather than a theoretical calibration based on a set of site theoretical requirements. A HEC-RAS calculation was thought of as a solution but it could not be used to produce the H_a/H_b pairs to be used for submergence correction since there is a weir structure between the point of stage measurement upstream (H_a) and a point of stage measurement downstream (H_b).

The mean daily stage data for W1H012 was converted to discharge using Equation 1 for the period of record and this was used for calibration and validation. Figure 3.13 shows flows from the two DTs which also confirmed that the current DT over-estimated the flows.

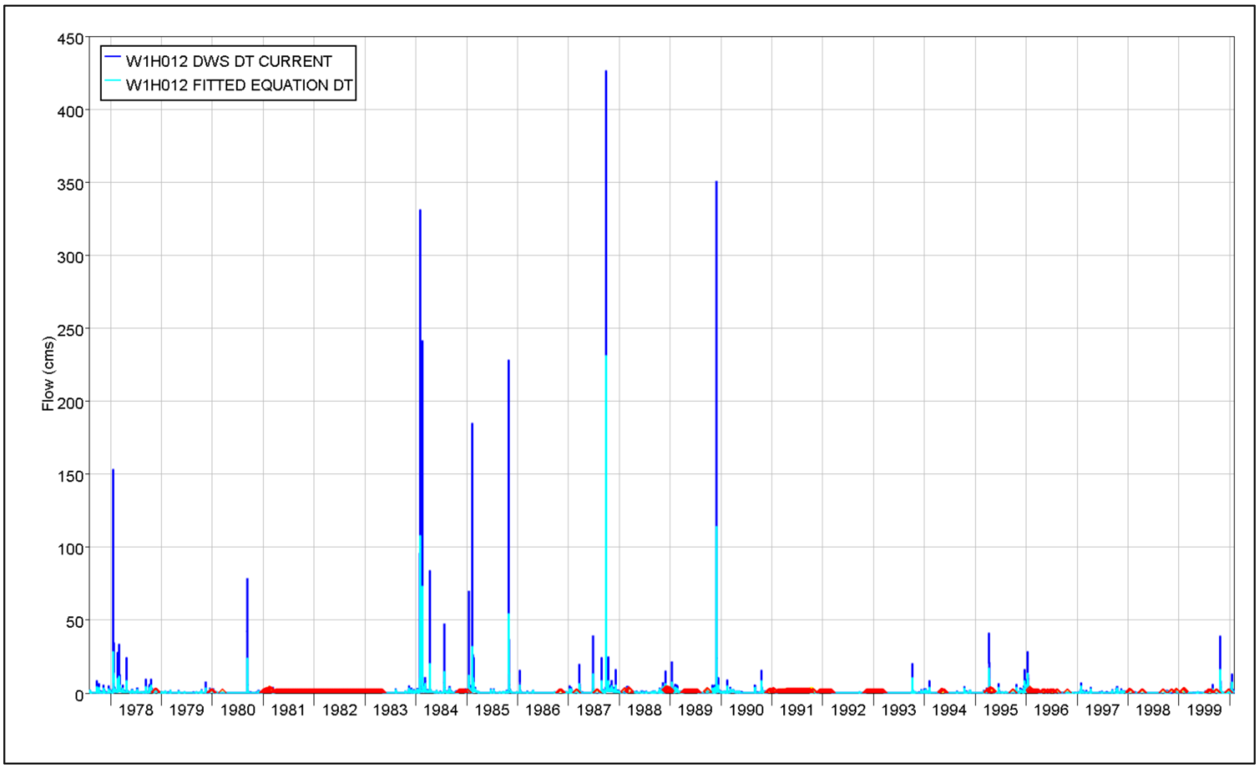


Figure 3.13: Current DWS DT and fitted equation DT flows at W1H012 (Red points –missing data)

3.4 Land Use Data

The land use data has been acquired from the South African National Land-Cover (NLC) 2013-14 sourced from the Department of Environmental Affairs (DEA) and produced by GEOTERRAIMAGE (GTI) (Figure 3.14). The 2013-14 South African National Land-cover dataset has been generated from digital, multi-seasonal Landsat 8 multispectral imagery, acquired between April 2013 and March 2014. The land-cover dataset, which covers the whole of South Africa, is presented in a map-corrected, raster format, based on 30x30m cells equivalent to the image resolution of the source Landsat 8 multi-spectral imagery (GTI, 2015). The Mlalazi Catchment is dominated by three main land use types; sugarcane farming, indigenous forest in the Ngoye Hills and small subsistence farming by the rural community.

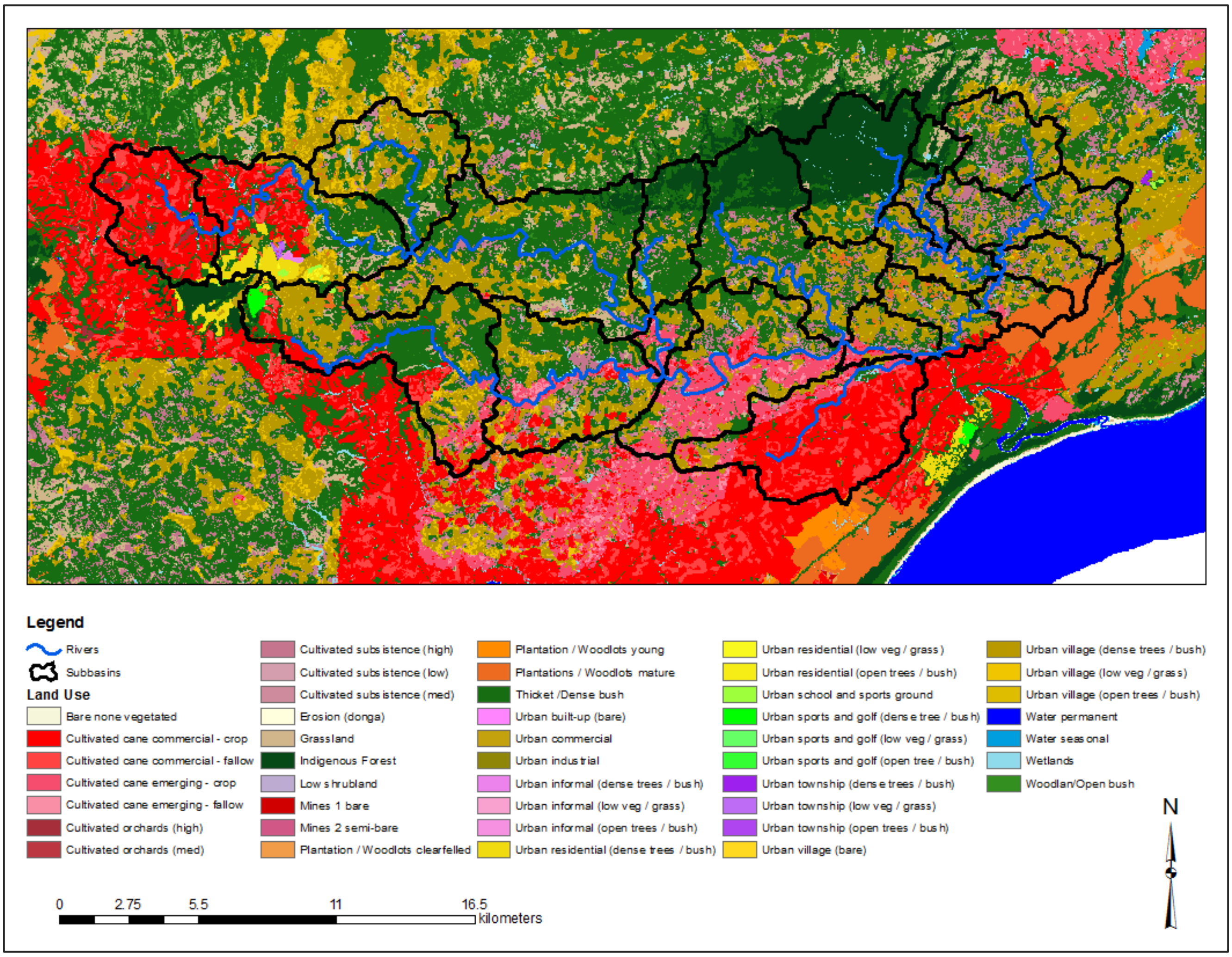


Figure 3.14: Land use of the study Catchment (Data Source, GTI, 2015)

Generally where there is a land use of commercial sugarcane in the Catchment, best management practices for soil conservation are being practised. An example is shown in Figure 3.15, where strips of sugarcane at an initial growth stage can be seen planted perpendicular to the slope of the land. This area with sugarcane is characterised by well drained soils with humid topsoil. The sugarcane is burnt before being cut down for harvesting, and the stems are also dug out of the soil after harvesting every two to three years. The soil is left fallow for some period before it is ploughed to form ridges and furrows for new plantations.

Figure 3.15: Commercial sugarcane land use (Source, Google Earth - 28 May 2018)

The subsistence farming in this catchment as shown in Figure 3.16 does not necessarily conform to best soil conservation practices. These are small farming practice for household vegetables and maize in the summer which is dry land and mostly depends on rainfall for the water requirements. The land preparation through ploughing does not result in deep furrows or ridges since mechanical machineries are not used, but it is done manually. Subsistence farming also includes the rural community growing small scale (block) sugarcane (DWS, 2015).

Figure 3.16: Subsistence farming fields (Source, Google Earth – 28 May 2018)

3.5 Soils Data

The generalised soil maps data of South Africa was obtained from the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW). This data is available at a 1: 250 000 scale and the initial source is the National Land Type Survey (Land Type Survey Staff, 1972-2006) which started in 1970.

The land type survey is a reconnaissance survey that followed an inventory rather than a “fixed legend” approach. The percentages of various soil components found in any particular mapping unit were estimated without restriction of the rigid system of classes, which resulted in approximately 7 100 inventory tables constituting an inventory of soils of South Africa. It was problematic to abstract data at high level because of the absence of uniform class structure, but this was overcome by identifying a set of 28 broad soil patterns for the purpose of increasing the readability of the land type maps. Broad soil patterns were subsequently reorganised mainly on the basis of paedogenesis and land use capability, into 19 generalised soil patterns, organised into nine soil groups (ARC-ISCW), these data for the study area is shown in Figure 3.17. The generalised soil patterns and the soil group descriptions are given in Table 3.4.

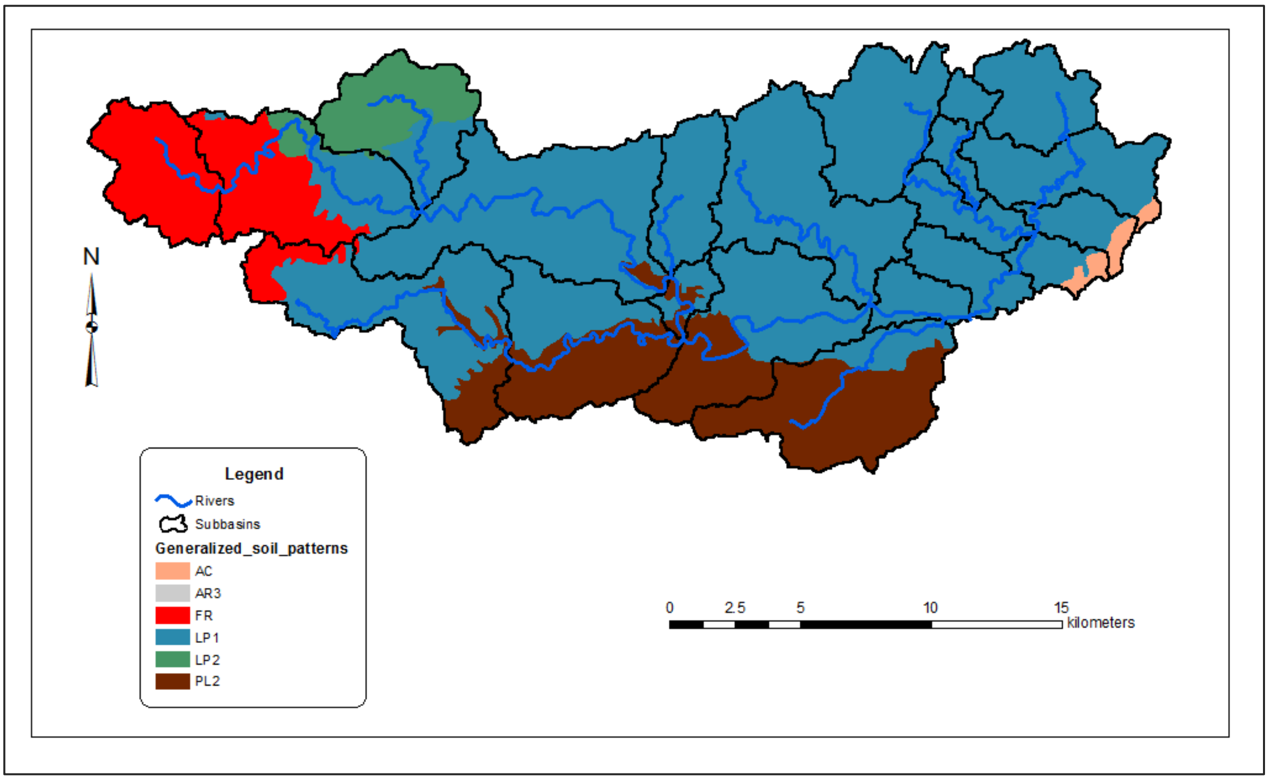


Figure 3.17: Generalised Soil Patterns Data (Data Source, ARC-ISCW staff, 2004)

Table 3.4: Generalised Soil Pattern data Description

Code	**Group**	**Soil Pattern Description**
AC	Red-Yellow well drained soils generally lacking a strong texture contrast	Red and yellow soils with low to medium base status.
AR3	Sandy Soils	Greyish, sandy soils.
FR	Red-Yellow well drained soils generally lacking a strong texture contrast	Red and yellow soils with a low base status and a humid topsoil horizon.
LP1	Soils with limited Pedological development	Soils with minimal development, usually shallow, on hard or weathering rock, with or without intermittent diverse soils. Lime rare or absent in the landscape.
LP2	Soils with limited Pedological development	Soils with minimal development, usually shallow, on hard or weathering rock, with or without intermittent diverse soils. Lime generally present in part or most of the landscape.
PL2	Soils with a Strong Texture Contrast	Soils with a marked clay accumulation, strongly structured and a non-reddish colour. They may occur associated with one or more of vertic, melanic and plinthic soils.

The Mlalazi Catchment including the catchment of the Ntuze River is dominated by soils with usually shallow minimal development, on a hard or weathered rock and with lime rare or absent in the landscape. This dominant pattern is directly related to the land use of urban village with dense trees and dense bushes as shown above in Figure 3.14. The area with sugarcane is dominated by red and yellow soils with a low base status and humic topsoil, while an area covered with commercial plantations also has red and yellow soils but with low to medium base status.

The soil data and land use data was used in deriving baseline parameters in the SMA model before calibration. In the setting up of the erosion and sediment transport process it was important to obtain the soil erodibility (K-factor), vegetation cover index (C-factor) and topography factors (LS). All these three factors are required as input into the MUSLE model for simulation of erosion and they were obtained from Le Roux *et al.,* (2008). The variation of these data over the Mlalazi Catchment is shown in Figure 3.18, Figure 3.20 and Figure 3.21.

The K-factors were assigned to all land types by Le Roux *et al.,* (2008) using the Soil Loss Estimator of South Africa (SLEMSA) model based on the assessment of the surface soil texture, surface soil structure, profile permeability and soil depth of the dominant soils. The sources of the soil information used were the soil maps (Soil Survey

Staff. 1973-1987) which was used to obtain soil erodibility rating for the individual soil series of the Binomial Soil Classification System of SA (MacVicar *et al.,* 1977) and the erodibility values were linked to corresponding soil series in the Land Type Inventories (Land Type Survey Staff, 1972-2006) to be spatially displayed on a scale of 1:250 000.

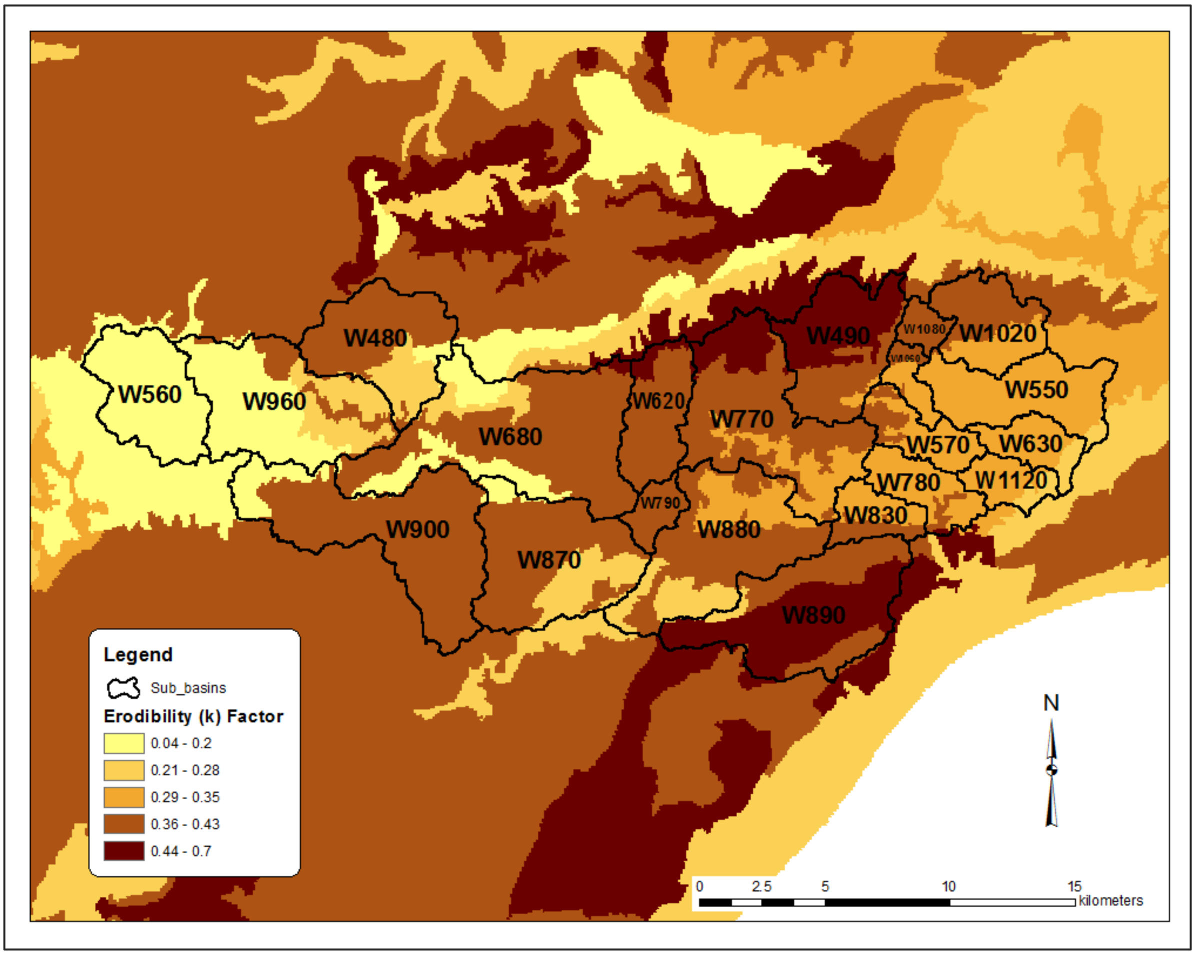


Figure 3.18: Erodibility factor (Data Source, Le Roux et al., 2008)

The K-factor describes the difficulty of eroding the soil. The study area has land with steep slopes and high erodibility factors at the Nyoye Forests and generally dominated by land with moderate susceptibility to erosion. An example of some visible erosion gullies is shown in Figure 3.19 below.

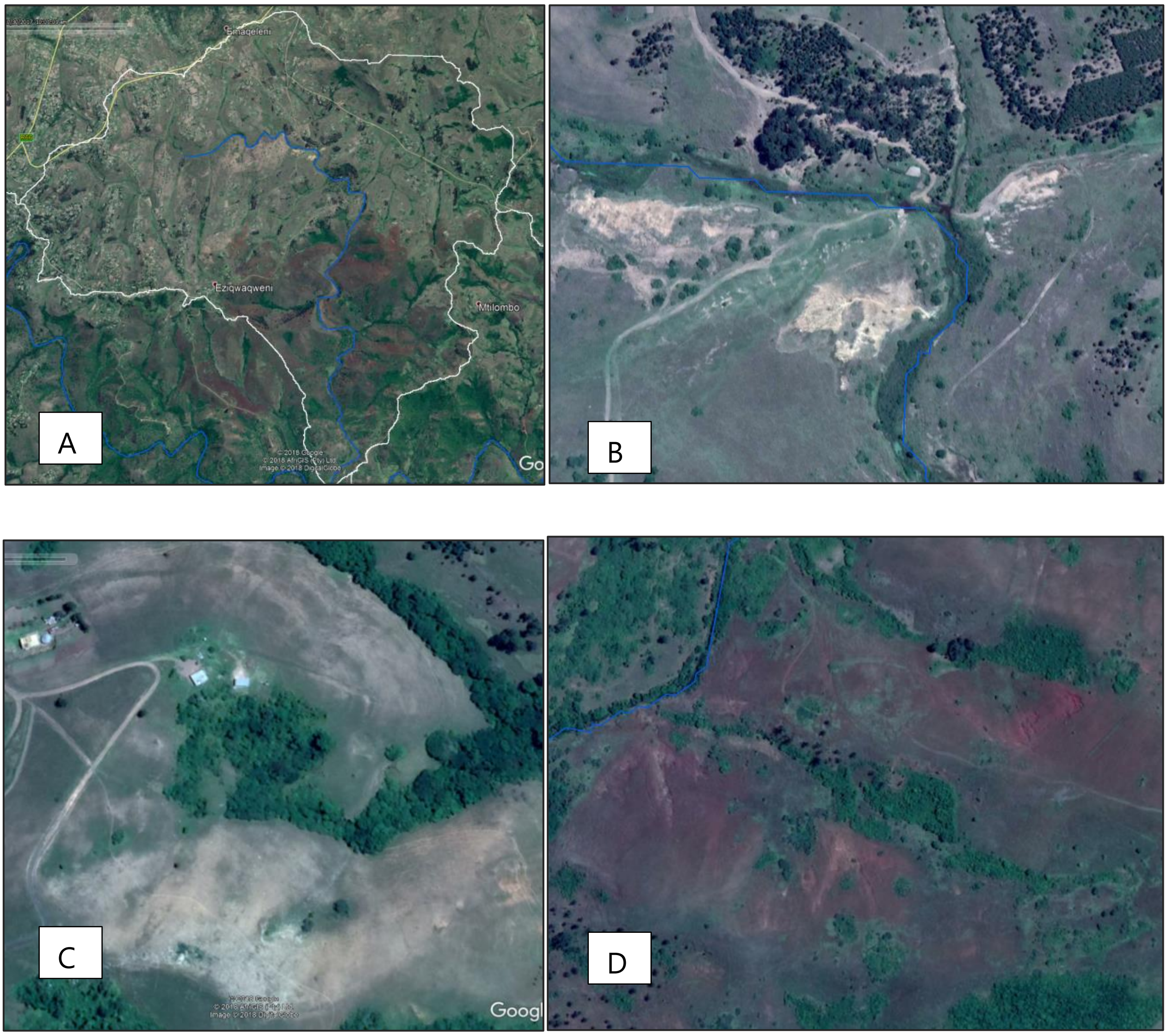


Figure 3.19: Sub-Catchment with moderate to high erosion (A) and erosion gullies (C-D), (Google Earth – 28 May 2018)

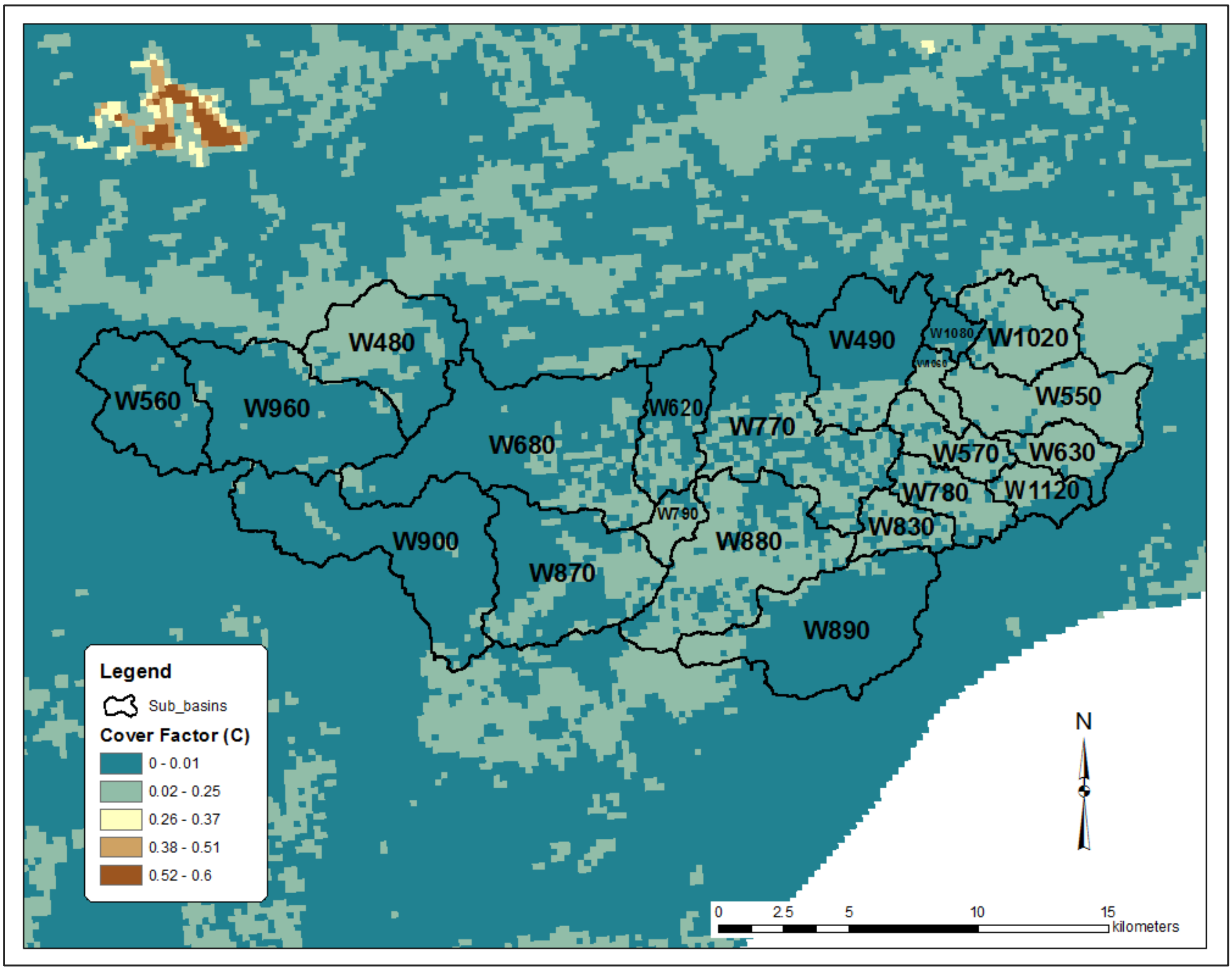


Figure 3.20: Cover factor (Data Source, Le Roux et al., 2008)

Vegetation cover index or cover management factor (Figure 3.20) describes the influence of plant canopy on surface erosion. It is the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. This data for SA was produced by Le Roux *et al.*, (2008) using remote sensing techniques where NDVI was used as an indicator of vegetation growth determined from Moderate Resolution Imaging Spectroradiometer (MODIS) images taken between 2000 and 2004. C-values were assigned through regression equations between vegetation cover (National Land Cover, 2000) and MODIS-derived spectral index (NDVI). The C-factor was estimated using equations based on data from Wischmeier and Smith (1978).

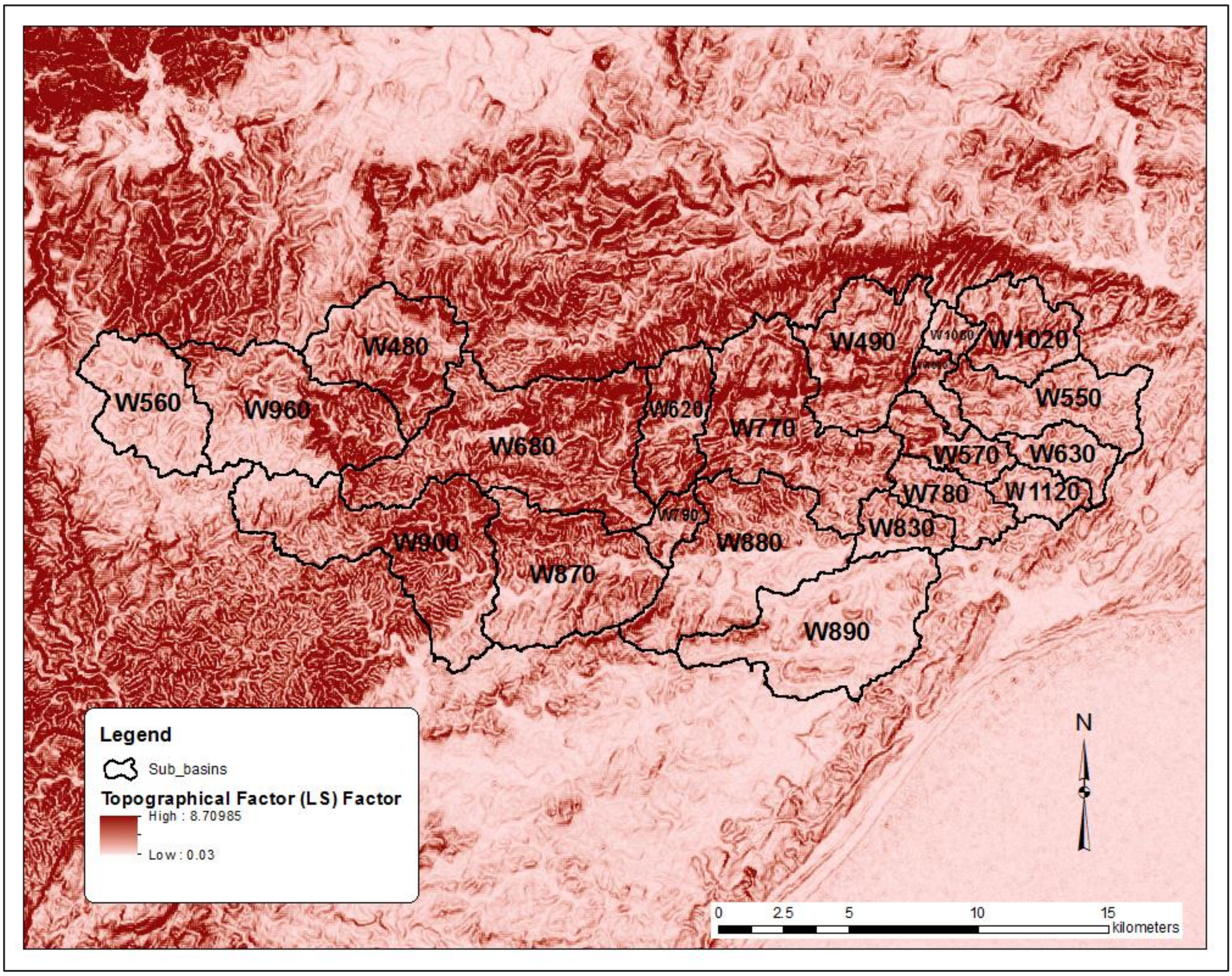


Figure 3.21: Topographical factor (Data Source Le Roux et al., 2008)

The topographical factor (LS) describes the susceptibility to erosion due to effects of slope length (L) and slope steepness (S). LS-factor for South Africa was derived by Le Roux *et al*., (2008) and these data were extracted from 20 m resolution DEMs (GISCOE, 2001) by means of the widely used stream power equation of Moore and Burch, (1986; Moore and Wilson, 1992).

CHAPTER 4: MODEL CONFIGURATION AND SETUP

The configuration of the HEC-HMS model involves the setup of the physical components of the catchment (basin) drainage network that control the flow and sediment processes. The catchment needs to be configured as a network of discrete sub-catchments with relatively homogeneous hydrological characteristics. The derivation, specification of these sub-catchments and parameterised characteristics are summarised in the following sections.

4.1 Data Processing using HEC-GeoHMS

The derivation of the sub-catchments in the study area was derived using the HEC-GeoHMS tools in ArcGIS. HEC-GeoHMS is a set of ArcGIS tools specifically designed to process geospatial data and create input files for HEC-HMS model. The basin model contains discrete sub-catchments with relatively homogenous hydrological elements and their connectivity representing the movement of water in the drainage system from source to sink (outlet). The network configuration was derived from the topographical features using a DEM. Spatial data preparation for the basin model was done in ArcGIS 10.2 software package, with the use of three extension tools; Spatial Analyst, 3D Analyst and HEC-GeoHMS.

4.1.1 DEM and pre-processing

As part of developing the HEC-HMS Project components in HEC-GeoHMS, the DEM was first reconditioned to remove imperfections using the modified river network. This eliminates the possible undesirable side effect of fictitious islands near the stream centreline. The DEM reconditioning method allows the user to adjust the elevation of the stream cell based on the input of a river network. A hydrologically corrected and depressionless DEM was created by filling the artificial depressions or pits by increasing the elevation of the pit cells to the level of the surrounding terrain; this is done to remove imperfections of the DEM created using various interpolation routines that can create minor artificial features in the surface.

4.1.2 Sub-catchments and stream delineation

The hydrologically corrected DEM is used as the starting point for delineating sub-catchments and river reaches. It was used as an input to derive eight spatial layers (datasets) that collectively describe the drainage pattern of the watershed and allows for stream and sub-catchment delineation. The first five datasets derived were grid layers that represent the flow direction in each cell, flow accumulation over connected cells, stream network, stream segmentation, and watershed delineation.

- Flow direction defines the direction of the steepest descent for each terrain cell (raster pixel).
- Flow accumulation determines the number of upstream cells draining to a given cell that defines the drainage area upstream of the cell.
- The main channel characteristics within each sub-catchment and the stream channels (segments) linking each sub-catchment with specified accumulation levels, are derived from the network of sub-catchments.
- Stream segmentation divides the stream grid into segments or linkage channels which are the sections of the stream that connect two successive junctions (confluence), a junction and an outlet, or a junction and the drainage divide.

Drainage areas with a flow accumulation greater than a user-defined threshold are used to establish the network of sub-catchments. The sub-catchments represent areas that should have relatively uniform hydrological characteristics such as land use and can be represented by one parameter value (Figure 4.1). The default of one per cent of the largest drainage area in the entire DEM was used to establish the initial network of sub-catchment that generally has uniform characteristics. The smaller the size threshold specified the greater the number of sub-catchments to be delineated. However, several of the Ntuze sub-catchments were configured to coincide with the weir catchments with the exception of the three smallest gauges (W1H014, W1H016 and W1H017). A schematic of the stream network is shown in Figure 4.2.

Figure 4.1: Sub-catchments with relatively uniform land use

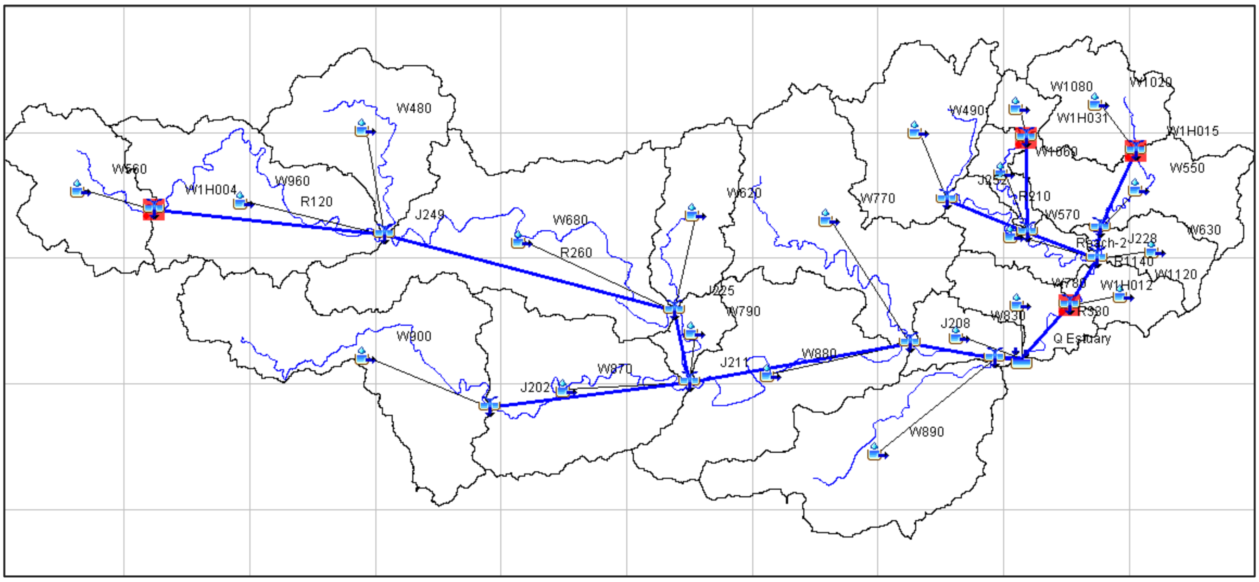


Figure 4.2: HEC-HMS Project Area for the Mlalazi Catchment generated by HEC-GeoHMS

4.1.3 Project setup and Basin Processing

During the project setup in HEC-GeoHMS, the user is responsible for extracting data from the various raster layers described in the study area section. This is used to develop the necessary information to configure the initial HEC-HMS project parameter values. For extraction of data for the project area a control point at the downstream outlet was specified, this location represents the downstream boundary for the HEC-HMS project. For the Mlalazi Catchment the downstream boundary of the project was chosen as the confluence of the Mlalazi River and Ntuze tributaries where they flow into the Mlalazi Estuary (Figure 4.1).

During the model development, the basin processing was repeated several times to establish the sub-catchments delineations for the Mlalazi Catchment to coincide with monitoring gauges because these locations are to be used for model calibration. This was done by using basin subdivision; basin merge and river merge functions in HEC-GeoHMS. After the physical characteristics of streams and sub-catchments have been defined for the project area, the time of concentrations for each sub-catchment was estimated in HEC-GeoHMS in accordance with the Natural Resource Conservation Service (NRCS) TR-55 methodology.

4.2 Model Structure and Components

HEC-HMS has been developed to simulate the hydrological responses in a catchment to rainfall and evaporation processes leading to runoff and sediment production. A simplified schematic of the relative components are shown in Figure 4.3.

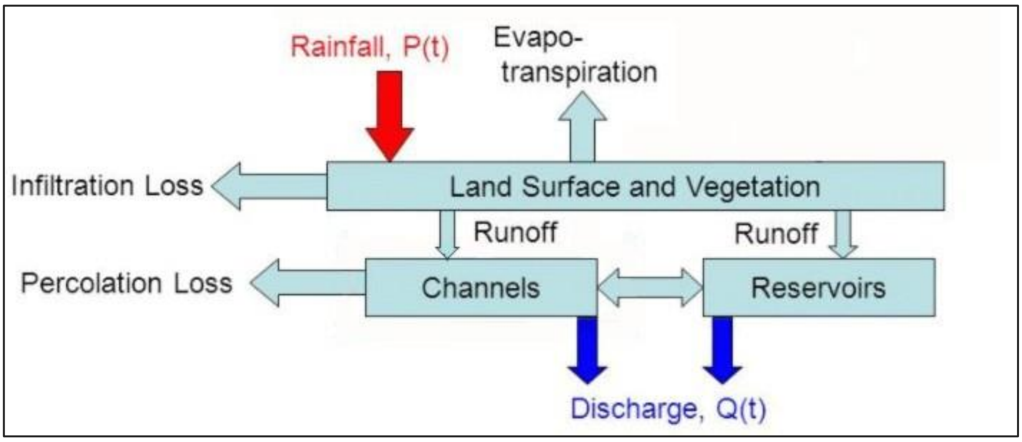


Figure 4.3: Main features of HEC-HMS (adapted from Cleveland, 2011)

The model does not incorporate groundwater flux but does allow water loss through infiltration and percolation to soil water storage zones where it can be released as delayed base flow. Since the hydrology of the study area is dominated by hillslope processes and not groundwater flow, this is assumed to be representative of the dominant hydrological regime for this study.

The primary components of the modelling system (Figure 4.4) are as follows:

- Catchment configuration of sub-units linked by a network of channels formulated in the basin model;
- Meteorological processes of rainfall and evaporation formulated in the meteorological model,
- Control specifications regulating the transfer of water through various storage zones during selected periods configured in the control model.

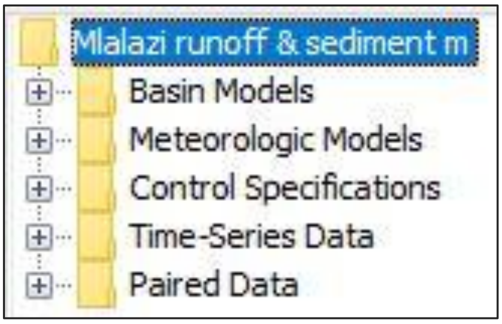


Figure 4.4: Main components of the HEC-HMS model

The meteorological model calculates the precipitation and evaporation series for each sub-catchment of the basin model. HEC-HMS requires the specification of simulation controls for each run.

Control specifications are one of the main components in the configuration of the HEC-HMS project. Their principle purpose is to control when simulations start and stop, and what time interval is used in the simulations. In addition to these three components of the HEC-HMS model system is the times series data and the paired data component. The time-series and paired data component establishes the data base for input data required as parameters or boundary conditions in the basin and meteorological models

4.3 Basin Model

The basin model simulates the flow of precipitation through the canopy with interception losses from evaporation, surface storage/ponding on the hillslope, infiltration and percolation storage. Deep percolated water can returned to stream channel as base flow, the runoff to sub-catchment outlet and erosion on hillslope. The Basin model was setup for both event and continuous simulations with the difference being in the rainfall loss and the base flow component selected.

4.3.1 Rainfall loss component

For the event simulation, the initial and constant-rate loss method was selected for calculating losses. According to USACE (2000) this method has been used successfully in hundreds of studies throughout the USA. It is easy to setup and use and includes only a few parameters necessary to explain the variation in runoff volumes. This method does predict total losses well and can be applied only on catchments with observed data since it lacks direct physical relationship of parameters and catchment properties.

The SMA method was not selected for event modelling because a detailed account of the movement and storage of water through the system was not necessary for single storms. According to USACE (2000) the SCS CN method does not consider rainfall intensity and the infiltration rate continuously decreases towards zero during storms of long duration. The deficit and constant method is recommended for long term simulations, while the Green and Ampt method has not found wide use and it is less parsimonious.

The concept of initial and constant-rate loss is that the maximum potential rate of rainfall loss, Lr, is constant throughout an event. An initial loss, Li, is added into the model to represent interception and depression storage. The rainfall excess at time t, Re_t, is then given by USACE, (2000):

$$Re_t = \left\{ \begin{array}{cl} 0 & if \sum R_i < Li \\ R_t - \; Lr & if \sum R_i > Li \; and \; R_t > Lr \\ 0 & if \sum R_i > Li \; and \; R_t < Lr \end{array} \right\} \tag{2}$$

Where R_t is the rainfall depth during the time interval Δt. The initial and constant rate method includes three parameters which represent basin initial condition, physical properties of the basin soil and physical properties of the land use, which are:

- Initial loss Li, (mm) (The initial condition loss parameter defines basin initial condition, wherein if the basin is in a saturated condition, Li will approach zero and if the basin is dry, then Li will represent the maximum rainfall depth that can fall over the basin with no runoff).
- Constant loss rate, Lr (mm/hr) (The constant loss rate is the ultimate infiltration capacity of the soils (USACE, 2000).
- Impervious area of the sub basin, Ai (%).

For continuous simulation, methods available in HEC-HMS are the SMA and; deficit and constant-rate loss model. The one layer deficit and constant-rate loss model is suitable for simple continuous modelling, and the 5-layer SMA model is suitable for continuous modelling of complex infiltration and evapotranspiration (ET) environment (Cunderlik and Simonovic, 2004).

The SMA model was selected because it accounts in detail for movement and storage of water through the system. It is suitable both for wet and dry season behaviour. Given rainfall and potential evapotranspiration the model computes basin surface runoff, groundwater flow, losses due to ET, and deep percolation over the entire basin (USACE, 2000).

The SMA model is based on Leavesley *et al*. (1983) Precipitation-Runoff Modelling System. In the SMA model, the river catchment is represented by a series of interconnected storage layers. There are four different storages in the SMA Model:

- Canopy-interception storage (rainfall captured on trees, shrubs and grasses that is lost to evaporation and does not reach the soil profile).
- Surface-depression storage (water held in shallow surface depressions that is subsequently lost to evaporation or delayed infiltration).
- Soil-profile storage, Ss (water stored in the top soil layer; water held in soil pores and water attached to soil particles due to tension).
- Groundwater storage, Gs (model can include either one or two groundwater storage layers that act as storage of shallow surface drainage water and deep percolation water).

The SMA model computes flow into, out off, and in between the storages as follows (USACE, 2000):

a) **Precipitation**: This is a direct input to the SMA system.

b) **Evapotranspiration** (ET). ET is modelled as vaporization of water directly from the soil and vegetative surface, and transpiration through plant leaves. In the SMA model, potential ET demand is computed from monthly pan evaporation depths, multiplied by monthly-varying pan correction coefficients, and scaled to the time interval. When ET is from interception storage, surface-depression storage or from upper soil zone, actual ET (AET) is equivalent to potential ET (PET). When PET is drawn from the tension zone, the AET is a percentage of the PET (USACE, 2000):

$$AET = PET \, . f(CTs, Ts) \qquad (3)$$

Where *CTs* is the current tension zone storage and Ts is the maximum tension zone storage. ET is modelled in HEC-HMS only if no precipitation occurs, if precipitation occurs during the time interval, ET is not modelled.

c) **Infiltration**: The SMA model computes the potential infiltration volume (PIV), as:

$$PIV = If - \frac{CSs}{Ss} If \tag{4}$$

Where If is the maximum soil infiltration rate, CSs is the current soil storage, and Ss is the maximum soil storage.

d) **Percolation**. The percolation rate from soil profile into groundwater layer 1, *CSp*, is computed as:

$$CSp = Sp\left(\frac{CSs}{Ss}\right)\left(1 - \frac{CGs}{Gs}\right) \tag{5}$$

Where Sp is the maximum soil percolation rate, CSs is the current soil storage, Ss is the maximum soil storage, *CGs* is the current storage in the groundwater layer 1, and Gs is the maximum storage in groundwater layer 1. Similarly, the percolation rate from groundwater layer 1 to 2, CGp is given by:

$$CGp = Gp\left(\frac{CGs}{Gs}\right)\left(1 - \frac{CGs}{Gs}\right) \tag{6}$$

Where Gp is the maximum groundwater percolation rate.

e) **Surface Runoff:** Surface runoff is the Precipitation-Interception rate that exceeds the infiltration rate and overflows the surface depression storage. This volume of water is direct runoff.

f) **Groundwater flow.** The rate of groundwater flow is computed as:

$$GW_{t+1} = \frac{CSp + Gs_t - PGp_i - 0.5Gw_t\,.T}{RGs_i + 0.5TS} \tag{7}$$

Where GW_t, is the groundwater flow rate at the beginning of the time interval *t*, CSp is the actual soil percolation rate, PGp_i is the potential percolation rate from groundwater layer *i*, RGs_i is the groundwater flow routing coefficient from storage *i*, and *T* is the simulation time step. The volume of groundwater from the river basin is computed as:

$$GW = 0.5(GW_{t+1} + GW_t)\mathrm{T} \tag{8}$$

4.3.2 Direct runoff component

The direct runoff component refers to the transformation of excess rainfall into point runoff (direct runoff) from the sub-catchment channel outlet. USACE (2000) provides general recommendations for choosing a direct runoff method with options depending upon availability of information for calibration or parameter estimation, appropriateness of model assumptions and user preference and experience. The Clark unit hydrograph (Clark, 1945) was selected to calculate the direct runoff for event and continuous simulation. This is a frequently used technique for modelling direct runoff resulting from individual storm events (Sabol, 1988, Nelson *et al.,* 1999, Fleming and Neary, 2004). The method is particularly valuable for unusually shaped catchments containing several different physiographic areas (Sabol, 1988). It has also been used by Mulder and Kelbe (1991).

The kinetic-wave method and Mod Clark method are other options in HEC-HMS, the kinetic-wave method is based a conceptual model which is data intensive and based on a finite difference equations, while the Mod Clark is a distributed parameter model which can be used with gridded data.

The same Clark unit hydrograph method used for event simulations was also used for the continuous model to transform excess rainfall into direct runoff. The water that exceeds the infiltration rate and overflows the surface depression storage in the SMA model is the input to direct runoff component. The parameters for this method are the time of concentration and the surface storage coefficient that can be estimated through calibration if observed rainfall and streamflow data is available.

The Clark unit hydrograph method derives a catchment unit hydrograph by representing two key processes in transformation of excess rainfall to runoff: translation and attenuation:

- Translation is based on a synthetic time-area histogram and the time of concentration, Tc. The time-area histogram specifies the basin area contributing to flow at the outlet as a function of time.
- Attenuation is modelled with a linear reservoir method (HEC, 2006). The reservoir represents the aggregated impacts of all basin storage, St. The average outflow from the reservoir during a period t is given by (USACE, 2000) :

$$O_t = C_A I_t + C_B O_{t-1} \tag{9}$$

Where I_t is the inflow to storage at time, t and C_A and C_B are routing coefficients given by:

$$C_A = \frac{\Delta t}{St + 0.5\Delta t} \, and \, C_B = 1 - C_A \tag{10}$$

Where Δt is the computational time step. The required parameters of the Clark method are:

- Time of concentration, Tc (hr)
- Storage coefficient, St (hr)

4.3.3 Base flow component

Base flow is the sustained runoff of prior rainfall that was stored temporarily in the catchment soil (subsurface) profile, from the current storm (USACE, 2000). Base flow can also have a component of flow of water that returns to the stream or land surface from groundwater aquifers. The HEC-HMS model includes three methods for modelling base flow: constant monthly, exponential recession and linear reservoir volume accounting model (Cunderlik and Simonovic, 2004).

In events modelling, base flow plays a significant role in the formation of flood hydrograph. Base flow component is important for modelling recession limbs of flood hydrographs as well as for more accurate estimation of flood volumes (Cunderlik and Simonovic, 2004). The exponential recession method was selected for modelling base flow in event simulations. This is because the method is also often used as a technique for base flow separation and groundwater recharge estimation (Arnold *et al.,* 2000). This method is suitable for basins where the volume and timing of base flow is strongly influenced by rainfall events (USACE, 2000).

Other methods included in HEC-HMS for base flow modelling is the constant monthly and linear reservoir. The latter method can only be used in conjunction with the SMA loss method. The constant monthly method is a simple approach that uses a constant base flow at all simulation time step falling within a particular month.

The recession model has been used often to explain the drainage from a natural storage in a catchment (Linsley*, et al.,* 1982). It defines the relationship of B_t, the base flow at any time t, to an initial value as:

$$B_t = Bi\,.Rc^t \tag{11}$$

Where Bi is the initial base flow at time t_o, and Rc is the exponential decay constant. The parameters of the recession method are:

- Initial base flow, Bi
- Recession constant, Rc
- Threshold, Td

The initial flow is equal to the base flow at the beginning of the simulation. The recession constant describes the rate of base flow decay. It is the ratio of base flow at time t to the base flow one day earlier (t-1). The threshold is the point on the hydrograph where base flow replaces overland flow as a source of flow from the basin (USACE, 2000).

The linear-reservoir base flow model was selected for use in conjunction with the continuous SMA model for continuous simulations. In this model, outflows from the SMA groundwater layers are inflows to base flow linear reservoirs. The outflow from the two linear reservoirs is combined to compute the total base flow for the catchment. The required parameters of the linear reservoir base flow model are:

- Storage coefficient, Bs (hr),
- Number of reservoirs, Br

4.4 Flow Routing Model

River flow routing is a technique for determining the propagation of flow from one point in a river to another. Flows are routed along a river channel to help account for storage and the attenuation of flood peaks. The direct runoff at the sub-catchment component is translated and attenuated as it propagates through the network of downstream river channels. This is water that has not infiltrated or been stored on the catchment and propagates over and just beneath the catchment surface (USACE, 2000). The river flow routing hydrograph characteristics are depicted in Figure 4.5.

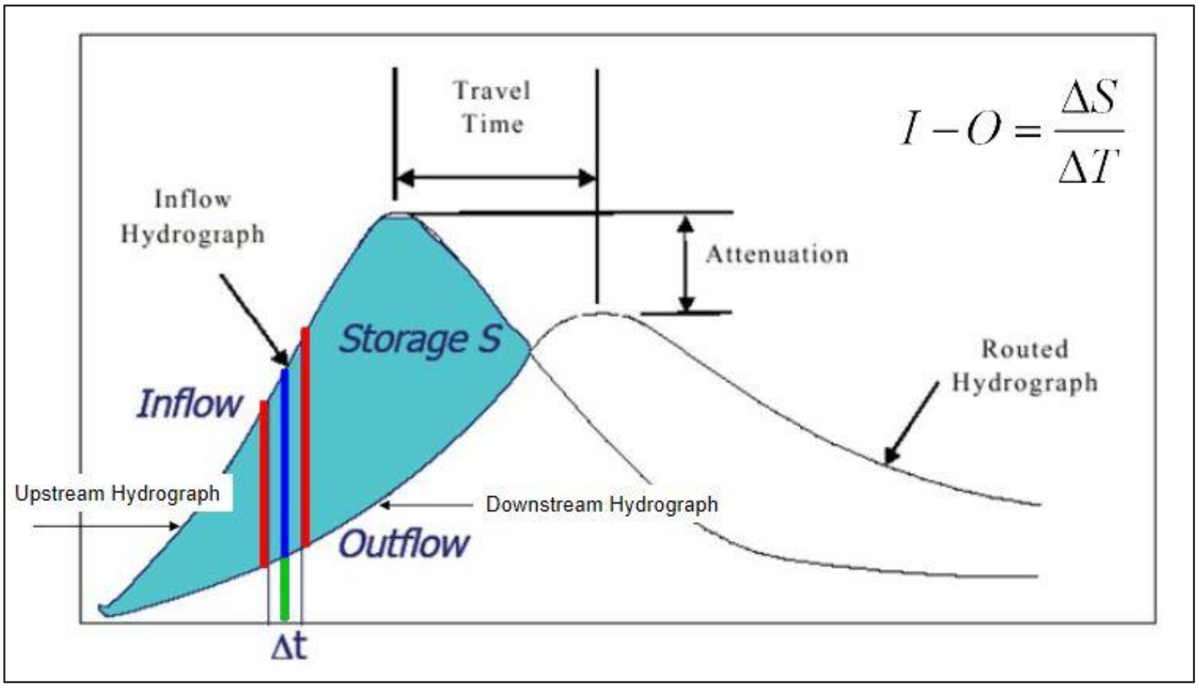


Figure 4.5: Flow routing hydrographs (Cleveland, 2011)

The propagation characteristics of interest are peak flows, time to peak, duration of hydrograph and flow attenuation. These characteristics are among others greatly affected by the geometric characteristics of the river channel and floodplain. The geometry of a river entails cross-sectional shape, bed form, longitudinal form and branching. In mathematical representations the river is represented by a simple cross-sectional shape, such as rectangular, triangular or trapezoidal, and this cross-section is assumed to be prismatic over the river under consideration (Singh, 2004). Flow routing in rivers is governed by the laws of conservation of mass, momentum and energy which is expressed as continuity, momentum and energy equations.

Flow routing models can be broadly classified into hydrologic and hydraulic models. Hydrologic models are based on a spatially lumped form of the continuity equation and express storage as a function of inflow and outflow (Singh, 1988). This equation does not explicitly involve any spatial variability and expresses the flow routing variable as a function of only time at a particular location. Lumped flow routing models includes the Modified Puls, Muskingum method and a series of reservoir models. Hydraulic models are based on the full or simplified version of the St. Venant equations. The simplified hydraulic models include the kinetic wave, diffusive wave, gravity wave, and quasi-steady state (Singh, 2004). Flows in hydraulic models are calculated as a function of space and time throughout the system.

There are six methods included in the HEC-HMS model to compute river routing: (1) lag, (2) kinematic wave, (3) modified Puls, (4) Muskingum, (5) Muskingum-Cunge standard section, and (6) Muskingum-Cunge 8-point section. The Muskingum-Cunge which is a hydrologic flow routing model was selected for river flow routing. This model is popular and easy to use, but the main advantage of choosing a hydrologic approach is that it greatly improves computational efficiency and speed, and reduces the amount of detail field data that traditionally would be required for hydraulic flow routing models (Weinmann and Laurenson, 1979). The Muskingum-Cunge model also has an advantage over other hydrologic techniques such as Modified Puls or the simple Muskingum method as it is comparable to the diffusion wave routing (Cunge, 1969; Miller and Cunge, 1975); it produces consistent result which are reproducible and its coefficients are physically based (Cunge, 1969). This model does not simulate backwater events (Reid, 2009), however the study area does not have significant tributary inflows or dams that could cause backwater effects.

The Muskingum-Cunge model is based upon solution of the continuity equation and the diffusion form of the momentum equation. The combination of the two equations using a linear approximation yields the convective diffusion equation (Miller and Cunge, 1975).

4.5 Erosion and Sediment Transport Component

Soil erosion and sedimentation deposition by water involves the processes of soil detachment, transport, and deposition of sediment over a surface. Detachment of sediment from the soil surface is as a result of raindrop impact and overland flow. Rainfall detachment is caused by the locally intense shear stresses generated at the soil surface by raindrop impact (Loch and Silburn, 1996), while overland flow causes a shear stress to the soil surface which if it exceeds the cohesive strength of the soil (critical shear stress) also results in sediment detachment.

There are four main types of erosion processes: sheet, rill, gully and instream erosion. For simplification in erosion modelling, sheet erosion and rill erosion are often considered together as overland flow erosion detaching sediment from the soil surface only (Merritt, *et al.,* 2003). Raindrop impact is not an important factor in terms of flow resistance or sediment particle detachment for gully flows (Bennett, 1974). Instream erosion involves the direct removal of sediment from stream banks (lateral erosion) or the stream bed due to the erosive capacity of the flowing water. All these erosion types do not necessarily occur in isolation from one another. They are influenced by the landscape factors as well as rainfall characteristics. The dominant erosion processes would be expected to follow a downslope sequence of splash-sheet-rill-gully (Loch and Silburn, 1996). In many catchments worldwide, gully erosion has been identified as being a major source of sediments entering the waterways as they usually have high delivery ratios when well connected to streams (Merritt, *et al.,* 2003).

A prime reason for selecting the HEC-HMS model is its ability to simulate erosion and sediment transport component. In HEC-HMS each erosion method computes the total sediment load out of a sub-basin during a storm and deposited into the channel at the catchment outlet. The available methods in HEC-HMS for simulating soil erosion from the catchment are the Modified Universal Soil Loss Equation (MUSLE) and the Build-up wash-off erosion method. The latter is designated for urban environments and was not considered in this study. The MUSLE is an empirical soil erosion model that simulates the generation of overland sediments from surface runoff, and this method works best in agricultural environments where it was developed (HEC, 2015). This method was considered suitable for the simulation of soil erosion from the Mlalazi Catchment since it corresponds to the rural nature of the catchment dominated by subsistence farming agriculture.

MUSLE surface erosion method will allow a computation of sediment yield from the catchment. This method has been widely verified around the world and also in South Africa (Kienzle *et al.,* 1997). Sediment yield from the catchment is calculated using the MUSLE Equation as shown in Equation 12 (Williams, 1975).

$$Sed = 95 \cdot (Q_{surf} \times q_{peak})^{0.56} \times K \times LS \times C \times P \qquad (12)$$

Where Sed is the sediment yield for a given event (tons), Q_{surf} is the surface runoff volume (m^3), q_{peak} is the peak runoff rate (m^3/s), K is the erodibility factor, LS is the topographical factor, C is the cover and management factor, and P is the support practice factor.

The instream sediment transport component of the HEC-HMS model includes multiple methods for modelling sediment transport and erosion or deposition within the channel. Most of the sediments that are transported are deposited in the stream network prior to reaching the catchment outlet (Merritt, *et al.,* 2003). The concept of sediment transport potential is used to describe this sediment transport process in the channel and this is because the sediment process within a stream is directly linked to the capacity of the stream to carry eroded soil. If the stream can transport more sediment than is contained in the inflow, additional sediment will be eroded from the stream bed and entrained in the flow. However, if the flow in the reach cannot transport the sediment of the inflow, sediment will settle and be deposited on the river bed (HEC, 2015). The available methods in HEC-HMS to calculate the sediment transport potential of the channel are: Ackers-White, Engelund-Hansen, Laursen Copeland, Meyer-Peter Muller, Toffaleti, Wilcock, Yang and Krone Parthenaides (HEC, 2015). The Ackers-white method was chosen for sediment transport potential for Mlalazi Catchment.

Sediment transport includes the deposition and additional stream bed erosion, these processes are simulated by the sediment routing method. The channel sediment routing methods available in HEC-HMS includes, Fishers Dispersion, Linear Reservoir, Uniform equilibrium and Volume Ratio (HEC, 2015). For the Mlalazi Catchment the volume ratio method was used, it links the transport of sediment to the transport of flow in the channel using a conceptual approach. This method models relatively large distances between calculation point well (HEC, 2015). For each time interval, sediment from the upstream elements is added to the sediment already in the reach. The deposition or erosion of the sediment is calculated for each grain size to determine the available sediment for routing. The proportion of available sediment that leaves the reach is assumed equal to the proportion of stream flow that leaves the reach during the same interval. It means that all grain sizes are transported through the reach at the same rate, even though erosion and deposition are determined separately for each grain size.

The level of complexity introduced through the selection of the various sub-model options is dependent on the available data or information for the study area. Many of the parameter values required for these various options are unknown and/or obtained from other studies presented in the hydrological literature. Consequently, it is necessary to calibrate or validate the parameter during the development of the model if there is the required data.

4.6 Meteorological Model

The meteorological component defines the precipitation distribution over the basin with space and time (USACE, 2000). In HEC-GeoHMS a tool is available that can create specified hyetograph, user gauge weights and inverse-distance models from a network of monitoring gauges distributed in and around the catchment.

In the present version (4.2) of HEC-HMS the meteorological component can be used to model the temporal and spatial distribution of rainfall and evapotranspiration using several user specified methods. All rainfall distribution methods available in HEC-HMS use an assumption that the rainfall is distributed uniformly over a representative catchment area for a given period of time or duration. The gridded method can be used only with gridded SMA infiltration method of the HEC-HMS distributed basin model and was not considered in this project because only point meteorological data was available for the desired period of simulation.

For the Mlalazi Catchment project the Inverse Distance Model (IDM) was created by inputting a gauge layer of available rain gauge stations in and around the project area. The IDM was chosen for use since observed daily data for the project area contains missing values. This method is useful when observed rainfall data contains missing values that should not be set to zero. It is not sensitive to gauges with missing values since a closest inverse gauge without missing record can always be selected for point rainfall distribution.

In the IDM, sub basin hyetograph is computed for node locations that are positioned within a watershed such that they provide adequate spatial coverage of precipitation in the watershed. A quadrant system is drawn centred on the node. This is illustrated in Figure 4.6. Weights are computed and assigned to the gauges in inverse proportion to the square of the distance from the node to the gauge.

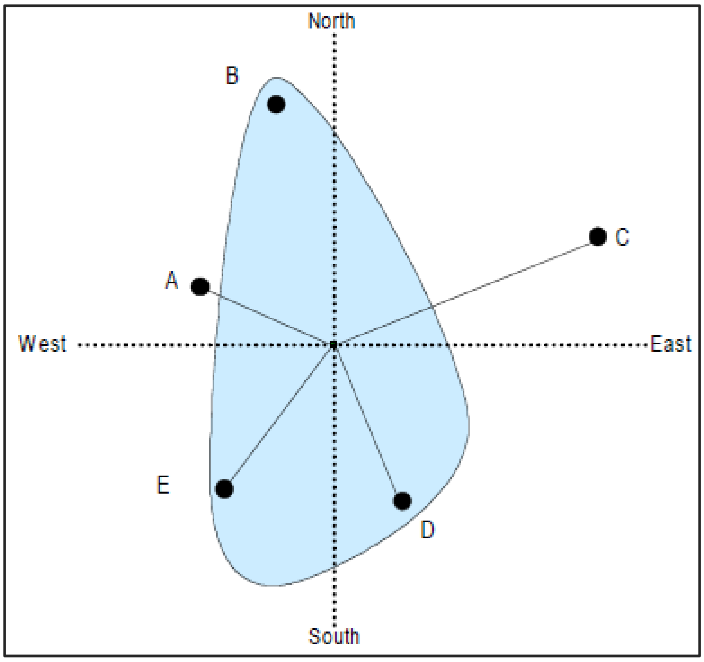


Figure 4.6: Illustration of the inverse-distance method

A weight for the closest rain gauge which does not have missing data is computed in each quadrant as the inverse squared distance between the gauge and the node. For example, the weight for gauge C in Figure 4.6 in the north-eastern quadrant is computed as (USACE, 2000):

$$W_{c=} \frac{\frac{1}{d_c^2}}{\frac{1}{d_c^2}+\frac{1}{d_D^2}+\frac{1}{d_E^2}+\frac{1}{d_A^2}} \qquad (13)$$

Where W_c is the weight assigned to gage C, and d_x is the distance from node to gauge x. the closest rainfall gauge in each quadrant is determined separately for each time step. In general the next closest gauge in the quadrant is automatically used when the closest gauge has missing data (USACE, 2000). When the weights are computed, the node hyetograph ordinate at time t is computed as:

$$P_{node}(t) = W_A P_A(t) + W_C P_C(t) + W_D P_D(t) + W_E P_E(t) \qquad (14)$$

Where $P_x(t)$ is the precipitation at gauge x and time t.

4.7 Flow Model Calibration and Validation

The set of parameters in the basin model that need to be determined from available sources or improved through calibration process have been described above. Calibration and validation could only be done for the flow model based on available data. The erosion and sediment transport model was not calibrated and validated because there are no observed sediment data in the Mlalazi Catchment. This limitation was overcome by estimating input parameters based on data from Le Roux et.al. (2008) and data from the HRU reports (Mulder and Kelbe, 1991).

Calibration is a process of adjusting model input parameters to make modelled hydrographs reasonably match the observed hydrograph (Uzair and Koran, 2017). The USEPA (1999) refers to validation (can also be called verification) as the process of testing the calibrated model using one or more independent data sets. This is a key criteria to test model performance because it assess whether the model retains its generality; that is a model that has been adjusted extensively to match a particular events might lose its ability to predict the effects of other events that are not included in the data used in the calibration process (Uzair and Koran, 2017).

Two approaches are available for simulating hydrological response to meteorological events that depend on the purpose. Event based model provide an estimate of flow from the catchment for various extreme types rainfall “events” such as 1:100 year flood. These events generally operate at short time steps due to the very rapid nature of changing hydrological conditions. Alternatively, HEC-HMS can simulate long term “continuous” sequences of flow from a catchment that include these extreme events. Under these conditions, computational constraints require less stringent time steps.

An event and a continuous based approach were both used in the configuration of the model. Calibration and validation was done for delineated sub-basins with flow gauging station W1H012; W1H015; and W1H004 for the runoff model. In order to obtain reasonably correlation between observed and simulated hydrographs, initial values were determine, an optimization trial (auto calibration) was run in HEC-HMS and evaluated using the Nelder and Mead (1965) method. This method used the sum of squared residuals for the objective function in order to identify the sensitive parameters that were subsequently manually calibrated.

4.7.1 Event based approach

The main features identified and manually adjusted for event based calibration using daily observed data running at 6 hour time step to simulate a reasonable hydrographs were the following:

- Peak flow rate;
- Time to peak (affected mainly by surface runoff);
- Recession curve (represents surface-intermediate-base flow); and
- Base flow (represents groundwater/ soil storage that will affect the transport of sediments between events.

4.7.2 Continuous based approach

The calibration for continuous simulations to determine the rainfall-runoff parameters was carried out using daily data running at a 1 day time step for the period of 9 years

(01Aug1977 - 31Jul1986). This was followed by the validation process using daily data for a period of 10 years (02Dec1986 - 01Dec1999).

The continuous flow model performance was evaluated for both calibration and validation using statistical measures which are provided for in the HEC-HMS model and are used to measure the goodness-of-fit between modelled and observed hydrograph. The objective functions and statistical measures used are the Nash-Sutcliffe Efficiency (NSE) and the overall Root Mean Square Error (RMSE). The NSE expresses the proportion of variance of the recorded runoff that can be accounted for by the model and provides a direct measure of the ability of the model to reproduce the recorded flows (Boughton, 2006). NSE value ranges from -∞ to 1 and NSE = 1 indicates that all estimated flows are the same as the observed flows (Boughton, 2006). In general an NSE value greater than 0.6 suggest a reasonable modelling of runoff and NSE values greater than 0.8 suggest a good modelling of runoff for catchment yield studies (Chiew and McMahon, 1993). Uzair and Koran (2017) had also indicated that an NSE goodness-of-fit value ranging from 0.5 – 1 is an excellent calibration and such a model can be applied for planning and designs.

RMSE is also frequently used to measure the difference between observed and modelled values as it represents the sample standard deviation from the observed values. The RMSE values tend to zero for perfect agreement between observed and simulated values (Shamsudin and Hashim, 2002). Equations 15 and 16 were used to compute NSE and RMSE respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \bar{Q}_{obs,i})^2} \quad (15)$$

Where $Q_{obs} =$ observed flow (m^3/s); $Q_{sim} =$ simulated flow (m^3/s) and $\bar{Q}_{obs}$ (m^3/s) is the mean of the observed flow, $i =$ number of the day and $n =$ total number of time steps.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2\right]^{\frac{1}{2}} \quad (16)$$

Where the variables are defined as in Equation 15.

CHAPTER 5: RESULTS AND DISCUSSION

The results of literature review are presented in Chapter 2 (Literature Review) where the HEC-HMS was selected as the suitable model to be used for the Mlalazi Catchment. The result of the creation of the DEM with a required accuracy is presented in Chapter 3 (Study Area and Data), where the geomorphology of the study area is presented after the DEM was created during the model development stage. Chapter 4 has presented the model configuration and the selection of process methods of the model. This chapter will present and discuss the HEC-HMS model flow calibration and validation results, as well as the continuous simulated catchment flows and sediment load.

5.1 Flow Calibration

5.1.1 Event based Calibration

This event calibration was based on how well the important features of a simulated storm hydrograph fit the observed hydrograph. The two main features of the model are the sub-catchment yield and the channel routing that will affect the storm hydrograph. Both are important in the sediment production and transportation. The combined yield must correlate closely to the combined runoff for a specific area while the shape of the hydrograph represents the combined contributions from the storm, intermediate and base flow components. These are examined for selected conditions that represent a contribution of a distributed storm events during the monitoring period between 1984 and 2000.

An event based calibration was done on two selected storm events which could result in erosion and sediments formations. The simulations were done at a 6 hourly time step for the station W1H012. The results of the two cyclonic storm events selected for calibration are shown in Figure 5.1 and Figure 5.2, these were Domoina (31 January 1984) and Imboa (17 February 1984) respectively. The parameters obtained from the model calibration are given in Table 5.1.

Table 5.1: Calibration parameters for event calibration at W1H012 catchment

Modelling Method	**Model**	**Parameter**	**Modelled Value**
Runoff Volume (Loss)	Initial and constant	Initial loss (mm)	1.2064
		Constant Rate (mm/hr)	2.4284
Base flow	Recession	Initial Discharge (m^3/s)	0.02
		Recession Constant	0.8839
		Threshold Flow (m^3/s)	0.14291

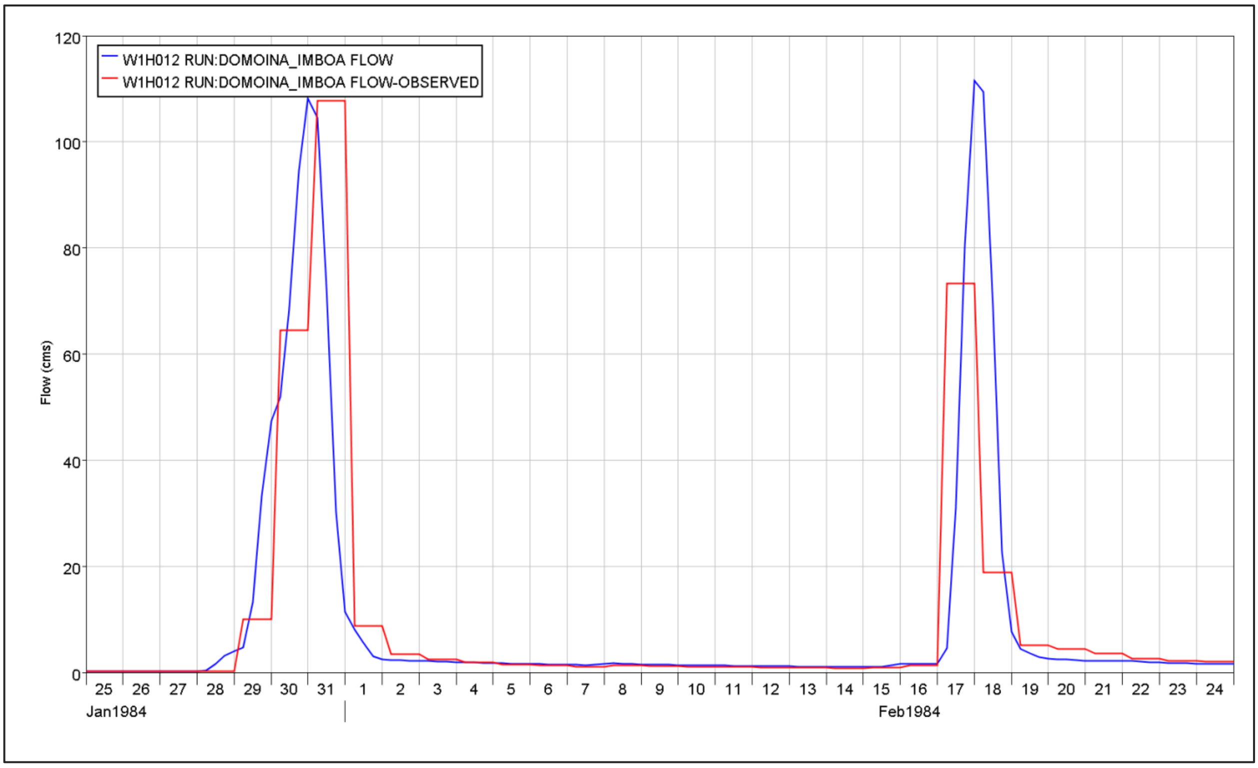


Figure 5.1: Observed and simulated hydrographs for two storm events (Linear Scale)

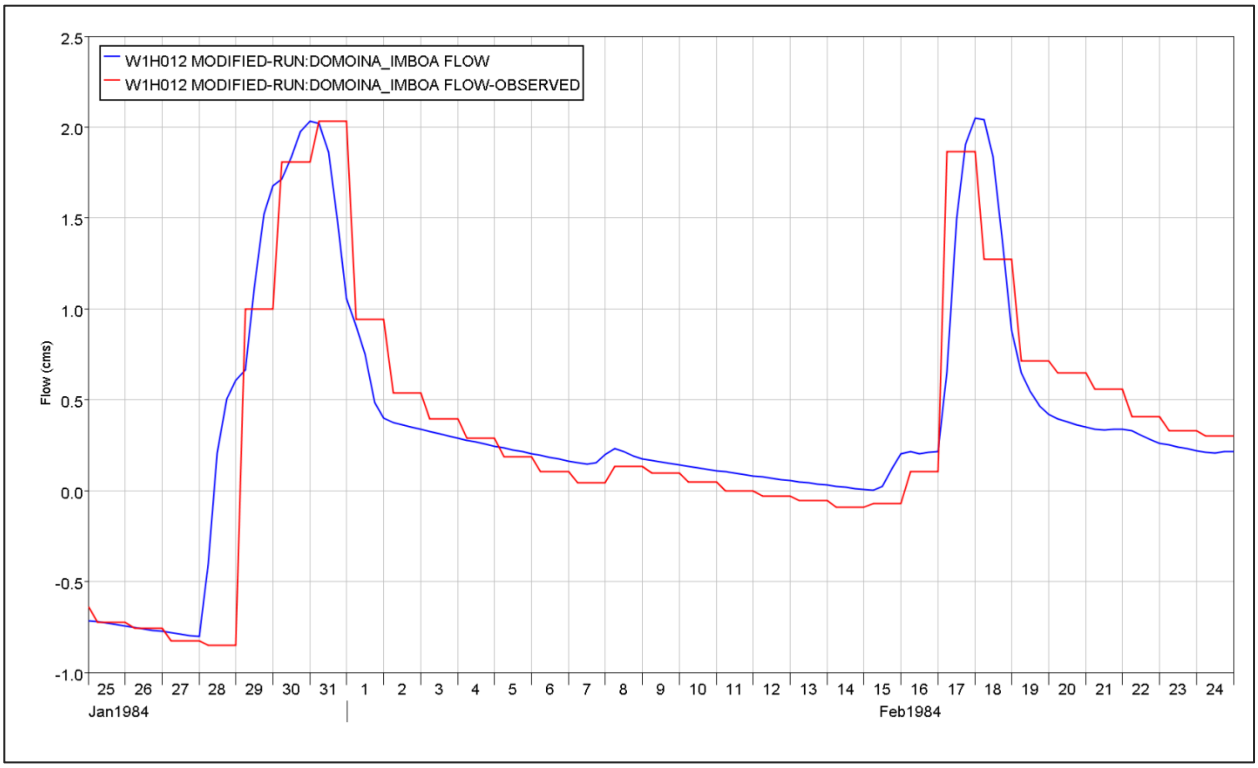


Figure 5.2: Observed and simulated hydrographs for two storm events (Log Scale)

The simulated hydrograph matches the observed hydrograph well; but the simulated peak flow for Imboa was over estimated. However, the meteorological record used in these runs gives similar rainfall amounts for Domoina and Imboa as 194 mm and 178 mm respectively, so it is expected that the simulated peaks should be close in magnitude in direct contrast to the measured peaks. Under these circumstances the model simulated peak flow for Imboa is acceptable even though it is higher than the observed peak flow due to inherent errors in either the flow or the rainfall records.

5.1.2 Continuous based Calibration

The HEC-HMS continuous model calibration was carried out by comparing daily simulated runoff with observed streamflow at the outlet of delineated sub-catchments for W1H015 and W1H012. These two stations catchments are nested and are of different size. The Soil Moisture Accounting (SMA) parameters obtained from the model auto calibration are given in Table 5.2.

Table 5.2: Auto Calibration SMA Parameters for continuous modelling

SMA Parameter	**Catchment Station**	
	W1H015	W1H012
Max rate of infiltration (mm/hr)	3.3433	4.571322
Soil Storage (mm)	79.193	114.698
Tension Storage (mm)	11.863	13.211826
Soil Percolation (mm/hr)	9.6467	4.9952
GW 1 Storage (mm)	50.095	4.11523
GW 1 percolation (mm/hr)	12.777	13.88954
GW 1 coefficient (hr)	27.125	39.41356
GW 2 Storage (mm)	93.542	72.63342
GW 2 percolation (mm/hr)	7.2213	5.943966
GW 2 coefficient (hr)	89.527	151.39457

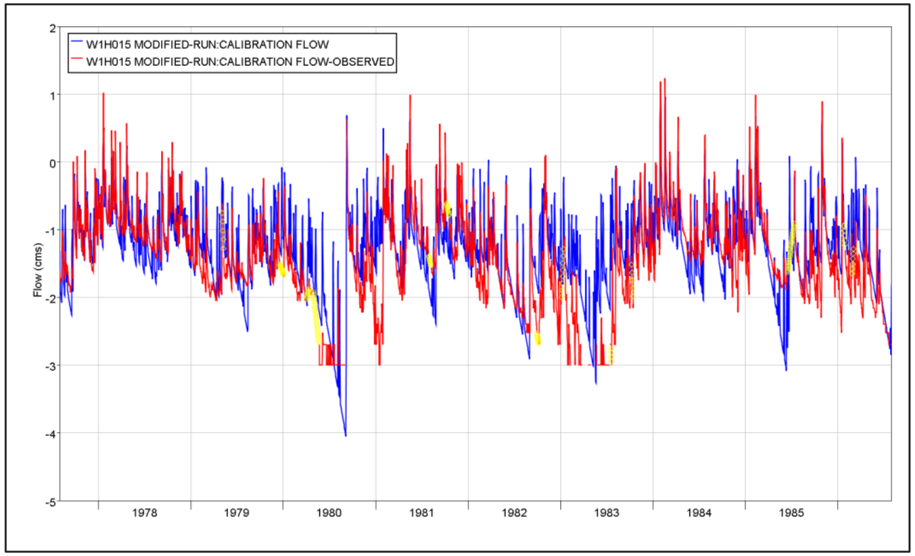
The simulate NSE for the calibration for W1H015 is 0.71, and 0.78 for W1H012. These NSE values obtained suggest a good result for calibration of runoff; the ranges of NSE are discussed in detailed in the earlier Chapter 4. The simulated RMSE of calibration for W1H015 was 0.3 m^3/s and 1.4 m^3/s for W1H012. The RMSE for the calibration period tend to be reasonably close to zero for station W1H015 and for W1H012 it was reasonable. These results obtained are considered satisfactory and acceptable for runoff simulations.

The study area is characterised by unreliable rainfall data and observed streamflow data with missing records, and prone to errors especially at high flows, that could have affected the NSE and RMSE values for the continuous based calibration. The RMSE and NSE values obtained from calibration results are shown in Table 5.3 below.

Table 5.3: Performance measures of the model

Gauge Catchment	**Error function**	**Calibration Period**
W1H015	NSE	0.71
	RMSE	0.3 (m^3/s)
W1H012	NSE	0.78
	RMSE	1.4 (m^3/s)

The calibration period simulated runoff and their comparison to observed stream flow on a log scale for stations W1H015 and W1H012 are given in Figure 5.3 and Figure 5.5, and the cumulative yield for the same period in Figure 5.4 and Figure 5.6 respectively. For description of the plots, the yellow is the missing data symbol; the red line is observed data, while the simulated data is always presented by a blue line in all the result plots.



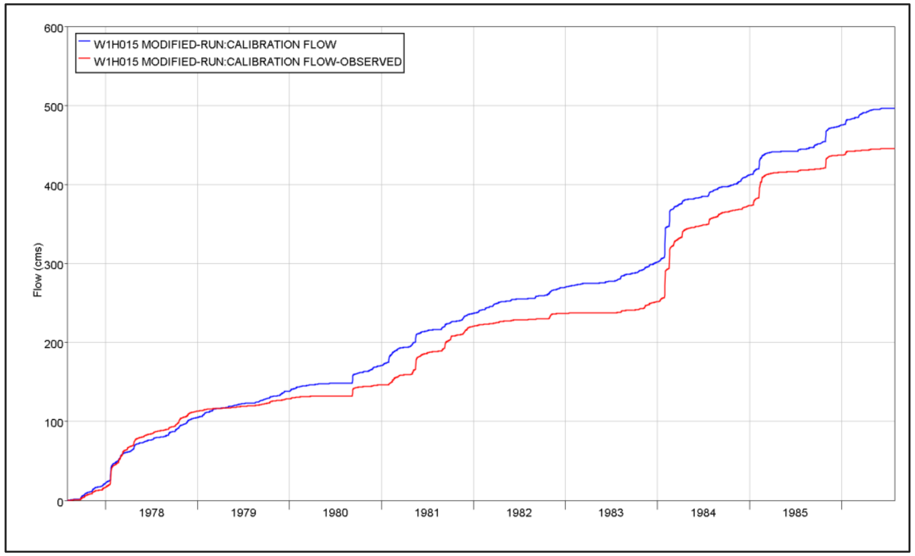
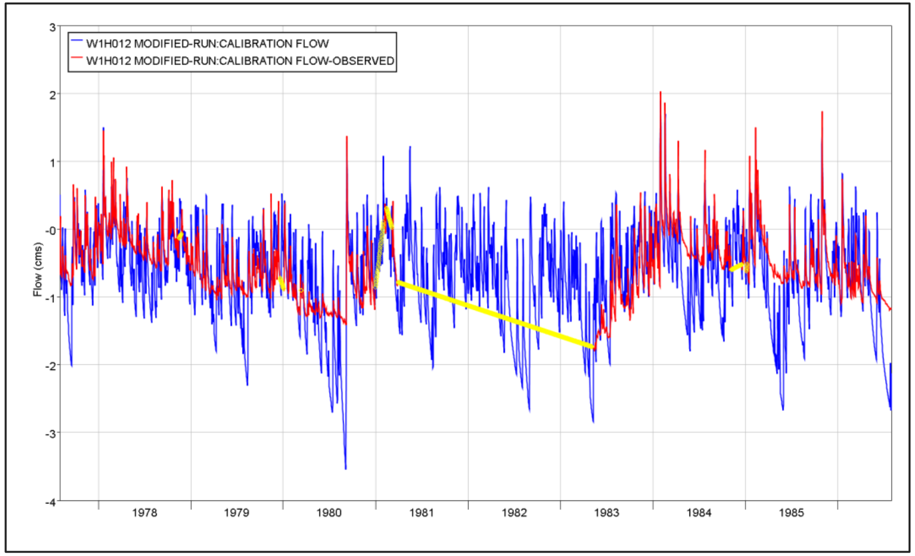


Figure 5.3: W1H015 Observed and simulated streamflow (Log Scale)

Figure 5.4: W1H015 Cumulative observed and simulated streamflow



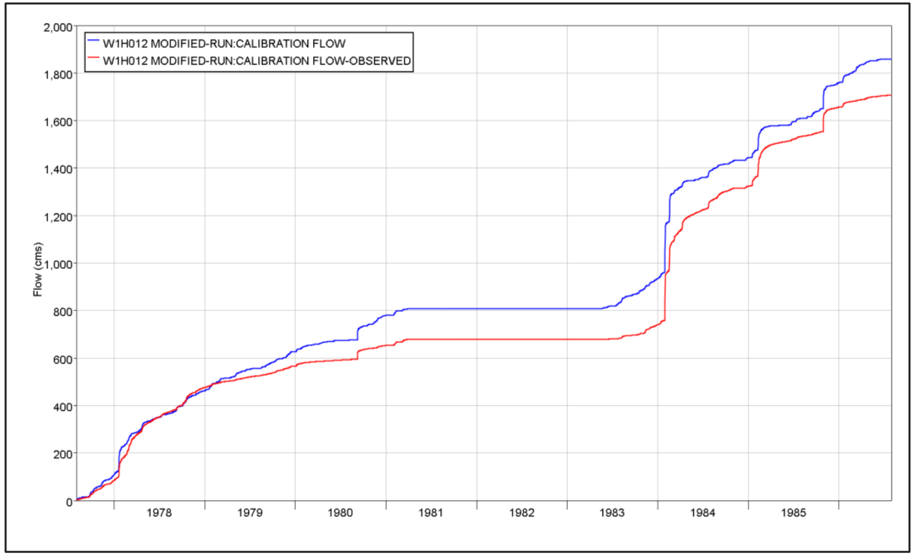


Figure 5.5: W1H012 Observed and simulated streamflow (Log Scale)

Figure 5.6: W1H012 Cumulative observed and simulated streamflow

Generally for the calibration period for W1H015, the peak flows and low flows were well simulated. However, during this period for W1H012 peak flows and low flows were slightly underestimated.

5.2 Flow Validation

5.2.1 Event based Validation

Two independent storm events in September 1987 and November 1989 shown in Figure 5.7 and Figure 5.8 were selected for validation at W1H012 sub-catchment to test how well the calibrated parameters predict runoff from other independent storm events.

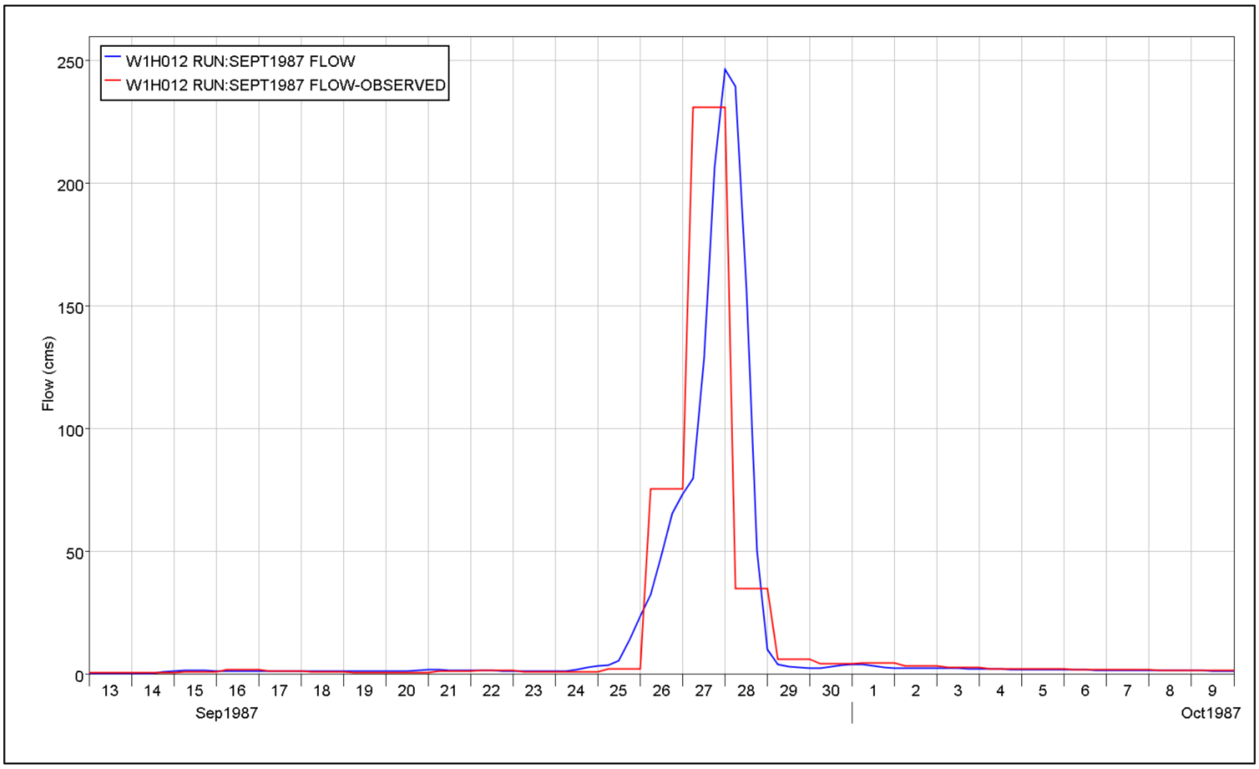


Figure 5.7: Observed and simulated flows for validation storm event (September 1987)

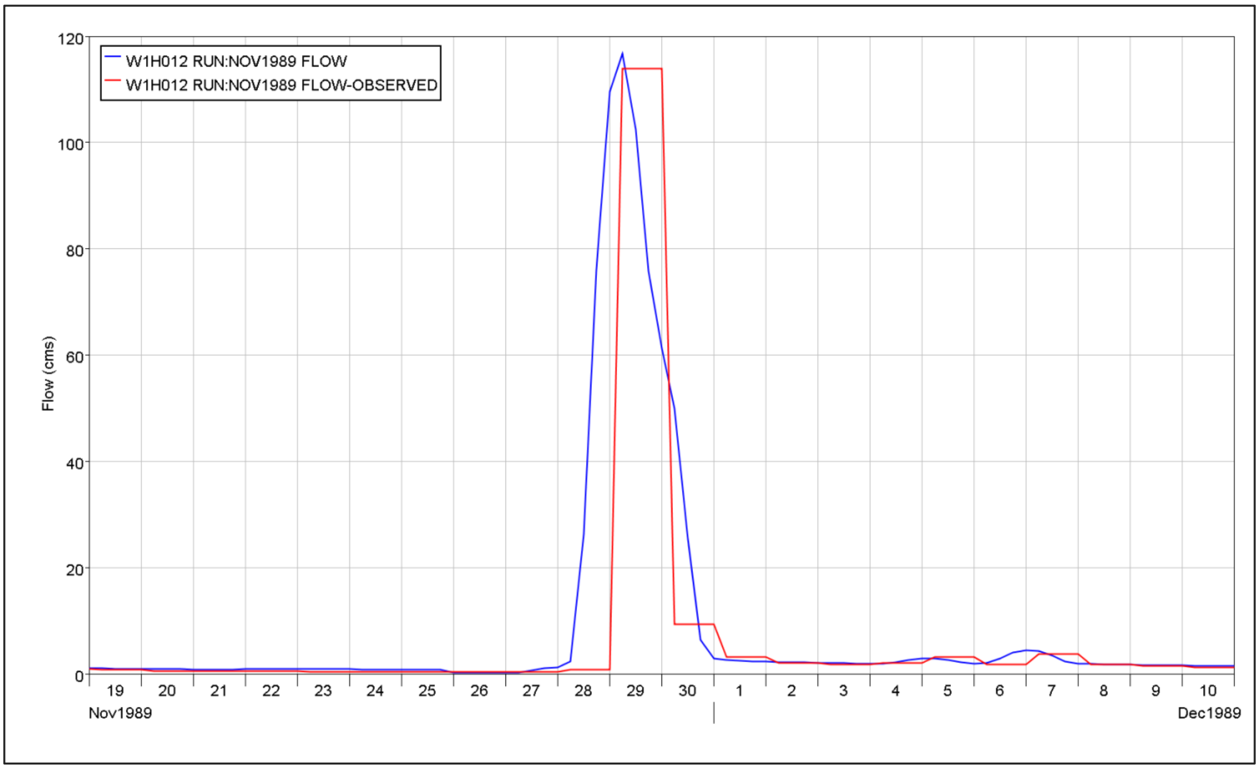


Figure 5.8: Observed and simulated flows for validation storm event (November 1989)

Both simulated storm events show good agreement between the predicted and observed storm hydrographs. However, the November 1989 peaked early than the observed hydrograph. This possibly is because of the difference in time steps, where the simulation was for a 6 hour time step and the observed data was daily.

5.2.2 Continuous based Validation

The simulated NSE for the validation period for station W1H015 was 0.62 and the RMSE was 0.4 m^3/s. The NSE for W1H012 was also 0.62, while the RMSE was 2.8 m^3/s (Table 5.4). The results obtained for the validation period are satisfactory and considered acceptable for rainfall-runoff simulations based on the condition that the NSE is greater than 0.6 that is a good model performance, and the RMSE of 2.8 m^3/s is reasonable although not the closest to zero.

Table 5.4: Performance measures of the model

Gauge Catchment	Error function	Validation Period
W1H015	NSE	0.62
	RMSE	0.4 (m^3/s)
W1H012	NSE	0.62
	RMSE	2.8 (m^3/s)

Generally for the validation period, the peak flows and low flows were well simulated for W1H015 (Figure 5.9 and Figure 5.10). For W1H012 most peaks were well estimated but some were slightly underestimated (Figure 5.11 and Figure 5.12). For the rest of the validation period low flows simulated series closely matched observed values with a slight tendency to underestimated them.

It is interesting to note that from the validation period at W1H015 and W1H012 the simulated results starts to over-estimate the flow from 1987 going forward. This appears just after the 1987 flood (~ 1:100 year event). This suggests that the catchment conditions may have changed and the river might have been impacted by the flood resulting in the overestimation of extreme event flows based on the set parameters. The overall validation results were good and confirmed that the calibrated parameters are sufficiently valid for estimation of flows for the Mlalazi Catchment.

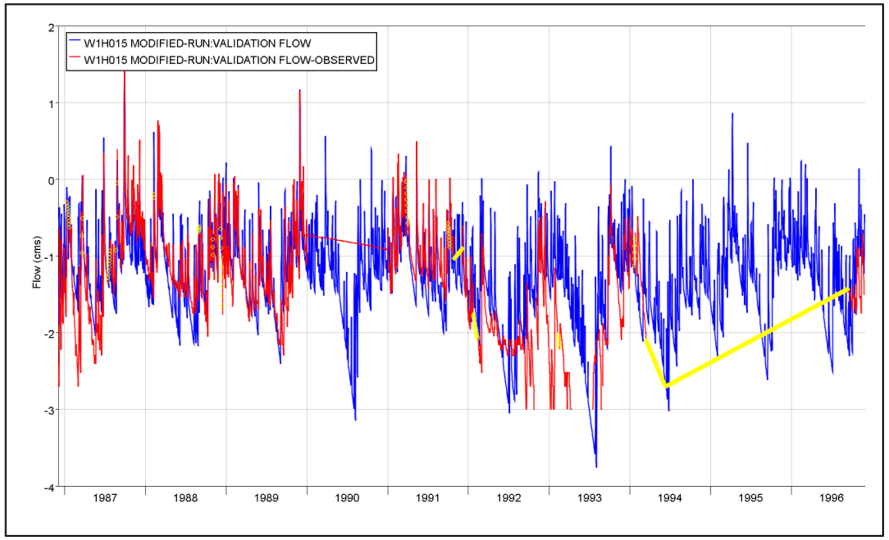


Figure 5.9: W1H015 validation period observed and simulated flow (Log Scale)

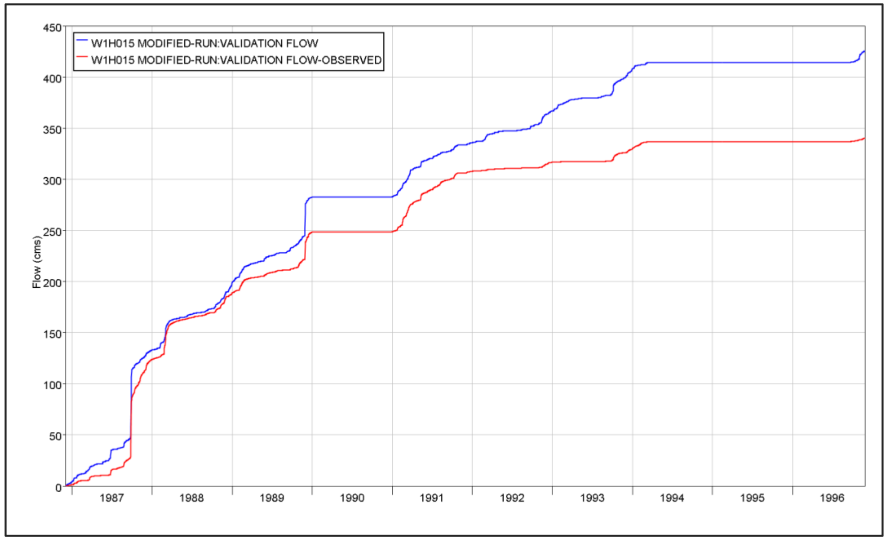


Figure 5.10: W1H015 validation period cumulative streamflow

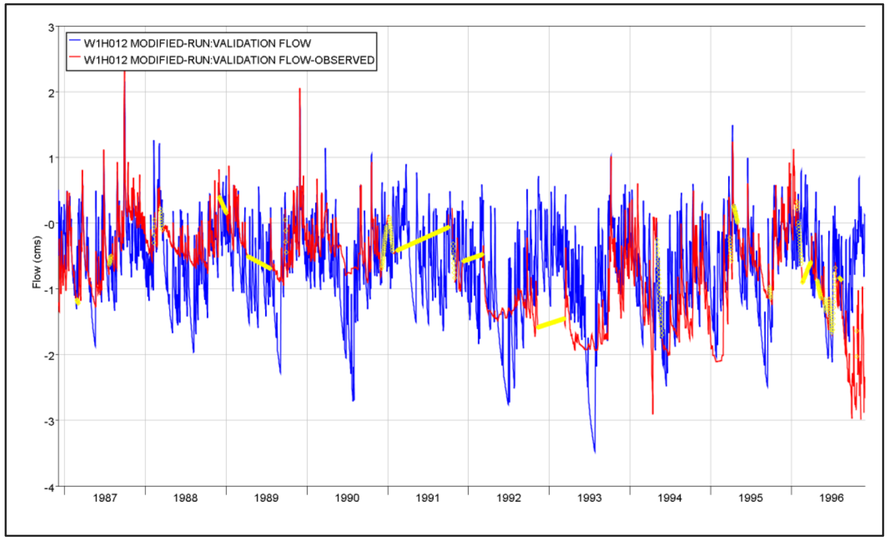


Figure 5.11: W1H012 validation period observed and simulated flow (Log scale)

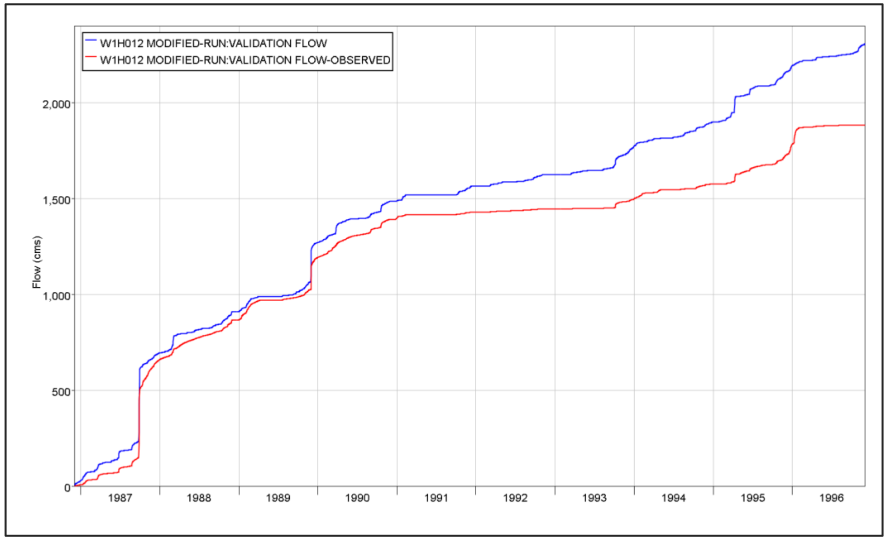


Figure 5.12: W1H012 validation period cumulative streamflow

5.3 Mlalazi Catchment Runoff and Sediment Simulation Results

Following the configuration of the model for Mlalazi Catchment, its calibration and validation, the model was applied to a long term continuous simulation of flows and sediment load series from the Mlalazi Catchment. The flows were computed on a daily time step from January 1950 to March 2018 (68 years). There was no observed data to enable the calibration of the sediment load model, so the MUSLE sediment erosion model was not calibrated but the setup was based on input parameters taken from data already available from other studies in the area (Le Roux *et.al.*, 2008; Mulder and Kelbe, 1991; Mulder and Kelbe, 1992). The accuracy of the simulated sediment data was judged on the basis of the results that should be comparable to other regional studies if they are to be accepted, for example a study by Msadala et al. (2010). The range of parameters which were used for each sub-basin for the erosion model and their descriptions are given in Table 5.5. The results of the daily flows and sediment loads are shown in Figure 5.13, while Table 5.6 shows the statistical variables of these two simulated data series.

Table 5.5: Mlalazi Catchment range for MUSLE erosion model parameters, description and sources

Parameter	**Description**	**Source**	**Range**
Erodibility Factor (K)	Describes the difficulty of eroding the soil. The factor is a function of soil texture, structure, organic matter content, and permeability. *Typical values range from 0.05 (Loamy sand) to 0.75 (Silty and clayey loam soils).* The higher the K factor the difficult it is to erode the soil.	Le Roux *et al.*, (2008)	0.18 – 0.43
Topographical Factor (LS)	Describes the susceptibility to erosion due to length and slope. *Values range from 0.1 (Short, flat slopes) to 10 (long, steep slopes)*. Long, steep slopes have more erosion than short, flat slopes.	Le Roux *et al.*, (2008)	1 – 7.5
Cover and Management Factors (C)	Describes the influence of plant canopy on surface erosion. *Value ranges from 1.0 (bare) to 0.1(covered soils), as small as 0.001 for forest soils.*	Le Roux *et al.*, (2008)	0.05 -0.5
Practice factor (P)	Describes the effect of soil specific soil conservation practices (best management practices). Agriculture practices could include, terracing or strip cropping.	n/a	1

Furthermore the simulated flows were converted to flow depth (mm) to make them comparable to the depth of rainfall received on the Mlalazi Catchment. The conversion was done using Q (mm/d) = Q (m^3/s)*86400 sec/d*1000 mm/m / Catchment Area

(397 000 000 m^2). The plot of three rainfall stations used and the simulated runoff in mm depth for the same period is given in Figure 5.14.

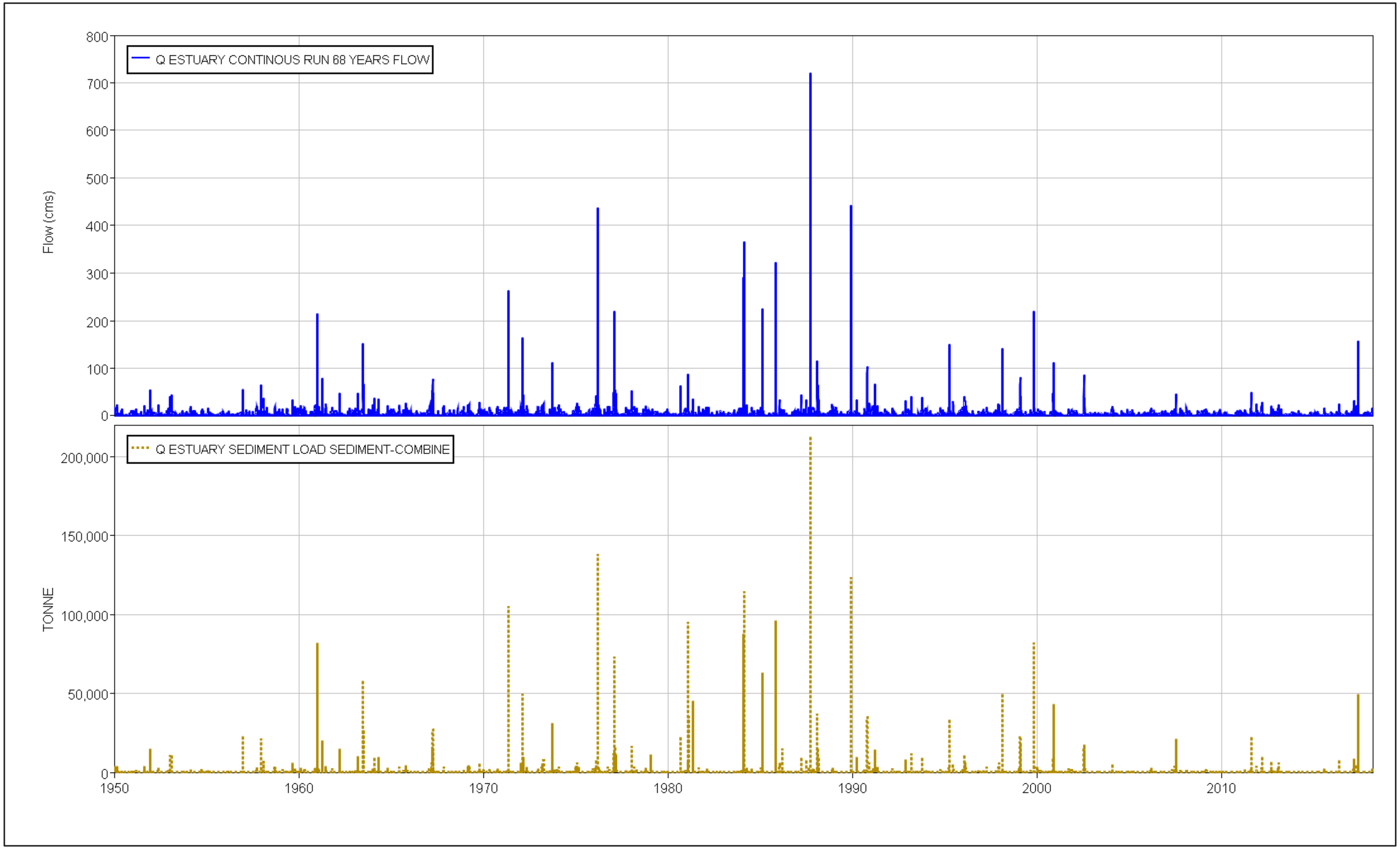


Figure 5.13: Daily simulated flows (m^3/s) and sediment load (tonnes/day) from Mlalazi Catchment discharge into the Mlalazi Estuary at the confluence of the main tributaries.

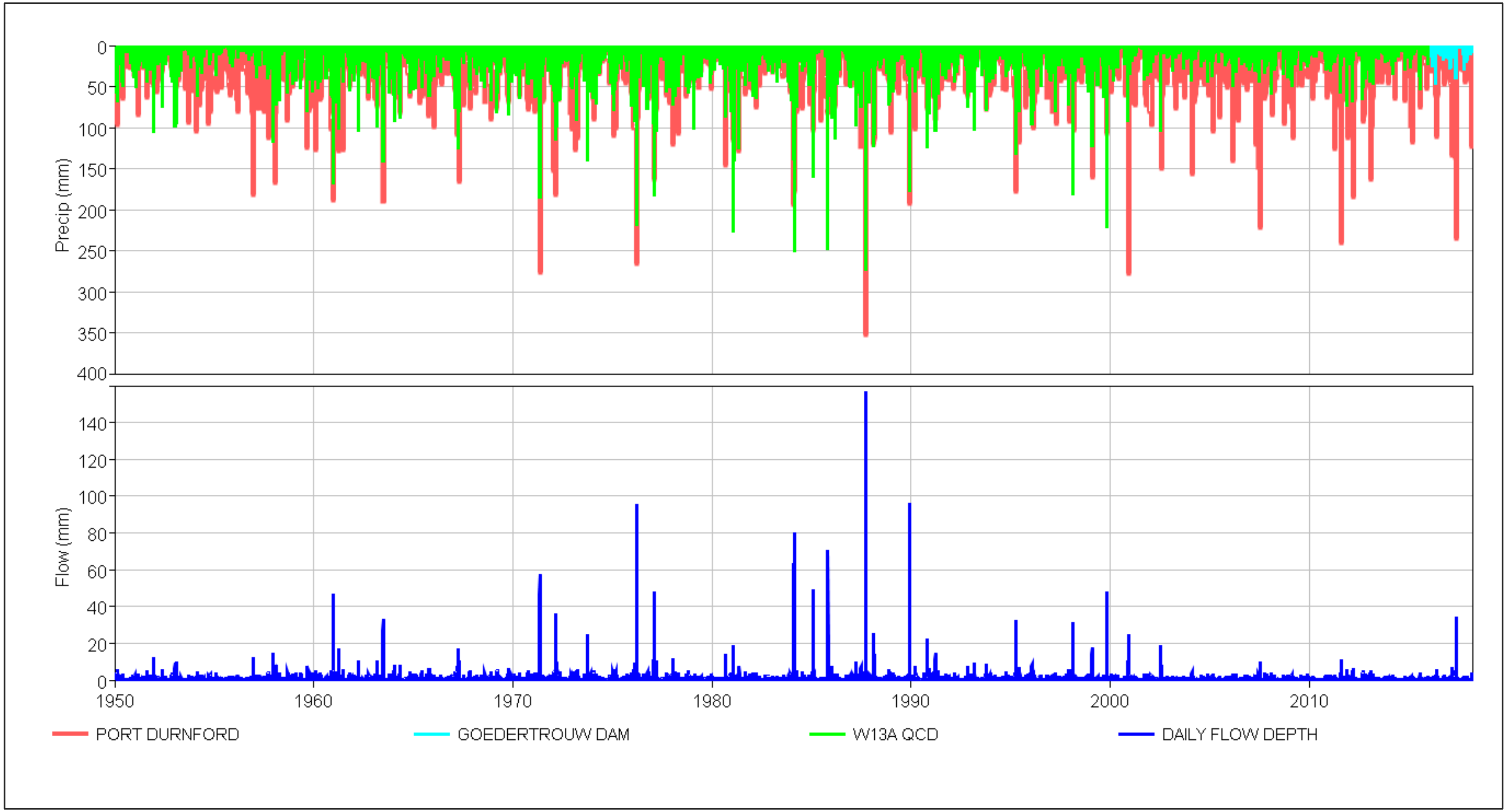


Figure 5.14: Simulated flow depth (mm/day) and Rainfall (mm/day)

Table 5.6: Statistical variables of simulated flows and sediment load

Statistical Variable	**Daily simulated Flows (m^3/s)**	**Daily simulated Sediment Load (tonne)**
Minimum Value	$2.69 * 10^{-4}$	$2.92 * 10^{-26}$
Mean Value	2.76	207.61
Maximum Value	720.11	212772.31
Standard Deviation	11.64	3258.32
Skew Coeffcient	29.37	34.49

The most extreme event experienced during the period of simulation was in 1987 wherein a daily rainfall amount between 260 mm and 350 mm that was recorded for this catchment produced a runoff of approximately 150 mm in depth. This event has also yielded a sediment load of approximately 210 000 tonnes per day.

From Figure 5.14 presented above, it can be noted that the rainfall data series from 2000 to the end of the simulation period has shown a significant difference, with W13A showing less rainfall records compared to Port Durnford. This has sigficantly affected the resultant simulated runoff and sediment yield from the catchment. This period fell outside the monitoring period for most of the surrounding stations, which meant that the derivation of centroid station W13A rainfall data series was dependent on only one station which was Eshowe Municipality. This is a manual station which could have been subjected to various errors and there was no luxury for comparison with records from other stations and/or the filling of suspected data. It is also believed that after 2006 the quality control over data from SAWS was stopped.

A frequency analysis plot shown in Figure 5.15 was computed in HEC-DSS for the simulated daily flows. This was to be able to identify the reccurrence intervals of different peak discharges out of the catchment as a resultant of rainfall extreme events.

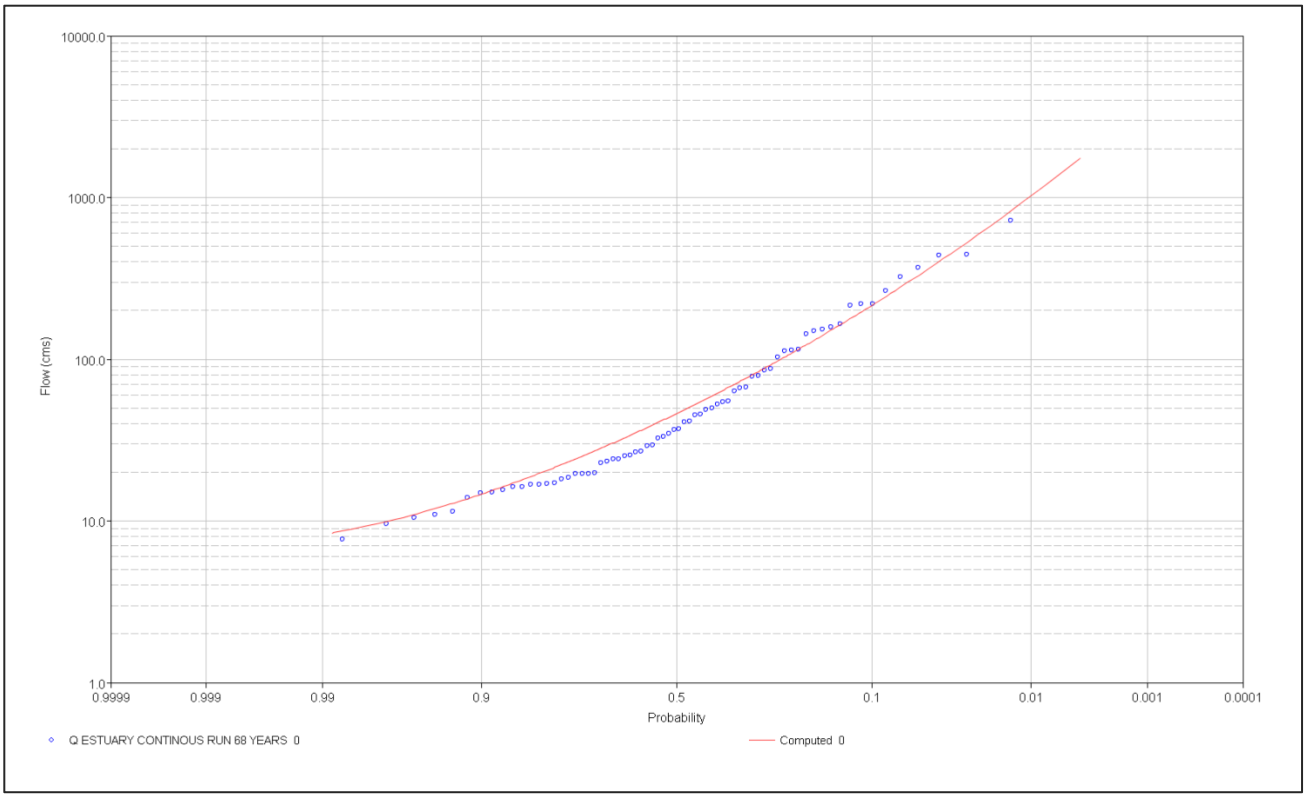


Figure 5.15: Simulated flow (m^3/s) frequency plot

From the frequency plot, the 1:100 recurrence interval flood event will result in a flow of approximately 1000 m^3/s. A simulated event which is estimated to be close to a 1:100 flood occurred in the September 1987 flood where the flow was recorded at 723 m^3/s. The 1:50 flood will yield a flow of 449 m^3/s, an event closer to this from the simulated flows was experienced in November 1989. The 1:10 flood will yield 200 m^3/s of flows, and these event were experienced in December 1960, February 1977, February 1985, and October 1999.

The sediment load resulting from the Mlalazi Catchment were for further analysis cummulated from tonnes per day to tonnes per year, subsequently this was converted to sediment yield (t/km^2.a) by dividing the tonnes per annum by the area of the Mlalazi Catchment (397 km^2). A frequency plot of the sediment yield per annum shown in Figure 5.16 was computed using a statistical analysis tool in HEC-DSS.

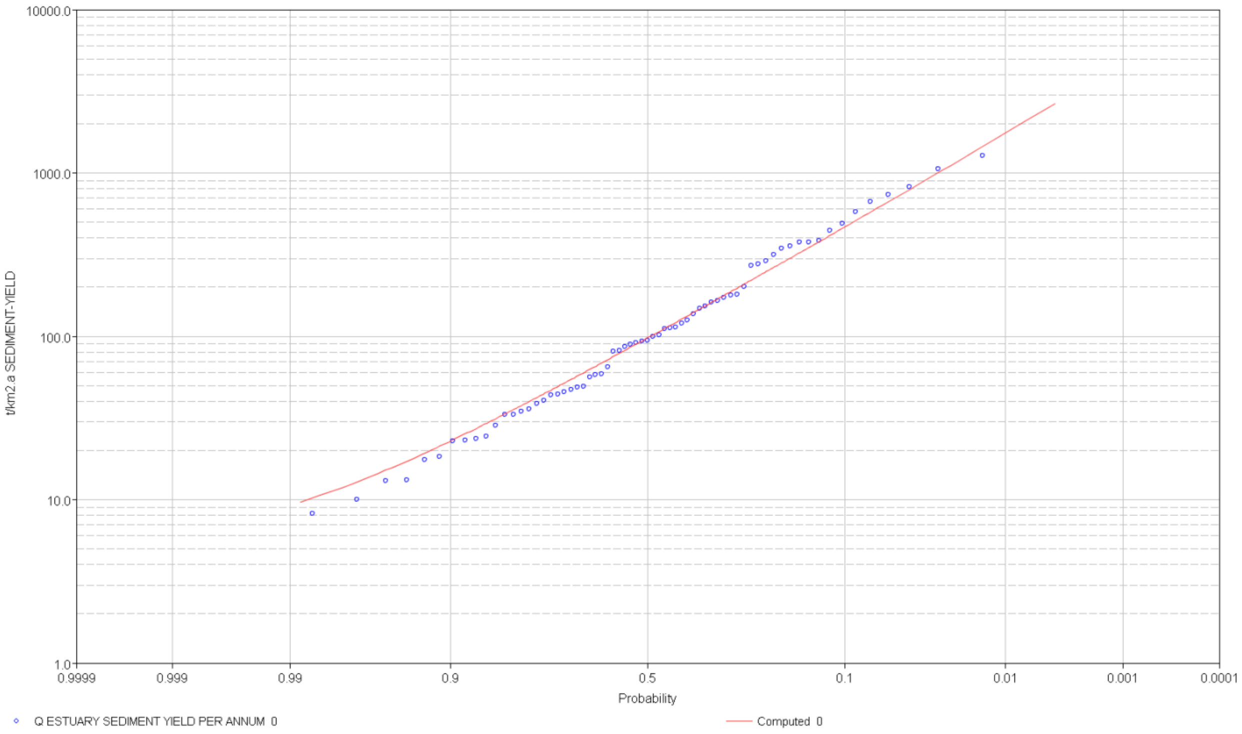


Figure 5.16: Simulated sediment yield (t/km^2.a) frequency plot

The sediment yield frequency plot has shown that for the 1:100 recurrence flood event the yield from the Catchment is estimated to be 1100 t/km^2.a, and the yield for the 1:10 event is 500 t/km^2.a. The credibility of the sediment yield results was obtained by comparison of these results with other studies of sediment loads done in the area. It was found that these results are comparable to the regional results of KZN from a study by Msadala *et al*. (2010) who found that a 1:100 storm event will yield 1050 t/km^2.a and a 1:10 event will yield sediments of 700 t/km^2.a. The average sediment yield of the Mlalazi Catchment for the period of simulation was 192 t/km^2.a. The cumulative sediment load out of the Catchment for 68 years was approximately just above five million tonnes, shown in Figure 5.17 below.

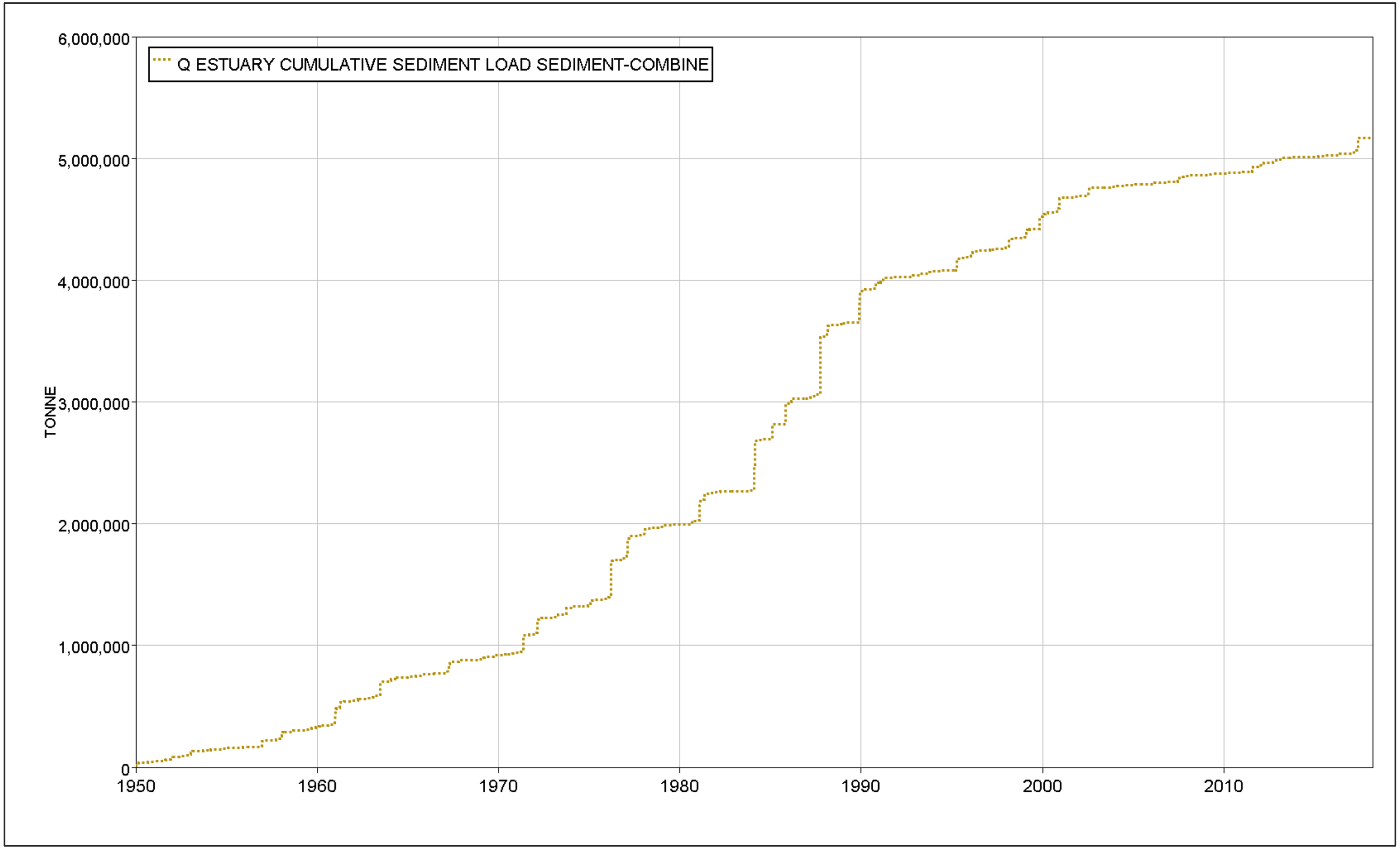


Figure 5.17: The simulated cumulative sediment load from the Mlalazi Catchment from 1950 to 2018

In order to establish information of sediment grainsize distribution along the two main tributaries (Mlalazi and Ntuze River) and erosion from different land use sections, sediment yield data were further analysed and presented based on grain sizes (sand, gravel, silt and clay). This was achieved by dividing the sediment load per day (tonnes) by the catchment area contributing to the point selected, to result in tonnes per day per square kilometre of area (SQKM). The grain sizes results presented below are for the following areas: W1H004 catchment (Figure 5.18); W1H012 station which covers much of the Ntuze River tributary catchment (Figure 5.19) and a point on Mlalazi River before confluence with Ntuze River (Figure 5.20).

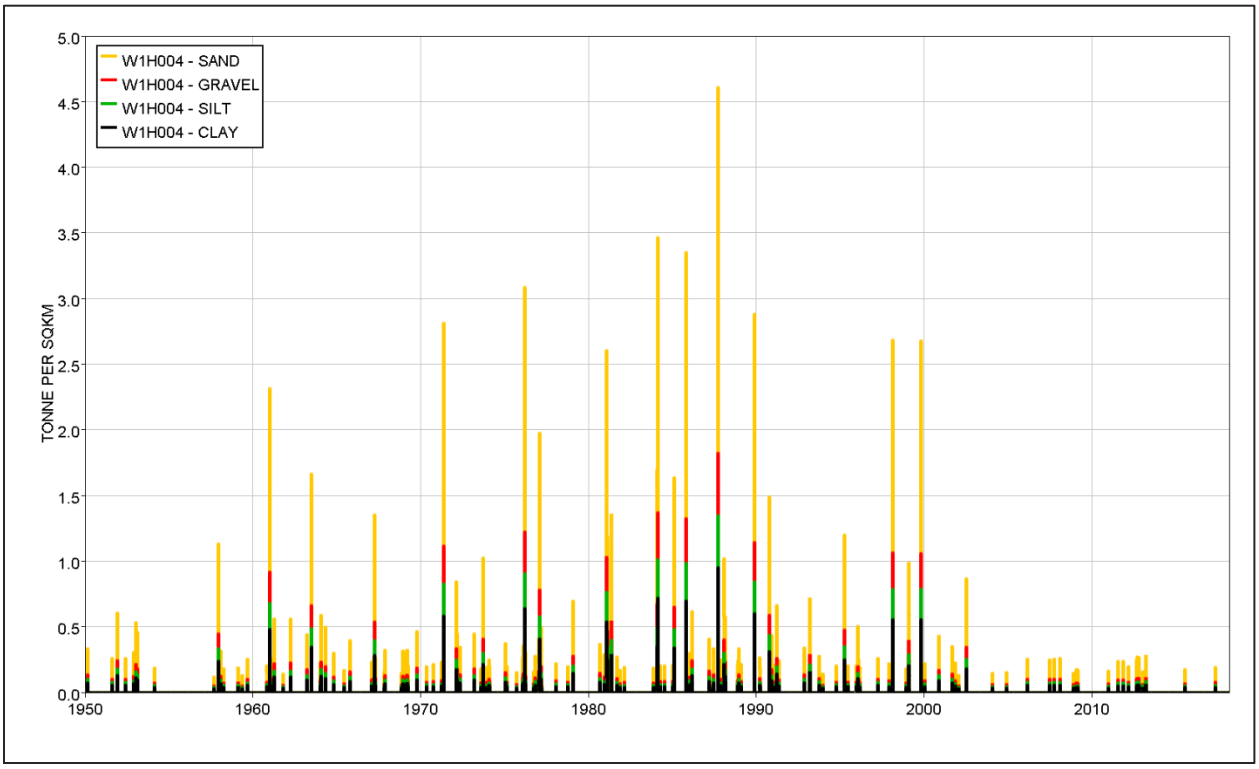


Figure 5.18: W1H004 Catchment simulated sediment grain size distribution (tonnes/day.km^2)

The catchment of station W1H004 which its sediment yield as a result of erosion is presented above is a catchment dominated by a land use of commercial sugarcane plantation. Results have showed that the sediments produced are constituted by mostly sand and gravel. During the 1:100 year flood event experience in September 1987 this catchment produced a daily sediment yield of approximately 4.6 tonnes per square km of sand and 1.8 tonnes per square km of gravel. This gave an indication that from a catchment with land use of commercial sugarcane plantation we do not expect sediments to be dominated by clay and silt.

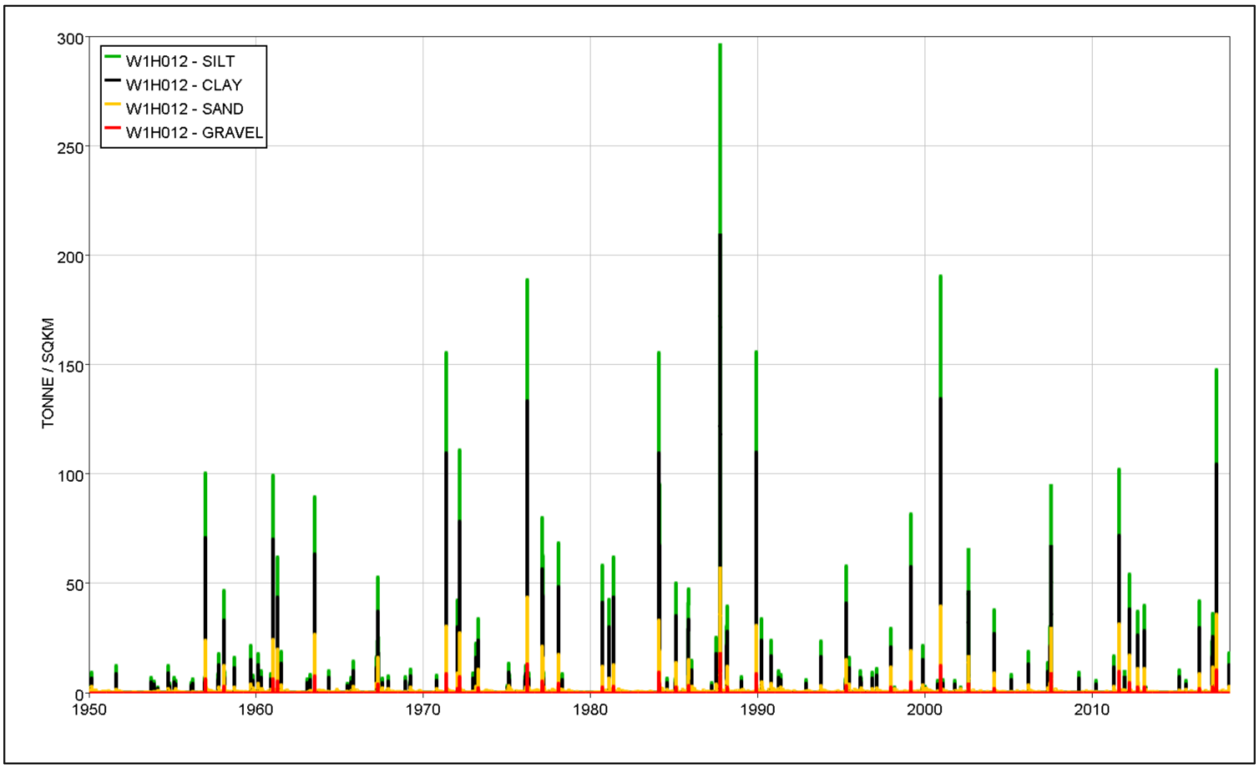


Figure 5.19: W1H012 Catchment simulated sediment grain size distribution (tonnes/day.km^2)

The W1H012 Catchment covers most of the catchment of the Ntuze River. This is the tributary of the Mlalazi River which is dominated by land use of subsistence cultivation and urban village with low vegetation to dense or open trees. The sediment yield grain size distribution from this catchment on the Ntuze River is dominated by mostly silt and clay. The 1:100 year event (September 1987) has yielded daily sediments of approximately 300 tonnes per square km of silt and 210 tonnes per square km of clay.

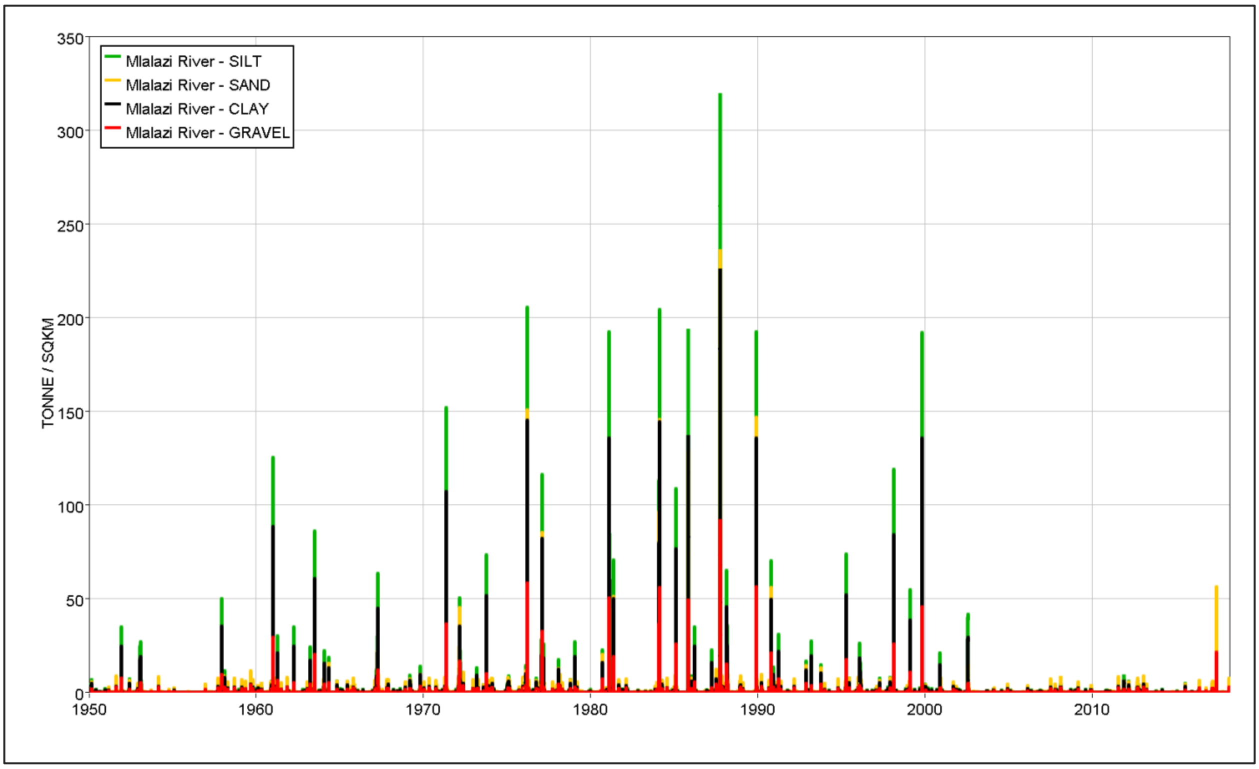


Figure 5.20: Mlalazi River simulated sediment grain size distribution (tonnes/day.km^2)

The sediment grainsize distribution of the catchment contributing to the Mlalazi River at a point before confluence with Ntuze River is presented above. The dominant land uses are commercial sugarcane, urban residential, dense bush, cultivation and subsistence cultivation. The grainsize distribution of the sediments simulated is dominated by mostly silt and sand. The 1:100 event has produced a daily sediment yield of approximately 320 tonnes per square km of silt and 240 of sand. Because both the Mlalazi River and Ntuze River at confluence which is an outlet to the Mlalazi Estuary are dominated by silt, clay and sand, it means that the distribution of sediment grain sizes entering the Mlalazi Estuary will be constituted of mostly silt, clay and sand.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The Mlalazi Estuary is prone to degradation from changing fluvial processes which will result in increased sediment yields from the catchment into the estuary; this could lead to management interventions such as mechanical breaching of the mouth to remove the sediments. This however, will need to be an objective decision to be made as opposed to a subjective one, based on the best available information. In the interest of objectivity in decision making, a need arises to assess the catchment and estuary systems using the best information that is frequently derived from numerical models which provide results that are comparable, reproducible and enable the prediction of effects from causes. It is for this reason that the HRU – University of Zululand is conducting a study funded by the WRC which aims at deriving hydrodynamic information of the Mlalazi Estuary which will assist in decision making and be applicable in other estuaries of similar hydrological conditions such as the Siyaya Estuary which is has been closed for an extended period of time. The necessity for that study was also because the Mlalazi Estuary’s Rapid Ecological Water Reserve (EWR) study by DWS (2015) was based on low confidence simulated monthly flows and no sediment information. This illustrated that there is no daily or sub-daily flow and sediment data for the Mlalazi Catchment which could be used to derive estuary hydrodynamic information. The EWR study was aimed at assisting DWS in making informed decisions regarding the authorisations of future water use and the magnitude of the impacts of the proposed developments on the water resources in the catchment, and to provide the input data for classification of the areas of the water resources.

The aim of this study was, as part of the study by the HRU, to derive reliable best estimates of the flows and sediments load out of the Mlalazi Catchment which is to be routed to the estuary catchment. This is because flows, erosion and sediment transport are the main drivers which may impact the opening and the closing of the estuary mouth. Given that these data is not measured for the Mlalazi Catchment as a whole, the hypothesis tested was that a physically based, numerical simulation model is the most pragmatic tool for the derivation of hydrodynamic information in catchments with limited observed data.

A literature reviewed of MIKE SHE, ACRU, SHETRAN, HEC-HMS and SWAT as suitable models with the capacity to achieve the required results was conducted for the purpose of this study to select a suitable model for application in the Mlalazi catchment. The MIKE SHE and SHETRAN could not be used because they are commercial products that were not freely available. The ACRU model although being an open source was not selected because it does not allow the routing of sediments. SWAT has data intensive requirements that were not available for the catchment. The HEC-HMS model was selected as the preferred model because it allowed some hydrological processes to be simulated using empirical or parameter fitting process models, rather than using mostly physical sub-models which will require measured data which might not be available for Mlalazi Catchment.

The Mlalazi Catchment is characterised by rainfall records that were not reliable and not always consistent with streamflows. This study had a limited series of observed flow data that did not cover the catchment adequately. However, this was overcome by using delineated sub-catchments for stations with data on the Ntuze Catchment for calibration. The results were extrapolated to other sub-catchments which are not gauged but have similar catchment characteristics. It was critical in this study to analyse the accuracy of the flow data used for calibration, this was because the rainfall data and streamflow data did not always correspond to one another, especially for extreme events. The flow gauging station W1H012 mostly used for calibration and validation was overestimating flows for extreme events which made it difficult to calibrate the model successfully. This was overcome by using a fitted equation discharge table produced from current gauging and slope area method to calibrate and validate the model. It was a lesson learnt that because a discharge table is a theoretical relationship, it can be prone to errors especially at high flows which could be due to submergence effect and as a result a flood event could be overestimated. This suggests that after any flood event, it is important that the flood marks are surveyed in order to determine the magnitude of the flood event accurately.

The HEC-HMS model was configured in HEC-GeoHMS and setup. A hydrologically correct and depressionless DEM derived formed the basis of the derivation of all geospatial and input files into HEC-HMS Model. Since HEC-HMS is a semi-distributed model, sub-basins were divided based on similar land use and location of flow gauges which allowed for input data to be lumped for some catchments. An event based and a continuous based approach for model calibration has allowed a configuration of a model would be able to simulate other storm events in future. The overall results of the calibration and validation of the continuous simulations were good and confirmed that the calibrated parameters are sufficiently valid for estimation of flows for the Mlalazi Catchment. The flows were then computed on a daily time step from January 1950 to March 2018 (68 years) for use in the study by the HRU.

There was no observed data to enable the calibration of the sediment yield model, so the MUSLE sediment model was not calibrated but was setup based on input parameters taken from data already available from other studies in the area. The accuracy of the simulated sediment data was evaluated on the basis that the results should be comparable to other regional studies. The sediment yield simulations have shown that for a 1:100 recurrence flood event the yield from the catchment is 1100 t/km^2.a, the yield for the 1:10 event is 500 t/km^2.a. It was found that the sediment results are comparable to the regional study by Msadala et al. (2010) who found that a 1:100 storm event will yielded 1050 t/km^2.a and a 1:10 event yielded sediments of 700 t/km^2.a. This study of Mlalazi Catchment has found that the distribution of sediment grain sizes entering the Mlalazi Estuary will be constituted of mostly silt, clay and sand respectively.

It was concluded that the use a calibrated HEC-HMS model in the Mlalazi Catchment which is characterised by limited observed data was the most pragmatic approach to derive the best estimates of the flows and sediment yield information for the Mlalazi Catchment, information that was lacking in the EWR (2015) study. If the Hydrological Research Unit (HRU) of the University of Zululand is to be reinstituted, it is recommended that the flow gauge W1H012 should be resurrected since it has proven to be crucial for catchment studies. It is also recommended that the DWS as part of its monitoring network should consider monitoring sites for sediment load in the Mlalazi Catchment since this data is not monitored for the catchment as a whole. This is because the sediment transport is also one of the drivers of the estuary dynamics.

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APPENDIX

Table A.1: MUSLE erosion model input parameters for Mlalazi Catchment

Basin	**Cover factor (C)**	**Erodibility Factor (K)**	**Topography Factor (LS)**
W560	0.003	0.18	1.06
W960	0.003	0.22	5.14
W480	0.15	0.42	6.6
W680	0.09	0.27	6.7
W620	0.09	0.39	5.5
W900	0.03	0.38	3.3
W870	0.15	0.31	1.15
W790	0.15	0.38	3.7
W770	0.09	0.39	2.58
W880	0.15	0.33	2.5
W890	0.03	0.43	1.4
W1020	0.15	0.38	4.8
W550	0.15	0.34	3.6
W490	0.03	0.42	2.27
W1080	0.03	0.42	3.29
W1060	0.15	0.38	1.85
W570	0.15	0.37	3.09
W630	0.15	0.27	3.35
W1120	0.15	0.27	2.19
W780	0.15	0.38	2.36
W830	0.15	0.38	3.04

ANNEXURE A: CANDIDATE'S ORIGINALITY DECLARATION (RESEARCH PAPERS, MINI-DISSERTATIONS, DISSERTATIONS AND THESES)

ORIGINALITY DECLARATION

Full Names and Surname	Khathutshelo Joshua Rasifudi
Student Number	201454749
Title of dissertation/thesis	Simulation of catchment runoff, erosion and sediment transport using a transient numerical model for Mlalazi Catchment

I acknowledge that I have read and understood the University's policies and rules applicable to postgraduate research, and I certify that I have, to the best of my knowledge and belief, complied with their requirements.

In particular, I confirm that I had obtained an ethical clearance certificate for my research (Certificate Number UZREC 171110-030 PGM 2018/592) and that I have complied with the conditions set out in that certificate.

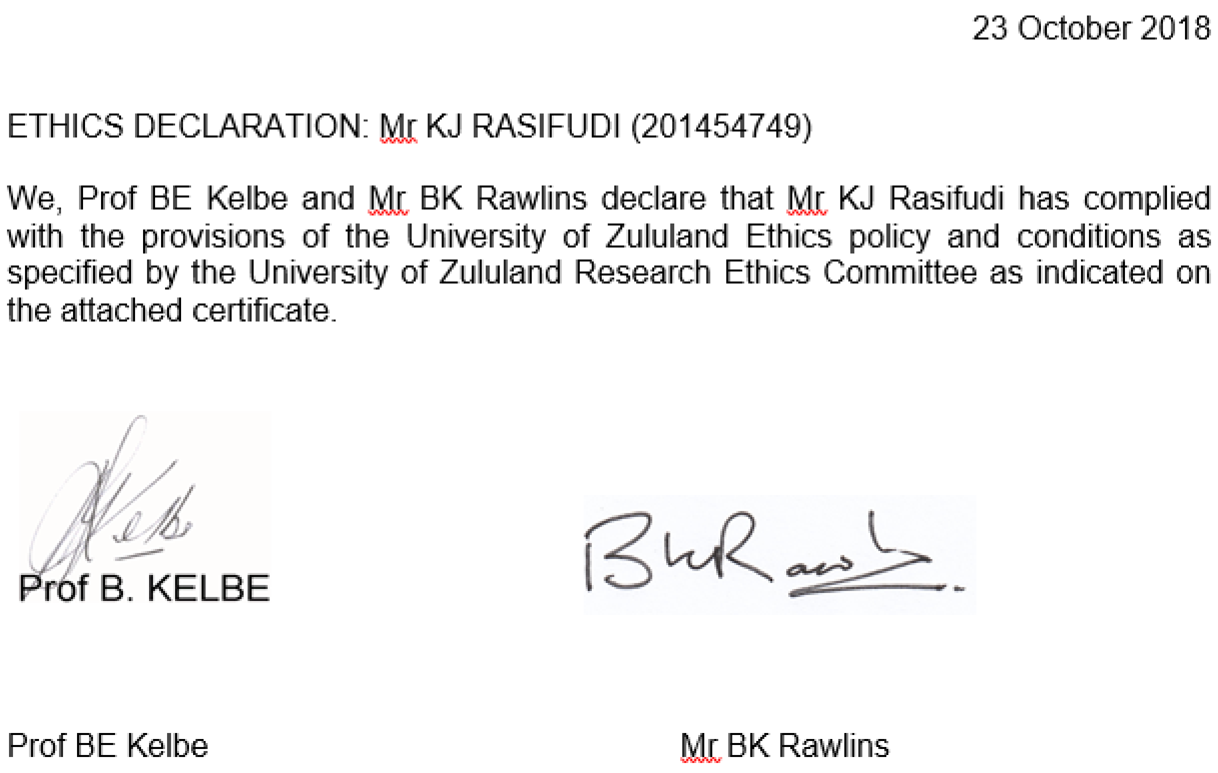
I further certify that this dissertation is original, and that the material has not been published elsewhere, or submitted, either in whole or in part, for a degree at this or any other university.

I declare that this dissertation is, save for the supervisory guidance received, the product of my own work and effort. I have, to the best of my knowledge and belief, complied with the University's Plagiarism Policy and acknowledged all sources of information in line with normal academic conventions.

I have subjected the document to the University's text-matching and/or similarity-checking procedures.

Candidate's signature	
Date	25/10/2018

ANNEXURE B: UNIVERSITY'S RESEARCH ETHICS DECLARATION AND CERTIFICATE



23 October 2018

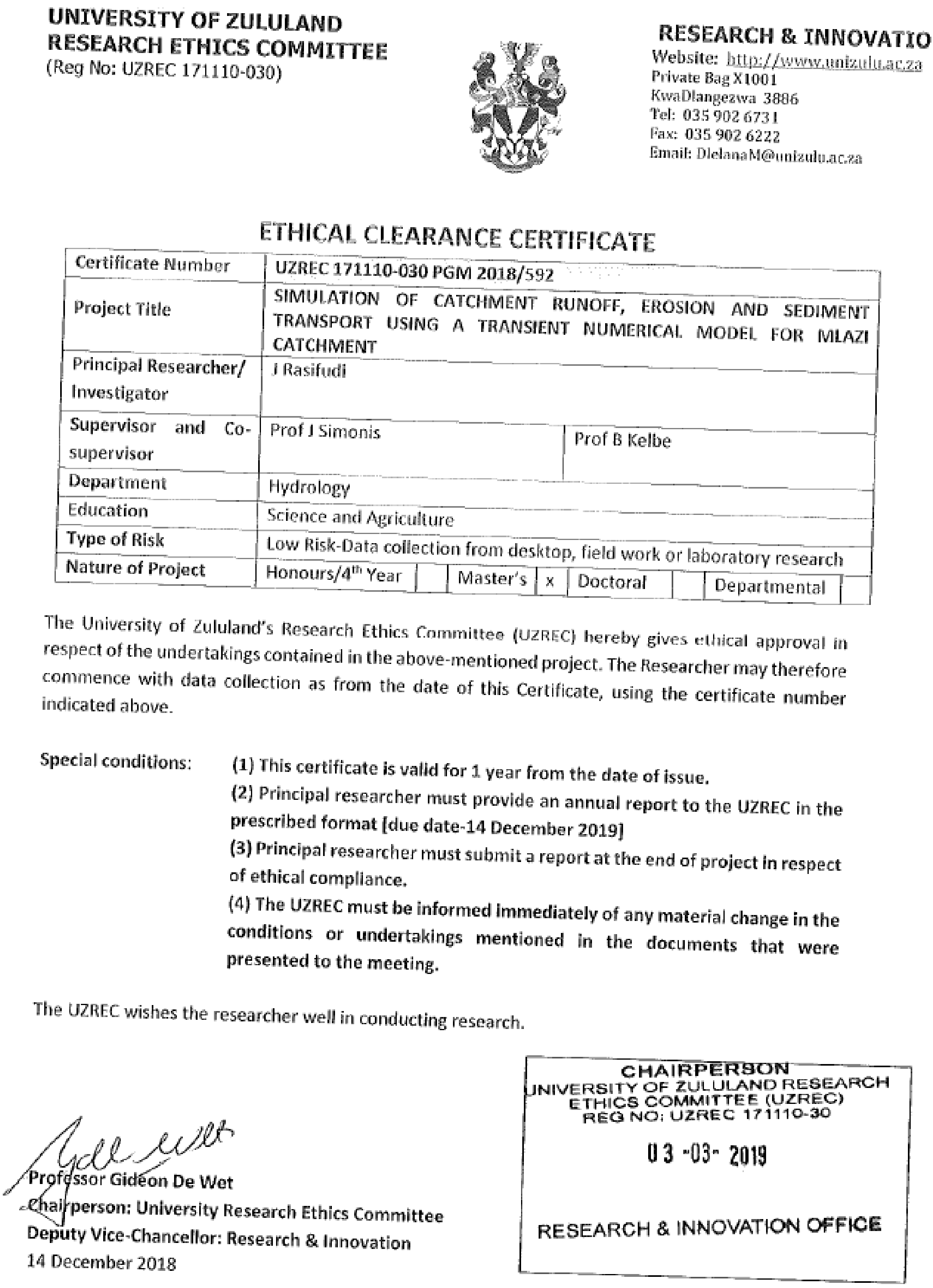
ETHICS DECLARATION: Mr KJ RASIFUDI (201454749)

We, Prof BE Kelbe and Mr BK Rawlins declare that Mr KJ Rasifudi has complied with the provisions of the University of Zululand Ethics policy and conditions as specified by the University of Zululand Research Ethics Committee as indicated on the attached certificate.

Prof B. KELBE

Prof BE Kelbe

Mr BK Rawlins



UNIVERSITY OF ZULULAND
RESEARCH ETHICS COMMITTEE
(Reg No: UZREC 171110-030)

RESEARCH & INNOVATION
Website: http://www.unizulu.ac.za
Private Bag X1001
KwaDlangezwa 3886
Tel: 035 902 6731
Fax: 035 902 6222
Email: DlelanaM@unizulu.ac.za

ETHICAL CLEARANCE CERTIFICATE

Certificate Number	**UZREC 171110-030 PGM 2018/592**	
Project Title	SIMULATION OF CATCHMENT RUNOFF, EROSION AND SEDIMENT TRANSPORT USING A TRANSIENT NUMERICAL MODEL FOR MLAZI CATCHMENT	
Principal Researcher/ Investigator	J Rasifudi	
Supervisor and Co-supervisor	Prof J Simonis	Prof B Kelbe
Department	Hydrology	
Education	Science and Agriculture	
Type of Risk	Low Risk-Data collection from desktop, field work or laboratory research	
Nature of Project	Honours/4th Year ☐ Master's ☒ Doctoral ☐ Departmental ☐	

The University of Zululand's Research Ethics Committee (UZREC) hereby gives ethical approval in respect of the undertakings contained in the above-mentioned project. The Researcher may therefore commence with data collection as from the date of this Certificate, using the certificate number indicated above.

Special conditions:

(1) This certificate is valid for 1 year from the date of issue.

(2) Principal researcher must provide an annual report to the UZREC in the prescribed format [due date-14 December 2019]

(3) Principal researcher must submit a report at the end of project in respect of ethical compliance.

(4) The UZREC must be informed immediately of any material change in the conditions or undertakings mentioned in the documents that were presented to the meeting.

The UZREC wishes the researcher well in conducting research.

Professor Gideon De Wet
Chairperson: University Research Ethics Committee
Deputy Vice-Chancellor: Research & Innovation
14 December 2018

CHAIRPERSON
UNIVERSITY OF ZULULAND RESEARCH
ETHICS COMMITTEE (UZREC)
REG NO: UZREC 171110-30
03 -03- 2019
RESEARCH & INNOVATION OFFICE