Developing Methods for Converting Digitised Rivers into a Hydrological Drainage Network

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Background

In this study techniques were investigated to create a South African river network that is repeatable and applicable to all the water catchments in South Africa. The methodology was implemented on two selected catchments and aimed to produce a network that will contain rivers similar to the 1:250 000 scale topographic maps at an accuracy that is equivalent to the 1:50 000 scale.

Spatial databases of drainage networks are invaluable in many fields, for example spatial analysis and hydrological modelling. River lines in a hydrological network must be seamlessly connected and must have flow direction. Hydrological modelling is an essential component of water resource management and the importance of river network databases is evident in the extensive efforts that have been undertaken to date in attempting to develop standard river network datasets for South Africa.

These efforts date back to the 1990s when the Department of Water Affairs started projects to produce improved river lines for use in GIS modelling from the country's 1:50 000 topographic maps. Resource Quality Services (RQS) and the Directorate of Spatial and Land Information Management worked on river networks visible on the 1:500 000 scale and the 1:50 000 scale topographic maps, respectively. The aforementioned 1:500 000 spatial dataset was completed after 10 years while the latter is still in process.

The Department of Rural Development and Land Reform – Chief Directorate: National Geo-spatial Information (NGI) is responsible for the 1:50 000 topographic maps (including river lines). The focus of these datasets is on the geographic representation of the data. Their utility remains and continues to be substantially constrained by numerous inconsistencies and inaccuracies imparted by compilation from aerial photographs. The major inaccuracies include: a) some gaps between tributaries and main streams, b) isolated and incomplete river lines, c) inconsistency in density of river coverage between map sheets and d) numerous instances in which lines do not point downstream.

River networks are not only important for hydrology, but also many other disciplines such as anthropology, ecosystems, groundwater recharge, epidemiology and geomorphology. An example where a South African hydrological network has been useful outside the hydrological domain is the epidemiological study of cholera in the Thukela by Bertuzze et al. (2008) who made use of the RQS 1:500 000 river network.

Aim and Objectives

The aim was to develop a semi-automated methodology for creating a robust, country wide, accurate river network coverage for use in GIS projects and other planning initiatives in South Africa. This was achieved by applying the following objectives in two selected catchments:

- Creation of river networks through improvement of 1:50 000 river lines from NGI. River lines should be seamlessly connected, contain flow direction and attributes such as stream order and perennial status.

- Adopting suitable modelling approach to select river lines from SRTM flow paths for trans-boundary catchment areas.
- Mapping of vegetation from remote sensing data, as supportive information in arid environments, such as the D42 study site, where trees are sometimes confined to the banks of ephemeral rivers.
- Mapping of open water bodies from remote sensing imagery as supportive information in identifying river lines and perennial status of river.

Methodology

The methodology was applied to a portion of the Molopo catchment (Tertiary catchment D42) in the Northern Cape Province and the Mzimvubu catchment (Secondary catchment T3) in the Eastern Cape Province.

The Molopo catchment falls in a low rainfall regime area with a groundwater mean annual recharge of only 0.1-5 mm and is located on the border of South Africa, Botswana and Namibia. The area is drained by the Nossob, Auob and Molopo rivers and is 250 000 km^2 in size of which 57 000 km^2 (23%) is within the borders of South Africa.

The Mzimvubu River catchment is classified as a primary catchment and falls in a sub-humid climate with a groundwater mean annual recharge of 12-70 mm. It has a drainage area of 19 826 km^2 and a flow length of approximately 350 km from north to south.

<u>Developing of the river editing tool</u>

The River Editing tool developed for this project simplifies the editing of both line features and attribute data. Amongst others it has the following functionality:

- Automatically applying flow direction of stream lines from a DEM.
- Automatically applying flow direction from the mouth of a river network.
- Finding loops in the river network.
- Selecting upstream or downstream line segments from a specified position.
- Assigning attributes to all selected stream lines.
- Calculating stream order of river segments in a river network.

The River Editing tool was used to calculate stream order values for four different stream order types (Strahler, Horton, Shreve and Hack). During the calculation of the stream orders the distance of the longest upstream path in the river network was also calculated and stored.

<u>Remote sensing imagery and derived products used to improve the river centre lines</u>

Remote sensing imagery was useful in correcting errors in the river centre line data and also to identify the perennial status of streams. The following products were used as backdrop during manual editing of the data:

- NGI colour aerial photography: Molopo and Mzimvubu catchments.
- SPOT 5 imagery (2005-2011): Molopo and Mzimvubu catchments.
- Landsat 8 imagery (2000, 2014): Molopo catchment (trans-boundary area).
- Water classification (NDWI) from SPOT 5 imagery: Mzimvubu catchment.
- Unsupervised classification of water from SPOT 5 imagery: Mzimvubu catchment.
- Vegetation classification: Molopo catchment.

Extraction of river networks from SRTM flow paths

The river centre lines of NGI are only available for South Africa. Flow paths were therefore calculated from the hydrologically improved DEM for cross-border areas of the Molopo catchment. A threshold of 100 was used to indicate the start of flow paths from a flow accumulation grid.

River networks were selected from flow paths, taking into consideration homogeneous areas with respect to drainage density (DD) and environmental variables such as precipitation, landcover, soils and terrain. This task was based on the conjunctive use of digital elevation data and environmental parameters in a grid-based GIS. The landscape was manually stratified into drainage density classes.

Two parameters that showed a high correlation with DD were the Arenosols soil group and mountainous areas. Particular characteristics of Arenosols are low reserves of weatherable minerals and low silt:clay ratios. The mountainous areas were derived from the SRTM DEM. They had a high DD while Arenosols had a low DD. All areas were ranked according to rainfall and vegetation with sparser vegetation and higher rainfall areas resulting in higher DD.

Conclusion and recommendations

River networks were successfully developed for the Molopo and Mzimvubu catchments. This was achieved through the following:

- Development of river editing tool
- Calculation of flow paths from a DEM
- Extraction of river networks from SRTM flow paths
- Derivation of supporting information from imagery

The networks were in sharp contrast to each other, mainly due to the huge difference in rainfall and steepness of terrain. The Mzimvubu catchment has a well-defined river network with a high DD, while the river network of the Molopo catchment is intermittent with a low DD. The Molopo catchment had numerous small river networks, which were not connected to the main stem, but ended in pans. The perennial status of streams in the Mzimvubu river was either perennial or non-perennial, while the streams in the Molopo could be ephemeral or non-perennial.

The four different stream order types that were calculated make it possible to do subsets of the river network. For example, it was illustrated that it is possible to select stream lines at the same level of detail that are displayed on the 1:250 000 maps from the 1:50 000 dataset. The calculation of stream order took a considerable amount of time. For example, for the complete secondary catchment T3 (122 423 line features) it took 161 hours, while tertiary catchments T31 (15 705 features) and T34 (25 233 features) took 4 and 10 hours to complete, respectively.

A product was developed indicating the number of times that surface water was classified from the SPOT 5 mosaics for the period 2005-2011. By applying some level of interpretation the following information can be derived from this dataset:

- Perennial status of large rivers
- Area covered by dams
- Selecting the most significant branch in braided systems

For the Molopo catchment it was not possible to classify open water, due to the fact that the river beds were mostly dry. A classification of vegetation was done instead and was included as one of the layers used as backdrop during the editing of stream lines. Riparian vegetation often indicated the actual position of streams, when it was unclear on the colour image itself.

The River Editing tool was successfully tested on a large dataset such as the Mzimvubu River network (124 528 line segments).

The River Editing tool was found to be very useful during the editing of the data to develop river networks. Some of the functions take some time to execute, but it is significantly faster than manual editing. A large improvement from previous versions of the river line data is that most streams have recently been connected by NGI.

Remote sensing imagery was useful in correcting errors in the river centre line data and also to identify the perennial status of streams from derived products.

NGI must be informed of corrections that were done so that the corrections can also be made on the master dataset hosted by them and incorporated in future.

The following follow-up studies are proposed:

- River networks should be developed for the whole country from the NGI dataset. This has to be considered the master dataset and any improvements should be returned to NGI. Since NGI is continuously improving their data the process of developing river networks for all catchments in SA has to be repeated at regular intervals (perhaps every 10 years).
- A dataset of mountains should be developed for SA. Currently such a dataset does not seem to be readily available.
- Two studies that could be done for the Molopo catchment specifically are:
    - Lineament analysis based on different satellite data could contribute to the detection of near-surface fault and fracture zones with potential influence on dissolution processes in sub-terrain waterways.
    - The patterns and surface alignments of karst ($CaCO_3$) features are often associated with joint patterns, faulting and folding. Channels in karst groundwater are formed from rock dissolution along planes or discontinuities. Therefore, the relationship between the occurrence of depressions, karst development and the tectonic pattern could be investigated by using remote sensing and GIS.

Capacity building

The research studies of two members of the project team benefited from this project. Harold Weepener is studying for a PhD degree at the Geography and Environmental Studies Department of the University of Stellenbosch. His thesis is titled: "Application of earth observations and geographical information systems for water resource database development". Simone Pretorius is registered at the University of Pretoria to conduct her MSc at the Centre for Environmental Studies at the Faculty of Natural and Agricultural Sciences. Her research project is titled: “Sediment Yield Modelling of the Tsitsa River Catchment”

Institutional capacity building included the Agricultural Research Council, Department of Water Affairs and National Geo-spatial Information.

The Mzimvubu River network was also used as a key dataset in another WRC-funded project entitled “Sediment yield modelling in the Mzimvubu river catchment” (K5-22431).

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Name	**Organization**
Mr W Nomquphu	Water Research Commission
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LIST OF ABBREVIATIONS

ARC – Agricultural Research Council

ARVI – Atmospherically Resistant Vegetation Index

ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer

CDSM – Chief Directorate: Surveys and Mapping

CIR– Colour Infrared

CSIR – Council for Scientific and Industrial Research

DD – Drainage Density

DEM – Digital Elevation Model

DWA – Department of Water Affairs

ETM+ – Enhanced Thematic Mapper Plus

EVI – Enhanced Vegetation Index

FAO – Food and Agricultural Organization

GIS – Geographical Information System

GRS – Grid Reference System

GSD – Ground Sample Distance

HRes – High resolution

ISODATA – Iterative Self-Organizing Data Analysis Techniques A

iTIS – integrated Topographic Information System (iTIS)

MSS – Multispectral Scanner

MIR– Mid Infrared

MNDWI – Modified Normalised Difference Water Index

NDVI – Normalised Difference Vegetation Index

NDWI – Normalised Difference Water Index

NGI – Chief Directorate of National Geospatial Information

NIR – Near Infrared

NTIS – National Topographic Information System

NVI – New Vegetation Index

OBIA – Object-Based Image Analysis

R – Red

RGB – Colour (Red, Green, Blue)

RQS – Resource Quality Services (Department of Water Affairs)

SANSA – South African National Space Agency

SAVI – Soil Adjusted Vegetation Index

SOTER – Soils and Terrain Digital Database

SPOT – Système Pour l'Observation de la Terre (lit. "System for Earth Observation")

SRTM – Shuttle Radar Topography Mission

SWIR – Shortwave Infrared

TM – Thematic Mapper

USGS –.United States Geological Survey

UTC – Coordinated Universal Time

UTM – Universal Transverse Mercator

VI – Vegetation Indices

WGS84 – World Geodetic System 1984

WRC – Water Research Commission

GLOSSARY

Aquifer	Rock mass or layer that readily transmits and holds groundwater.
Artesian water	Artesian water is confined in an aquifer between impermeable beds and is under pressure, like water in a pipe. When a well or fracture intersects the aquifer, water rises in the opening, producing a flowing well or an artesian spring
Aspect	Compass direction of steepest downhill slope
Digital Elevation Model	A Digital Elevation Model (DEM) represents the spatial distribution of elevations above some arbitrary datum in a landscape
Elevation	Height above mean sea level or local reference
Flow accumulation	The accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output grid
Gauging station	A gauging station is a site on a river which has been selected, equipped and operated to provide the basic data from which systematic records of water level (stage) and discharge may be derived. Essentially it consists of a natural or artificial river cross-section where a continuous record of stage can be obtained and where a relation between stage and discharge can be determined
Geometric correction	The process of removing geometric distortions on digital images.
Hillshade	A shaded relief grid derived from a DEM by considering the illumination angle and shadows
Hydrology	The study of water as a complex but unified system on the earth. This includes the study of both subsurface and surface pathways of water flow. Flow across a surface will always be in the steepest down-slope direction
Image classification	Grouping image pixels into categories or classes to produce a thematic representation
Infrared	The region of the electromagnetic spectrum that includes wavelengths from 0.7µm to 1 mm.
ISODATA	An algorithm used in unsupervised classification that permits the number of clusters to change from one iteration to the next by merging, splitting and deleting clusters.
Map projection	The manner in which the spherical surface of the Earth is represented on a flat (two-dimensional) surface.
Mosaic	A process of stitching images together so one large, cohesive image of an area can be created.

Orthorectification	The process of reducing geometric errors inherent within photography and imagery. The variables contributing to geometric errors include, but are not limited to camera and sensor orientation, systematic error associated with the camera or sensor, topographic relief displacement, and Earth curvature.
Pixel	The smallest element of an image that can be individually processed. The more rows and columns of pixels, the finer the image detail that can be resolved.
Pour point	An outlet, or pour point is the point at which water flows out of an area. This is the lowest point along the boundary of the watershed
Remote sensing	Collection and interpretation of information about an object without being in physical contact with the object.
Ridge	Cells with no upstream contributing area
Sink	A sink is defined as a cell or a set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. In other words, a depression is a grid cell that does not have a lower neighbour and therefore represents a barrier to flow
Slope	Rate of change of elevation
Spatial resolution	A measure of the smallest angular or linear separation between objects.
Spectral band	A well-defined continuous range of wavelengths in the electromagnetic region.
Spectral index	A single number derived from an arithmetic operation of two or more spectral bands.
Texture	The visual impression of coarseness or smoothness caused by the variability or uniformity of image tone or colour
Unsupervised classification	An image classification technique in which the computer assigns pixels to categories with no instructions from the operator.
Watershed	A watershed is an area that drains water and other substances to a common outlet as concentrated drainage. Other common terms for a watershed are: basin, catchment, drainage region or contributing area. This area is normally defined as the total area flowing to a given outlet, or pour point.

1 INTRODUCTION

1.1 Background and importance

Spatial databases of drainage networks are invaluably important for hydrological studies and play in important role in guiding the formulation and implementation of appropriately informed water management policies. River lines that contain some level of spatial intelligence are required by Geographic Information Systems (GIS) and numerical hydraulic/hydrological modelling systems. Spatially intelligent river lines have to be seamlessly connected and must have flow direction and attributes such as stream order and perennial status. The importance of intelligent river-line databases is demonstrated by the extensive efforts that have been undertaken to date in attempting to develop standard river network datasets for South Africa (SA).

These efforts date back to the 1990s when the Department of Water Affairs started projects to produce improved river lines for use in GIS modelling from the country's 1:50 000 topographic maps. Resource Quality Services (RQS) and the Directorate of Spatial and Land Information Management worked respectively on river networks visible on the 1:500 000 scale and the 1:50 000 scale topographic maps. The aforementioned 1:500 000 spatial dataset was completed after 10 years, while the latter-mentioned dataset is still in process.

The Department of Rural Development and Land Reform – Chief Directorate: National Geo-spatial Information (NGI) is responsible for the 1:50 000 topographic maps (including river lines). The focus of these datasets is on the geographic representation of the data. Though compilation of more accurate river lines is still an ongoing process the available datasets fall short of meeting the broad requirements of the geo-spatial community because they are generally incapable of supporting the requirements of hydrological modelling. Their utility remains and continues to be, substantially constrained by numerous inconsistencies and inaccuracies. The major inaccuracies include a) Some large gaps between tributaries and main streams, b) isolated and incomplete river lines and c) numerous instances in which lines do not point downstream.

DWAF (2006) lists the following usages for such a river-network coverage:

- It provides a background vector coverage for mapping the national Department of Water Affairs' monitoring points.
- It is important for various modelling tasks and for deriving river profile and valley characteristics
- It can be used for river classification
- It can be used as a network model of South African drainage for use in systems such as BASINS (EPA, 2004)

Remotely sensed data and digital elevation data that became available over the last few years offers considerable potential for organised improvement in river line data including:

- High resolution (HRes) images that have been acquired by National Geospatial Information (NGI) since 2008. All images secured by NGI are acquired by HRes digital sensors in both colour (RGB) and colour infra-red (CIR) at a Ground Sample Distance (GSD) of 0.5 m.

- A set of cloud-free SPOT 5 images from the Satellite Applications Centre (SAC) for every year from 2006 to 2012. Each image contains four bands at a GSD of 10 m and one panchromatic band at a GSD of 2.5 m. The images were also mosaicked as pan-sharpened colour images.

- Two global, high resolution digital elevation models (DEMs), namely the Shuttle Radar Topography Mission (SRTM) DEM (USGS, 2006; Farr & Cobrick, 2000) and the Aster Global DEM (GDEM) (METI and NASA, 2011. Weepener et al. (2012) showed that such DEMs can be employed to delineate connected flow paths with flow direction and stream orders. However, flow paths cannot directly be interpreted as stream lines as the density of streams varies. This is illustrated in Figure 1 which shows the variation between flow paths derived from the same source (SRTM DEM) by two different studies. Figure 1A illustrates streams digitised by NGI compared to flow paths derived from the SRTM DEM in Figure 1B by Lehner et al. (2006) and Figure 1C by Weepener et al. (2012).

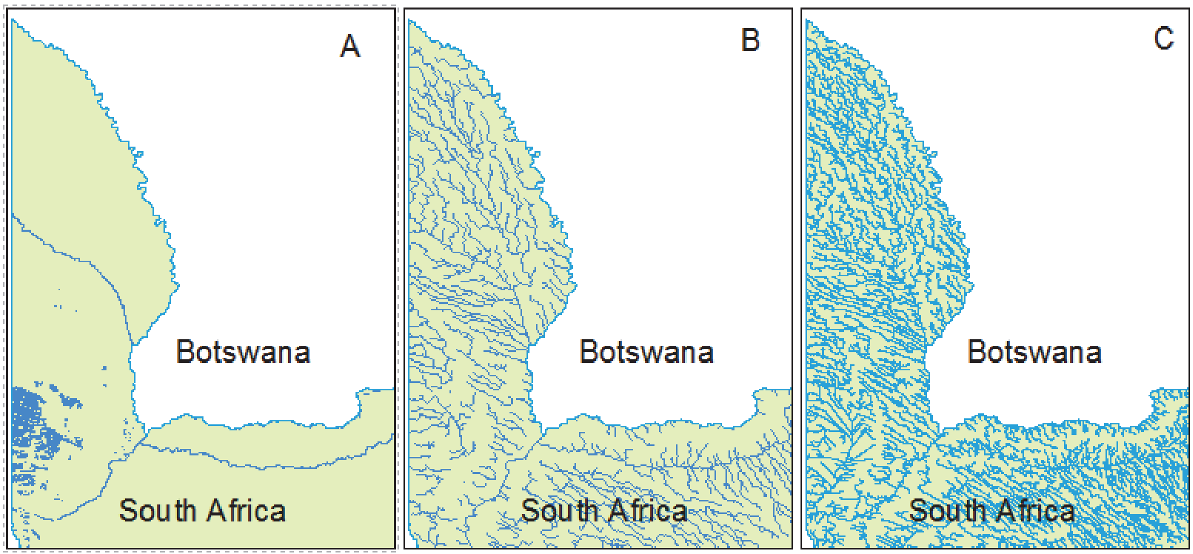
- 

Figure 1 (A) Streams digitised by NGI compare to flow paths derived from the SRTM DEM by (B) Lehner et al. *(2006) and (C) Weepener et al. (2012).*

1.2 Aim and Objectives

The aim was to develop a semi-automated methodology for creating a robust, country wide, accurate river network coverage for use in GIS projects and other planning initiatives in South Africa. This was achieved by applying the following objectives in two selected catchments:

- Creation of river networks through improvement of 1:50 000 river lines from NGI. River lines should be seamlessly connected, contain flow direction and attributes such as stream order and perennial status
- Adopting suitable modelling approach to select river lines from SRTM flow paths for trans-boundary catchment areas.

- Mapping of vegetation from remote sensing data, as supportive information in arid environments, such as the D42 study site, where trees are sometimes confined to the banks of ephemeral rivers.
- Mapping of open water bodies from remote sensing imagery as supportive information in identifying river lines and perennial status of river.

1.3 Research approach

It is proposed here to develop a semi-automatic methodology to compile, a robust and accurate river-network coverage for use in GIS projects. The methodology will be implemented on two selected catchments and aim to produce a network that will contain rivers similar to the 1:250 000 scale topographic maps at an accuracy that is equivalent to the 1:50 000 scale (the intention is for the whole country to be completed with follow-up projects).

Criteria for selecting the two catchments are described in Section 2. The methodology developed in this study will be repeatable and applicable to the remaining catchments in South Africa.

Figure 2 provides a schematic presentation of the processes applied in this project to create river networks.

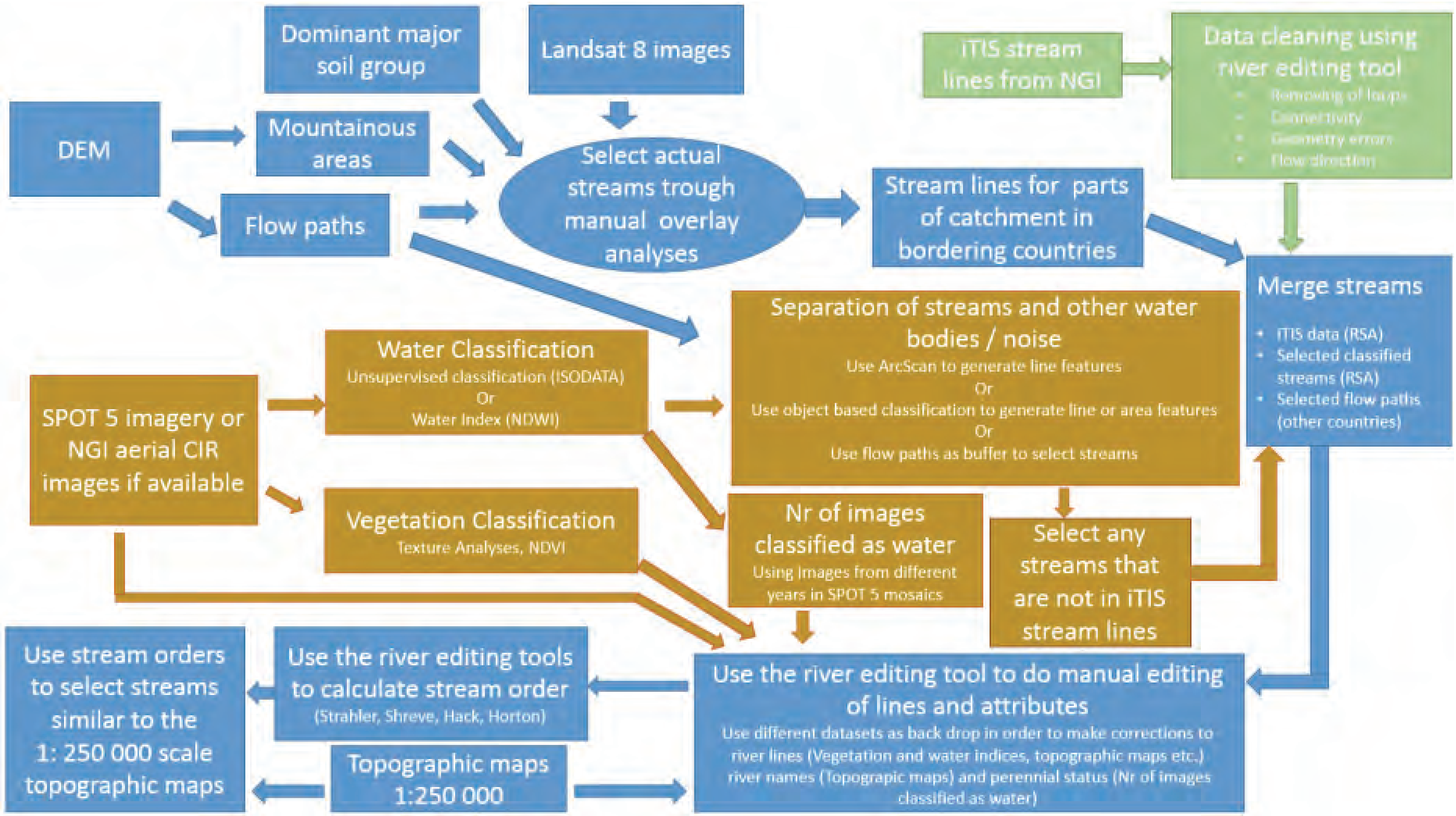


Figure 2 Schematic presentation of the processes applied to create river networks.

1.4 The structure of the report

This project report is organised into five main chapters as follows:

Chapter 1 provide the introduction which will focus on the background of the research and stating the problem statement, subsequently resulting in the highlighting of the aims and objectives. Chapter 2 describe the two study areas and baseline datasets of the project. Chapter 3 provide the methodology followed to develop river networks for the two study areas. The results and discussion is provided in chapter 4. Finally chapter 5 presents the conclusions from the study and recommendations.

2 DESCRIPTION OF STUDY AREAS AND BASELINE DATASETS.

Two catchments were selected for this study on the basis of the following criteria:

- Rainfall was used as one of the criteria in order to ensure inclusion of areas with markedly different rainfall regimes. Because of this consideration, one study area was in high rainfall area and the other in a low rainfall area. This parameterization was reasoned to be ideal for confident digitization of river lines from SPOT 5 images in the high rainfall regime, which is associated with active channels that can easily be identified from these images, while it is very difficult to map river lines in dry areas because most rivers are extremely intermittent to the extent that they are difficult to identify on images covering flat and sandy landscapes.
- One study area to be on the border of South Africa to test the continuity of the dataset when it changes over to using SRTM flow paths only;

The procedures described in this report were only applied to the two study areas. Input datasets were however selected to cover the whole country and to be readily available, in order to expand the project to the rest of the country when required. Some regional datasets were required for the trans boundary area of catchment D42. Both the national and regional datasets that were used in this project will be described.

2.1 Molopo catchment

The Molopo catchment (Tertiary catchment D42) falls in a low rainfall regime area with a ground water mean annual recharge of only 0.1 to 5 mm and is located on the border of South Africa, Botswana and Namibia. The area is drained by the Nossob, Auob and Molopo rivers and is 25 000 000 ha in size of which 5 700 000 ha (23%) is within the borders of South Africa. Most of catchment D42 receives between 100 mm and 300 mm annual rainfall with the exception of the Eastern part of the catchment as well as the Western part in Namibia, which both receive more than 300 mm annual rainfall. Figure 3 illustrates the main tributaries of the Molopo catchment.

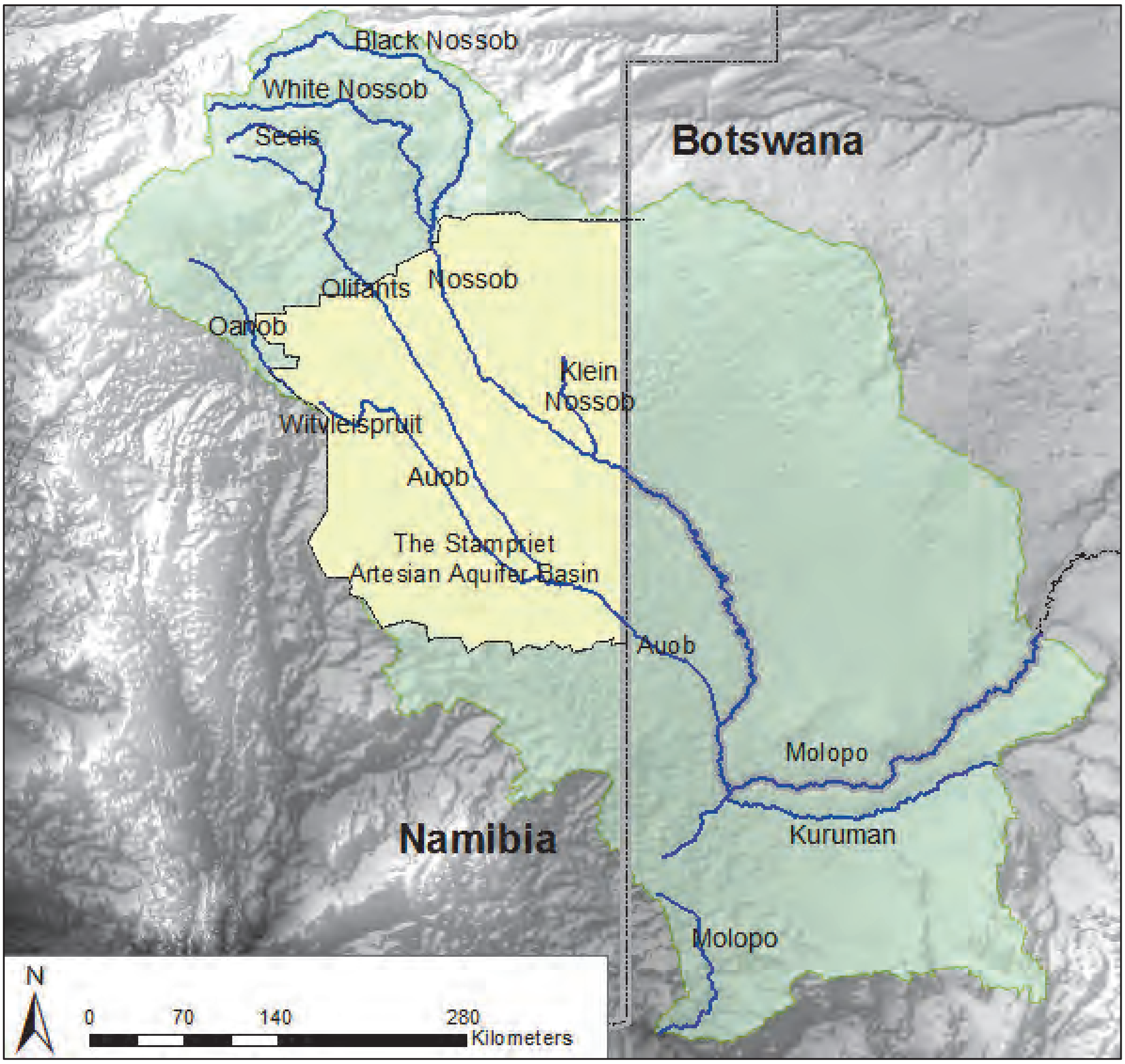


Figure 3 The main tributaries of the Molopo catchment. The Namibian part of the Stampriet artesian aquifer basin is indicated in yellow.

Tertiary catchment D42 is drained through the Molopo river into the Orange river just downstream from the Augrabies waterfall. The Molopo- and Kuruman rivers originate in catchment D41, which was not included in this study. The Kuruman River originates south east of Kuruman, where it is fed by various springs, most notably the Great Koning Eye, Little Koning Eye and the Kuruman Eye, while the Molopo River emanates from the area to the east of Mafikeng, where it is fed by various springs, most notably the Molopo Eye and the Grootfontein Eye. The Kuruman river has its confluence with the Molopo River at Andriesvale, in close proximity to the Nossob/Molopo confluence. The Molopo River surface flows decreased significantly and are not reaching the Main stem of the Orange River anymore (van Veelen and Baker, 2009). Spinage (2012) writes that the Molopo is known to have broken its banks in 1894 below its confluence with the Kuruman because of flooding in the latter and sediment in the former. Moffat (1842) asserted it was once a large river emptying itself into the Gariep at a distance below the waterfall.

The main river bed of the Molopo river is currently covered by sand dunes that cross the original path at 90 degrees. In the year 2000 when the Molopo was in flood the water ended up in a pan about 6 kilometres west from the place where the Molopo previously turned south. Rivers in catchment D42 do not really have smaller tributaries. This is mainly caused be the low rainfall, relative flat terrain and the Kalahari sand dunes, which covers most of the catchment. Small streams do appear in dune streets, but ends quickly in interdune depressions or in one of the numerous pans in the area. The large rivers are however well defined with wide sand beds and often deeply carved into the landscape. Indicating that there was previously significantly more water flow than is currently the case.

The two main rivers that flow into catchment D42 from Namibia are the Nossob and Auob rivers. The confluence of the Nossob and Auob is near Twee rivieren, the main entrance to the Kgalagadi trans frontier park. Most of the water in the Namibian part of catchment D42 is accumulated in the Khomas Hochland Plateau, which receives between 300 mm and 450 mm rainfall per year. The main rivers in the Khomas Hochland Plateau are the following:

- The White Nossob and Black Nossob join each other to form the Nossob near the edge of the plateau
- The confluence of the Olifants and Seeis is also near the edge of the plateau to form the Olifants

Elevation ranges from 450 m at the confluence of the Molopo into the Orange to 2450 at the upper reaches of the Oanob river in the Khomas Hochland Plateau.

Towards the West of the catchment (In Namibia) the Oanob receives its water from both the Khomas Hochland and Rehoboth Plateaus. The Oanob river ends just before the start of the Witvlei spruit (near the town Kalkrand), which joins the Auob river to form the Auob river at Stampriet. The Oanob river most probably feeds into the Stampriet Artesian Aquifer.

There are a number of dams in the upper reaches of the rivers in the Namibian part of the catchment (van Veelen and Baker, 2009), however, there are no significant rivers or dams in the Botswana part of catchment D42. The Otjivero Main Dam and Otjivero Silt Dam are located on the upper reaches of the White Nossob River in Namibia, approximately 100 km to the to the east of Windhoek. The Daan Viljoen Dam and Tilda Viljoen Dam are located at Gobabis. The Daan Viljoen Dam is an in-channel dam on the Black Nossob River, which impounds flood waters. The water is then pumped into the larger Tilda Viljoen Dam (off-channel), located nearby. Water is also transferred from the Otjivero Main Dam into the Tilda Viljoen Dam via a 110 km pumped pipeline.

The drainage systems in the arid to semi-arid areas of the study area, have become defunct. These characteristics reflect the long and varied climatic and tectonic history of the continent and its distinctive topographic arrangement.

In arid environments, such as the D42 study site, trees are sometimes confined to the banks of ephemeral rivers. Apart from short-lived surface waters that remain after rainstorms, most water resources are underground and are there for difficult to map using remote sensing.

The dominant soils in the arid and semi-arid parts of the catchment comprises Arenosols, or soils developed on transported soils in which the degree of soil formation and horizon differentiation is either weak or absent. Particular characteristics of Arenosols are low reserves of weatherable minerals and low silt: clay ratios. Colours are usually red in upland sites and dune ridges, yellow in flat areas, and grey in bottomland sites (in the major drainage lines). The parent material of Arenosols is aeolian sand or sand derived from aeolian or through the deposition of extensive sheets of pedisediment or hillwash as escarpments receded and pediments came to dominate the landscape.

Units of the Kalahari Group constitute the most extensive body of terrestrial sediments of Cenozoic age in in southern Africa. Isopachs of the Kalahari Group show very clearly the presence of large paleovalley systems where thicknesses of Kalahari Group sediments are as great as 210 m. Paleovalleys run in a north-south direction between ridges of Olifantshoek and Transvaal Supergroup rocks and link up with a large valley running northeast-southwest along the Botswana border (Partridge, et al., 2006). Throughout the area the thickest part of the Kalahari appear to coincide with the occurrence of Dwyka Group rocks, and deposition of Kalahari Group sediments may have been partly controlled by the presence of Dwyka valleys.

The Kalahari basin formed as a response to the down-warping of the interior of southern Africa, probably in the Late Cretaceous. The down-warping, along with possible uplift along epeirogenic axes, back-tilted rivers into the newly formed Kalahari basin and resulted in deposition of the Kalahari Group (Haddon & McCarthy, 2005). The authors also indicate that a period of relative stability during the mid-Miocene saw the silcretisation and calcretisation of the older Kalahari Group lithologies.

Studies have shown that a combination of the relatively low permeability of the Kalahari sands and the low rainfall prevalent in the study area precludes recharge of groundwater aquifers by rainfall where sand cover exceeds about 15 m. It is therefore, assumed that the relatively good aquifers formed by the lower units of the Kalahari Group are recharged laterally from distant sources. In some areas, such as around Stampriet in Namibia, artesian conditions are present and analysis of these waters indicates slow replenishment over tens of thousands of years (Vogel et al.,1981). Table 1 lists recorded dates when the main rivers in the Molopo catchment were in flood.

Table 1 Recorded floods in the Molopo catchment (adapted from Spinage, 2012)

Year	Kuruman	Molopo	Nossob	Auob
1806			*	
1820	*			
1879				*
1891-1892	*		*	
1894		*		
1896		*		*
1915		*		*
1917-1918	*		*	
1920		*		
1933-1934	*	*	*	*
1963				*
1974-1977	*			
1987				*
1988-1989	*		*	
2000	*			
2014	*	*	*	*

2.2 The Mzimvubu River Catchment

The Mzimvubu River Catchment (Secondary catchment T3) is classified as a primary catchment and falls in a sub-humid climate with a ground water mean annual recharge of 12 to 70 mm and is located in the Eastern Cape Province and partially in KwaZulu-Natal. It has a drainage area of 19 826 km^2 and a flow length of approximately 350 km from north to south. The Mzimvubu River takes its source from the Drakensberg and is fed by mainly 5 tertiary rivers/catchments namely the Tsitsa, Tina, Kinira, Mzimvubu and Mzintlava, from west to east respectively. After a flow length of approximately 200 km, the Tsitsa River flows into the Tina River, which flows into to Mzimvubu River less than 5 km downstream from abovementioned confluence. The Kinira River flows into the Mzimvubu after a flow length of approximately 150 km, whereas the Mzintlava River flows into the Mzimvubu River after a flow length of approximately 200 km. Approximately 50 km northwest from Port St Johns, the Mzimvubu River continues to meander through several deep gorges until reaching the main catchment outlet in the ocean at Port St Johns.

With the Mzimvubu river forming tertiary catchment T36 from the river mouth up to the confluence of the Tina and Tsitsa rivers which form respectively tertiary catchments T34 and T35. Tertiary catchment T32 are upstream from the confluence of the Mzimvubu and Kinira rivers, while T33 covers the area of the Kinira river as well as the area between the confluences of the Mzimvubu river with the Mzintlava and Tina rivers. The Mzintlava river forms tertiary catchment T31. Figure 4 illustrates the catchment boundaries with the main rivers.

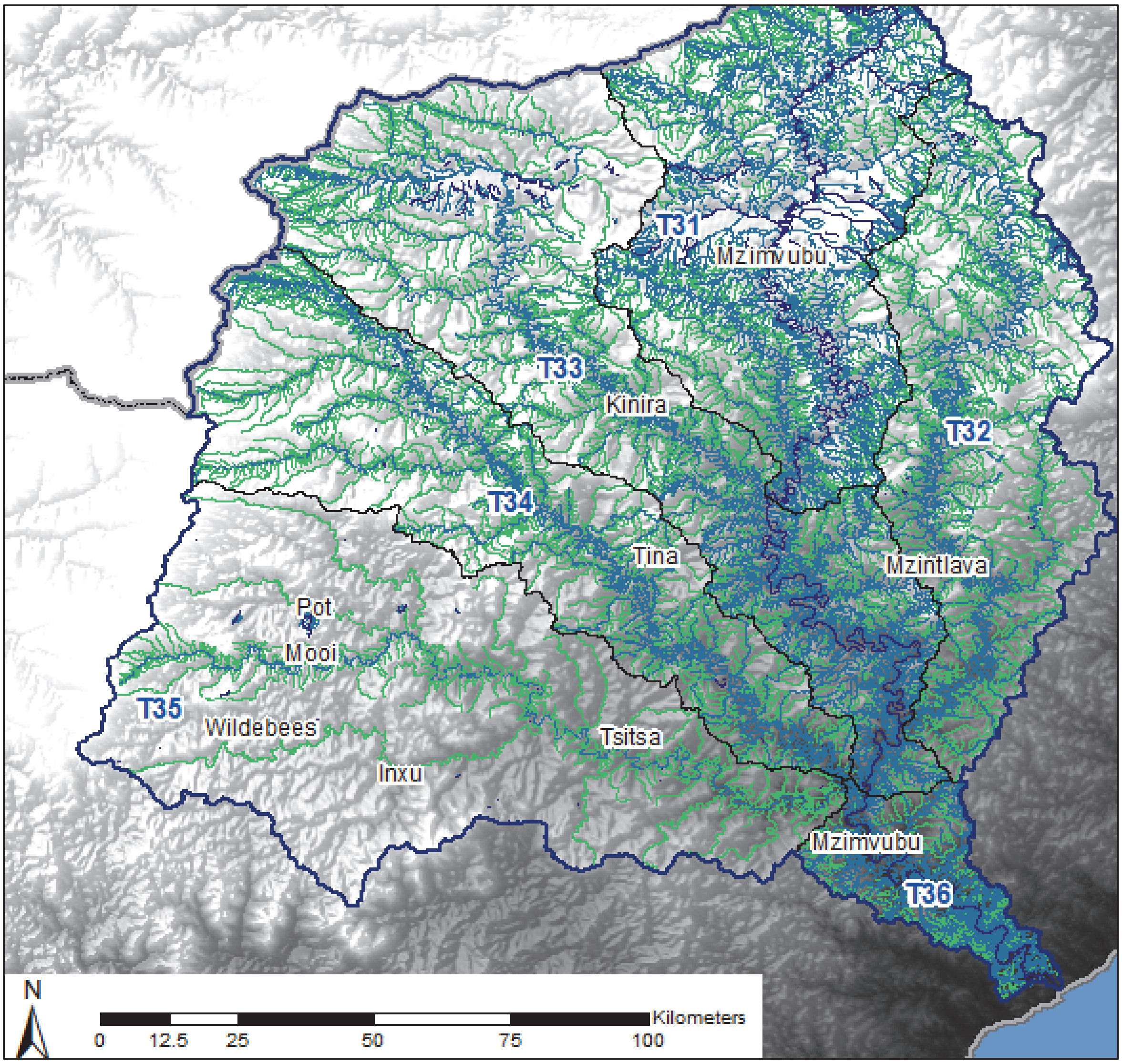


Figure 4 The catchment boundaries with the main rivers of the Mzimvubu catchment.

Connectivity of the main rivers mentioned above is not influenced by large dams, but several small dams occur in their tributaries along the axial valleys. A total of 104 relatively large farm dams and reservoirs, ranging between ≤0.1 and 80 ha, have been mapped from SPOT 5 imagery by Le Roux, 2014). The three largest dams in the catchment are Crystal Springs in T32C, Roodeberg Dam in T32B and Mountain Dam in T33A with capacities of just over 1 million m^3 (Midgley, Pitman and Middleton, 1990).

The rivers in the catchment are fed by several tributaries and therefore have a relatively high drainage density. This is mainly caused by high rainfall and complex landforms. The climate is characterized as sub-humid with the mean annual rainfall ranging from 625 mm in the lower inland plains to 1,415 mm in the mountain chains. Landforms range from very steep mountain slopes (40%) of the Drakensberg to gently undulating footslopes (2%) and nearly level valley floors. Elevation range from sea level at the catchment outlet in the southeast to 3,000 m in the Drakensberg Mountains bordering Lesotho. The catchment therefore has a significant drop in elevation from the upper reaches of the Tina river in the Drakensberg to the mouth of the Mzimvubu river in the Indian ocean. The catchment is characterised by three prominent/steep escarpment areas including the Drakensberg

Mountains also known as the Great Escarpment, followed by mountain ranges that separates the Highlands from the mid-slopes, and a third relatively steep drop in elevation approximately 50 km inland from the coast.

The geology consists of a succession of sedimentary layers of the Quaternary age (Council for Geoscience, 2007). The coastal region is dominated by Table Mountain sandstone with steep sea cliffs characteristic of the Wild Coast. A major fault, caused by the breakup of Gondwanaland approximately 130 million years ago, separates the sandstone cliffs and a section of shale rich units of the Ecca series further inland. Approximately 10 km inland from the outlet, is another geological fault worth mentioning. This fault consists of a large Karoo dolerite sill that protrudes through the catchment, separating the southern section of shale units of the Ecca series and a northern section of Diamictite of the Dwyka series (polymictic clasts, set in a poorly sorted, fine-grained matrix). Further inland, the oldest materials are Adelaide mudrock with subordinate sandstone. The latter is succeeded by various layers of sedimentary deposits including mudstones of the Tarkastad, Molteno and Elliot Formations. The next layer consists of fine-grained sandstone and siltstone of the Clarens Formation capped by Drakensberg basaltic lava in the most upper catchment area. Formations are all characterized by Karoo dolerite injections appearing as sills, sheets and dykes. In addition to alongside river valleys, a large patch of alluvium deposits occur just north of Cedarville.

2.3 National datasets

National baseline datasets that were used in this project include:

- Pan-Sharpened colour mosaics of SPOT 5 imagery prepared by South African National Space Agency (SANSA)
- Aerial photography captured by the Chief Directorate: National Geospatial Information (NGI) of the Department of Rural Development and Land Reform.
- River centre lines captured by NGI.
- Gauging station data

2.3.1 SPOT 5 imagery

The images acquired by SPOT Earth Observation Satellites are useful for studying, monitoring, forecasting and managing natural resources and human activities. The SPOT-5 earth observation satellite was placed into orbit in May 2002. The satellite provides an ideal balance between high resolution and wide-area coverage suitable for application at medium scale of between 1:25 000 and 1:10 000. The SPOT 5 satellite completes a circular orbit of the earth every 26 days has a swath width of 60 km.

The Spot 5 multispectral satellite sensor captures images in five bands. The characteristics of the spectral bands are illustrated in Table 2.

Table 2 Spectral bands and resolutions of SPOT 5 imagery (Astrium, 2012).

Spectral bands	Pixel size	Spectral resolution
Panchromatic	2.5 m	0.48-0.71 µm
Green	10 m	0.50-0.59 µm
Red	10 m	0.61-0.68 µm
Near infrared	10 m	0.78-0.89 µm
Shortwave infrared (SWIR)	20 m	1.58-1.75 µm

SPOT uses a unique A21 code for each scene (Astrium, 2013). For example: 51354050611090808381T, is better shown as 5-135,405-061109-080838-1-T where:

- 5 is the satellite number (scene acquired by SPOT 5);
- 135,405 are the coordinates of the scene on the SPOT Grid Reference System (GRS);
- 061109 is the acquisition date in YYMMDD format (i.e. 9 November 2006);
- 080838 is the acquisition time in HHMMSS format (i.e. 08 hours, 08 minutes, 38 seconds UTC);
- 1 is the instrument number (here: HRV1);
- T is the spectral mode (here: T for panchromatic).

The last letter of the code indicates the type of image. For example:

T = panchromatic

J = multispectral

The South African National Space Agency (SANSA) prepared annual Pan-Sharpened colour mosaics for the whole country from 2006 to 2011. The Pan-Sharpened mosaics have a pixel size of 2.5 m, whereas as the original bands have a pixel size of 10 m. SANSA use the A21 code of SPOT for the pan sharpened images, with the letters JT at the end. The images used in the mosaics were chosen because they were cloud free and obtained generally at random periods during the year, although the majority were obtained during winter when cloud cover is minimal over most parts of the country.

The processing of the imagery to Level 3B involved orthorectification (positioning and elimination of distortion in the images), pansharpening (transforming lower resolution colour images into higher resolution colour images), true colour conversion, colour balancing, manual editing to reduce cloud cover and eliminate “no data areas” (Campbell, 2012).

2.3.2 NGI aerial photography

Since 2008, all images secured by National Geospatial Information (NGI) were acquired by High resolution (HRes) digital sensors in both colour (RGB) and colour infra-red (CIR) at a Ground Sample Distance (GSD) of 0.5 m. The aim is to produce a new set of imagery covering the whole country every three years. See Tables 3 and 4 for the spectral bands and resolutions of RGB and CIR images.

Table 3 Spectral bands and resolutions of RGB images captured by NGI.

Spectral bands	Pixel size	Spectral resolution
Blue	0.5 m	0.4-0.58 µm
Green	0.5 m	0.5-0.65 µm
Red	0.5 m	0.59-0.675 µm

Table 4 Spectral bands and resolutions of CIR images captured by NGI.

Spectral bands	Pixel size	Spectral resolution
Near infrared	0.5 m	0.675-0.85 µm
Green	0.5 m	0.5-0.65 µm
Red	0.5 m	0.59-0.675 µm

RGB (Red, Green, Blue) ortho-rectified images are used as the basis for NGI's major products including being a major stand-alone product supplied to clients. However NGI only ortho-rectify certain areas in CIR, as required for their internal LandUse/LandCover purposes. The CIR images are a prerequisite for the two proposed procedures for signature-based discrimination of rivers. There are currently no orthorectified CIR images available for the two study areas of this project, but it is believed that this dataset may be useful in future for other areas. NGI aerial photos were therefor only used as backdrop during visual inspection of the accuracy of river lines in this study.

2.3.3 River centre lines

The South African river centre line data sets were developed as part of the 1:50 000 topographic map series, dating back to 1937 (Wonnacott, 2010). The Chief Directorate: National Geo-spatial Information (NGI), previously Chief Directorate: Surveys and Mapping (CDSM), of the Department of Rural Development and Land Reform is responsible for developing and maintaining these maps (Duncan & Smit, 2012).

Vorster (2003) provides a brief history of the development of digital vector data sets for South Africa. Capture of GIS data from the1:500,000 national map series would commence in 1988 with the acquisition of the first GIS system, named ReGIS. The pilot project would be completed in 1992 and would serve as a prototype for the eventual National Topographic Information System (NTIS). Maintenance of this pilot 1:500,000 database ceased in 1996. The second stage of development consisted of the creation of the NTIS proper, consisting of the raster to vector conversion of the 1:50,000 national map series. The raster to vector conversion process commenced in 1988 with the GIS population and structuring commencing in 1992 and completed in 1997. Intergraph's GeoMedia Professional 3.0 replaced the ReGIS GIS in 1999.

Post 1997 has seen continued maintenance of the system where newly compiled topographically captured data has replaced the initial data captured, which is cartographic in nature (Vorster, 2003). Various feature types, omitted during the initial capture, have been captured and general maintenance and partial clean-up procedures have been implemented.

The integrated Topographic Information System (iTIS) portal is currently being developed by NGI (2013). It will provide intranet and internet users access to the iTIS using a Web Feature data Server (WFS), Geography Markup Language (GML) data Server, Web Map Service (WMS) and access to imagery.

The fields in the dataset received from NGI are illustrated in Table 5.

Table 5 Fields in iTIS data

GID	FEA_R_DATE	SOURCE_ACC	SAGD_S_DES
CUID	ATT_R_DATE	ENTITY_NAM	PIPE_TYPE
FEAT_T_ID	CAP_SOURCE	GEOM_TYPE	Edited
FEAT_TYPE	CAP_METHOD	SAGD_F_TYP	Shape_Leng
JOB_NR	SOURCE_DES	SAGD_S_TYP	Enabled
EST_RV_DAT	SOURCE_CUR	SAGD_F_DES	

Of specific interest are the “ENTITY_NAM” and “FEAT_TYPE” fields, which contain the name of the river and perennial status respectively. The CUID field is not currently populated, but will be used in future to uniquely identify any feature in the system.

The river centre lines on the topographic maps were initially developed for presentation purposes and were not suitable for numerical hydraulic/hydrological modelling as they were not seamlessly connected and without flow direction. With the continuous improvements that NGI make to the topographic data it is necessary to update these datasets from time to time for modelling purposes.

2.3.4 Gauging station data

The Department of Water Affairs hosts several data sets for the monitoring of surface water, which includes (DWA, 2012):

- near real-time stage, flows and rainfall received from more than 400 stations;
- daily flows, dam level and rainfall information in the Vaal and Orange River System;
- weekly state of approximately 180 dams in South Africa;
- dam Optimisation: Routing through dams showing capacity, inflow and outflow;
- routed hydrographs showing actual and predicted stage and flows in major rivers in South Africa; and
- flow lines and levels over a range of flows from Vaal to Bloemhof Dam.

Station data can be downloaded from https://www.dwa.gov.za/hydrology/hymain.aspx.

2.4 Regional datasets

Regional baseline datasets that were used in this project include:

- Hydrologically improved DEM and flow paths
- Landsat 8 imagery
- Hydrologically improved DEM
- Dominant major soil group in the SOTER data
- Landcover
- Rainfall

2.4.1 Landsat 8 imagery

Landsat 8 images consist of nine spectral bands with a spatial resolution of 30 meters for Bands 1 to 7 and 9 (USGS, 2014). The resolution for Band 8 (panchromatic) is 15 meters. Thermal bands 10 and 11 are useful in providing more accurate surface temperatures and are collected at 100 meters. Approximate scene size is 170 km north-south by 183 km east-west. The characteristics of the spectral bands are illustrated in Table 6.

Table 6 Spectral bands and resolutions of Landsat 8 imagery (USGS, 2014)

Bands	Wavelength	Pixel size
Band 1 – Coastal aerosol	0.43-0.45 µm	30 m
Band 2 – Blue	0.45-0.51 µm	30 m
Band 3 – Green	0.53-0.59 µm	30 m
Band 4 – Red	0.64-0.67 µm	30 m
Band 5 – Near Infrared (NIR)	0.85-0.88 µm	30 m
Band 6 – SWIR 1	1.57-1.65 µm	30 m
Band 7 – SWIR 2	2.11-2.29 µm	30 m
Band 8 – Panchromatic	0.50-0.68 µm	15 m
Band 9 – Cirrus	1.36-1.38 µm	30 m
Band 10 – Thermal Infrared (TIRS) 1	10.60-11.19 µm	100 * (30) m
Band 11 – Thermal Infrared (TIRS) 2	11.50-12.51 µm	100 * (30) m

Landsat 8 was launched on the 11th of February 2013. Landsat 8 data as well as data from other satellites in NASA's Landsat series of satellites are provided for free on EarthExplorer (http://earthexplorer.usgs.gov/) and GloVis (http://glovis.usgs.gov/) within 24 hours of acquisition. With the first Landsat satellite being launched in 1972 this data set provide a wealth of information for future research.

2.4.2 Hydrologically improved DEM

A Digital Elevation Model (DEM) is a collection of data files that contain the elevation of the terrain over a specified area, usually at a fixed grid interval over the surface of the earth and which can be displayed as a three-dimensional layer of the land surface. Data from NASA's Shuttle Radar Topography Mission (SRTM) (CGIAR, 2008) provides 90 m Digital Elevation Model (DEM) coverage for approximately 80% of the earth's surface. The DEM was created from dual stereoscopic radar signals, providing topographical detail suitable for mapping scales of 1:50 000 and coarser. The DEM files have been joined into a seamless global coverage (like a mosaic), and are available for download as 5^o x 5^o tiles. The official version (2.1) of the data can be downloaded as tiles from http://dds.cr.usgs.gov/srtm/. Various unofficial versions of the data exist, e.g. version 3 and 4 (http://srtm.csi.cgiar.org), but these are heavily processed and positional shifts have been introduced.. A continuous DEM was created by Weepener et al. (2012) for southern Africa by filling voids in the SRTM DEM, version 2.1, using 20 m contour lines and the ASTER Global DEM. The resulting DEM covered the area between 19ºS and 35ºS and 12ºE and 36ºE. It includes the whole of South

Africa, Swaziland and Lesotho and large parts of Namibia, Botswana, Zimbabwe and Mozambique. The void filled DEM still contained 4 203 626 sinks (areas surrounded by higher elevation values) which made the DEM unreliable for delineating flow paths and catchment areas. To overcome this limitation, the DEM was hydrologically improved by carving the RQS 1: 500 000 rivers into the DEM and applying an automated impact reduction approach. The impacts of sink filling and channel carving were compared for each sink to choose the appropriate method.

2.4.3 Dominant major soil group in the SOTER (FAO, 1995) data

The world soils and terrain (SOTER) database provide a uniform resource map for the southern African region at a scale of 1:1 000 000. SOTER units consist of a distinctive, often repetitive, pattern of land form, lithology, surface form, slope, parent material and soil. The soil classification used in the short description of the dominant major soil groups as defined by the World Reference Base for Soil Resources (FAO, 2007) that can be found in catchment D42 are listed here:

2.4.3.1 Arenosols

Arenosols comprise sandy soils, including both soils developed in residual sands after in situ weathering of usually quartz-rich sediments or rock, and soils developed in recently deposited sands such as dunes in deserts and beach lands. Corresponding soils in other classification systems include Psamments of the US Soil Taxonomy and the sols minéraux bruts and sols peu évolués in the French classification system of the CPCS (1967). Many Arenosols belong to Arenic Rudosols (Australia), Psammozems (Russian Federation) and Neossolos (Brazil).

2.4.3.2 Calcisols

Calcisols accommodate soils in which there is substantial secondary accumulation of lime. Calcisols are common in highly calcareous parent materials and widespread in arid and semi-arid environments. Formerly used soil names for many Calcisols include Desert soils and Takyrs. In the US Soil Taxonomy, most of them belong to the Calcids.

2.4.3.3 Cambisols

Cambisols combine soils with at least an incipient subsurface soil formation. Transformation of parent material is evident from structure formation and mostly brownish discoloration, increasing clay percentage, and/or carbonate removal. Other soil classification systems refer to many Cambisols as: Braunerden (Germany), Sols bruns (France), Brown soils/Brown Forest soils (older US systems), or Burozems (Russian Federation). FAO coined the name Cambisols, adopted by Brazil (Cambissolos); US Soil Taxonomy classifies most of these soils as Inceptisols.

2.4.3.4 Leptosols

Leptosols are very shallow soils over continuous rock and soils that are extremely gravelly and/or stony. Leptosols are azonal soils and particularly common in mountainous regions. Leptosols include the: Lithosols of the Soil Map of the World (FAO-UNESCO, 1971-1981);

Lithic subgroups of the Entisol order (United States of America); Leptic Rudosols and Tenosols (Australia); and Petrozems and Litozems (Russian Federation). In many national systems, Leptosols on calcareous rocks belong to Rendzinas, and those on other rocks to Rankers. Continuous rock at the surface is considered non-soil in many soil classification systems.

2.4.3.5 Regosols

Regosols form a taxonomic remnant group containing all soils that could not be accommodated in any of the other RSGs. In practice, Regosols are very weakly developed mineral soils in unconsolidated materials that do not have a mollic or umbric horizon, are not very shallow or very rich in gravels (Leptosols), sandy (Arenosols) or with fluvic materials (Fluvisols). Regosols are extensive in eroding lands, particularly in arid and semi-arid areas and in mountainous terrain. Many Regosols correlate with soil taxa that are marked by incipient soil formation such as: Entisols (United States)

2.4.4 Land Cover

The Global Land Cover 2000 (GLC, 2000) map for Africa was used to evaluate land cover in the study area (JRC, 2003; Mayaux et al., 2003). The GLC 2000 database has been produced by an international partnership of 30 research groups coordinated by the European Commission’s Joint Research Centre (Bartholomé and Belward, 2005). The database contains two levels of land cover information – detailed, regionally optimized land cover legends for each continent and a less thematically detailed global legend that harmonizes regional legends into one consistent product. The land cover maps are based on daily data from the VEGETATION sensor on-board SPOT 4, though mapping of some regions involved use of data from other Earth observing sensors to resolve specific issues.

Some land cover classes appear only in Namibia. These are:

- Closed grassland
- Deciduous woodland
- Deciduous shrub land with sparse trees

The following natural vegetation landcover classes can be found in all three countries of tertiary catchment D42:

- Open grassland with sparse shrubs
- Open grassland
- Sparse grassland

Mayaux *et al.* (2003) describe these landcover classes.

2.4.4.1 Open grassland with sparse shrubs

Herbaceous cover between 15% and 40% and shrub canopy cover less than 20% (Mayaux et al., 2003). In dry conditions (<200 mm), shrublands tend to leave the room to open grasslands with a sparse shrub layer. Woody species include *Acacia* sp., *Balanites aegyptiaca*, *Grewia bicolor*, *Zyziphus* sp., *Maerua crassifolia*, *Boscia senegalensis*… Grasses are perennial species: *Stipagrostis* sp,. *Monsonia ignorata*, *Eragrostis* sp., *Aristida* sp., *Loudetia* sp.

2.4.4.2 Open grassland

Herbaceous cover between 5% and 15% without shrub canopy (Mayaux et al., 2003). In extreme conditions (50-100 mm rainfall), the shrub layer disappears. It can be depicted from satellite data by a very short vegetation period. Grasses are perennial species: *Stipagrostis* sp., *Monsonia ignorata*, *Eragrostis* sp., *Aristida* sp.

2.4.4.3 Sparse grassland

Herbaceous cover between 1% and 5% At the fringes of the desert, the herbaceous cover is very sparse (<5%). The inter-annual variability in the vegetation activity reflects the erratic character of rainfall (Mayaux *et al.,* 2003). Grasses are perennial species: *Stipagrostis* sp,. *Monsonia ignorata*, *Eragrostis* sp., *Aristida* sp. Succulents can also be present.

2.4.5 Climate surfaces

New *et al.* (2002) constructed a dataset of a 10' lat/lon mean monthly climatology of surface climate over global land areas, excluding Antarctica. The surfaces were interpolated from station means for the period centred on 1961 to 1990. Variables in the dataset include: mean temperature, diurnal temperature range, relative humidity, sunshine, ground-frost frequency, wet-day frequency, wind speed, and precipitation data.

Of specific interest to this study is the total annual precipitation surfaces that were prepared by New *et al.* (2002)

3 METHODOLOGY

This chapter will outline the methodology adopted in this study. It comprises the following:

- Development of river editing tool
- Calculation of flow paths from a DEM
- Extraction of river networks from SRTM flow paths
- Derivation of supporting information from imagery

3.1 Development of river editing tool

The River Editing tool developed for this project can be used to clean the river centre line data in ArcGIS (ESRI, 2012) version 10.1 or version 10.2. The river editing tool was developed to simplify the editing of both line features and attribute data. Amongst others it has the following functionality:

- Automatically applying flow direction of stream lines from a DEM.
- Automatically applying flow direction from the mouth of a river network.
- Finding loops in the river network.
- Selecting upstream or downstream line segments from a specified position.
- Assigning attributes to all selected stream lines
- Calculating stream order of river segments in a river network.

Some of the functions of the river editing tool are described in the following sub sections. The manual of the river editing tool is provided in Appendix A.

3.1.1 Repairing geometry errors

In ArcMap river centre lines are stored as poly lines. These lines consists of two points at the start and end of the line, called the from- and to nodes respectively, with points in between called vertices.

The river editing tool automatically runs a "Repair Geometry" function when the dataset is initially imported. This function inspects each feature in a feature class for geometry problems. Upon discovery of a geometry problem, a relevant fix will be applied, and a one line description will be printed identifying the feature as well as the problem encountered.

Unfortunately there were still some geometry errors in the data after the "repair geometry" was run. These errors had to be fixed manually and no easy solution could be found to search for these errors. Many of the tools in the river editing tool will not function correctly if the dataset contains geometry errors.

Some examples of geometry errors that were found are:

- Two identical lines on top of each other.
- Lines with a from node, but no to node.
- Lines where either the from- or to node are in the middle of the line.

3.1.2 Removal of loops

In order to obtain a tree-like single-line river network any loops have to be cut (Zhang *et al.*, 2008). The river editing tool has the functionality to show any loops that appear in a river network. Once the loops are identified they have to be removed manually.

Four kinds of loops were encountered in the data. The first is where islands appear in the river and steams on both sides were digitised. Zhang *et al*. (2008) explains that a manual decision has to be made where the main stream is kept and the smaller stream deleted. In cases where a stream were deleted that had one or more tributaries these tributaries were extended to the main stream. See Figure 5 as example. In this example there are two islands that were digitised differently. In the island on the left both streams surrounding the island were digitised while only one line, that goes through the island, was digitised for the island on the right.

Figure 5 A loop caused by an island in the river.

Another kind of loop was created when two streams from separate sub catchments touched each other. This is normally a digitising error and the lines had to be split. An example is highlighted by the red circle in Figure 6.

Figure 6 A loop caused by stream lines from separate sub catchments touching each other.

Some loops were caused by horse shoe bends. See Figure 7 as example.

Figure 7 A loop caused by horse shoe bends.

Lastly some sliver polygons were found. These are usually very narrow polygons caused through poor digitising. Sliver polygons are often not visible to the eye, when scanning through the data on screen in ArcMap. After running the “Find loops” tool in the River Editing tool one should rather open and use the table of the resultant polygons generated to navigate to each individual loops. See Figure 8 as example.

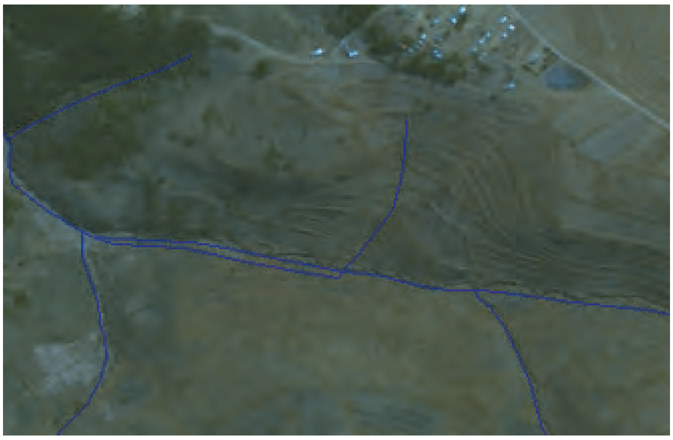


Figure 8 A loop caused by a sliver polygon.

3.1.3 Snapping of lines that are not connected

The trace upstream tool in the river editing tool was used to find lines in the river network that is not connected. These lines were visually inspected using aerial photography, before they were manually snapped if necessary.

Many streams were not connected to the main river network and were often a long distance away from the main river network. In these cases if no stream was visible on the aerial photography these lines were not edited to connect to the main river. If the stream was visible it was digitised to complete the connection with the main river network.

3.1.4 Errors identified in data

River lines were compared to aerial photography and SPOT 5 satellite imagery. A few obvious errors were found and these were manually corrected. Examples include cases where the flow path was wrongly digitised.

3.1.5 Set flow direction

The flow direction of the streams was enforced in three steps.

Firstly the flow direction was set with the River Editing tool using a DEM to find the highest node for each line. This function corrected most lines, but still had some wrong flow directions due to mistakes in the DEM, or when the elevation at both nodes is the same.

The River Editing Tool was also used to force the flow directions of the main river network as well as smaller networks in the catchment that did not drain into the main network. This function automatically corrects the flow direction of a network after the user identified the mouth of the river.

Lastly the streams were inspected visually and corrected manually where necessary.

3.1.6 Calculate stream order

The River Editing tool was used to calculate stream order values for four different stream order types (Strahler, Horton, Shreve and Hack). The four stream order types were also implement by Jasiewicz (2014) for the GRASS software and proved to be very useful.

The stream order values were stored in the following fields RE_Strahler, Re_Shreve, RE_Horton and RE_Hack. During the calculation of the stream orders an additional field, labelled “RE_UpstrLe”, were created. This field contains the distance of the longest upstream path in the river network. Hack’s stream order can be used to follow the stream associated with the “RE_UpstrLe” value. The longest upstream length from the river mouth in Port St Johns is for example 524 km. Similarly the longest upstream length of the Tina and Tsitsa rivers are respectively 283 km and 279 km from their confluence.

The stream order was calculated for the main river network as well as unconnected smaller networks.

The calculation of stream order takes a considerable amount of time. The calculation of the stream order for the complete secondary catchment T3 (122 423 line features) took for example 161 hours, while tertiary catchments T31 (15 705 features) and T34 (25 233 features) respectively took four and ten hours to complete.

The stream order functionality calculates stream order values for the different stream order types (Strahler, Horton, Shreve and Hack) all at once and places the value in the datasets table in a field named according to the stream order type i.e. Strahler values will be placed in a field named RE_Strahler, Horton values will be placed in a field named RE_Horton, etc.

The user can then use styling and labelling features of ArcMap to visually represent the different types of stream order in ArcMap.

3.1.6.1 <u>Horton's stream order</u>

Horton's (1945) stream order applies to the entire stream with the exception of segments or links, since the order on any channel remains unchanged from source until it "dies" in a higher order stream or in the outlet of the catchment. The main segment of the catchment is assigned the order of the whole catchment, while its tributaries are assigned the order of their own sub-catchments.

The algorithm applied, requires calculating Strahler's stream order first. Horton ordering (upstream) is then recalculated. To make a decision about proper ordering it uses Strahler ordering, and if both branches have the same Strahler order, it uses segment length to choose the actual link. The algorithm starts with the outlet, where the outlet link is assigned the corresponding Strahler order. Next it goes upstream and determines links according to Strahler ordering. If the orders of tributaries differ, the algorithm proceeds with the channel of highest order, if all orders are the same, it chooses that one with higher segment length rate.

The main advantage of Horton's ordering is that it produces natural stream ordering with main streams and its tributaries. The main disadvantage is that it requires Strahler's ordering. In some cases this may result in unnatural ordering, where the highest order will be ascribed to the channel which leads to the most branched parts of the catchment.

3.1.6.2 Strahler's stream order

Strahler's stream order (Strahler, 1952) is a modification of Horton's stream order which removes the ambiguity of Horton's ordering. Strahler's ordering is based on the hierarchy of tributaries. The ordering is applied according to the following rules:

- All links with no tributaries are assigned an order of 1
- Stream order only increases when streams of the same order intersect. Therefore the intersection of a first order and second order link will remain a second order link rather than create a third order link

3.1.6.3 Shreve's stream magnitude

Shreve's (1966) stream ordering assigns a magnitude of 1 for every initial channel. All links with no tributaries are assigned an order of 1. Stream order is additive downslope. When two links intersect, their magnitudes are added and assigned to the downslope link. The order number of a particular stream segment thus equals the total number of its tributaries up to channel heads.

3.1.6.4 Hack's main stream order

Hack's main stream ordering (Hack,1957) calculates main streams for the main catchment and every sub-catchment. The main stream of the main catchment is set to 1, and consequently all its tributaries receive order 2. Their tributaries receive order 3 etc. The order of every stream remains constant up to its source. The route of every main stream at a confluence is determined according to the maximum flow length value of the tributaries at this confluence. Thus the main stream of every sub-catchment is the longest stream. The biggest advantage of Hack's main stream order is the possibility to compare and analyse drainage network topology upstream according to main streams. Because all tributaries of the main channel have an order of 2, streams can be quickly and easily filtered and its proprieties and relation to the main stream can be determined. The main disadvantage of this method is the problem with the comparison of sub-catchment topology of the same order. Sub-catchments of the same order can be highly branched and widespread in the total catchment area or just a small sub-catchment with only one stream.

3.2 Calculation of flow paths from a DEM

Flow paths are usually calculated in three steps from a DEM. The first step is to calculate the flow direction for each cell. Once the flow direction is known the flow accumulation can be calculated. The accumulated flow to each cell is calculated, by accumulating the number of cells that flow into each downslope cell. The accumulated flow represents the amount of rain that would flow into each cell, assuming that all rain became runoff and there was no interception, evapotranspiration, or loss to groundwater.

Lastly a threshold is used to select flow paths. For example if the threshold is set to 500 a flow path would only start if the flow accumulation is more than 500. Larger thresholds will result in major flow paths, while smaller thresholds will include less significant flow paths.

3.3 Extraction of river networks from SRTM flow paths

River networks will be selected from flow paths, taking into consideration homogeneous areas with respect to drainage density and environmental variables such as climate, soils and terrain. This task is therefore based on the conjunctive use of digital elevation data and environmental parameters in a grid-based GIS environment which facilitates the delineation of areas of homogeneous drainage density. The landscape will be stratified into drainage density classes. This process will be guided by the premise that the purpose is not to derive a physical value of drainage density but to define areas with specific environmental conditions. After the delineation of areas with homogeneous drainage density, an optimum contributing area threshold that is required to initiate a channel will be objectively determined for each drainage density class. Thus, channel networks will be extracted by using different source areas. Validation will be performed by comparing the extracted river networks for the study areas with the river lines on topographic maps Landsat imagery.

In a similar study, Colombo et al. (2001) defined homogeneous drainage areas on the basis of environmental factors influencing channel initiation and, therefore, governing drainage density (DD). Colombo et al. assumed that low DD is favoured in regions of highly resistant or highly permeable subsoil material, under dense vegetation cover and where relief is low, while high DD is favoured in regions of weak or impermeable subsurface material, sparse vegetation cover and mountainous terrain.

The following spatial data sets are available at a regional scale and will be employed:

- Annual precipitation (New et al., 2002));
- Terrain (Mountainous areas, flow paths, etc.) derived from a hydrologically-improved SRTM DEM (Weepener et al., 2012);
- Soil information will be obtained from the SOTER data set (FAO, 1995);
- Global Land Cover 2000 (JRC, 2003);

3.4 Image processing

Mapping land cover classes such as water, trees, woody shrubs, grassland and bare soil from remote sensing imagery is the process of extracting information by interpreting satellite images based on the interpretation elements such as the image color, texture, tone, pattern and association information, etc. Different methods have been developed to do this. Those methods can be broadly grouped either as supervised or as unsupervised depending on whether or not true ground data are inputted as references. General steps involved in vegetation mapping include image preprocessing and image classification. Image preprocessing deals with all preliminary steps necessary to improve the quality of original images, which then results in the assignment of each pixel of the scene to one of the vegetation groups defined in a vegetation classification system or a membership matrix of the vegetation groups if fuzzy classification is adopted.

Traditionally image classification approaches were pixel based and relied on conventional statistical techniques. In the last few years, considerable advancements have been made in the development of object-based analysis where pixels with similar spectral and spatial properties are grouped as objects and traditional pixel based image analyses techniques are then applied on the objects to extract features of interest (Navulur, 2007).

Spectral indices are designed to map specific surface properties (e.g. plant biophysical). Ji (2009) defines a spectral index as a single number derived from an arithmetic operation (e.g., ratio, difference, and normalized difference) of two or more spectral bands. Spectral indices typically have high values for the surface property being mapped and low values for everything else.

The following sub sections describe the process and techniques used in this study.

3.4.1 Image pre-processing

Geometric correction is aimed to avoid geometric distortions from a distorted image and is achieved by establishing the relationship between the image coordinate system and the geographic coordinate system using the calibration data of the sensor, the measured data of position and altitude and the ground control points. Therefore, geometric correction usually includes the selection of a map projection system and the co-registration of satellite image data with other data that are used as the calibration reference. Images for this project were geometrically corrected to the UTM WGS84 projection, using ground control points and a DEM as reference for the X, Y and Z reference.

The information provided by a sensor may be insufficient for a given application such as large scale mapping, but might be ideal because of its multispectral properties. Image fusion of remotely sensed data with different spatial resolutions is an effective technique that has a good potential for improving vegetation classification. For example, in this study, SPOT 5 image fusion of high-resolution panchromatic and low-resolution multispectral were used and resampled to 2.5 m

3.4.2 Pixel based classification

According to Lu and Weng (2007) pixel based classification techniques can be grouped in supervised (e.g. Maximum likelihood, minimum distance, decision tree classifier, artificial neural network) and unsupervised classifications (e.g. Iterative Self-Organizing Data Analysis Techniques A (ISODATA), K-means clustering).

In supervised classification, the identity and location of some of the land cover types (e.g., water, urban, grass, bare soil etc.) are known a priori through a combination of fieldwork, interpretation of aerial photography, map analyses and personal experience (Hodgson et al., 2003). Homogeneous areas of known land cover classes are entered by the analyst as training sites. The characteristics of these training sites are used to train the classification algorithm.

The unsupervised approach is often used in thematic mapping such as for vegetation and land cover mapping from imagery. It is easy to apply and widely available in image processing and statistical software packages. Unsupervised classification, searches for natural groups, called clusters, of pixels present in the data by means of assessing the position of the pixels in the feature space (Ayhan and Kansu, 2012). A good example is the ISODATA classification that was developed by Ball and Hall (1965). This algorithm consists of iterative procedures. It assigns an arbitrary initial cluster vector first. The second step classifies each pixel to the closest cluster. In the third step, the new cluster mean vectors are calculated based on all the pixels in one cluster. The second and third steps are repeated until the gap between the iteration is small enough (or smaller than a preset threshold). Unsupervised classification methods are purely relying on spectrally pixel-based statistics and incorporate no prior knowledge of the characteristics of the classes being studied. The benefit of applying unsupervised classification methods is to automatically convert raw image data into useful information.

ISODATA can typically be applicable to:

- The design and pre-processing, by allowing the examination of the structure of multidimensional data in the original high dimensional space.
- Classification of patterns and providing an economical description of the classes of patterns against which pattern of unknown class can be compared and so assigned to a specific class.

The ISODATA classification was applied to SPOT 5 images for both study areas. For secondary catchment T3 a water classification was done, while it was used in the classification of riparian vegetation in tertiary catchment D42.

3.4.3 Object-based image analyses

Object-based image analysis (OBIA) allows analysts to use their knowledge about the environment and develop models that represent objects in the environment and their relationships (de Pinho, 2012).

The objects are created through a segmentation process, which groups pixels together as objects. Most pixel based techniques can also be applied to the objects. Additional criteria such as size, shape, context and texture, that can be included in models, make OBIA very powerful. Each of these criteria have many properties related to it.

An example of a shape related property that can be assigned to the objects is “Density”. The Density feature describes the distribution in space of the pixels of an image object (Trimble, 2012). The most “dense” shape is a square; the more an object is shaped like a filament, the lower its density. The density is calculated by the number of pixels forming the image object divided by its approximated radius, based on the covariance matrix.

OBIA was tested on sample images to classify rivers, but it was not applied to the whole study area.

3.4.4 Texture analysis

Texture, as it applies to image interpretation, is defined as the visual impression of coarseness or smoothness caused by the variability or uniformity of image tone or color (Avery and Berlin, 1992). The texture methods utilize the apparent roughness in the visible surface due to drastic changes in brightness between adjacent pixels. The texture model reduces the color signal in the image and maximizes the texture signal. This analysis technique capitalizes on the mutual information between results of smoothing the image with low-pass filters of two sizes (e.g., 3 × 3 pixels and 5 × 5 pixels).

Texture analysis was applied to SPOT 5 images for tertiary catchment D42 during the classification of riparian vegetation.

3.4.5 Spectral Indices

The proposed indices are applicable to images captured by multispectral sensors such as the Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper Plus (ETM+), Satellite Pour l'Observation de la Terre (SPOT) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

Spectral indices were applied to SPOT 5 images for both study areas. For secondary catchment T3 a water index was applied, while a vegetation index was applied during the classification of riparian vegetation in tertiary catchment D42.

3.4.5.1 <u>Spectral vegetation indices (VI)</u>

Spectral vegetation indices could provide an indication of riparian areas in dry areas. Spectral vegetation indices are used to enhance the vegetation signal in remotely sensed data and provide approximate measure of live, green vegetation. Spectral vegetation indices exploit the unique spectral signature of green vegetation as compared to spectral signatures from other earth materials such as soil.

However, these indices will not be applied for direct mapping of rivers in this study due to the challenges in separating riparian areas from other highly vegetated areas. We do recommend the usage of a vegetation index as supporting information during the manual digitizing of river lines.

Different vegetation indices have been developed based on the combinations of two or more spectral bands, assuming that multi band analysis would provide more information than a single one. Most vegetation indices use radiance, surface reflectance or apparent reflectance values in the red (R) and near infrared (NIR) spectral bands. These indices are correlated with various vegetation parameters such as green biomass, chlorophyll concentration, leaf area index, foliar loss, photosynthetic activity and more. Vegetation indices are also useful for image analysis such as change detection.

Examples include:

- Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1974)
- Soil adjusted vegetation index (SAVI) (Heute, 1988)
- Enhanced vegetation index (EVI) (Heute et al., 1997)

- Atmospherically resistant vegetation index (ARVI) (Kaufman and Tanre, 1992)
- New vegetation index (NVI) (Grupta et al., 2001)

In this study the Normalized Difference Vegetation Index, (NDVI) a basic vegetation index for measuring the 'greenness' of the earth's surface were used. A reasonable estimation of the density and coverage of green vegetation were determined by measuring how green the cover type on the earth's surface is. The formula to calculate NDVI is:

$$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{red} + \rho_{NIR}),$$

where ρ_{red} and ρ_{NIR} are the reflectance of Red and Near Infrared bands, respectively (Rouse *et al.*, 1974).

NDVI values can range from -1.0 to 1. Vegetation values typically ranged between 0.1 and 0.7. High NDVI values generally indicated increased degrees in the greenness and intensity of vegetation while low values were commonly characterised as rock and bare soil, and values less than 0 sometimes indicate clouds and water. Low values of NDVI do not necessarily denote lack of vegetation, but can also be an indication of phonological cycles and drought. NDVI can there for be used as an indicator of relative biomass and greenness if sufficient ground data is available. It is also highly correlated with climatic variables, and precipitation (Schmidt and Karnieli, 2000). The NDVI is successful as a vegetation measure, since it is sufficiently stable for seasonal and inter-annual comparison of vegetation growth and activity (Huete *et al.,* 2002).

3.4.5.2 <u>Spectral water indices</u>

Water bodies absorb almost all incident energy in the near and middle infrared wavelengths such that there is little energy reflected (Swain and Davis, 1978). This forms the physical basis for using remote sensing to detect water bodies.

The use of channel ratios, differences, and normalized differences for a relationship between remote sensing measurements and ground truth data is very common. An advantage of ratios and normalised differences is that they correct some of the atmospheric effects.

Figure 9 illustrates the reflectance of water, soil and vegetation over the spectral bands of SPOT 5 images. The spectral bands of SPOT-5 imagery are represented by the vertical grey bars with the numbers indicating the band names. The spectral data were derived from the California Institute of Technology Jet Propulsion Laboratory (2008). Water absorbs more light in the infrared portion of the electromagnetic spectrum than in the visible area. On the other hand vegetation and soil reflect more in infrared than in the visible portion of the electromagnetic spectrum. These characteristics make the separation of water features and other land cover such as vegetation and bare soil possible.

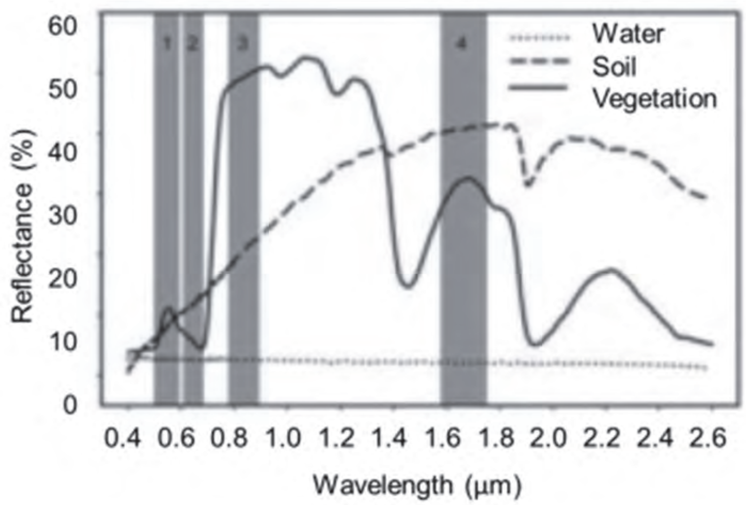


Figure 9 Spectra of water, soil, and vegetation samples (Ji et al.,2009).

The principal of a band ratio index is to divide the response of a visible band, such as green, by a NIR band response (Boland, 1976). According to McFeeters (1996) these band ratios supress the presence of terrestrial vegetation and soil features (which typically have much higher NIR reflectance than open water), while the presence of open water is enhanced.

McFeeters (1996) developed the normalized difference water index (NDWI) in an attempt to totally eliminate the soil and terrestrial features from the signature. It is defined as

$$NDWI = (\rho_{green} - \rho_{NIR})/(\rho_{green} + \rho_{NIR}),$$

where ρ_{green} and ρ_{NIR} are the reflectance of Green and Near Infrared bands, respectively.

Because its water information was overestimated due to noise from built-up areas, Xu (2006) modified the NDWI. The modified MNDWI was found useful for the extraction of water features where the region is dominated by built-up areas. The formula for calculating MNDWI is:

$MNDWI = (\rho_{green} - \rho_{SWIR})/(\rho_{green} + \rho_{SWIR})$, (1) where ρ_{green} and ρ_{SWIR} are the reflectance of Green and Shortwave Infrared bands, respectively.

Ji *et al.* (2009) tested the performance of different normalised difference water indices on mixed pixels. They simulated green, NIR, and SWIR bands for pure water, soil, and vegetation and various mixtures of these components. They concluded that the MNDWI, where the SWIR band is in the region of shorter wavelength (1.2 to 1.8 µm), has the most stable threshold, with the least impact from subpixel vegetation and soil components.

3.5 Classification of water

Three procedures have been developed for the classification of open water rivers. The first procedure makes use of a raster-to-vector conversion tool. The second procedure makes use of a pixel based classification and flow paths derived from a DEM and requires some user interaction. The third procedure is automated and makes use of object based classification.

The following procedures were applied to create stream lines and/or areas from the raster classification of open water in cases where no vector stream data is available. In cases where it is available, but inaccurate, at least the mainstreams can be replaced with better lines / polygons derived from satellite imagery.

3.5.1 Using ArcScan, an extension of ArcMap, to delineate stream lines

ArcScan (an extension of ArcMap) has the functionality to create vector data from scanned topographic maps and can also be used for any raster-to-vector conversion in general. For our purposes we investigated the vectorizing of the classification of open water to quickly get a better river line if it was wrongly digitised previously. The following figures illustrate the process for a sample area.

Figure 10 shows the river lines from NGI over a SPOT 5 image. The Wildebeest River can clearly be seen on the image, with the river line lying close to it.

Figure 11 shows the water classification over the SPOT 5 image. Note the noise that can be seen in the shadow areas as well as in the built-up area

In Figure 12 the automatically vectorized lines, derived from the classified image, are displayed in red, with a selection of these lines, representing the Wildebeest River, in Figure 13. The lines were manually selected to exclude any noise.

Figure 10 River lines from NGI displayed over a SPOT 5 image.

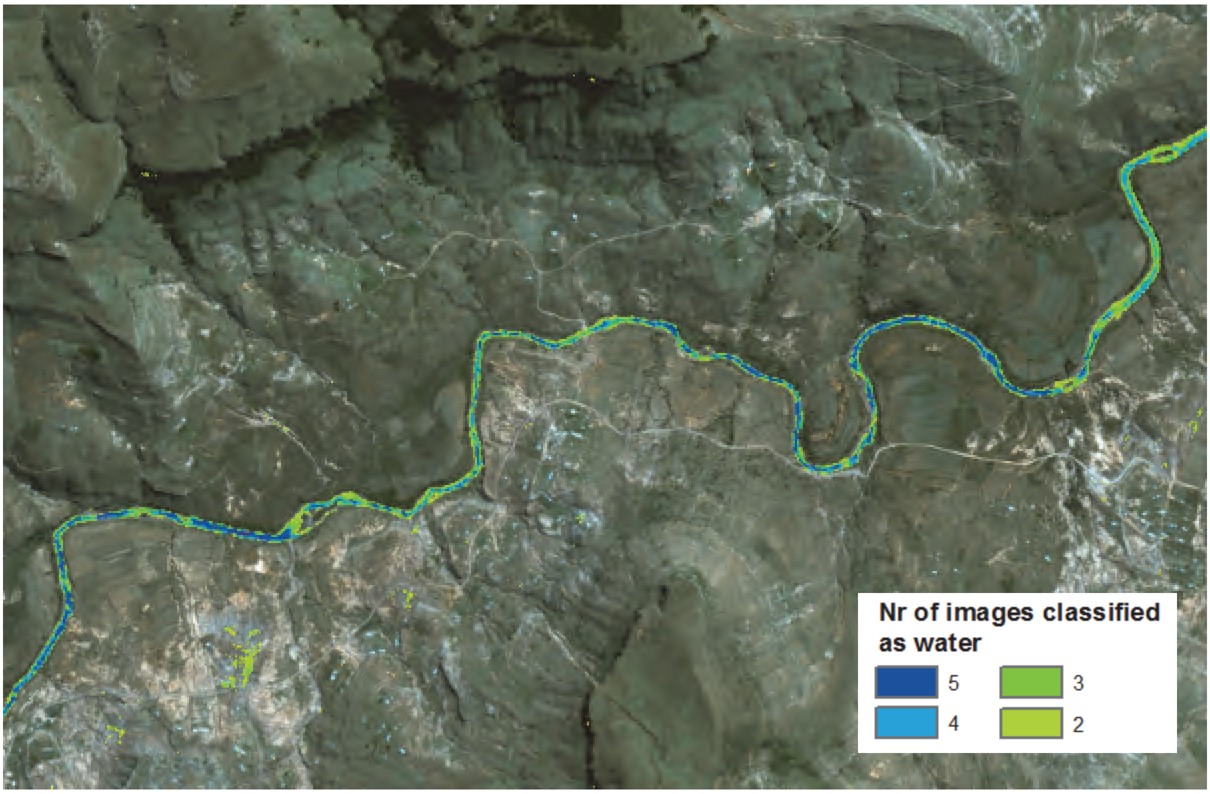


Figure 11 Classification of open water displayed over a SPOT 5 image

Figure 12 Classification of open water vectorised (Red lines).

Figure 13 The Wildebeest River, displayed in red, as selected from vectorised lines.

3.5.2 Use flow paths derived from a DEM to separate rivers from noise and other water bodies that were classified as water

ERDAS Imagine, a commercial software package, can be used to implement the following procedure (See Figure 14 for a sample classification):

Classify the image

- Run ISODATA unsupervised classification with 200 classes
- Select classes mapped as water
- Recode selected classes as water and everything else into another class.

Calculate flow path mask

- Create thematic flow accumulation data (See paragraph 4.4)
- Select major flow streams
- Recode selected classes as flow paths and everything else into another class.
- Run statistical filter: Minority 3X3 on flow paths
- Run statistical filter: majority 3X3
- This creates flow paths that are much wider than the original data.

Mask water classification with flow paths keeping only the water pixels that correspond with the wider flow path pixels.

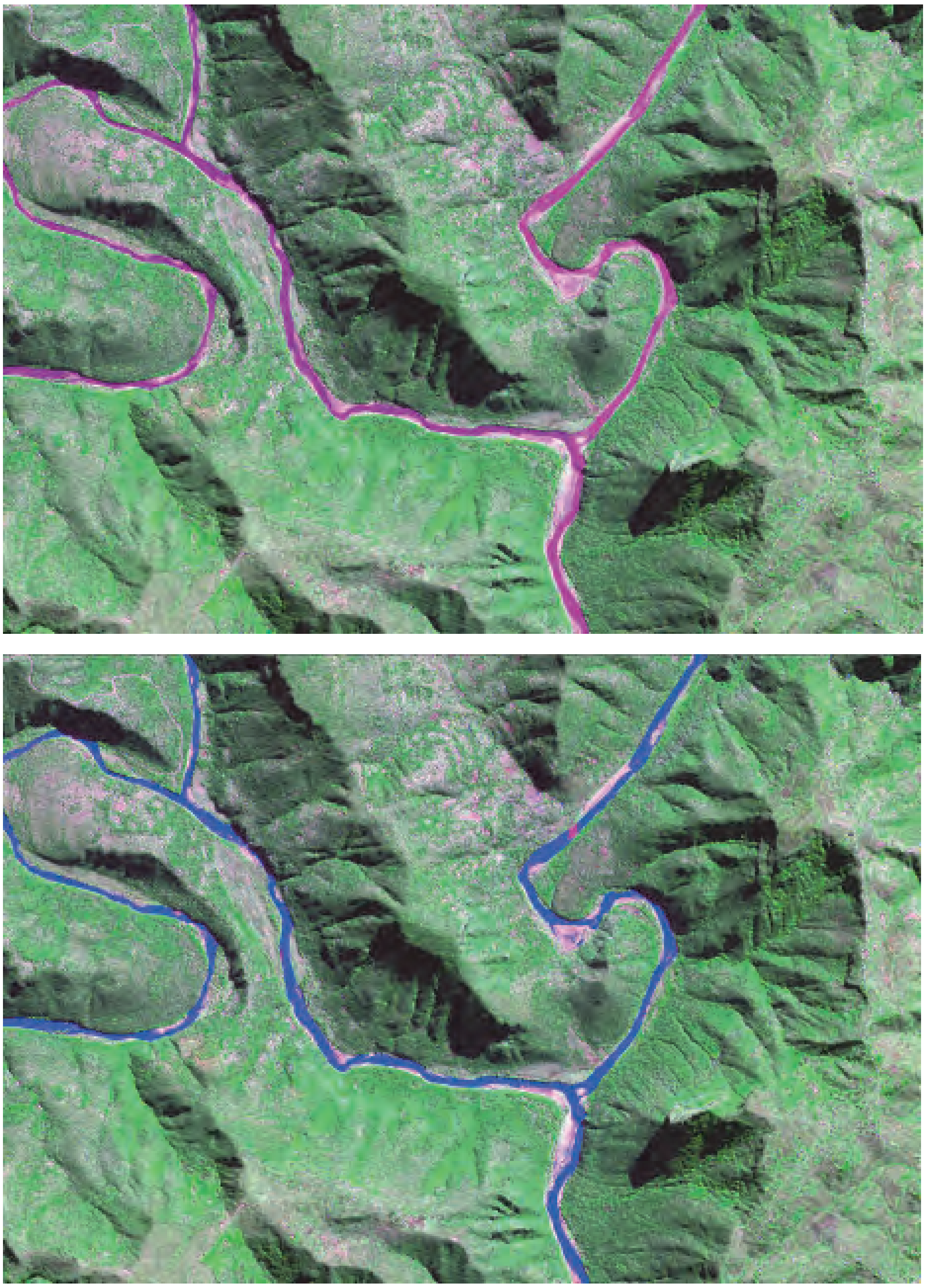


Figure 14 Example of pixel based classification of rivers. The unclassified false colour image is above and the classified image below (Water in blue)

3.5.3 Object based classification of rivers

Ecognition (Trimbe, 2012), a commercial software package, can be used to implement the following procedure (See Figure 15 for a sample classification):

- Calculate NDWI on the pansharpened SPOT 5 image (Using Erdas Imagine or ArcGIS)
- Import the four bands of the pansharpened SPOT 5 image as well as the NDWI image as a fifth band.
- Apply a Multi-resolution segmentation on all five bands

- Select all objects with MNDVI > 0.35 and Green > 90
- Recode selected classes as water and everything else into another class
- Merge all the objects classified as water.
- Select all objects classified as water with density > 1.3
- Remove the selected objects from the water classification

Figure 15 Example of object based classification of rivers. The unclassified false colour image is above and the classified image below (Water in blue)

3.6 Mzimvubu catchment

River centre lines were acquired from NGI for the Mzimvubu catchment (secondary catchment T3). The river lines were extracted from the iTIS portal. This paragraph illustrates the processes involved to get river lines from 1:50 000 topographic map dataset, as prepared by NGI, to adhere to requirements for a river network as required for hydraulic/hydrological modelling purposes.

3.6.1 Cleaning of spatial data in the Mzimvubu catchment

The river centre lines of the Mzimvubu catchment is a very large dataset, with a total of 124 528 line segments. To make the data more manageable the dataset was subdivided into the six tertiary catchments and merged together again after the edits were done. An extra field was added to the stream line dataset indicating the kind of error that was corrected. This was done so that the errors can be reported back to NGI for correction in their master data sets. The River Editing tool developed for this project has been used to clean the data.

The spatial data (stream lines) was cleaned in the following ways:

- Fixing of geometry errors
- Enforce flow direction
- Removing all loops.
- Snapping of unconnected stream lines
- Correction of wrong stream lines.

It is difficult to fix geometry errors because these errors often cause the software to crash. It is not only difficult to find the line segment with the geometry error, but once the line segment has been identified it is difficult to see what kind of error causes the problem.

The classifications described in point 7.3 were used as a backdrop to verify the accuracy of the main rivers. These classifications only showed main rivers, which were found to be within 40 meter, as required by NGI. The original SPOT 5 images as well as colour areal imagery of NGI was used as backdrop to verify and improve smaller tributaries. Stream lines found to be wrong were digitised manually from the imagery.

3.6.2 Use of remote sensing data and derived products to improve the spatial data in the Mzimvubu catchment

The GRS IDs and dates of Spot 5 images in SANSA's annual mosaics for the Mzimvubu catchment are listed in Figures 16 and 17 respectively. All the images received were captured between 09:49 and 10:29 in the morning. A few images could however not be used because they were not properly georeferenced, missed some bands or had problems with the band alignment.

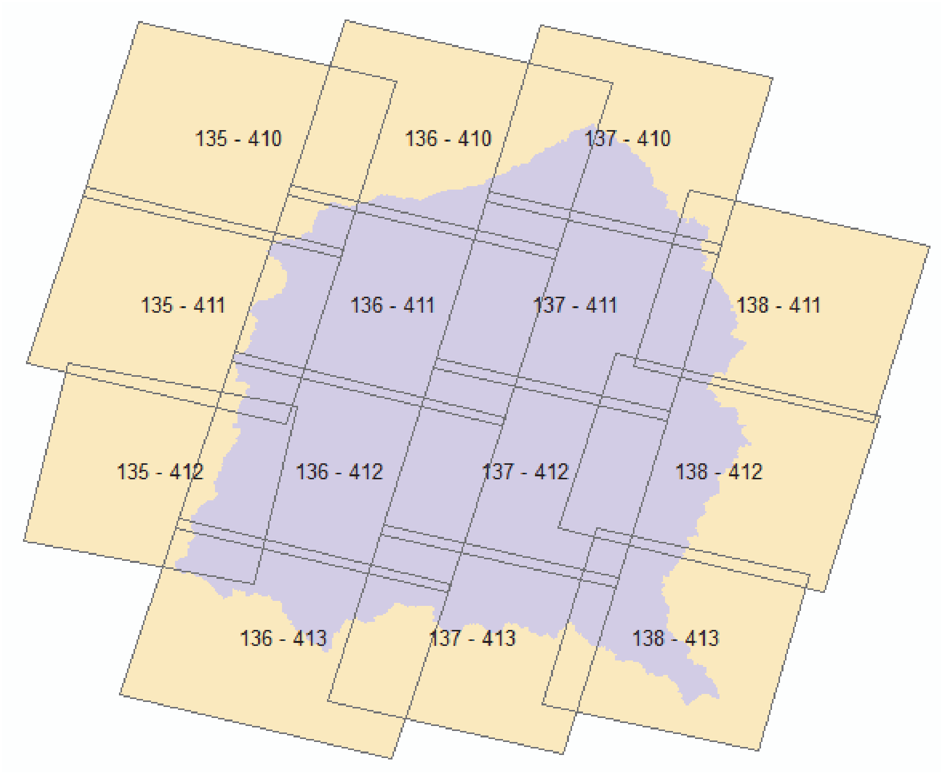


Figure 16 GRS IDs of Spot 5 images for the Mzimvubu catchment

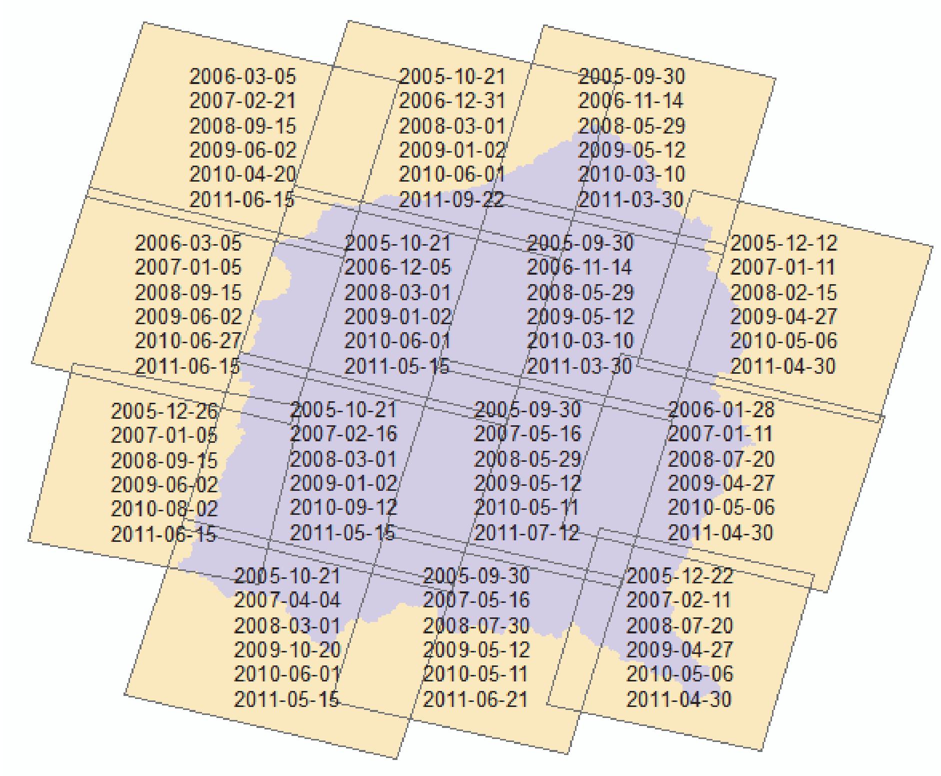


Figure 17 Dates of Spot 5 images in SANSA's annual mosaics for the Mzimvubu catchment

Two procedures were used to classify water from the SPOT 5 images namely the NDWI, water index and the ISODATA unsupervised classification. These two classifications were applied to all the available SPOT 5 images in the study area, providing up to six classifications between January 2005 and December 2011. The NDWI classification was done on the whole Mzimvubu catchment, while the unsupervised classification was only computed for tertiary catchment T35.

3.6.2.1 Application of the normalized difference water index (NDWI)

The normalized difference water index (NDWI) was used to classify open water for a series of SPOT 5 images (McFeeters, 1996). The NDWI is computed as follows:

$$NDWI = (\rho_{green} - \rho_{NIR}) / (\rho_{green} + \rho_{NIR}),$$

where ρ_{green} and ρ_{NIR} are the reflectance of Green and Near Infrared bands, respectively.

The formula will result in a value between -1 and 1, with the possibility that a pixel is water increasing from -1 to 1. A threshold for water has to be carefully selected. If the threshold is too high it might not pick up the water, while lower thresholds will have too much noise. Irrespective of the threshold it is difficult to separate water, shadows and burnt areas due to the similarities in pixel values and they will therefore normally fall in the same classification.

A threshold of 0.3 was used to classify open water. Up to six images were classified per SPOT tile as illustrated in figure 17. These images were then summarised to get the number of times that a specific pixel were classified as water. Figure 18 illustrates the NDWI classification of images over different dates, while the summarised result is shown in figure 19.

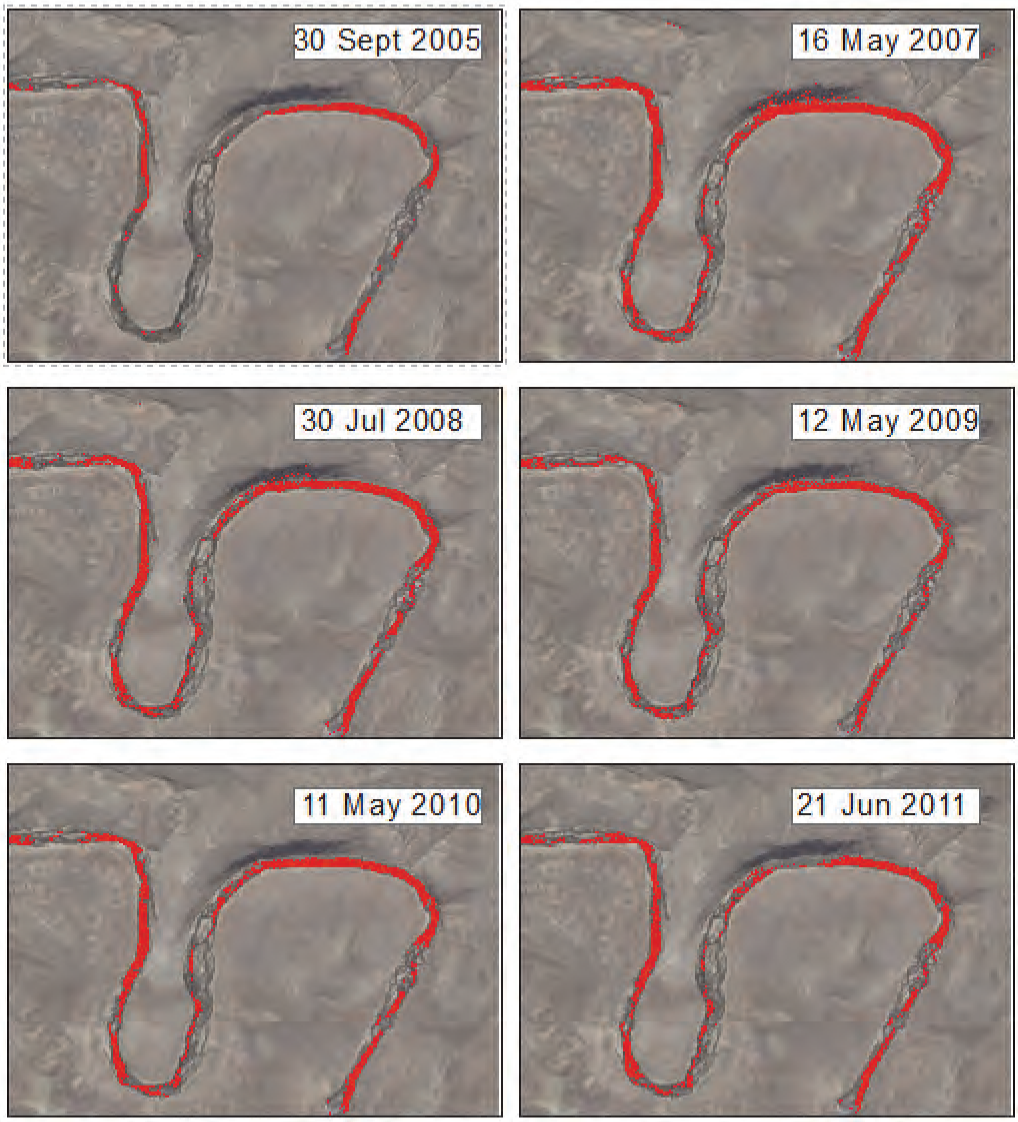


Figure 18 Water classification (Red) for different dates using the NDWI method. An aerial photo is displayed in the background

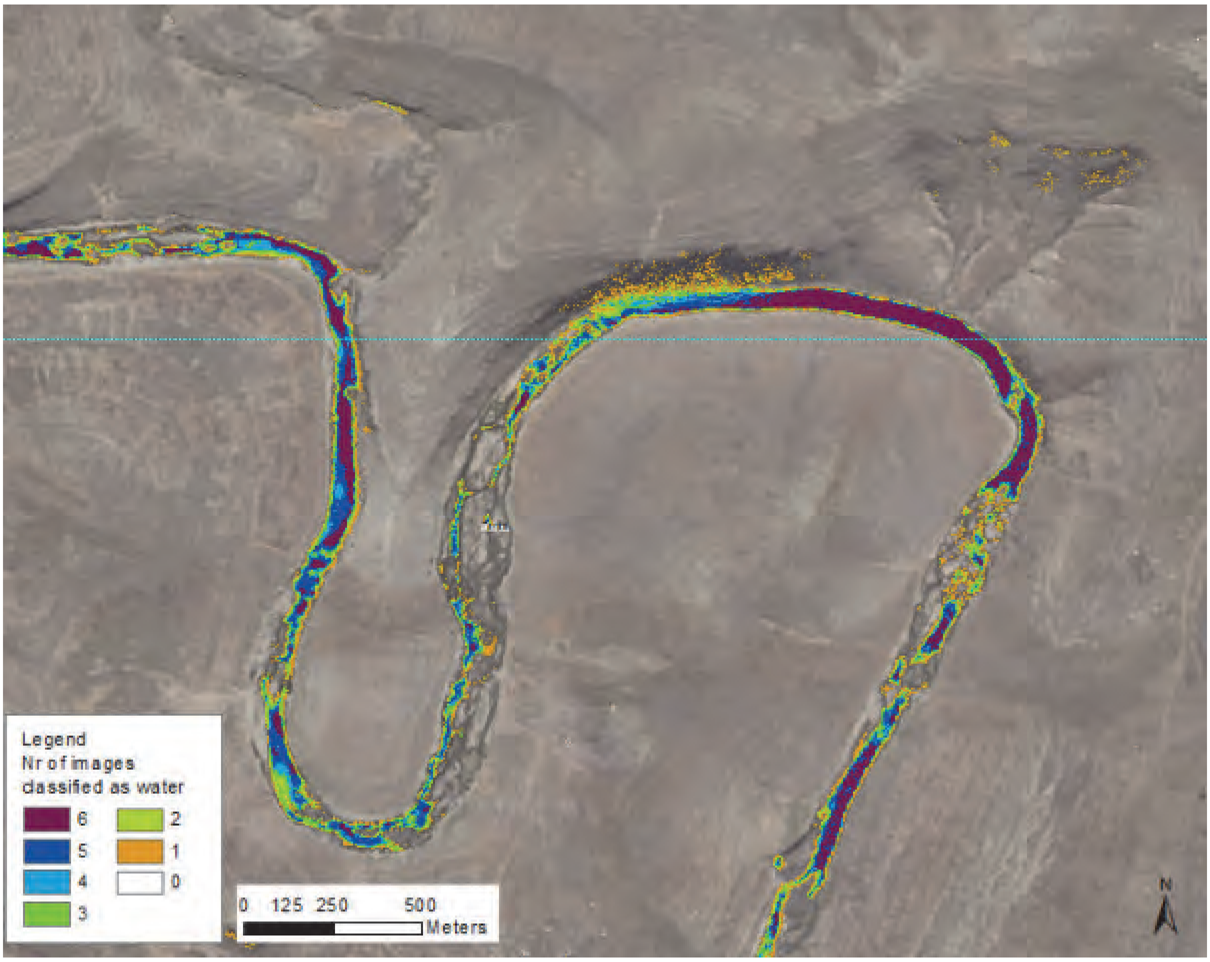


Figure 19 Number of years classified as water over a sample area (NDWI). An aerial photo is displayed in the background.

3.6.2.2 Application of a unsupervised classification

Unsupervised classification searches for natural groups, called clusters, of pixels present in the data by means of assessing the position of the pixels in the feature space (Ayhan and Kansu, 2012). Erdas Imagine's ISODATA classification that was developed by Ball and Hall (1965) was used.

The resulting clusters from the ISODATA classification were grouped manually into classes for water and everything else. Clusters representing water were identified by overlaying the classified image over the original image.

Up to six images were classified per SPOT tile. These images were then summarised to get the number of times that a specific pixel were classified as water. Figure 20 illustrates the unsupervised classification of images over different dates, while the summarised result is shown in figure 6. When comparing figure 21 (unsupervised classification) with figure 19 (NDWI) it is clear that areas with water were over classified with the unsupervised classification and under classified in the NDWI. The disadvantage with the unsupervised classification is therefor that some areas with no water (e.g. burned areas, shadows etc.) were wrongly classified as water. Although the NDWI did not effectively capture all the water pixels there are less noise emanating from the confusion of shadows and burnt areas with water.

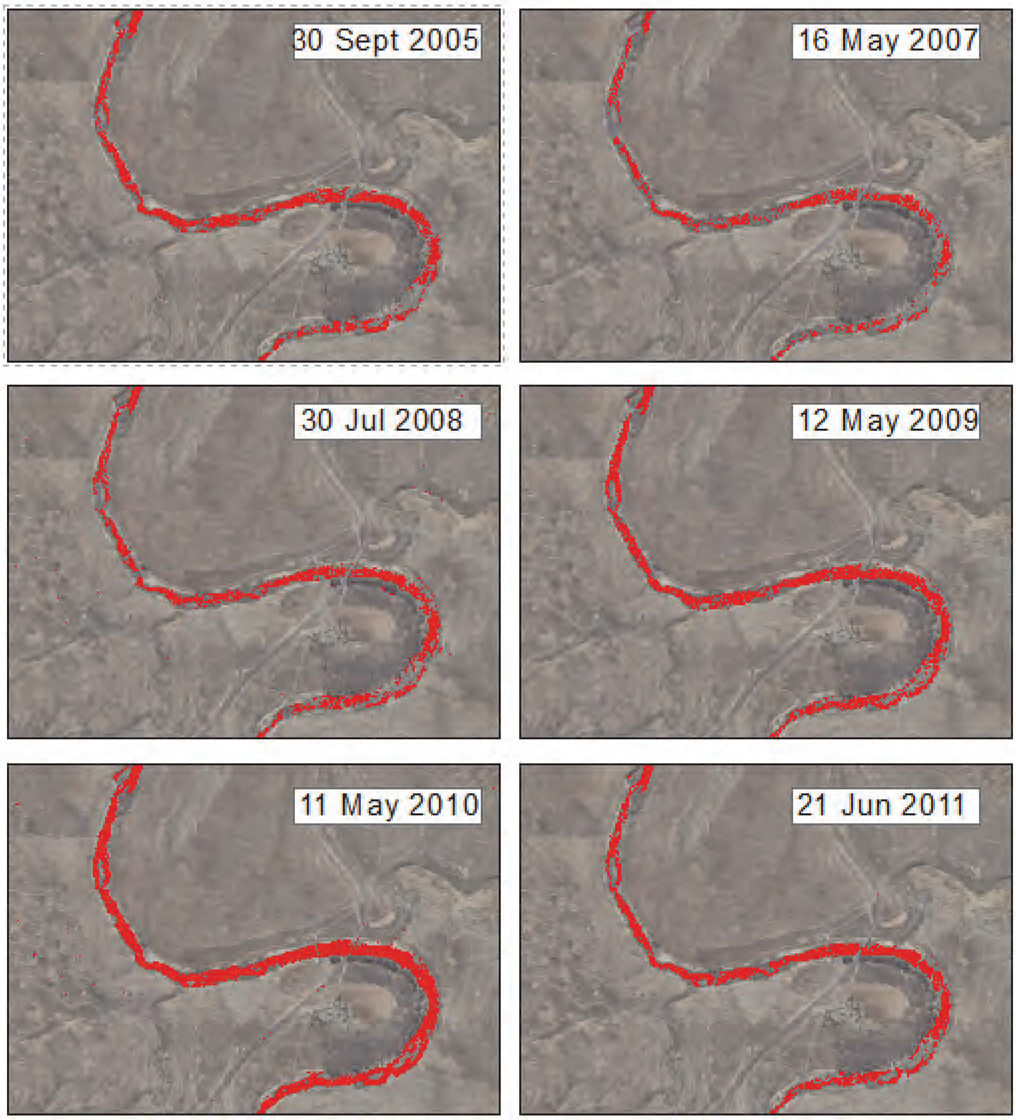


Figure 20 Water classification (Red) for different dates using the unsupervised classification method. An aerial photo is displayed in the background.

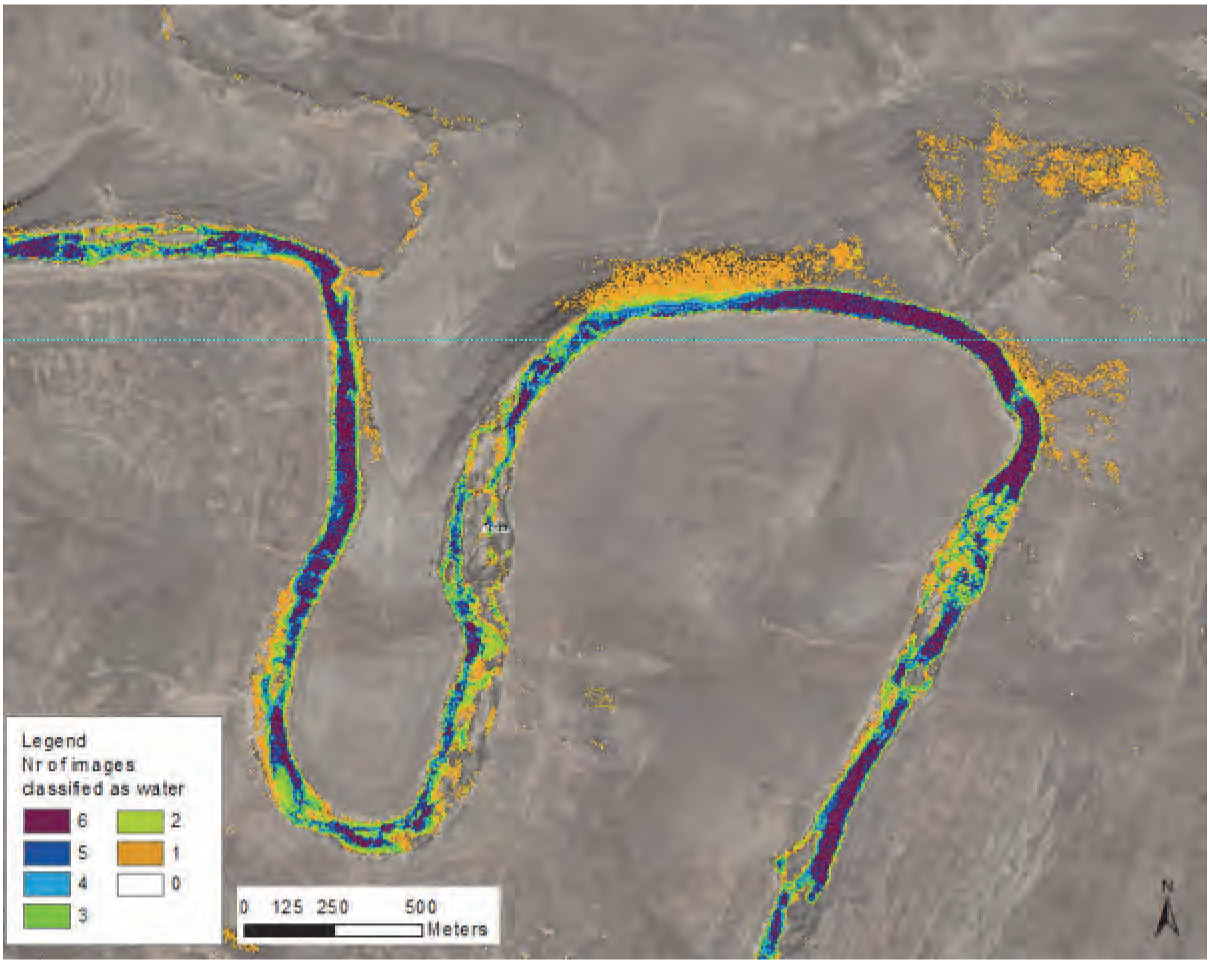


Figure 21 Number of images classified as water over a sample area (Unsupervised classification). An aerial photo is displayed in the background.

3.6.3 Cleaning of attribute data in the Mzimvubu catchment

Attributes in the final dataset included:

- River names
- Perennial status
- Stream order

Incorrect river names were corrected only if they appeared on the 1:250 000 map sheets. None of the rivers that fall in the 1:50 000 map sheet for Qumbu (3128) did have names, these names were added. Two useful functions in the river editing tool for the editing of names are the “trace downstream function and the ability to assign names to all selected lines.

The perennial status were verified and edited where necessary using the water classification composites as well as information from gauging stations. Only two classes were used in the Mzimvubu catchment namely:

- Perennial,
- Non perennial

Figure 22, illustrates the average monthly flow volume (in million cubic metres) along the different tributaries of the Mzimvubu river, as measured using gauging stations by the

Department of Water Affairs. The lowest monthly average flow (0.9) was measured in July in the Mooi River at Maclear and the highest flow (161) was measured in February in the Mzimvubu River at Ku-Makhola. These graphs indicate that all the main rivers in the Mzimvubu river network are perennial.

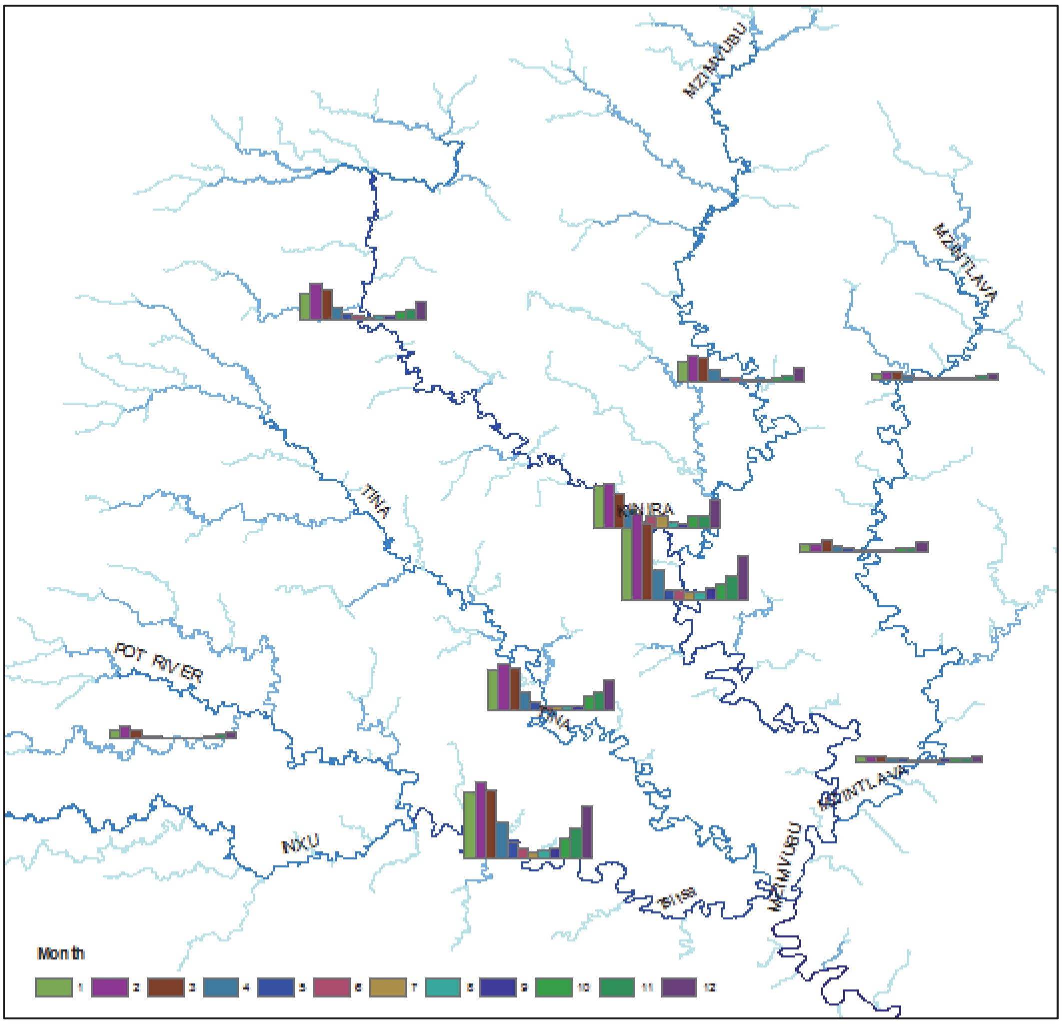


Figure 22 Average monthly flow volume in million cubic metres

Stream order for four different stream order types (Strahler, Horton, Shreve and Hack) were calculated with the river editing tool. During the calculation of the stream orders the distance of the longest upstream path in the river network for each line segment was also calculated and stored.

3.6.4 Selecting streams on 1:250 000 scale for the Mzimvubu catchment

The terms of reference of the project indicated that the deliverable of stream lines should be at the same level of detail that are displayed on the 1:250 000 maps. Stream order was used to select relevant streams from the 1:50 000 dataset. The following rule was used:

All streams with Strahler order > 1 and Horton order > 2.

Figures 23 and 24 show the difference in the level of detail on the 1:50 000 scale versus the 1:250 000 scale.

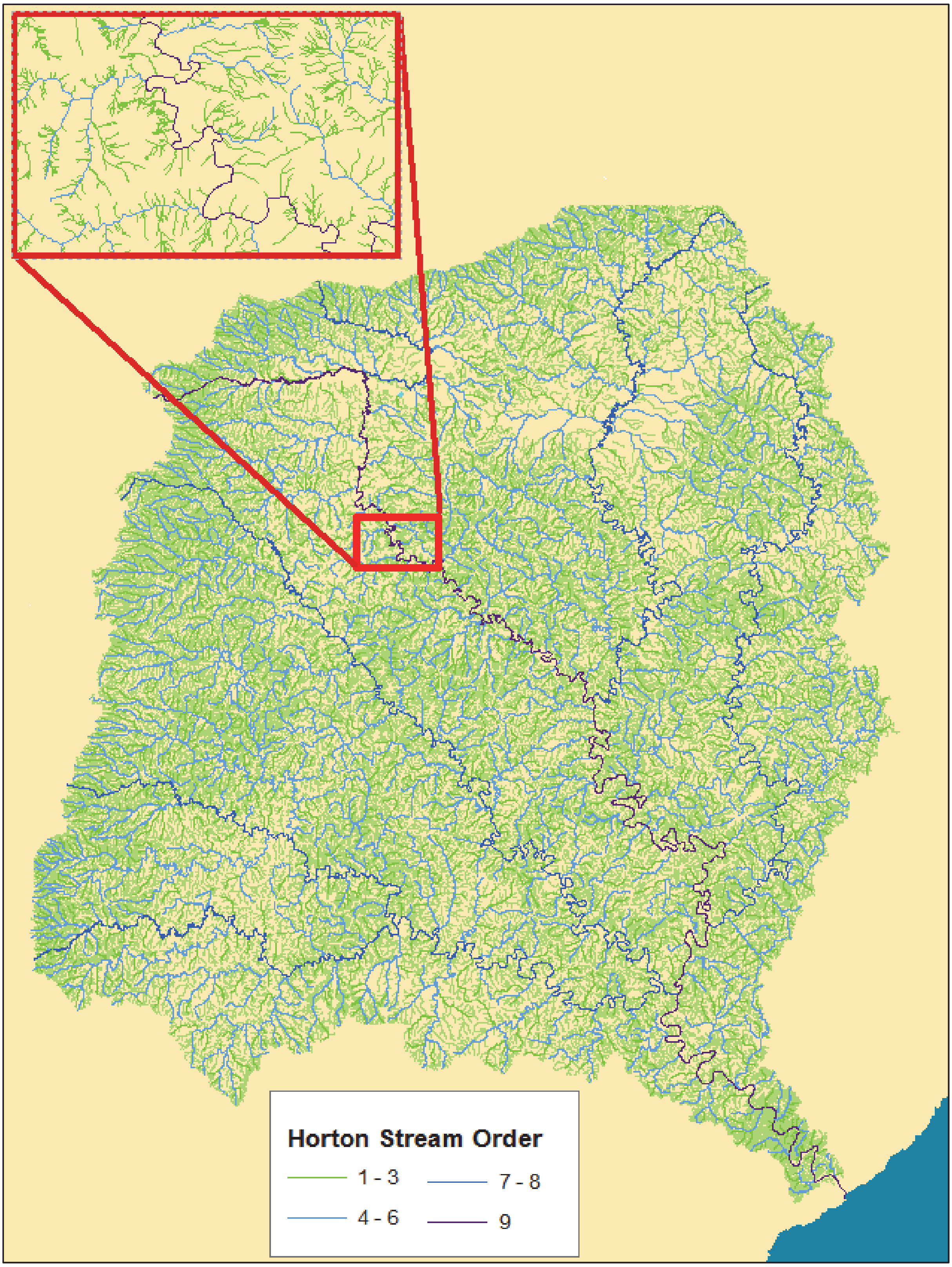


Figure 23 Streams of the Mzimvubu river at a detail level of 1:50 000 (124528 line features)

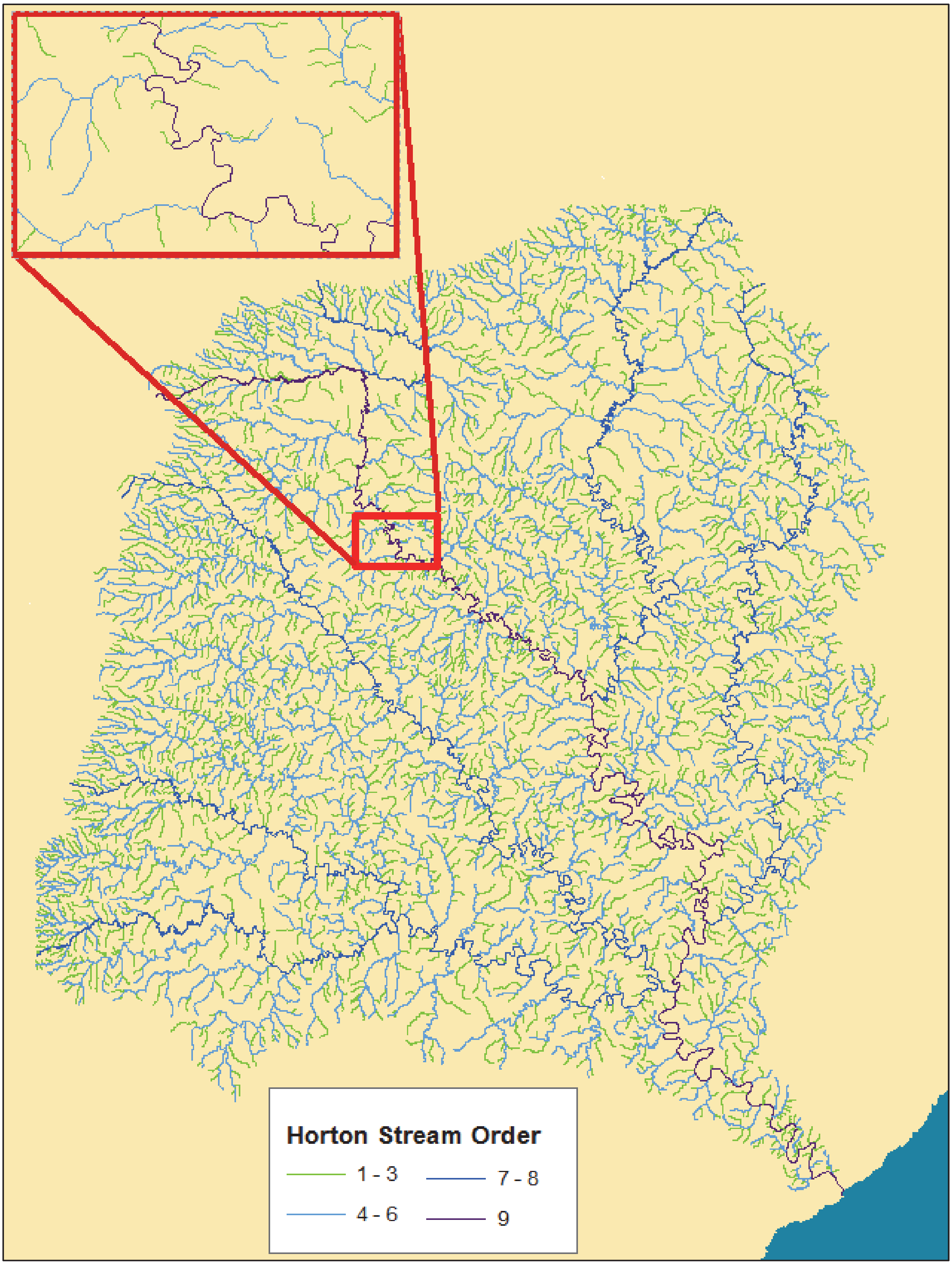


Figure 24 Streams of the Mzimvubu river at a detail level of 1:250 000 (26600 line features)

3.7 Molopo catchment

River centre lines were acquired from NGI for the South African part of the Molopo catchment (tertiary catchment D42). The river lines were extracted from the iTIS portal. For the trans boundary part of the catchment flow paths, derived from a DEM, was used. The actual river lines were selected from the flow paths and the two datasets were merged to create a complete river network for the Molopo catchment.

This paragraph illustrates the processes involved to get river lines to adhere to requirements for a river network as required for hydraulic/hydrological modelling purposes.

3.7.1 Cleaning of spatial data in the Molopo catchment

The River Editing tool has been used to clean the data. river centre lines. An extra field was added to the stream line dataset indicating the kind of error that was corrected. This was done so that the errors can be reported back to NGI for correction in their master data sets.

The spatial data (stream lines) was cleaned in the following ways:

- Fixing of geometry errors
- Enforce flow direction
- Removing all loops.
- Snapping of unconnected stream lines
- Correction of wrong stream lines.

The classification of riparian areas as well as the original SPOT 5 images and colour areal imagery of NGI was used as backdrop to verify and improve river center lines. Lines found to be wrong were digitised manually from the imagery.

3.7.2 Use of remote sensing data and derived products to improve the spatial data in the Molopo catchment

The dates of Spot 5 images in SANSA's annual mosaics for the Molopo catchment are listed in Figures 25.

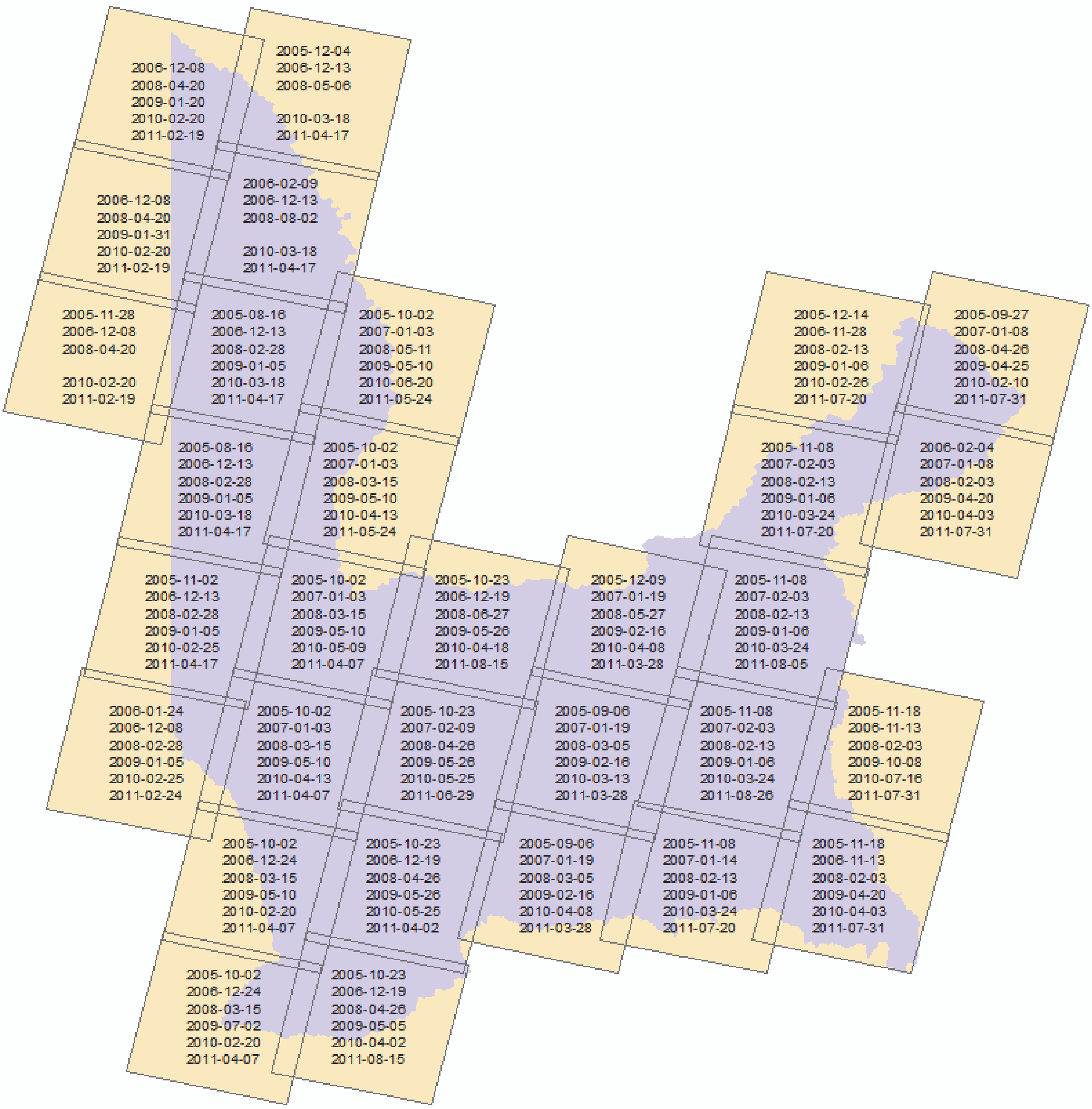


Figure 25 Dates of Spot 5 images in SANSA's annual mosaics for the Molopo catchment

3.7.2.1 Application of the normalized difference vegetation index (NDVI)

The Normalized Difference Vegetation Index, (NDVI) a basic vegetation index for measuring the 'greeness' of the earth's surface were used. A reasonable estimation of the density and coverage of green vegetation were determined by measuring how green the cover type on the earth's surface is. The formula to calculate NDVI is:

$$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{red} + \rho_{NIR}),$$

where ρ_{red} and ρ_{NIR} are the reflectance of Red and Near Infrared bands, respectively (Rouse *et al.*, 1974).

NDVI values can range from -1.0 to 1. Vegetation values typically ranged between 0.1 and 0.7. High NDVI values generally indicated increased degrees in the greenness and intensity of vegetation while low values were commonly characterised as rock and bare soil, and values less than 0 sometimes indicate clouds and water

It was observed during the study that the some vegetation types or vegetation structures had different spectral features in the images. This was mainly because of the difference in image acquisition date and because of the huge difference in vegetation types found in the province. Also, different vegetation types may possess similar spectra (spectrally shrubs and trees often resemble grassland), and thus cannot be safely distinguished and classified which make it very hard to obtain accurate classification results using the traditional unsupervised classification or scaling of vegetation indices according to fixed values. For this reason each image and VI was classified and scaled individually using the high resolution images on Google Earth and expert field knowledge of the study area.

The NDVI, unsupervised classification and texture analysis were combined using a script to extract pixels that fulfilled the criteria in each of the layers of being classified as a tree or shrub. These pixels were assigned a unique value in a new classification raster. The result being a potential map of tree and shrub cover for the South African part of the Molopo catchment on 2.5 meter resolution.

3.7.3 Cleaning of attribute data in the Molopo catchment

Attributes in the final dataset included:

- River names
- Perennial status
- Stream order

Incorrect river names were corrected only if they appeared on the 1:250 000 map sheets. Two useful functions in the river editing tool for the editing of names are the “trace downstream function and the ability to assign names to all selected lines.

The perennial status of all the streams in the Molopo catchment was classified as Ephemeral.

Stream order for four different stream order types (Strahler, Horton, Shreve and Hack) were calculated with the river editing tool. During the calculation of the stream orders the distance of the longest upstream path in the river network for each line segment was also calculated and stored.

3.7.4 River lines for the cross-boundary areas

The river centre lines of NGI are only available for South Africa. Flow paths were therefore calculated from the hydrologically improved DEM, prepared by Weepener *et al.* (2012). A threshold of 100 was used to indicate the start of flow paths from a flow accumulation grid.

As illustrated in Figure 1, in the introduction, flow paths do not represent actual rivers well in this study area. The Strahler stream order was therefore calculated and used to select actual streams from the flow paths at different levels of drainage density (DD) The drainage density was chosen through a visual interpretation of Landsat 8 imagery and a map indicating potential DD. This map was stratified into different density classes by means of a scoring system of factor maps that determine drainage density. The layer has values ranging from one (low DD) to five (high DD). Table 7 show the relationship that was applied between the DD rank and the Strahler stream orders.

Table 7 The relationship between the DD rank and the Strahler stream orders

DD	Strahler stream order
5	All flow paths
4	Flow paths with stream order greater than 1
3	Flow paths with stream order greater than 2
2	Flow paths with stream order greater than 3
1	Flow paths with stream order greater than 4

The following spatial data sets was used to create the potential DD map:

- Annual precipitation (New et al., 2002));
- Terrain (Mountainous areas, flow paths, etc.) derived from a hydrologically-improved SRTM DEM (Weepener et al., 2012);
- Soil information will be obtained from the SOTER data set (FAO, 1995);
- Global Land Cover 2000 (JRC, 2003);

A visual inspection of the dominant major soil group in the SOTER (FAO, 1995) data shows that the Arenosols group only have main river beds, while the other soil groups also include minor tributaries. Figure 26 illustrates the stream density for streams inside South Africa, overlaid over the dominant soil groups.

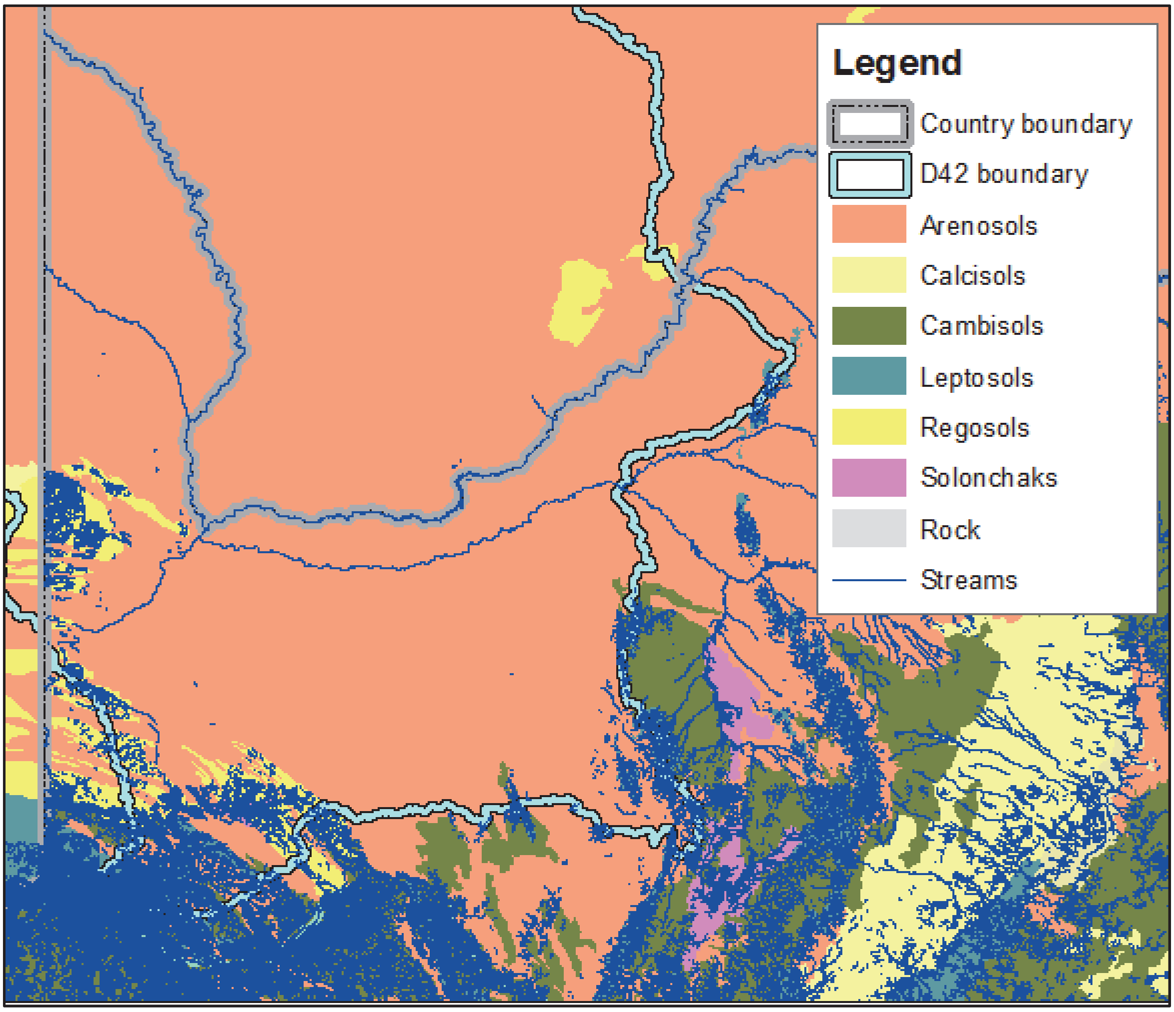


Figure 26 Streams inside South Africa, overlaid over the dominant soil groups.

It was challenging to separate mountainous areas from the many sand dunes in the study area. The following procedure was followed to calculate mountainous areas:

- Calculate the maximum and minimum elevation values of the 3x3 and 6x6 neighbouring cells for each cell in the DEM.
- Subtract the minimum elevation values from the maximum elevation values to create new grids that we will call Diff3 and Diff6 respectively. These grids contain the maximum relative height difference of the neighbouring cells. The grid derived from 6x6 neighbouring cells will be used to ensure that only significant features are selected, while the grid with the 3x3 neighbouring cells are used to define the boundary of the feature (If only the 3x3 neighbouring cells were to be used it would also capture dunes).
- Create a third grid by taking the median values of the 5x5 neighbouring cells for each cell in Diff3 (For the purposes of this report called median_grid). This is done to derive smoother boundaries of the features.
- Mountainous areas are now calculated as all areas where median_grid are greater than 20 meter and where diff6 are greater than 40 meter.

It is important to note that this procedure will not only extract mountains, but also large valleys / gorges. For the purposes of this project both mountains/hills and large valleys / gorges will result in higher density stream lines. If the two types of features have to be separated a last step can be added to the procedure which also incorporates the calculation of curvature.

Figure 27 illustrates the resulting map.

Figure 27 Mountainous areas in tertiary catchment D42

Annual precipitation and Landcover did not show such strong relationships with DD as mountainous areas and arenosols. Tables 8 and 9 were however still prepared to use landcover and rainfall respectively to get an indication of DD for areas that do not fall in either mountainous areas or arenosols.

Table 8 The proposed DD rank for land cover classes

Global Land Cover 2000	Rank (1 = low DD; 5 = high density DD)
Deciduous woodland	3
Deciduous shrubland with sparse trees	3
Closed grassland	3
Open grassland with sparse shrubs	3
Open grassland	4
Sparse grassland	4

Table 9 The proposed DD rank for annual precipitation classes

Annual precipitation	Rank (1 = low DD; 5 = high density DD)
100-200 mm	2
200-300 mm	3
300-400 mm	4
More than 400 mm	5

The following rules were applied to derive the potential DD map (See figure 28):

- DD = 5 for all mountainous areas
- DD = 1 if the major soil group in the SOTER (FAO, 1995) data is Arenosols
- Use the average of the rank between landcover and annual precipitation for all other areas.

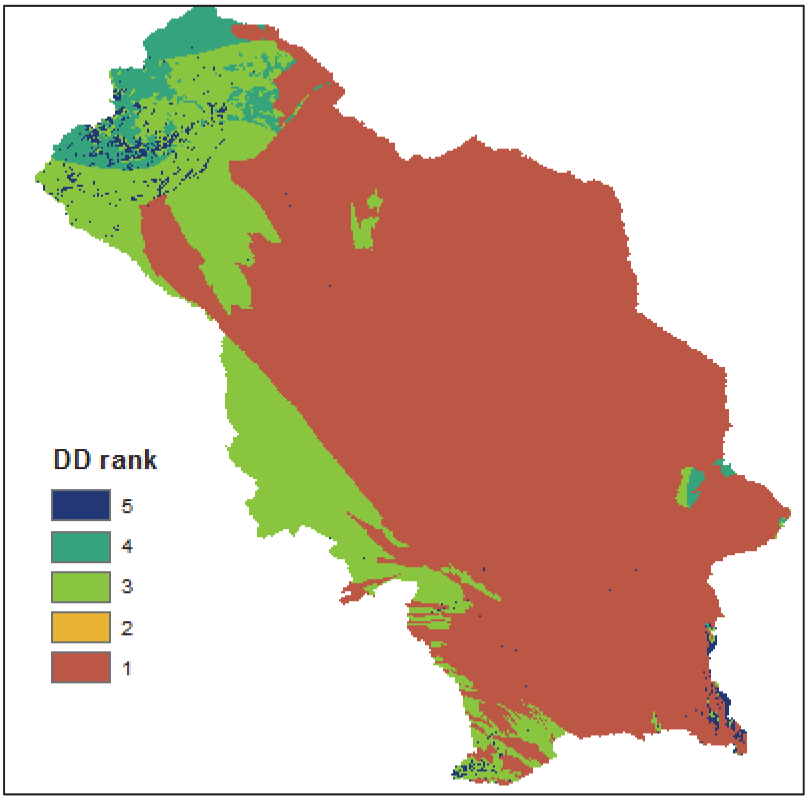


Figure 28 Potential DD map

3.7.5 Selecting streams on 1:250 000 scale for the Molopo catchment

The terms of reference of the project indicated that the deliverable of stream lines should be at the same level of detail that is displayed on the 1:250 000 maps. Stream order was used to select relevant streams from the 1:50 000 dataset. The following rule was used:

All streams with Strahler order > 1 and Horton order > 2.

4 RESULTS AND DISCUSSION

River networks were successfully developed for the Molopo and Mzimvubu catchments. The networks were in sharp contrast to each other, mainly due to the huge difference in rainfall and steepness of terrain. The Mzimvubu catchment has a well-defined river network with a high DD, while the river network of the Molopo catchment is intermittent with a low DD. The Molopo catchment had numerous small river networks, which were not connected to the main stem, but ended in pans. The perennial status of streams in the Mzimvubu River were either perennial or non-perennial, while the streams in the Molopo could be ephemeral or non-perennial. The difference is also evident in the four stream orders that were assigned to the two catchments (See maps in Appendix B). It will be possible to roll out the developed methodology to the whole country, with the exception of the models that were developed for the cross-border areas of the Molopo catchment since these models are area specific.

The River Editing Tool was developed to assist with the cleaning of existing river centre line data. The functionality of the tool focuses on the development of river networks from lines. Many processes were automated and simplified to assist the user. Some of the key functions include:

- Automatically applying flow direction of stream lines from a DEM.
- Automatically applying flow direction from the mouth of a river network.
- Finding loops in the river network.
- Selecting upstream or downstream line segments from a specified position.
- Assigning attributes to all selected stream lines
- Calculating stream order of river segments in a river network.

The tool is also very useful when attributes has to be assigned. The functionality to trace upstream or downstream allows the user to quickly find the river segments that has to be assigned the same name, or perennial status.

Remote sensing imagery was useful in correcting errors in the river centre line data and also for identifying the perennial status of streams. The following products were used as backdrop during manual editing of the data:

- NGI colour aerial photography: Molopo and Mzimvubu catchments
- Spot 5 imagery (2005-2011): Molopo and Mzimvubu catchments
- Landsat 8 imagery (2000, 2014)): Molopo catchment
- Water classification (NDWI) from SPOT 5 imagery: Mzimvubu catchment
- Unsupervised classification of water from SPOT 5 imagery: Mzimvubu catchment
- Vegetation classification: Molopo catchment

Two different procedures were used to classify water from SPOT 5 images namely unsupervised classification and NDWI. The open water classification was done for the whole Mzimvubu catchment for all available Spot 5 images in SANSA's annual mosaics (2006-2011) Up to six images were classified per SPOT tile. These images were then summarised to get the number of times that a specific pixel were classified as water. The results differed from area to area, but in general the NDWI seemed to under classify water, while the unsupervised classification over classified water. By applying some level of interpretation the following products can be derived:

- Perennial status of large rivers
- Area covered by dams
- To select the most significant branch in braided systems

A possible improvement could be to use a different NDWI threshold for each image, instead of the fixed threshold of 0.3 that was used in this exercise. It will however still be difficult to get a correct threshold for each image due to the fine balance that has to be maintained when noise (non water) increases with lower NDWI thresholds. This is supported by the fact that similar challenges were encountered with the unsupervised classification even though it was manually done for each image.

Atmospheric correction of the images before the calculation of NDWI could also narrow the gap between thresholds in different images. This may also improve the unsupervised classification method.

For the Molopo catchment it was not possible to classify open water, due to the fact that the river beds are mostly dry. A classification of vegetation was done instead and was included as one of the layers used as backdrop during the editing of stream lines. Riparian vegetation often indicated the actual position of streams, when it was unclear on the colour image itself.

5 CONCLUSION

River networks are not only important for hydrology, but also many other disciplines such as anthropology, ecosystems, groundwater recharge, epidemiology and geomorphology as illustrated by Rodriguez-Iturbe et al., 2009. An example where a South African hydrological network has been useful outside the hydrological domain is the epidemiological study of cholera in the Thukela by Bertuzze et al. (2008) who made use of the RQS 1:500 000 river network.

The river editing tool was found to be very useful during the editing of the data to develop river networks. Some of the functions take some time to execute, but the process is many times faster than manual editing. The river editing tool was successfully tested on a large dataset (124 528 line segments of the Mzimvubu catchment).

The four different stream order types that were calculated make it possible to do subsets of the river network. It was for example illustrated that it is possible to select stream lines at the same level of detail that are displayed on the 1:250 000 from the 1:50 000 dataset. The calculation of stream order takes a considerable amount of time. The calculation of the stream order for the complete secondary catchment T3 (122 423 line features) took a week of processing time, while tertiary catchments T31 (15 705 features) and T34 (25 233 features) took less than a day to complete.

Remote sensing imagery was useful in correcting errors in the river centre line data and also to identify the perennial status of streams from derived products.

NGI has to be informed of corrections that were done so that the corrections can also be made on the master dataset hosted by them and incorporated in future. A large improvement from previous versions of the river line data is that most streams have recently been connected by NGI.

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APPENDIX A: RIVER EDITING TOOL (USER MANUAL)

User Manual:
River Editing Tool version 1

K5/2164/1

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Table of Contents

1 Introduction

The river editing tool streamlines the digitising and editing of river line features. The tool runs in ArcGIS versions 10.1 or 10.2 with a standard license. The tool can be applied to shapefiles or geodatabases. This manual assumes that the user has a basic knowledge of Geographical Information Systems (GIS) and ArcGIS.

This tool simplifies the editing of both line features and attribute data. Amongst others it has the following functionality:

- Automatically applying flow direction of stream lines from a Digital Elevation Model (DEM).
- Automatically applying flow direction from the mouth of a river network.
- Finding loops in the river network.
- Selecting upstream or downstream line segments from a specified position.
- Assigning attributes to all selected stream lines.
- Calculating stream order of river segments in a river network.

2 Installation

The river editing tool can be installed in ArcMap 10.1 or 10.2 (standard license). To install the tool, simply double click the esriaddin file which can be recognised by the .esriaddin file extension (Figure 1).

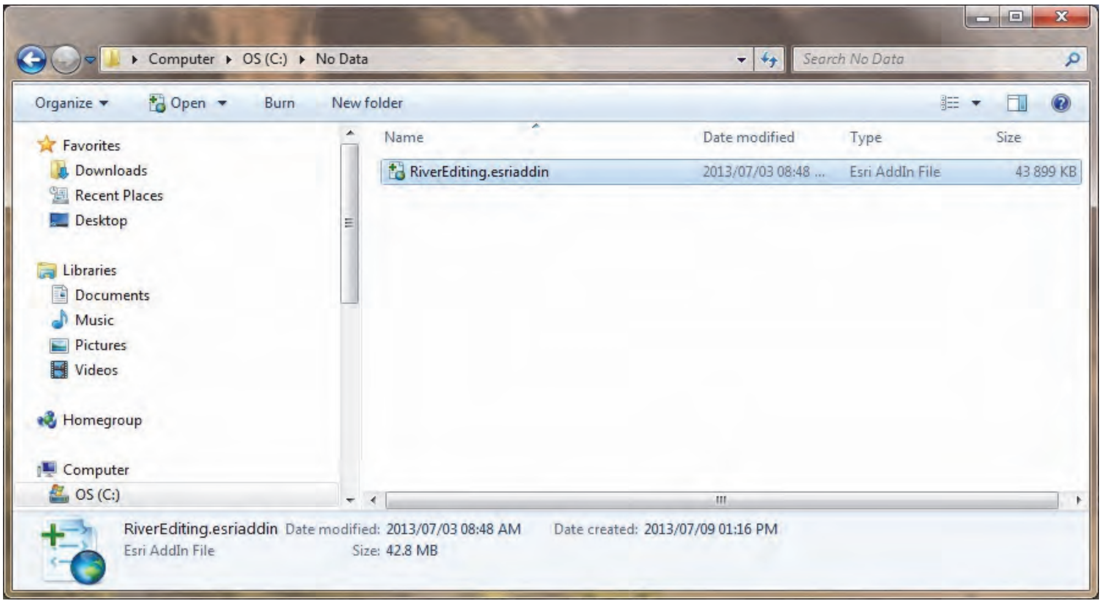


Figure 1: River Editing esriaddin file

After selecting the esriaddin file, an Installation Utility window will appear in which one should click on the Install Add-In button (Figure 2).

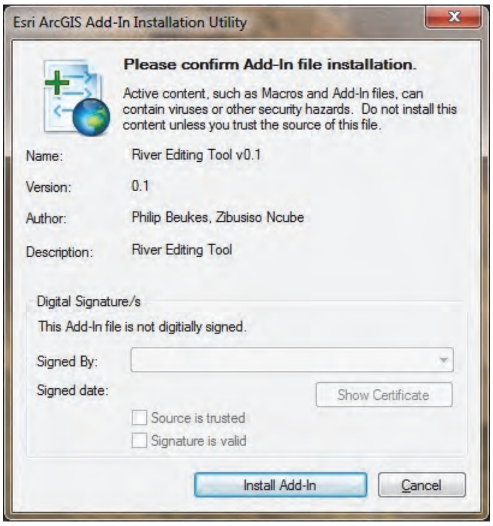


Figure 2: Installation Utility window

When installation is successful, click the OK button (Figure 3).

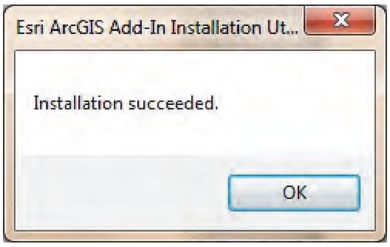


Figure 3: Installation success

3 Enabling the Toolbar

To enable the toolbar and its extension, if not yet enabled, go to ArcMap's Customize menu (Figure 4).

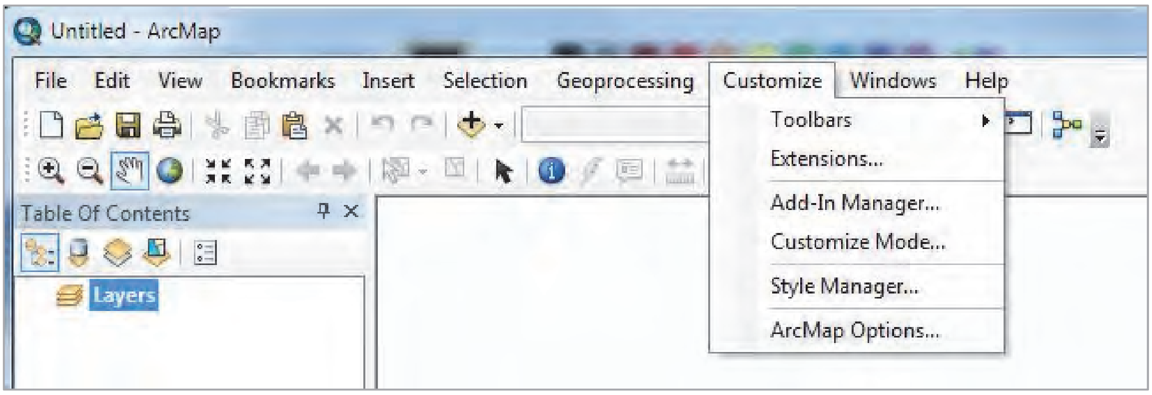


Figure 4: Customize menu

To enable the river editing extension select Extensions in the Customize menu and check the River Editing box (Figure 5).

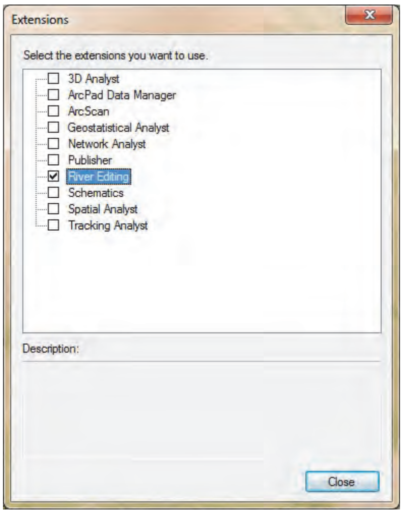


Figure 5: Check the River Editing extension

To enable the River Editing toolbar select Toolbars from the Customize menu, scroll down to River Editing v0.1 and check the adjacent box (Figure 6). To disable the toolbar, follow the same steps and click the box again to remove the check mark.

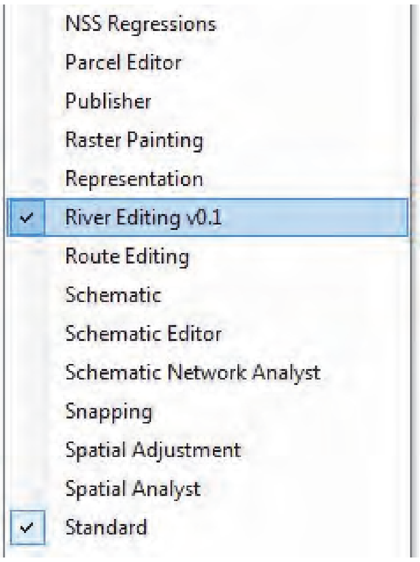


Figure 6: Select River Editing v0.1

The River Editing toolbar will appear (Figure 7).

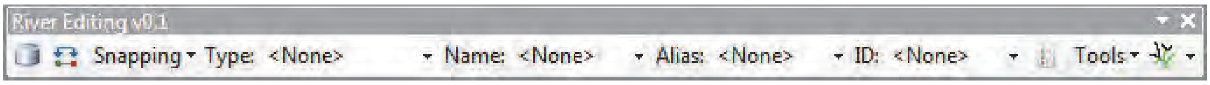


Figure 7: River Editing toolbar

4 Tools and Buttons

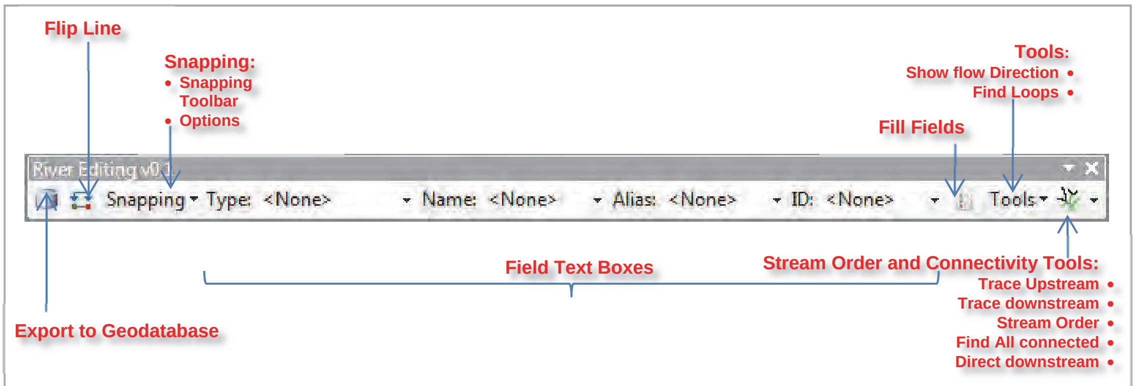


Figure 8: Tools and Buttons

4.1  Export to Geodatabase

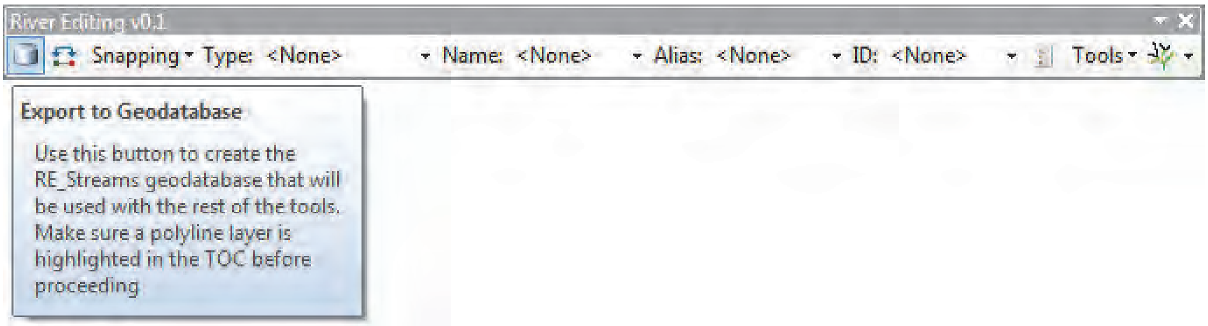


Figure 9: Export to Geodatabase button

Use the Export to Geodatabase button to export the selected shapefile to a geodatabase.

NOTE: Before exporting data to the geodatabase it should be projected to the projection that the user will be using for all the data and into one that lengths of rivers can be calculated for the purposes of other functionality within the tool

The Export to Geodatabase dialogue shown in Figure 10 will appear.

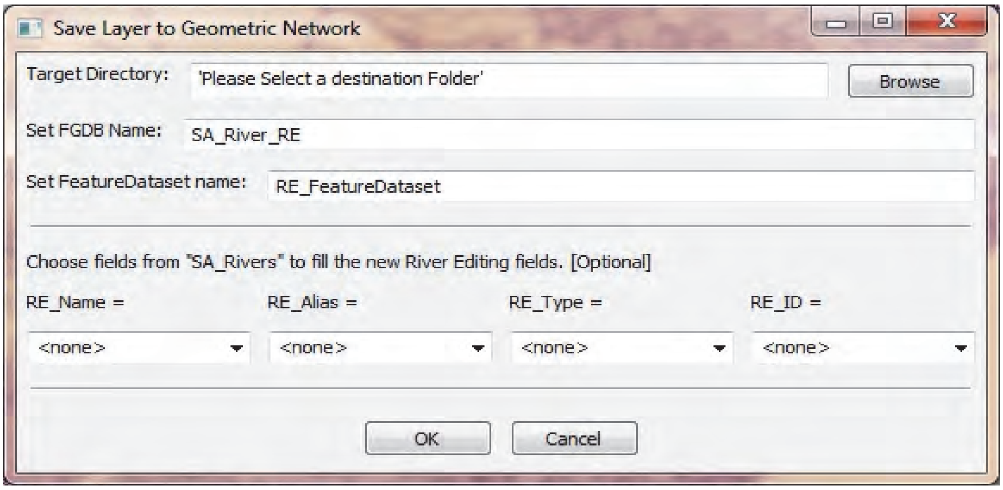


Figure 10: Export to Geodatabase dialogue

When exporting to the geodatabase, select a folder to place the geodatabase and click open (Figure 11).

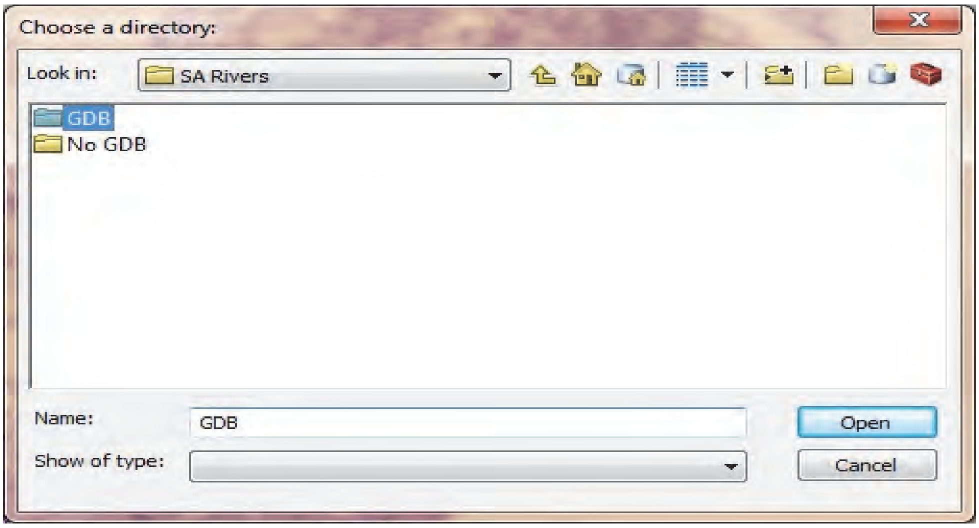


Figure 11: Select Geodatabase folder

Give the geodatabase as well as the feature dataset unique names, or leave the default names as allocated by the tool. A line feature class with the name RE_Streams will be created in the feature dataset. Choose fields from the source dataset that will be used to populate the newly created River Editing fields in the RE_Streams feature class (this last process is optional). The newly created River Editing fields are:

RE_Name: This field will contain the river names.

RE_Alias: This field will contain aliases of the river names.

RE_Type: This field will contain the type of river.

RE_ID: This field will contain special river IDs used to identify certain rivers or stretches thereof.

IMPORTANT GENERAL NOTE

Whenever the RE_Streams feature class has been edited manually, i.e. if the start or end point of a line is moved, or lines are added, deleted, merged or split, one should always run the **Calculate Nodes** function in order to recalculate/update the end and start node of every line. These end and start nodes are very important since without correct node data the tool will not function properly.
N.B.: If one is in any doubt whether or not to run the Calculate Nodes function after an edit, it is good practice to run it anyway.

4.2 Flip Line

Highlight a Line feature in the table of contents (TOC) and select the lines you want to flip with the Edit tool when in editing mode. Click this button (Figure 12) to flip only selected lines. To flip all lines do not select any lines and click the button. This can be done on any line feature, not just with the RE_Streams feature.

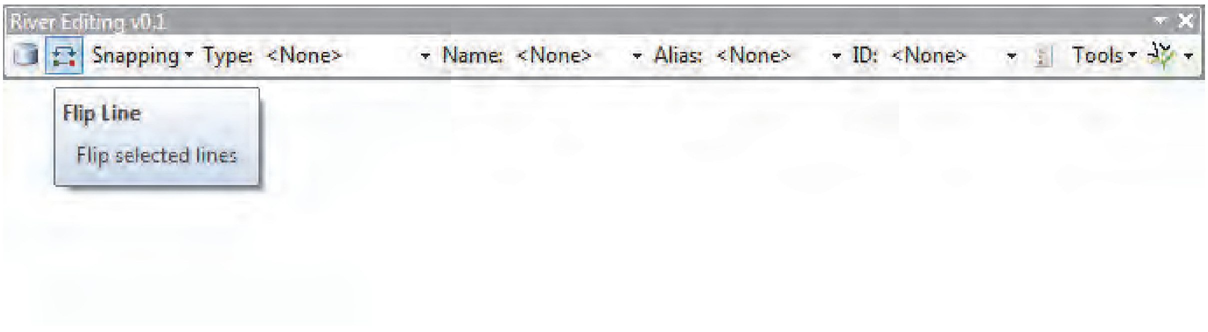


Figure 12: Flip Line button

An alternative to using the Flip Line button is to double click a line when in editing mode so that the vertices are visible, then right click that line and select Flip from the context menu that appears (see **Limitations and Known Bugs** about this type of Flip Line). However, it is preferable not to use this alternative Flip Line method.

4.3 Snapping

Snapping allows one to create features that connect to each other. The Snapping tool (Figure 13) enables one to switch the snapping on or off. If it is turned on, the editing pointer will snap to an edge or vertice element (depending on the selection on the tool) when it is near and within a certain tolerance of that element. Hover the mouse over the tool buttons to get more information. Of particular interest are the last two snapping options:

- Vertex Snapping – features being edited will snap to the nearest feature vertice within a specified distance.
- Edge Snapping – features being edited will snap to the nearest feature edge within a specified distance.

See section 6 for guidelines on editing line features.

Figure 13: Snapping tool

4.4 Field text boxes

Figure 14: Field text boxes within the toolbar

Enter a name in the Name box, an alias in the Alias box and an ID in the ID box. These values will be stored with each new feature created or existing feature edited (section 6). The respective values will be stored in the following fields:

- RE_Type
- RE_Name
- RE_Alias
- RE_ID

To change the stream type: Select a stream type from the Type dropdown box. Choose from **Non Perennial, Perennial** and **Ephemeral**.

4.5  Fill Fields

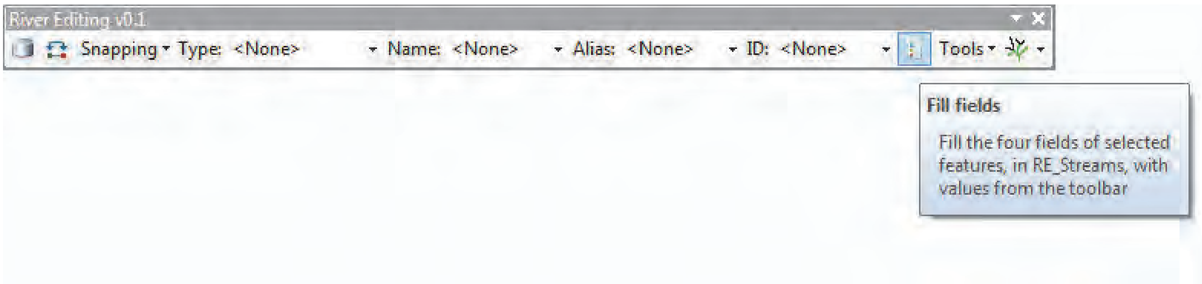


Figure 15: Fill fields button

On clicking the Fill Fields button (Figure 15) the fields of selected features will be filled with the information in the four textboxes of the river editing tool. The selection functionalities of the different tools are described in the following sections.

4.6 Tools

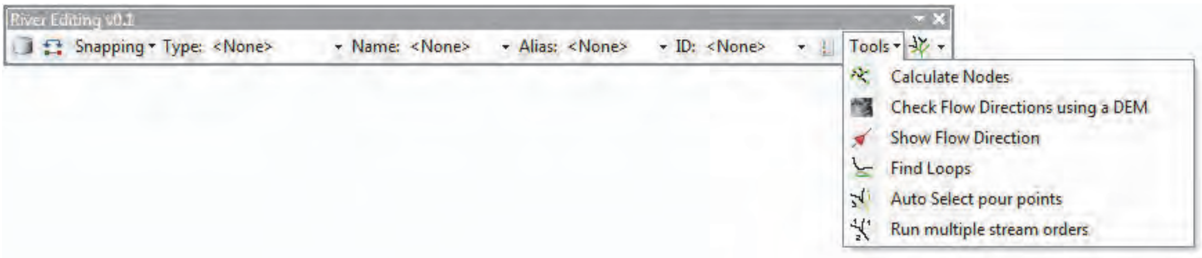


Figure 16: Tools menu

The Tools menu (Figure 16) contains pre-processing tools that aid the user in cleaning up their river data or preparing it for analysis or processing.

4.6.1 Calculate Nodes

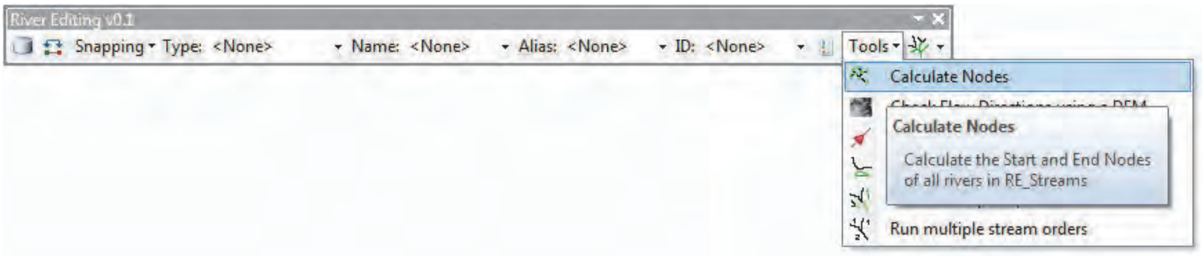


Figure 17: Calculate Nodes button

The Calculate Nodes button (Figure 17) creates and adds a node layer (nodes of the RE_Streams layer) onto the TOC to view the start and end nodes of all rivers in the river layer (see Figures 18 and 19). The nodes point layer itself is only required for the Check Flow direction using a DEM process; the rest of the time this layer can be removed from the TOC. But the results of the Calculate Nodes process are important and necessary for all other tools because it creates and/or updates the RE_From and RE_To values in the RE_Streams attribute table.

NOTE: Nodes should be recalculated after any edits have been done on the river data (add, modify, delete features, etc.) and after being saved, i.e. if any connectivity or stream order processes are to be run on that river layer (in this case the layer named RE_Streams)

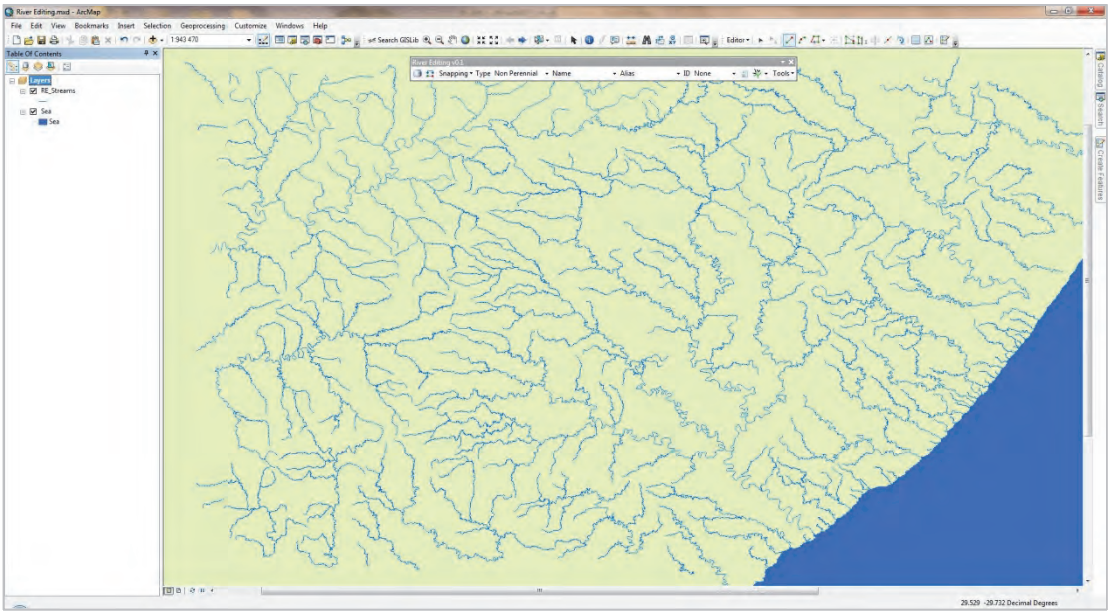


Figure 18: Before Nodes calculation

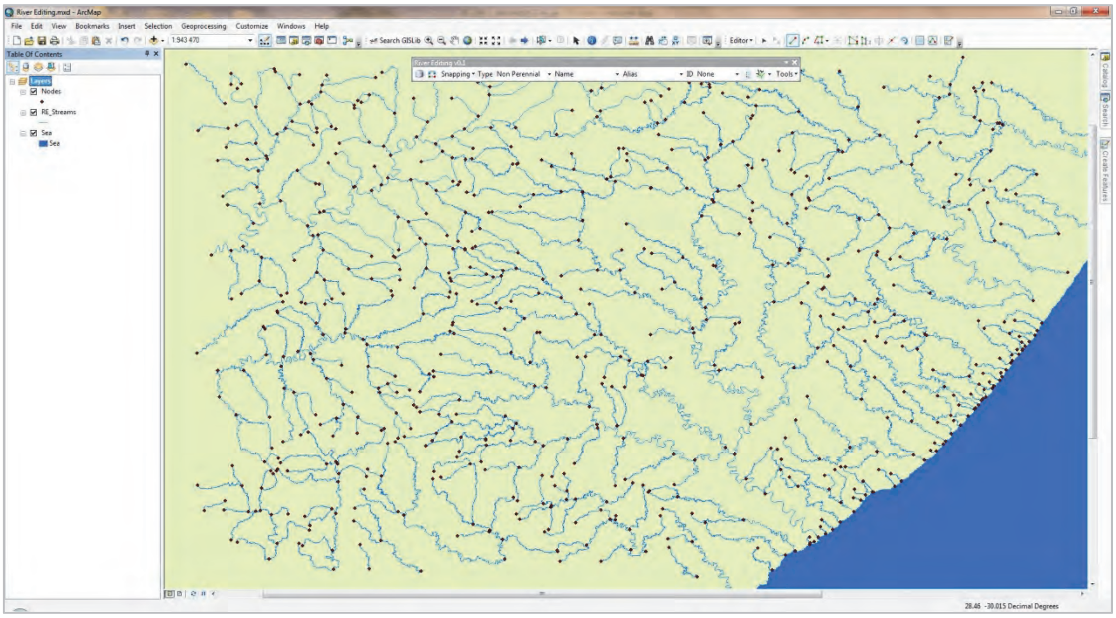


Figure 19: After Nodes calculation

4.6.2 Check Flow Directions using a DEM

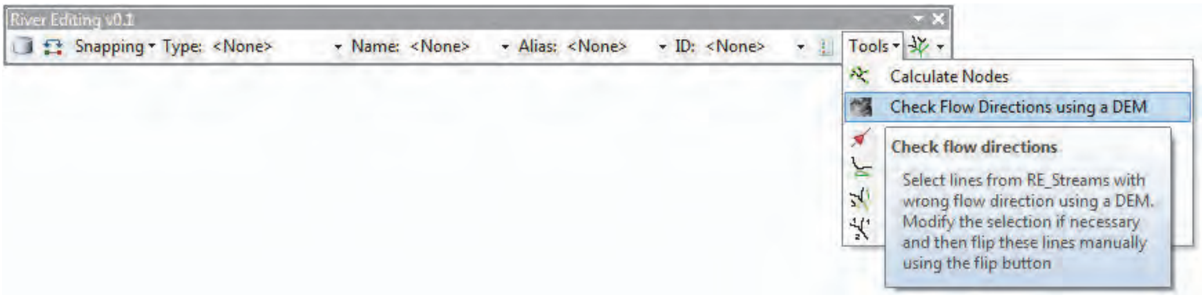


Figure 20: Check Flow Directions using a DEM button

The Check Flow Directions button (Figure 20) checks a river segments flow direction using height values from the DEM. It checks if the “From” point is higher than the “To” point; if not it highlights the segment that is not in this alignment so the user can flip it using the Flip tool.

4.6.3 Show Flow Direction

Figure 21: Show Flow Direction button

The Show Flow Direction button (Figure 21) allows the user to see the direction of flow in a river segment, using an arrow on the river element showing the flow path within that segment (see Figures 22 and 23).

To use:

1. Select the Rivers Layer (polyline layer) you want to show flow direction for in the ArcMap TOC.
2. Click on the Show Flow Direction button.

To remove, highlight the same layer and run the tool again.

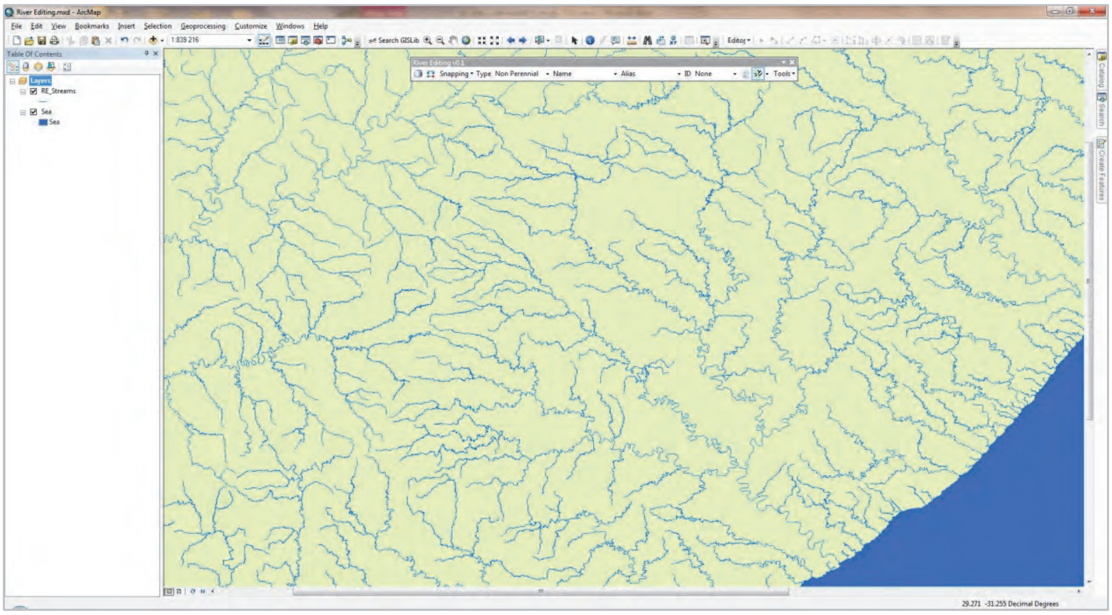


Figure 22: Rivers before Show Flow Direction procedure

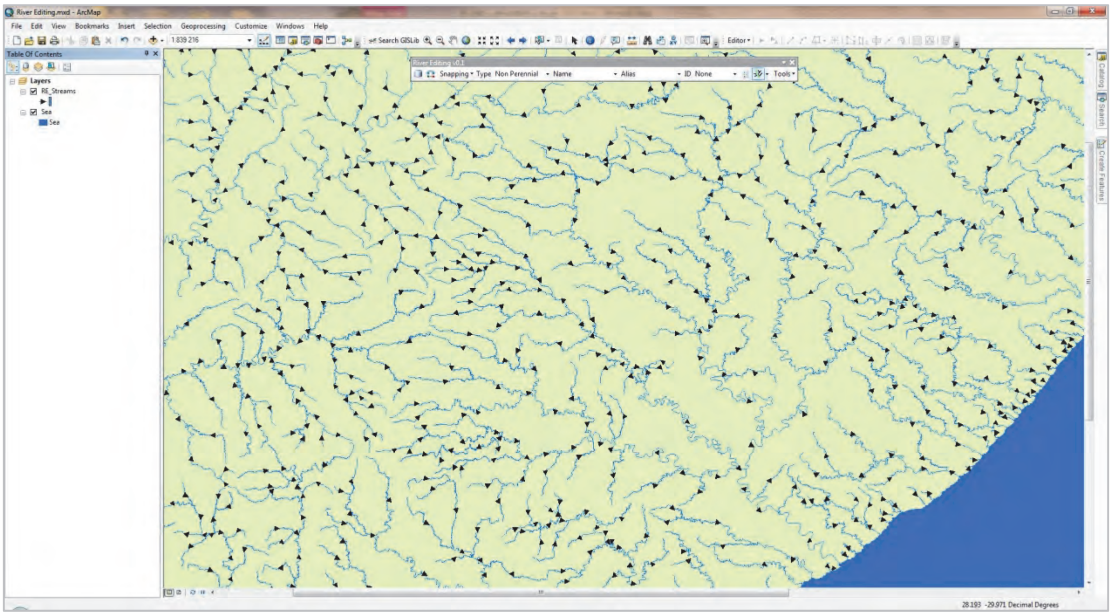


Figure 23: Rivers after Show Flow Direction procedure

4.6.4 Find Loops

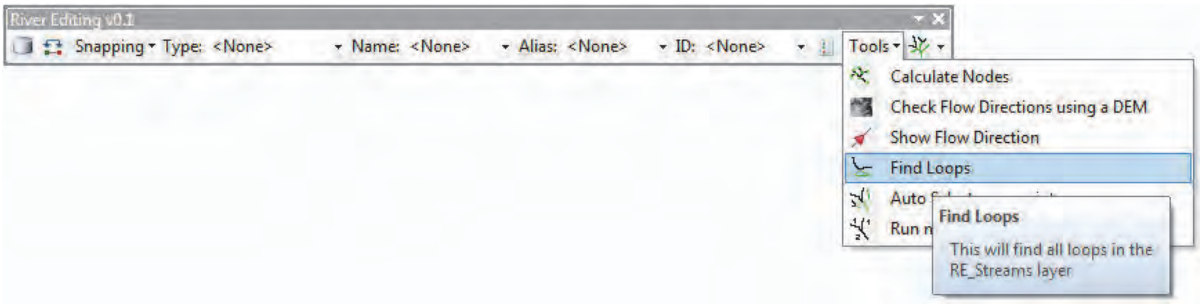


Figure 24: Find Loops button

Click the Find Loops button (Figure 24) to find all loops in the dataset, i.e. where the start and end point of that line/river segment is exactly the same. This is done in order to clean the data to prepare it for further processing, i.e. find the loops and delete them if necessary (see Figures 25-27).

To use:

1. Click on the Find Loops button.
2. The loops are highlighted and the user can go ahead and edit (select which line of the loop to remove) or remove the loops.

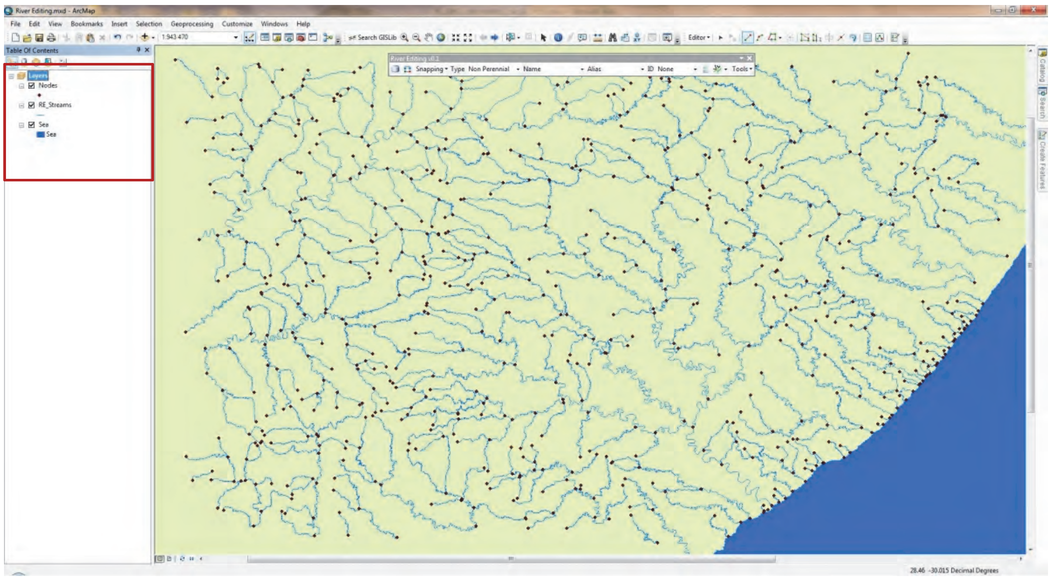


Figure 25: Table of contents before Find Loops only contains the Nodes, RE_Streams and another context layer

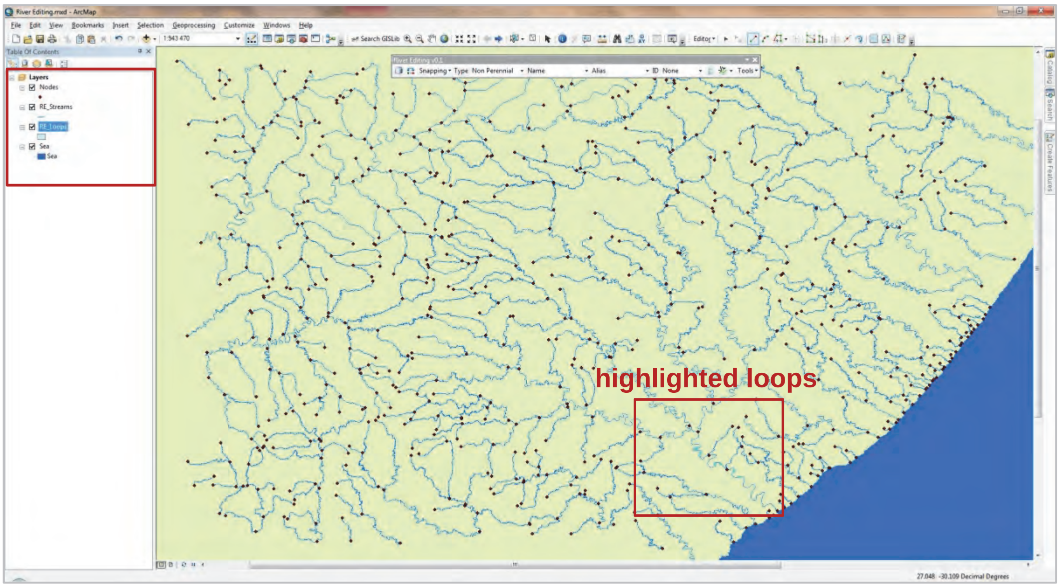


Figure 26: Table of contents after Find Loops now contains a loops polygon layer. The rectangle in the viewer shows an area where loops have been identified

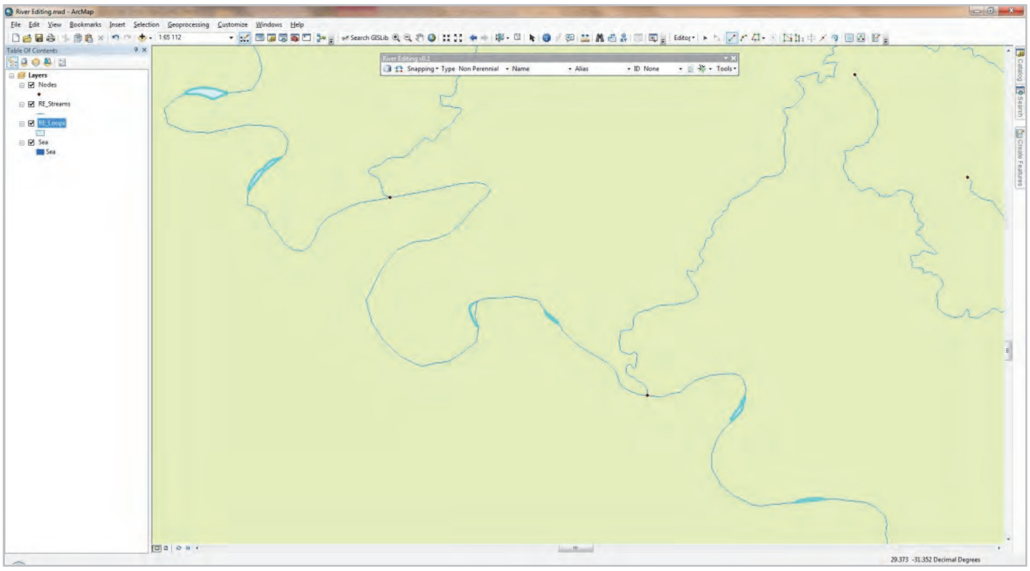


Figure 27: Zoom in view of loops

4.6.5 Auto Select pour points

Figure 28: Auto Select pour points

This will select all pour points from RE_Streams. From here the selection can be modified by manually adding or removing selections, and then normally running the multiple stream orders afterwards.

To use:

1. Click on Auto Select pour points.

4.6.6 Run multiple stream orders

Figure 29: Run multiple stream orders

This will run stream orders on all selected features in RE_Streams instead of running it manually.

To use:

1. Click on Run multiple stream orders.

4.7 Stream Order and Connectivity tools

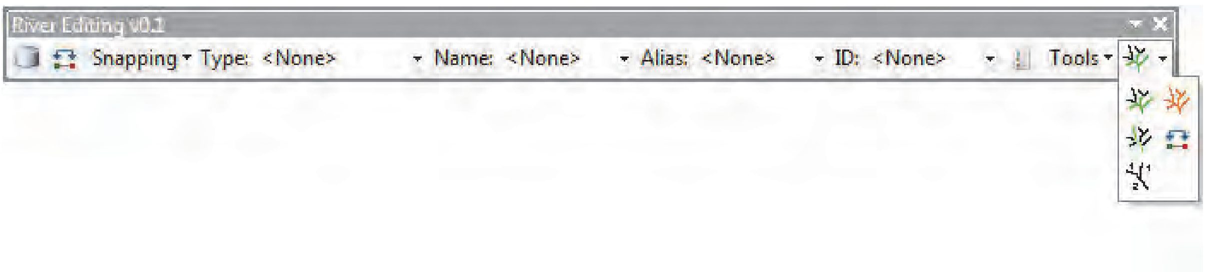


Figure 30: Stream Order and Connectivity tools menu

The Connectivity tools **Trace Upstream, Find All Connected, Trace Downstream** and **Direct Downstream** work in a relatively similar manner. Make sure that the RE_Streams layer is highlighted in the TOC when using these tools.

Generic method of use:

- User selects the tool by clicking on it and the selection cursor changes to a crosshair.
- User clicks on a river at the furthest point downstream of the network (for Trace Upstream, Find All Connected and Direct Downstream) from which they want the operation to start.
  OR
- User clicks on a river at the furthest point upstream of the network (Trace Downstream) from which they want the operation to start.

To use the individual tools a user clicks on the dropdown arrow on the menu, selects the tool from the menu by clicking on it, then uses the crosshair arrow to select the node from which the tool will work from. [Refer to **Generic method of use** above for individual connectivity tool usage.]

NOTE: After running a particular connectivity method or stream order calculation the results of that method are selected within the layer. The user can then use these selected results in conjunction with the fill fields functionality to add attributes to the selected rivers

4.7.1 Trace Upstream

Figure 31: Trace Upstream button

The Trace Upstream button (Figure 31) is used to find all reachable elements in the current river network that are upstream from the user specified point:

1. Select and click on the Trace Upstream button from the menu.
2. Click on the start point of the trace using the crosshair arrow to select by clicking on a starting node or junction.

NOTE: The start point of the trace is downstream from the resulting traced network identified or at the end of the river network

3. Trace will be performed giving the results shown in Figures 32-35.

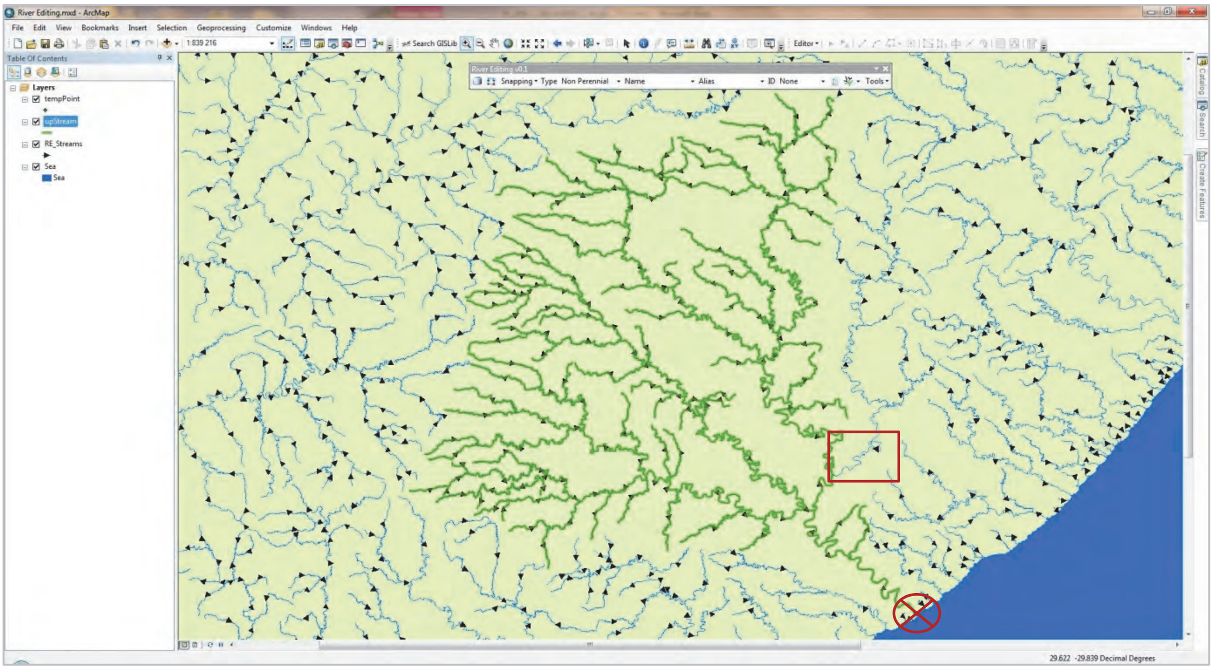


Figure 32: All streams upstream from point indicated by red crosshair.
Note that the river highlighted by the red rectangle is not flowing in a downstream direction

> ***NOTE: Notice the direction of the river arrows in the example above and the position of the point of clicking (indicated by red crosshair in Figure 32)***

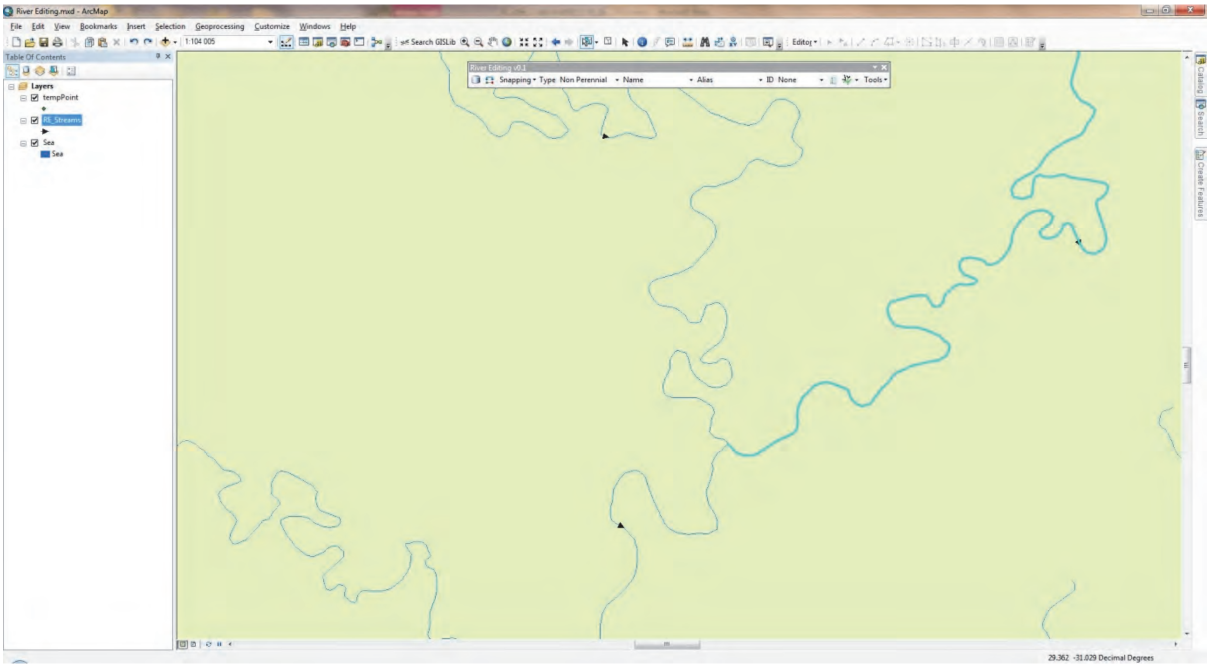


Figure 33: Zoom in view of river junction indicated by rectangle in Figure 32. Note that the highlighted river element is not flowing downstream, hence the trace did not go up that river branch

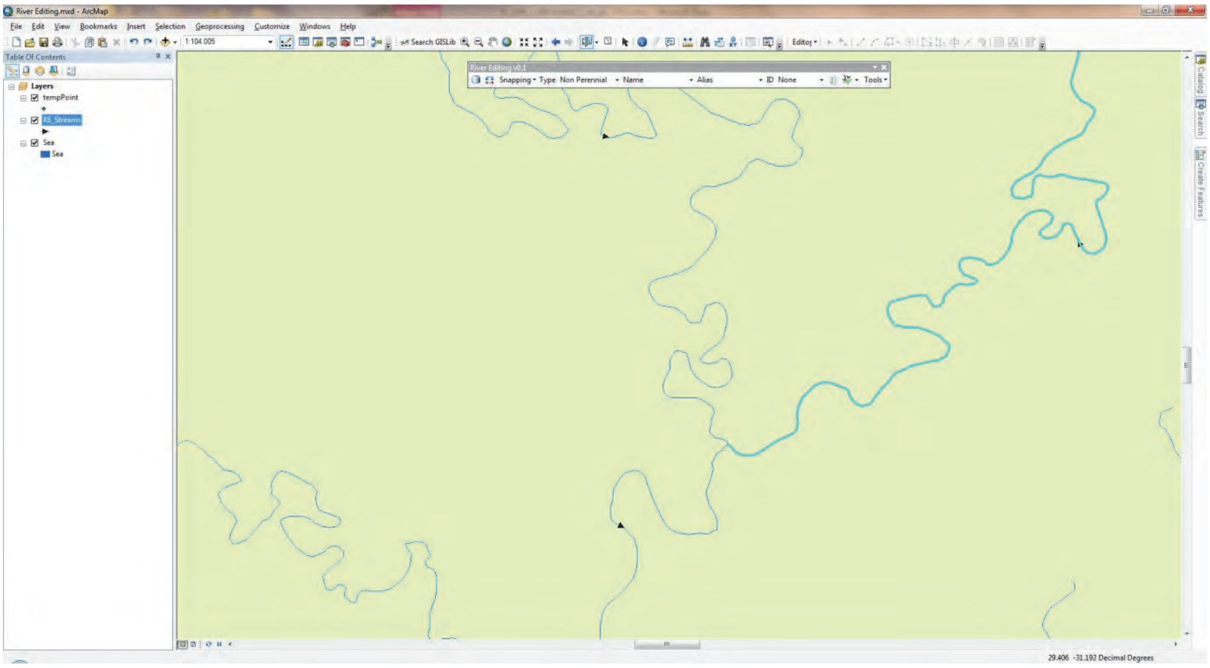


Figure 34: Zoom in view of river junction indicated by rectangle in Figure 32. Note that the highlighted river element after being flipped is now flowing downstream so the trace should now go up this branch

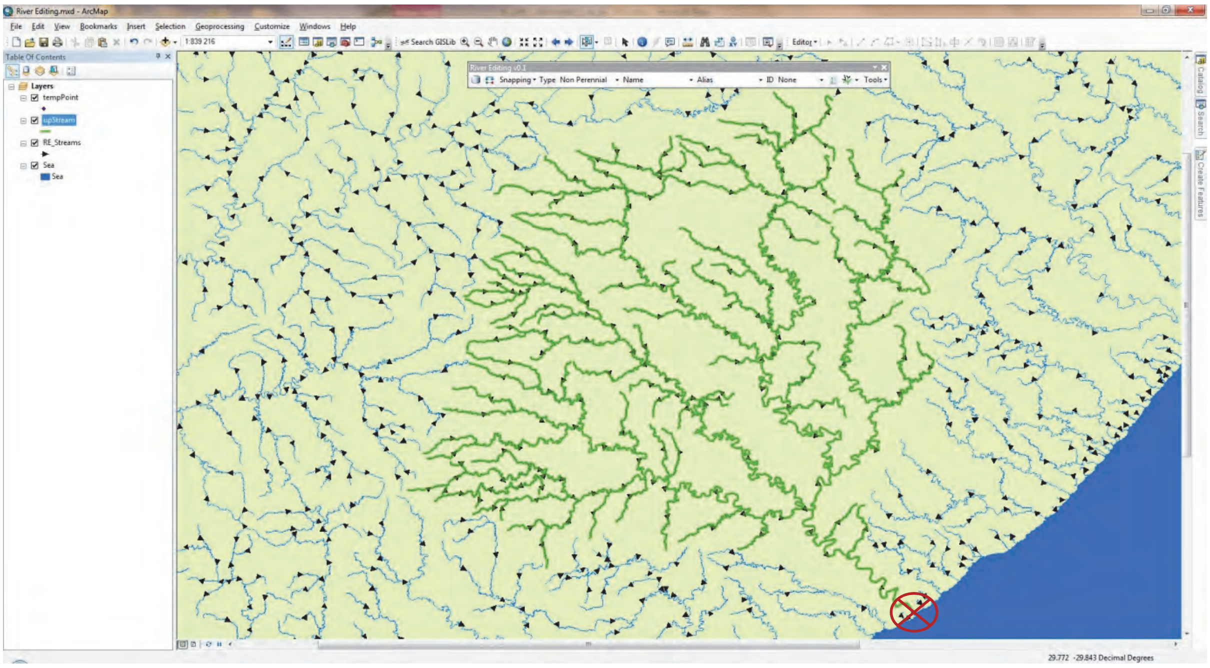


Figure 35: All streams upstream from point indicated by red crosshair (after all river elements have been made to flow in a downstream direction)

4.7.2 Trace Downstream

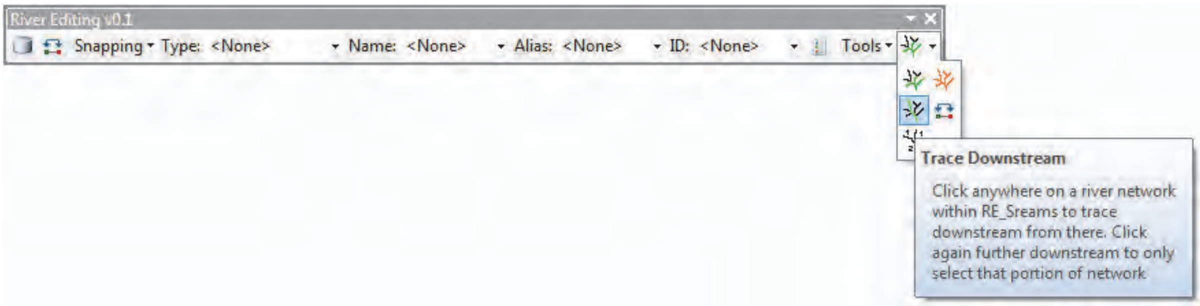


Figure 36: Trace Downstream button

The Trace Downstream button (Figure 36) is used to find all reachable elements in the current river network that are downstream from the user specified point:

1. Select and click on the Trace Downstream button from the dropdown menu.
2. Click on the start point of the trace using the crosshair arrow to select by clicking on a starting node or junction. Select Yes from the popup window to start a new trace.

> ***NOTE: The start point of the trace is upstream from the resulting traced network identified or at the start of the river network***

3. Trace will be performed giving the results shown in Figure 37.

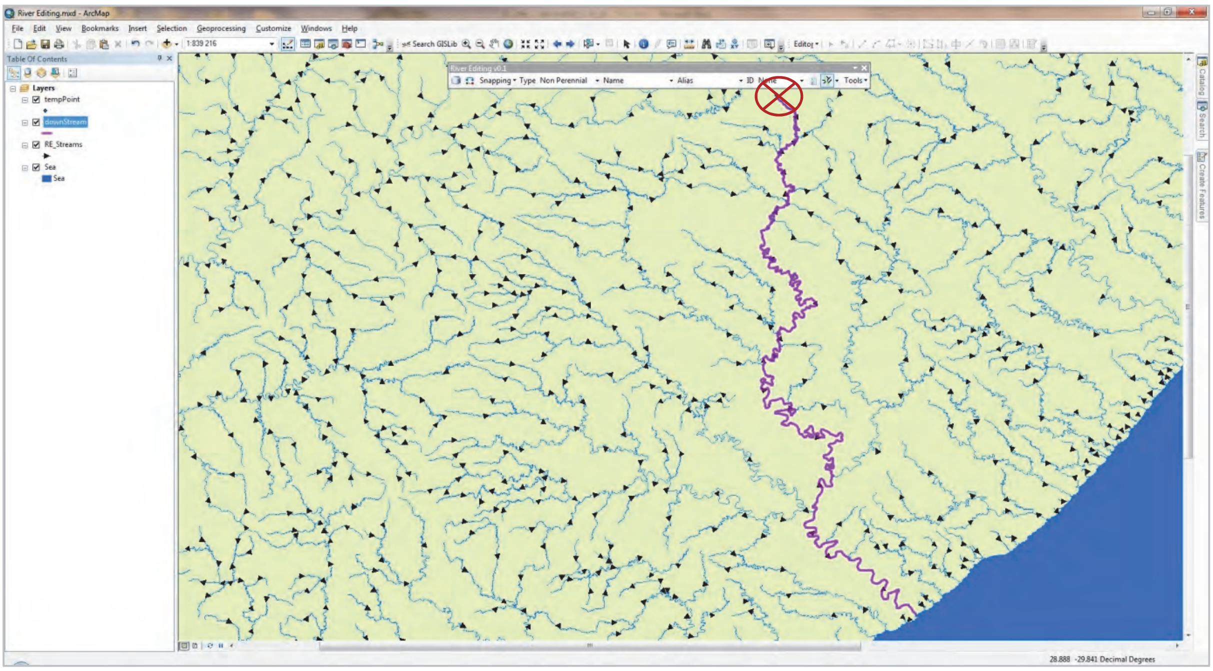


Figure 37: Downstream path from point indicated by red crosshair

4. If only a certain portion of the selected line is needed, click again with the same tool further downstream and select No from the popup menu. The only part that will be selected now is the portion between the two clicks.

4.7.3 Find All Connected

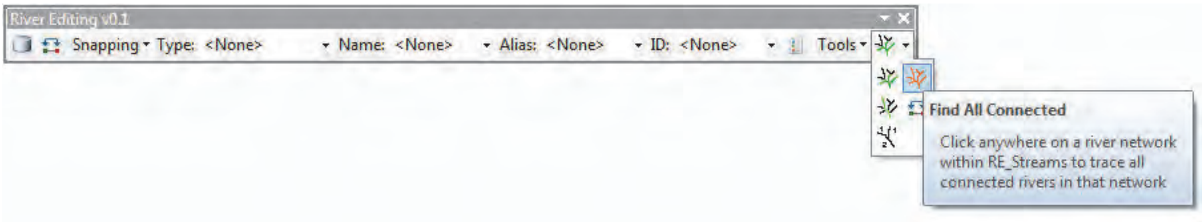


Figure 38: Find All Connected button

The Find All Connected button (Figure 38) is used to find all elements in the current network that are reachable from the specified point, i.e. streams connected in any way to the stream (upstream or downstream):

1. Select and click on the Find All Connected button from the dropdown menu.
2. Click anywhere on the trace using the crosshair arrow to select by clicking on a starting node or junction.
3. Trace will be performed giving the results shown in Figure 39.

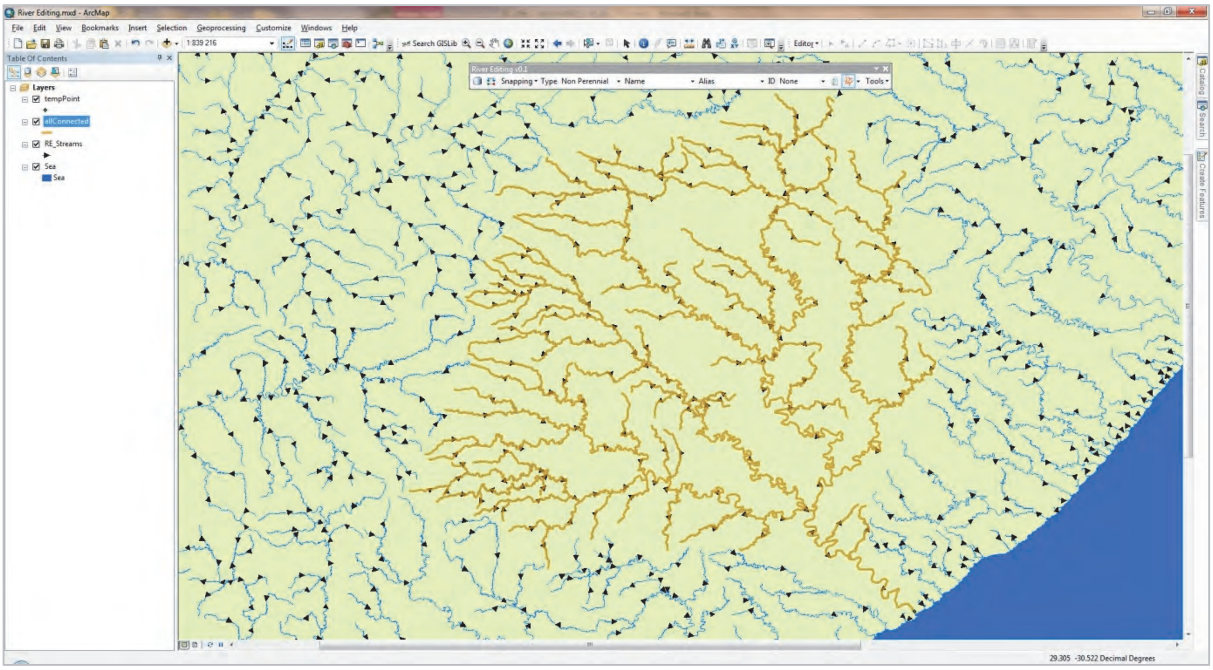


Figure 39: Find All Connected shows all streams connected in any way to the selected stream (upstream or downstream)

4.7.4 Direct Downstream

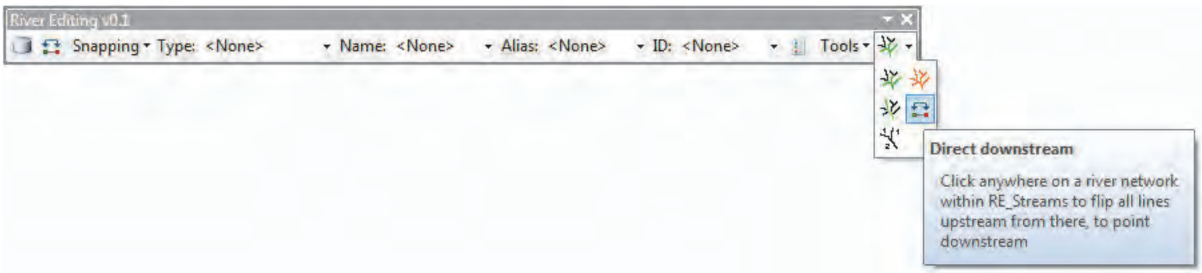


Figure 40: Direct Downstream button

The Direct Downstream button (Figure 40) will work on all the rivers upstream from the river end point (river mouth) that is clicked:

1. First click on the Calculate Nodes button in the Tools menu.
2. Click on the Direct Downstream button.
3. Click at the river end point (point to which you want all the upstream river segments to flow).
4. Trace will be performed giving the results shown in Figures 41-44.

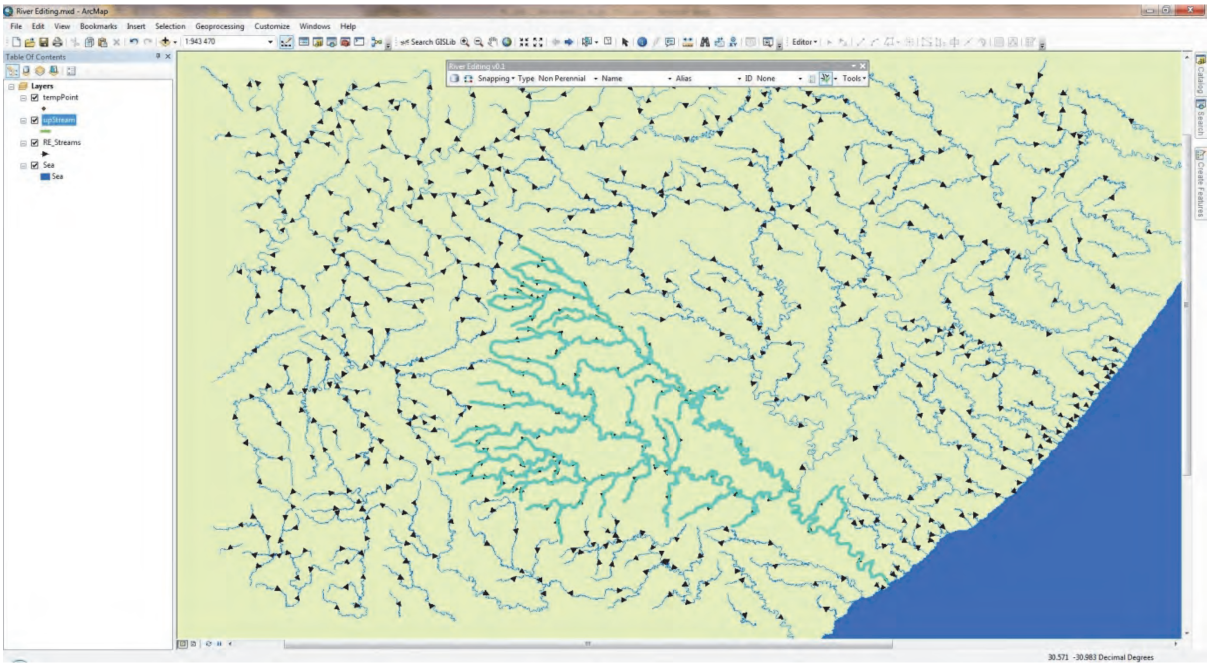


Figure 41: Trace upstream before a point downstream has been run

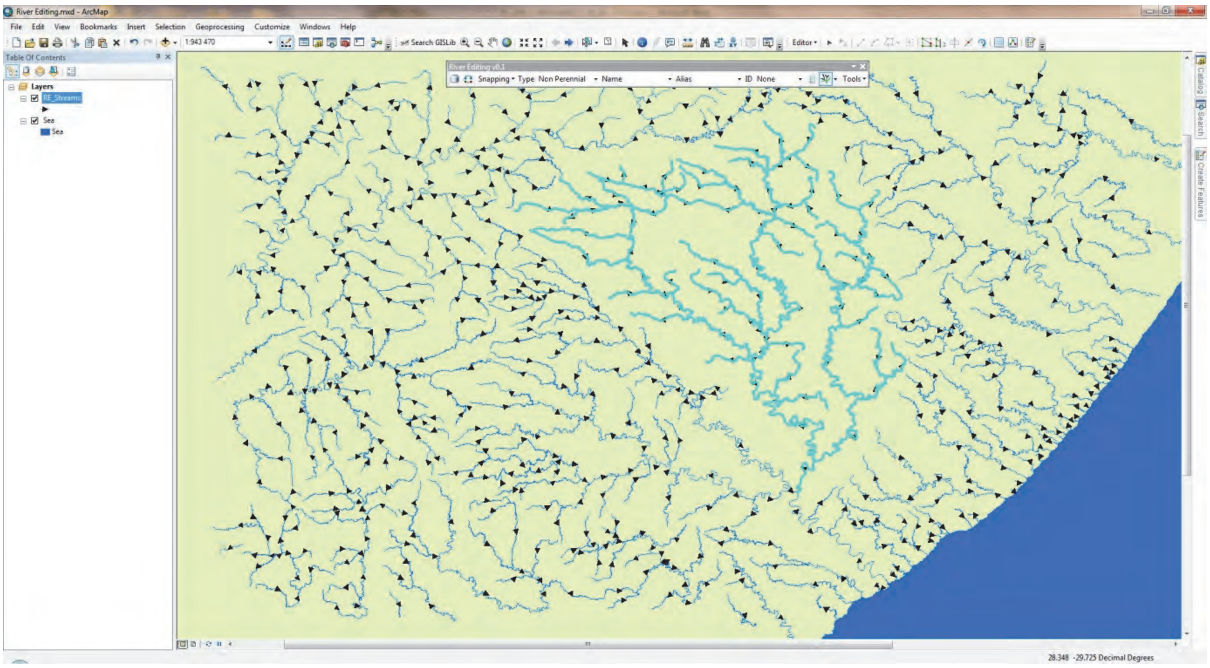


Figure 42: Rivers that are not pointing downstream highlighted for the purpose of identifying them

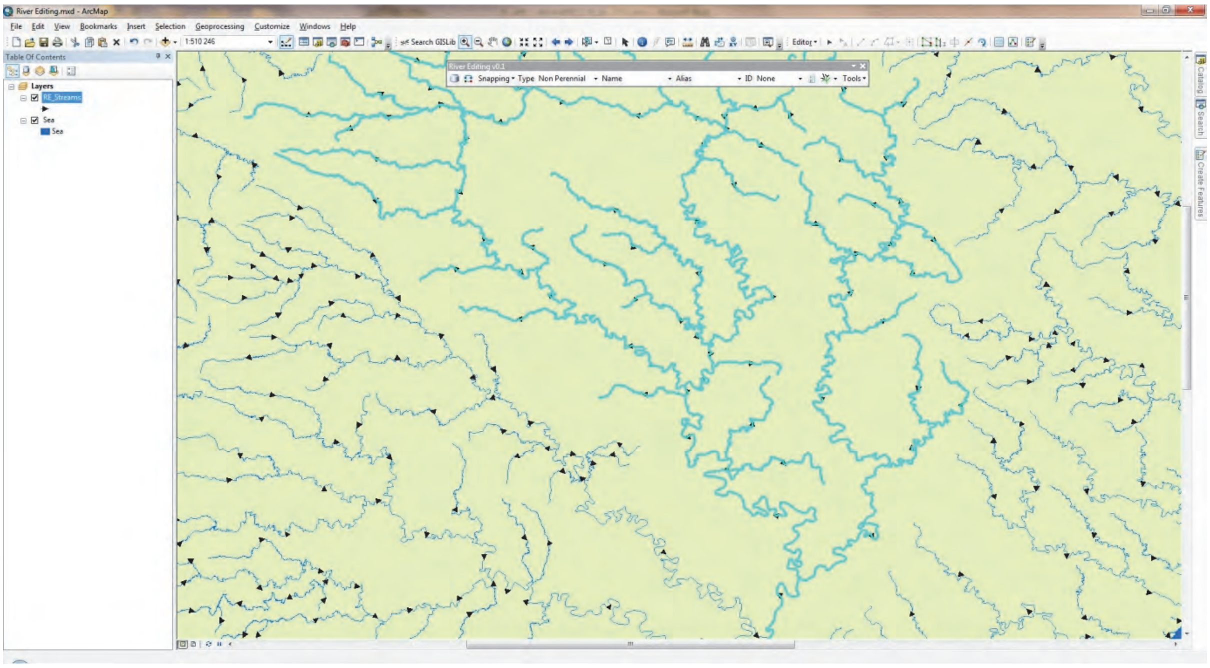


Figure 43: Zoom in to section shown in Figure 42 showing that the river flow direction is not pointing downstream

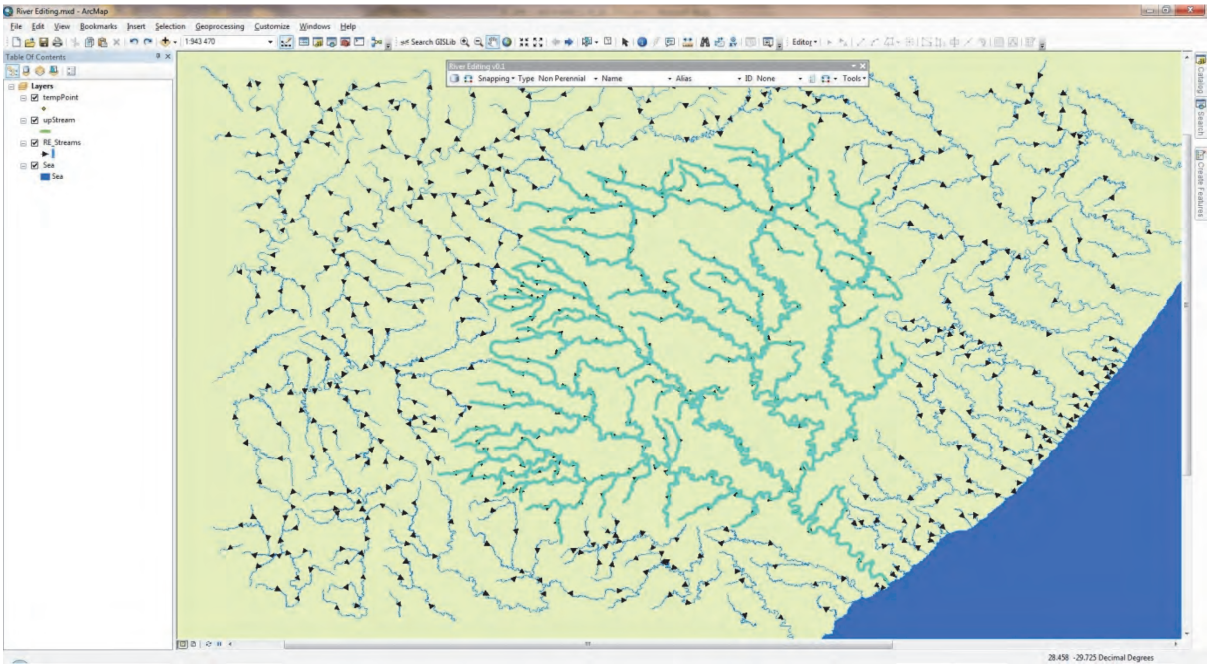


Figure 44: Trace upstream after a point downstream has been run

4.7.5 Stream Order

The Stream Order functionality calculates stream order values for the different stream order types (Strahler, Horton, Shreve and Hack) all at once and places the value in the dataset table in a field named according to the stream order type, e.g. Strahler values will be placed in a field named RE_Strahler, Horton values will be placed in a field named RE_Horton, etc. Make sure that the RE_Streams layer is highlighted in the TOC when using the Stream Order tool. The user can then use the styling and labelling features of ArcMap to visually represent the different types of stream order:

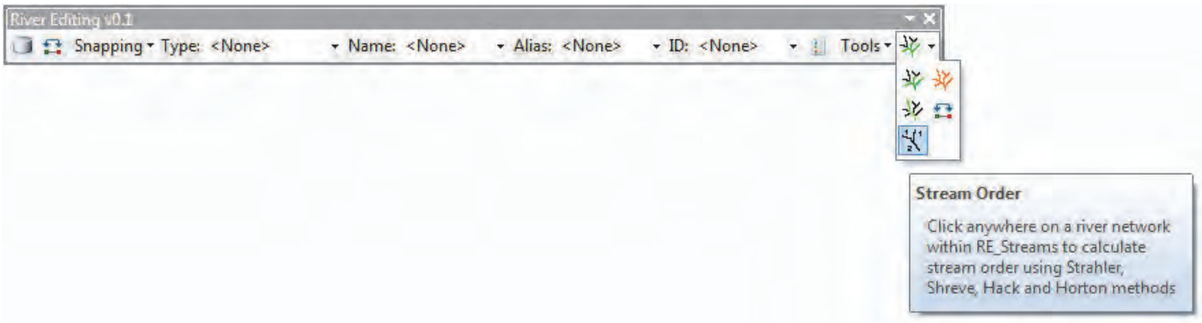


Figure 45: Stream Order button

1. Select and click on the Stream Order button from the dropdown menu (Figure 45).
2. Click on the start point of the stream order calculation using the crosshair arrow to select by clicking on a starting node or junction.
3. The calculation will be performed and the results placed in their respective columns in the table (see Figure 46).

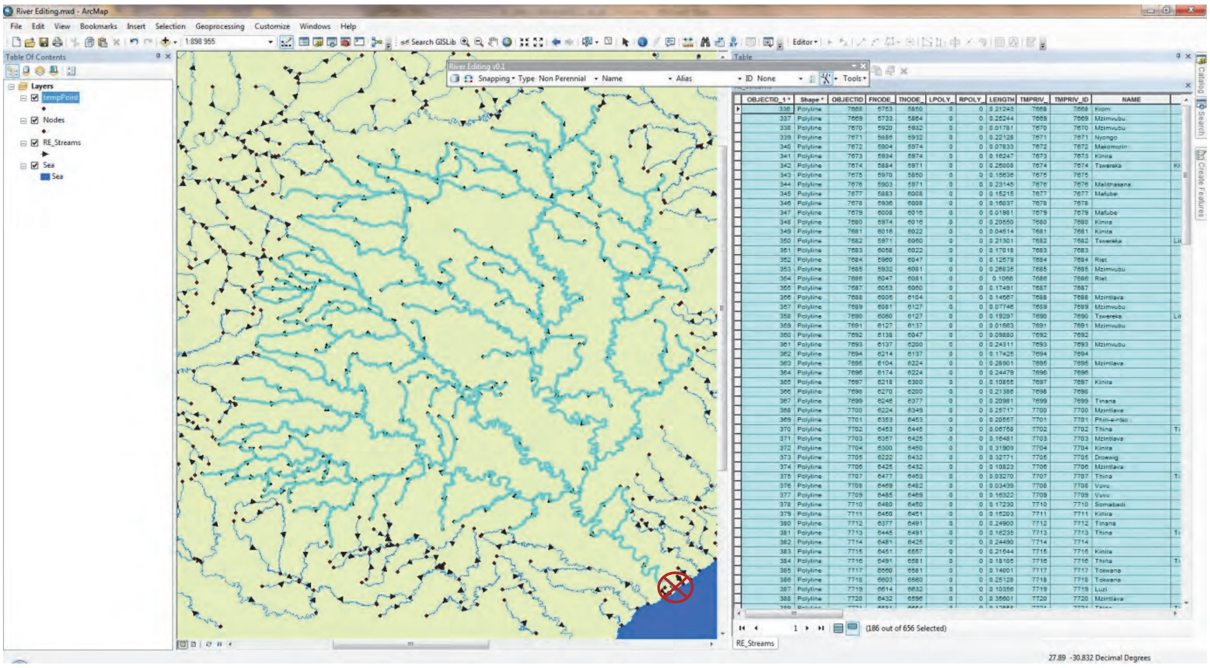


Figure 46: Stream order calculated for selected rivers showing the start point of the stream order calculation using red crosshair and table of results

4.7.6 Stream Order Methods

4.7.6.1 Strahler's stream order

Strahler's stream order is a modification of Horton's stream order which removes the ambiguity of Horton's ordering. In Strahler ordering the main channel is not determined; instead the ordering is based on the hierarchy of tributaries (see Figure 47). The ordering is applied according to the following rules:

1. If the node has no children then its Strahler order is 1.

2. If the node has one and only one tributary with Strahler greatest order i, and all other tributaries have order less than i, then the order remains i.
3. If the node has two or more tributaries with greatest order i, then the Strahler order of the node is i + 1.

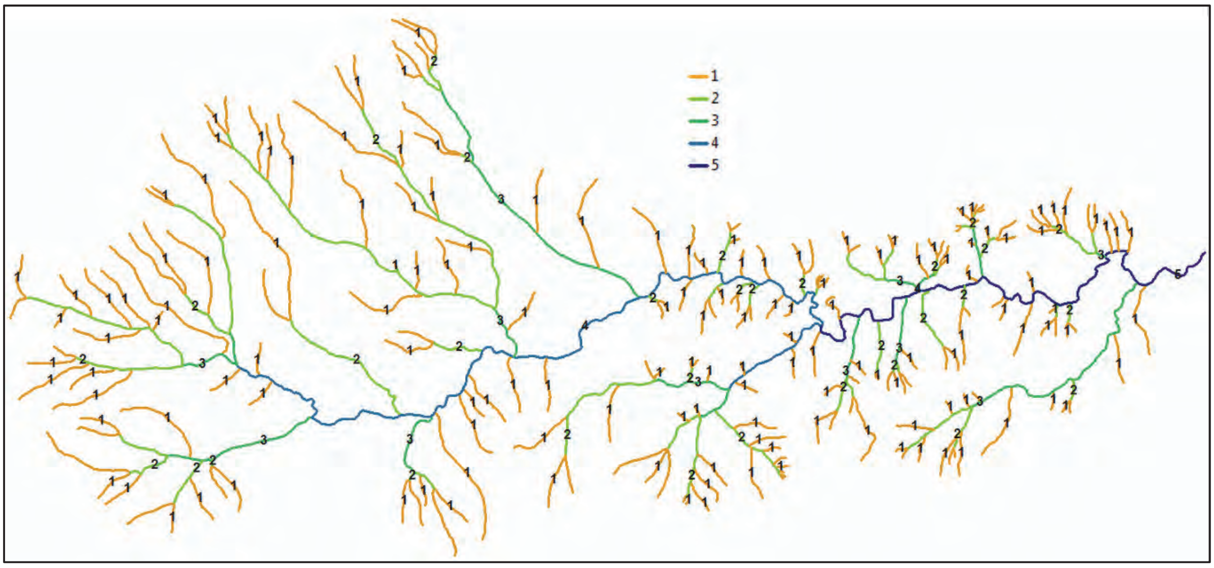


Figure 47: Example of Strahler's stream order classification

4.7.6.2 Horton's stream order

Horton's stream order applies to the entire stream with the exception of segments or links, since the order on any channel remains unchanged from source until it "dies" in a higher order stream or in the outlet of the catchment. The main segment of the catchment is assigned the order of the whole catchment, while its tributaries are assigned the order of their own sub-catchments (see Figure 48).

The algorithm applied requires calculating Strahler's stream order first. Horton ordering (upstream) is then recalculated. To make a decision about proper ordering it uses Strahler ordering, and if both branches have the same Strahler's order it uses segment length to choose the actual link. The algorithm starts with the outlet, where the outlet link is assigned the corresponding Strahler's order. Next it goes upstream and determines links according to Strahler ordering. If the orders of tributaries differ, the algorithm proceeds with the channel of highest order. If all orders are the same, it chooses the one with the higher segment length rate.

The main advantage of Horton ordering is that it produces natural stream ordering with main streams and its tributaries. The main disadvantage is that it requires Strahler ordering. In some cases this may result in unnatural ordering, where the highest order will be ascribed to the channel which leads to the most branched parts of the catchment.

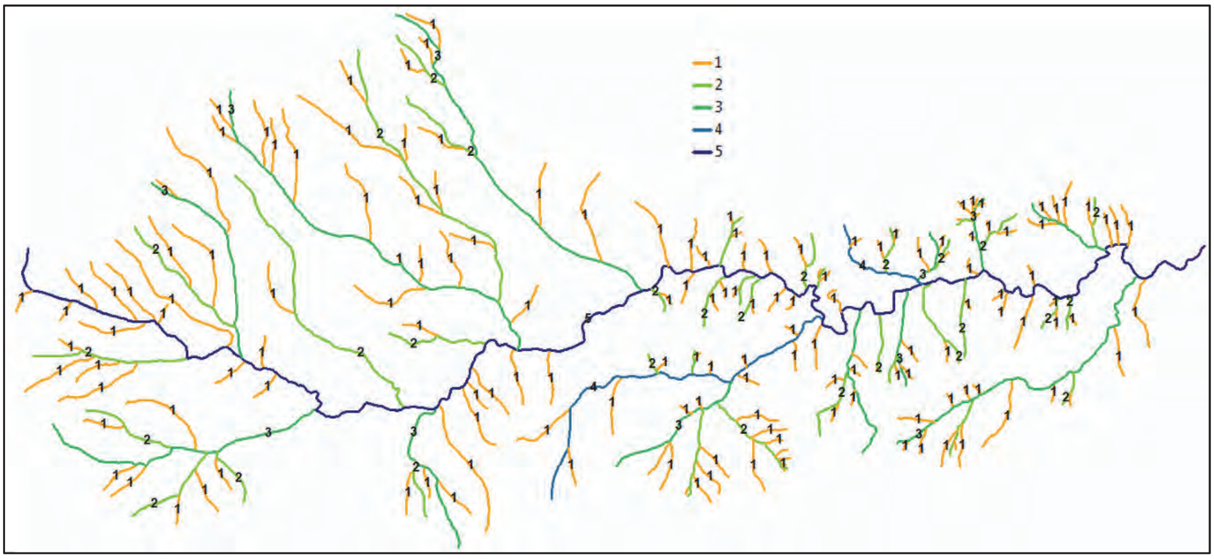


Figure 48: Example of Horton's stream order classification

4.7.6.3 Shreve's stream order

Shreve's stream order assigns a magnitude of 1 for every initial channel. The magnitude of the following downstream channel is the sum of the magnitudes of its tributaries. The order number of a particular stream segment thus equals the total number of its tributaries up to channel heads (see Figure 49).

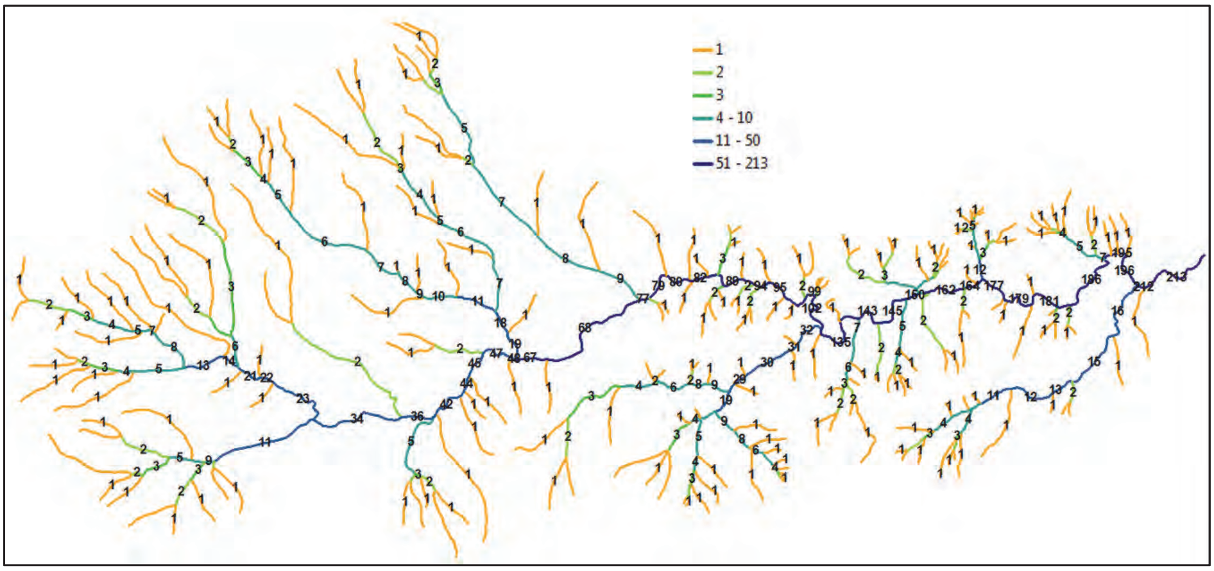


Figure 49: Example of Shreve's stream order classification

4.7.6.4 Hack's stream order

Hack's stream order calculates main streams for the main catchment and every sub-catchment. The main stream of the main catchment is set to 1 and consequently all its tributaries receive order 2, whilst their tributaries receive order 3, etc. (see Figure 50). The order of every stream remains constant up to its source. The route of every main stream at a confluence is determined according to the maximum flow length value of the tributaries at this confluence. Thus the main stream of every sub-catchment is the longest stream. The biggest advantage of Hack's stream order is the possibility to compare and analyse drainage network topology upstream according to main streams. Because all tributaries of the main channel have an order of 2, streams can be quickly and easily filtered and their properties and relation to the main stream can be determined. The main disadvantage of this method is the problem with the comparison of sub-catchment topology of the same order. Sub-catchments of the same order can be highly branched and widespread in the total catchment area or just a small sub-catchment with only one stream.

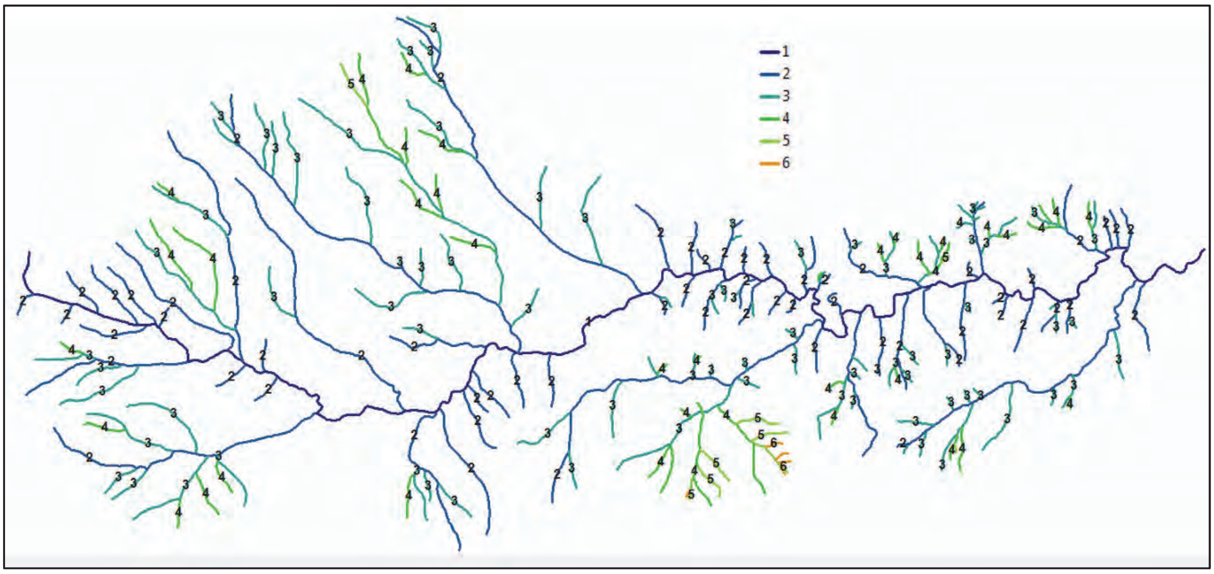


Figure 50: Example of Hack's stream order classification

5 Adding the Python Scripting Window

The Python Scripting window in ArcGIS is a very useful resource to use for some geoprocessing tasks as well as view output messages from Python developed modules or tools that pass messages to the user through this window. The main reason for using this scripting window is to pass messages back to the user from the tool, hence it is quite handy to have it open when the tool is malfunctioning so one can have an idea of what is going on.

Follow the step by step process to make sure the window is open in ArcMap.

The Python Scripting window can be opened in any ArcGIS desktop application from the standard toolbar by clicking the Python Scripting window button .

Figure 51: The Main menu and Standard toolbar

If the Standard toolbar is not available in the applications window then load it as follows:

1. Open ArcMap.
2. In the ArcMap Main menu click on Customize >>Toolbars, then scroll down and make sure the Standard menu is checked.

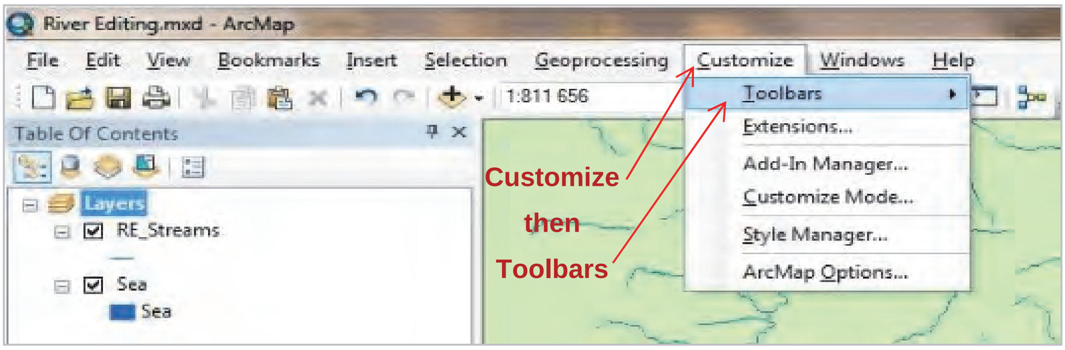


Figure 52: Turning on the Standard toolbar, Step 1

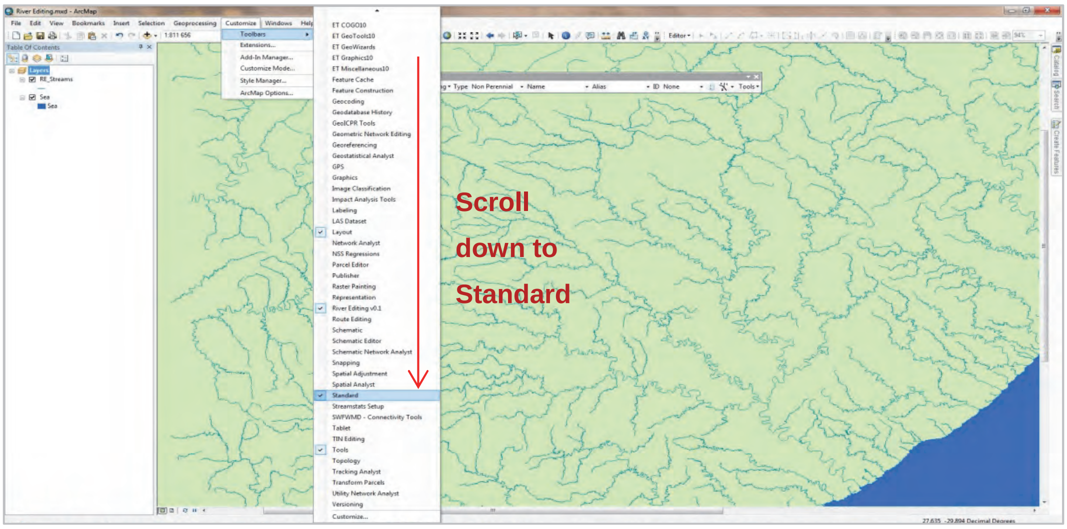


Figure 53: Turning on the Standard toolbar, Step 2a

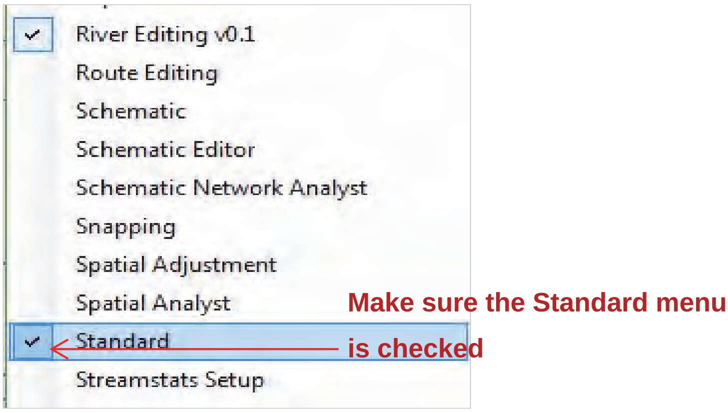


Figure 54: Turning on the Standard toolbar, Step 2b

3. On the Standard toolbar click on the Python Scripting window button 

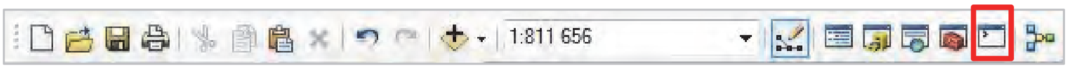


Figure 55: Standard toolbar with the Python Scripting window button highlighted in red rectangle

The Python Scripting window will open in the ArcGIS application.

Figure 56: Undocked Python Scripting window

4. Drag it and dock it at the bottom of your application window. This is done by clicking the bar at the top and dragging to your preferred docking location. The window can be undocked later.

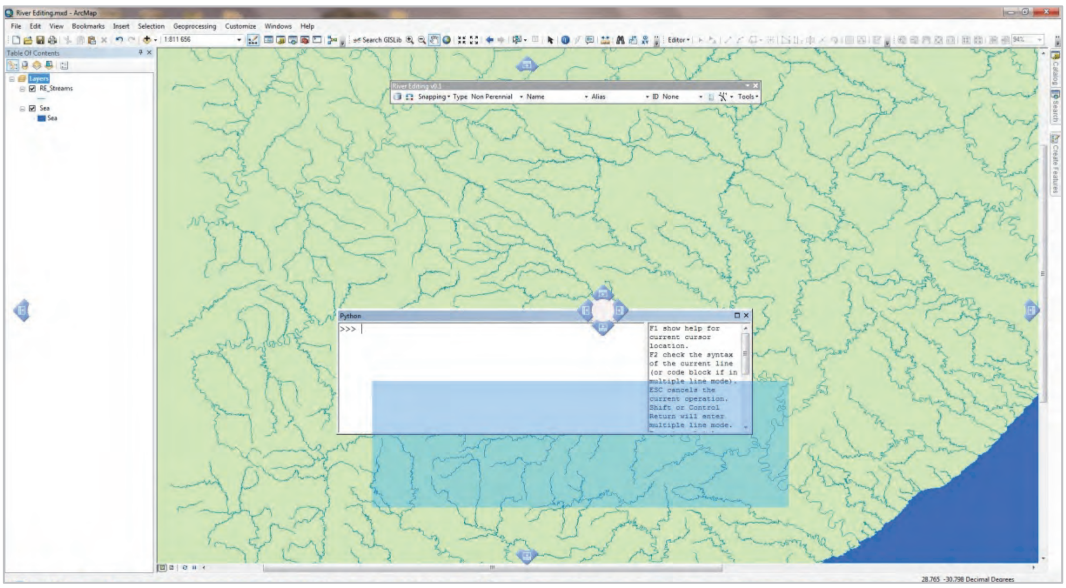


Figure 57: Dragging and docking the Python Scripting window

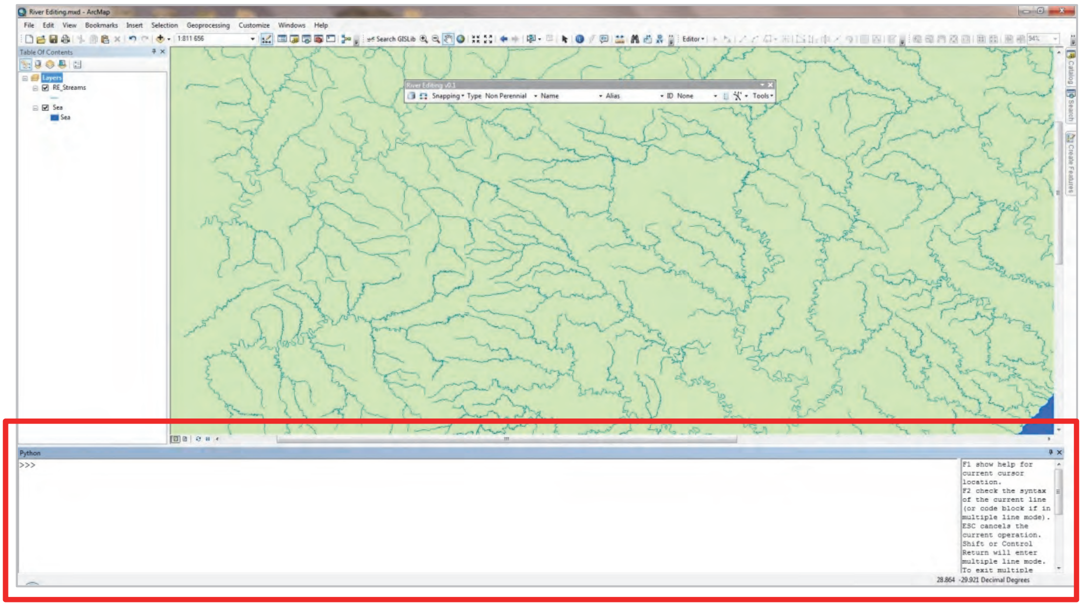


Figure 58: Docked Python Scripting window (docked at bottom of application window)

NOTE: Toolbars and other “dragable” application windows can be docked at the top or bottom or to the left or right side of the ArcGIS application. Alternatively, they can float (undocked) on the desktop while functioning as part of the application. When docking a toolbar or window it is moved and resized with the application's window

6 Editing Functionality

This section describes how to add a line to the Rivers shapefile and how to modify it:

1. Load the Rivers shapefile into ArcMap.
2. Highlight the layer you want the tool to work on in the TOC as illustrated in Figure 59.
3. Click the Add Fields button  to ensure that all four fields exist prior to editing.
4. Start editing through the Editor menu.

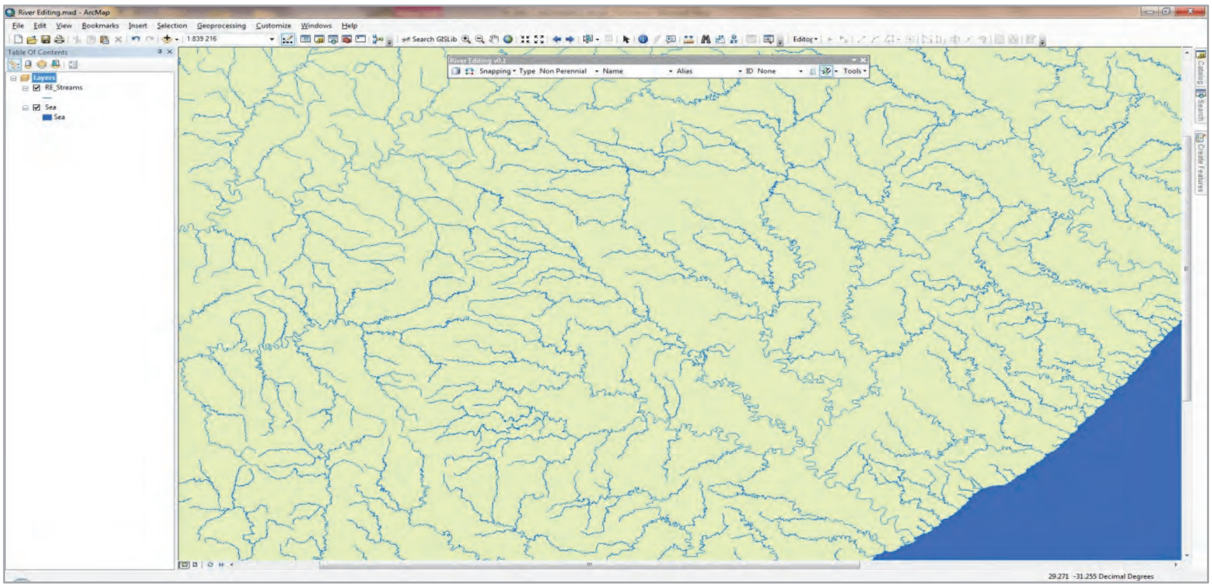


Figure 59: Highlight the relevant layer in the table of contents

When the editing session starts, a Create Features window will appear on the right of ArcMap (Figure 60).

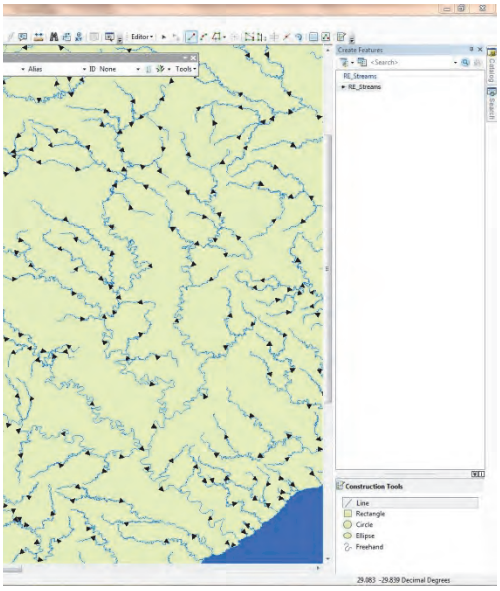


Figure 60: Creature Features and Construction tools windows

If the window does not appear, click on the Create Features button found on ArcMap's own Editor toolbar to enable the window.

Select the River shapefile you want to edit from the Create Features window, which will in turn select the line construction tool from the construction tool window situated below the Create Features window. Before you can start creating new features, first fill in values in the Attribute text boxes.

Now create your feature and double click to finalise it.

To modify a feature, simply double click it and drag the vertices to modify it. To exit the modify method, click anywhere next to the line in an open space.

Remember to save your edits by clicking on Save Edits in the Editor menu.

7 Limitations and Known Bugs

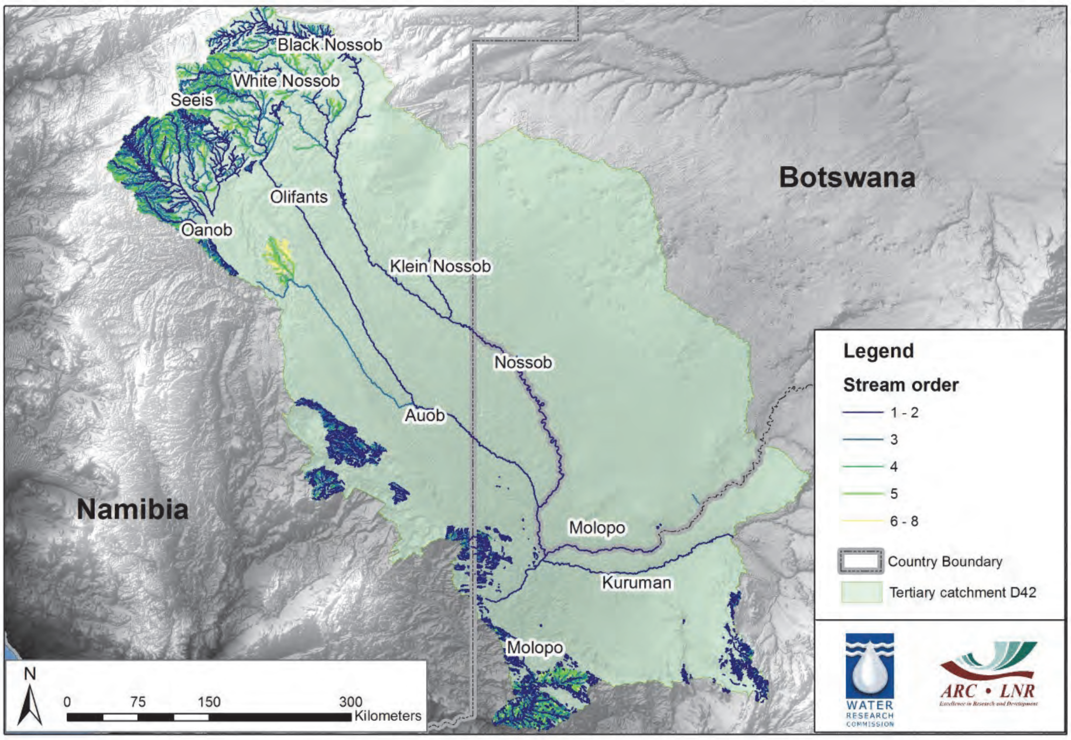
- **Geometric Networks** – Some tools will not work with a river network that has been put in a geometric network.

- **Manual Flip Line** – If one is in editing mode and flips the line by double clicking a line so that the vertices are visible, then right clicking that line and selecting Flip from the context menu that appears, it is important that the nodes are recalculated by clicking the Calculate Nodes button .

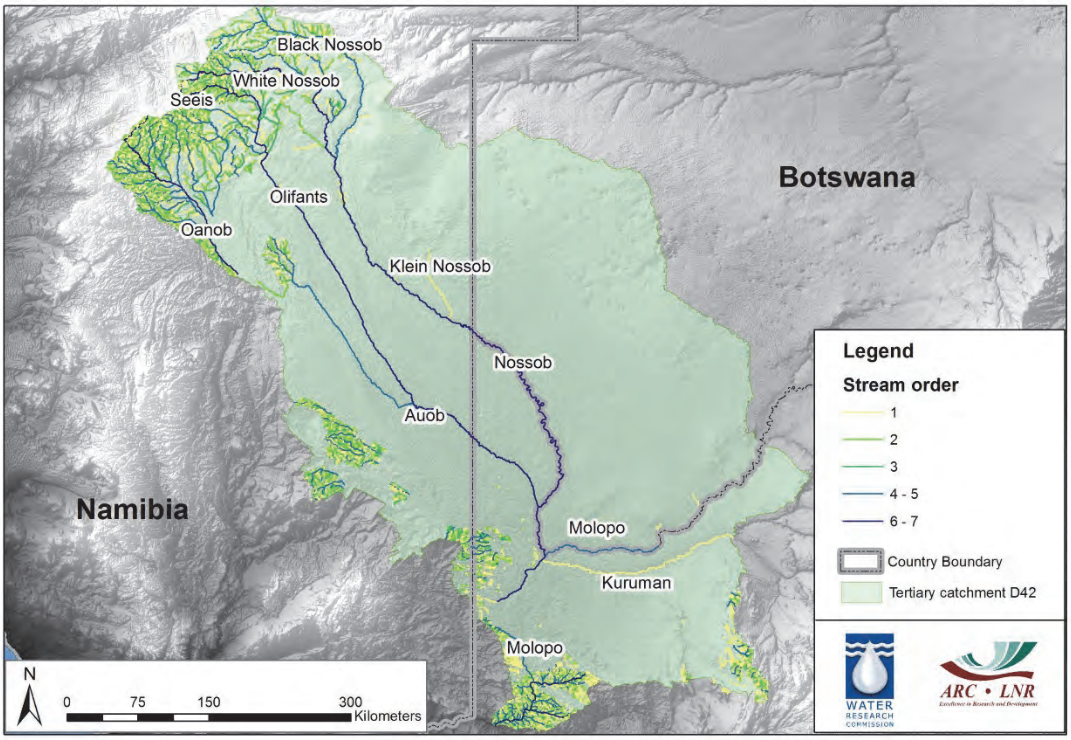
- **Memory Issue –** Because the Stream Order and Connectivity tools (described in section 4.7) make use of recursive functions, these tend to overwhelm the computer's processing memory if the amount of rivers selected for the stream order calculation is large.

APPENDIX B: MAPS

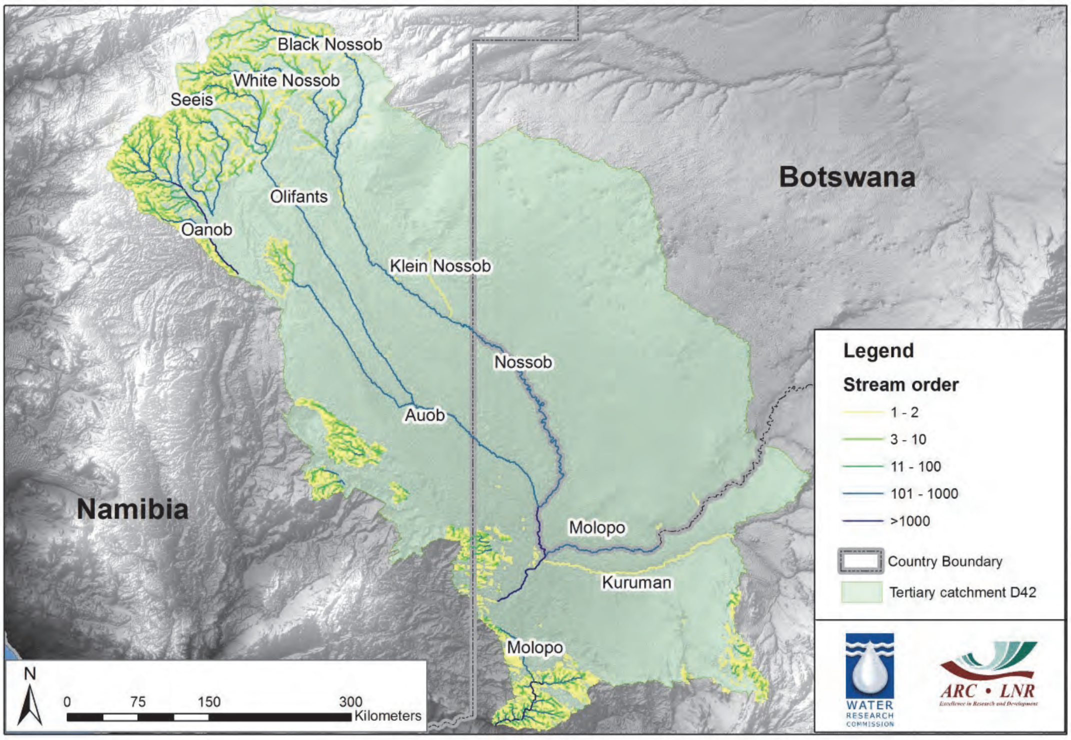
Stream network for the Molopo catchment using the Hack stream order



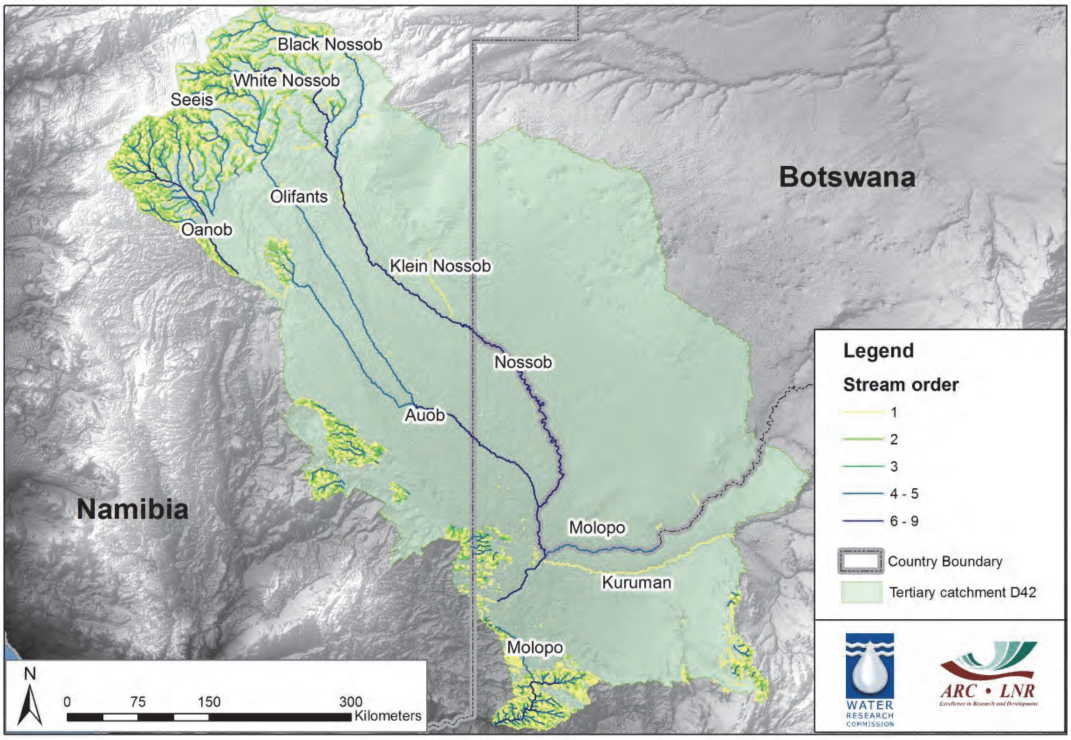
Stream network for the Molopo catchment using the Horton stream order



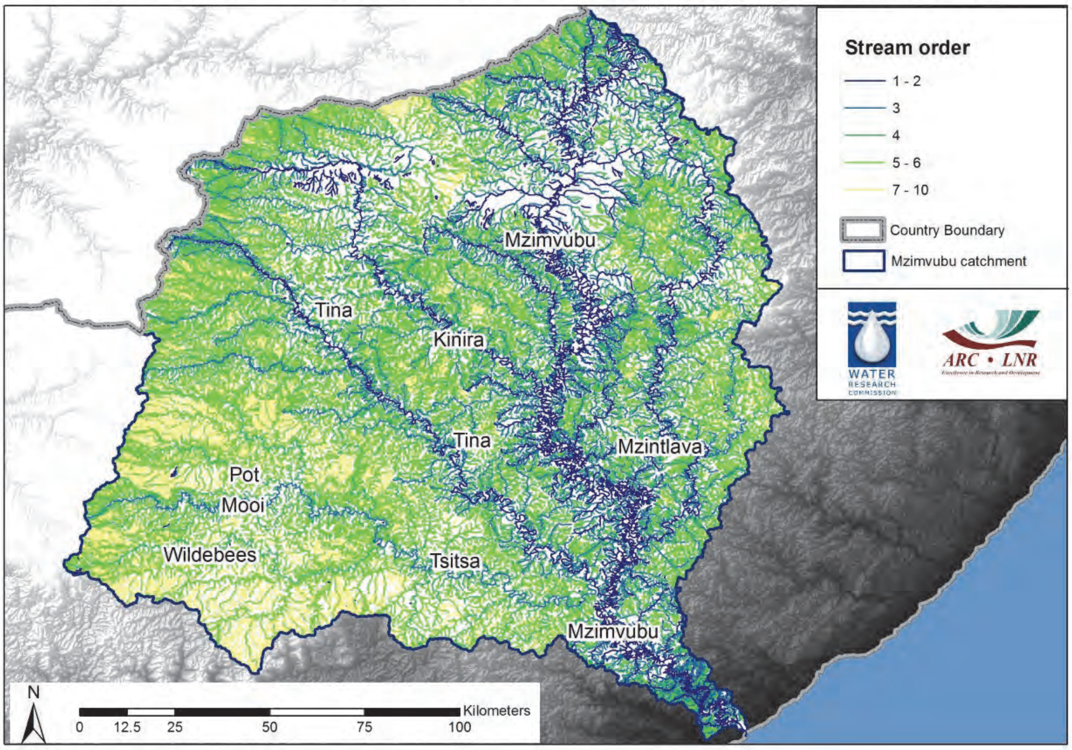
Stream network for the Molopo catchment using the Shreve stream order



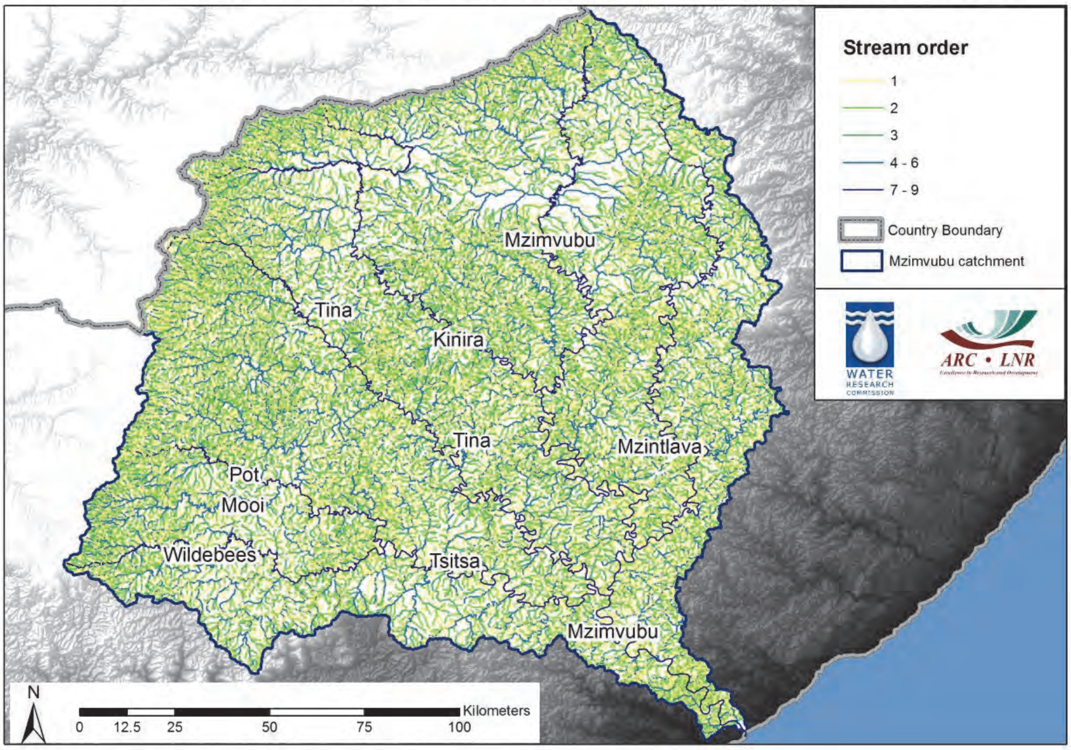
Stream network for the Molopo catchment using the Strahler stream order



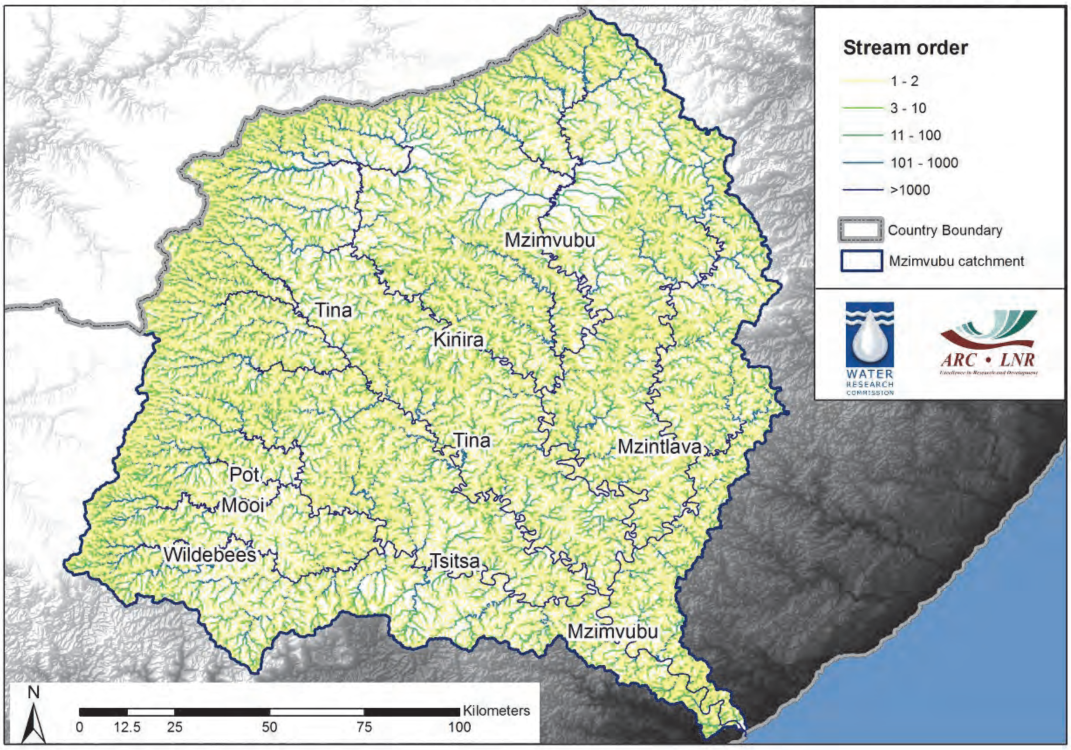
Stream network for the Mzimvubu catchment using the Hack stream order



Stream network for the Mzimvubu catchment using the Horton stream order



Stream network for the Mzimvubu catchment using the Shreve stream order



Stream network for the Mzimvubu catchment using the Strahler stream order