The Suspended Sediment Yield and Provenance of the Inxu River Catchment, Eastern Cape.

A thesis submitted in fulfilment of the requirements for the degree of

MASTER OF SCIENCE

Of

RHODES UNIVERSITY

By

NAMSO NYAMELA

February 2018

Abstract

The excessive deposition and accumulation of suspended sediment leads to the degradation of water resources such as dams and rivers. For the purpose of preserving and protecting these resources, suspended sediment needs to be managed, and its management should be catchment-wide and catchment-specific. This is certainly the case for the eroded Inxu River Catchment, which has been identified as a major contributor of sediment to the planned Lalini Dam on the Tsitsa River (a tributary of the Mzimvubu River). Knowledge of suspended sediment flux and catchment sources will aid the design of relevant strategies to manage suspended sediment production. Suspended sediment flux was determined from sediment samples that were collected using citizen-based monitoring techniques at calendar- and event-based sampling frequency, along with discharges estimated using stage-discharge relationships. Sediment source areas were identified by determining the suspended sediment contribution from major sub-catchments and observing similarities in the characteristics of the sub-catchments that produced the most sediment. The Inxu River Catchment produced 5.5 t/ha/yr between 01 May 2016 and 30 April 2017. When compared to modelled sediment yield (7 t/ha/yr) from Le Roux *et al.* (2015), modelled output was not far off from the measured results and both measured and modelled results identified similar sediment source areas. Q-SSC relationships observed at the Inxu River Outlet indicated that sediment was eroded from local areas and sub-catchment sediment contribution confirmed that most of the sediment was from the lower Inxu River Catchment. Within this area, the Ncolosi and Qwakele River Sub-catchments were major sediment source areas and were subject to widespread gully erosion. Gully erosion was prominent on gentle slopes, foot slopes and valley-bottoms that have concave slope curvature and lie on the Tarkastad Formation. This Formation is associated with some of the most dispersive soils in the area. Moreover, the catchment is vulnerable to erosion due to cultivation and subsequent land abandonment, continuous grazing and dense rural populations. Other studies in the Mzimvubu catchment identified similar catchment characteristics that contribute to excessive erosion. This study has successfully measured sediment yield and identified areas that should be targeted and prioritised for rehabilitation within the Inxu River Catchment. The findings could be applied to a wider catchment scale. The study has successfully demonstrated the use of citizen-based monitoring and desktop techniques and has also identified some pitfalls of this approach.

Key Words: *Suspended Sediment, Sediment Yield, Sediment Sources, Gully Erosion, River Catchment Management*

Plagiarism Declaration

I, Namso Nyamela, declare that this thesis is my own work and that participants have been listed and acknowledged. This thesis has not been submitted for a degree at another institution of higher education.

Acknowledgements

This project was made possible by the Department of Environmental Affairs Natural Resource Management Chief Directorate from which the Ntabelanga Lalini Ecological Infrastructure Project (NLEIP) is funded and supported. DEA-NRM funded the first year of study and all the field related costs from this project. The National Research Fund Department of Science and Technology Masters Innovation Scholarship funded the second year of study for this degree.

I would like to express gratitude to the following people and institutions without whom the success of this degree would not have been possible.

- **My supervisors**, Professor Emeritus Kate Rowntree and Dr Benjamin van der Waal. Thank you for all the wisdom and guidance that you shared over the past two years and for taking this journey with me as I grow academically. Thank you for continuously pushing me out of my comfort zone and believing in me.
    - **Kate**, thank you very very much for forwarding me the opportunity to grow academically under your expert guidance.
    - **Bennie**, thank you for all the technical skills and lessons you taught me. They have resonated in other spheres of life, especially those that developed competencies for the career ahead.
- **Dr Jay J. Le Roux**, thank you for sharing your data, knowledge and insight in the modelling and spatial analysis component of the project.
- **The Ntabelanga and Lalini Environmental Infrastructure Project (NLEIP):** Thank you for the opportunity to take part in a catchment management project and the lessons learnt from establishing and managing a project that “we fly as we build”. Special mention to Mike Powell and Karen Milne who have supported this project immensely and made sure everything was made possible.

Data collection and lab analysis was a collaborative effort between the researcher[1], research group members, field assistants, lab assistants and citizen-based technicians, in addition to the above-mentioned role players.

- **Support:**
  - Ms L.J. Bannatyne from whom this project was developed and from whom knowledge about the project was received;
  - Rhodes University Transport Department and the Department of Ichthyology and Fisheries Science for lending cars to facilitate field trips;
  - The Geography Department Support Staff, particularly Mr A. Ngoepe who prepared equipment prior to field trips and adhered to our needs.
  - Monde Ntsudu for the translation of read and signed material for the technicians and their chiefs; the Geography Department staff and students;
  - Dr W. Kadye for explaining mathematical concepts, Mr M. Ntantiso for explaining geological processes which improved the written report, Ms N. Kheswa for all assistance in remote sensing techniques, Ms D. Hodgson and Professor R. Fox for sharing GIS data.
  - Mrs S. Terry for providing lemons that were used as floats.

- **Assistants:**
  - Ms N. Mtati who managed all the field technicians;
  - Ms Z. Mase who was both field and lab assistant;
  - Mr V. Ntamo and Mr M. Trimalley who were lab assistants;
  - Mr Silulami Kungu who was responsible for cleaning jars;
  - Ad hoc field assistants: Matthew Hermon, William Liversage-Quinlan and Caitlin Mostert.

---

[1] Concerning data collection, the researcher was involved in the following ways: the selection of monitoring points; installation of all data collection instruments at monitoring sites, the maintenance of such instruments and downloading this data (as will be explained in relevant sections of this thesis); cross-sectional surveying, the collection of discharge data; the selection and training of citizen-based technicians who were responsible for collecting high frequency suspended sediment samples and organising all equipment used to collect suspended sediment samplesx; the collection of monthly suspended sediment samples; participating in the developed the suite of lab analysis techniques used, conducting lab analysis and the training of the lab technicians; requesting and putting together information used to identify sediment source areas. The researcher has analysed all discharge data and suspended sediment data following lab analysis.

- **From the catchment:**
    - **Technicians:** Babalwa Nqweniso, Pumza Kalane, Boniswa Mpopota, Khanyisa Nogaga, Nomncedi Mpehle, Luleka Mpehle, Zukisani Sagumbe, Andile Mazantsane, Phezile Ramswana, Sibusiso Wili, Amanda Mdutshane and their assistants.
    - **Rain gauges:** Nkosana Mthi, Jan Le Roux, Noluthando Mpehle, Nosandise Khebevu and Raymond Brown.
    - **Chiefs:** Chief G.S. Tyhali, who provided accommodation and assisted in communication with other traditional leaders. Chief M. Ranuga, who gave us his full support at every level and provided tremendous assistance as far as catchment research was concerned. Chief Vabaza and Mr Dipha, who allowed us to work in their areas.
    - **Headmen and support from members of the council and the community**. Particularly, Mr Samela, Mrs T Sagumbe, Ms Ntosh, Mr D. Wili, MamTolo and Majola, Mr Bodi, Mr Mtati and Mam' uPinkie Jokazi.

- **Family and friends** who played a huge role in keeping me healthy and motivated.
- **Professor P. Terry** for assistance with the written report.

Lord, thank you for the opportunity to study your creation.

Contents

Abstract ii

Plagiarism Declaration iii

Acknowledgements iv

List of Figures x

List of Tables xi

1 Introduction 1

- 1.1 Problem Statement 1
- 1.2 Study Context 2
- 1.3 Aim and Objectives 3
- 1.4 Thesis Structure 3

2 Literature Review 5

- 2.1 Introduction 5
- 2.2 The Importance of Suspended Sediment 6
- 2.3 Managing Suspended Sediment 7
- 2.4 Soil Erosion 7
- 2.5 Sediment Dynamics 10
- 2.6 Sediment Sources 14
  - 2.6.1 Sediment Source Provenance 14
  - 2.6.2 Sediment Source Type 14
- 2.7 Assessing Suspended Sediment 15
  - 2.7.1 Overview 15
  - 2.7.2 Hysteretic Loops 16
  - 2.7.3 Sediment Flux Monitoring 17
  - 2.7.4 Desktop Techniques 19
- 2.8 Conclusion 24
- 2.9 Chapter Summary 25

3 Study Area 26

- 3.1 Location 26
- 3.2 Climate and Hydrology 28
- 3.3 Topography 32
- 3.4 Geology and Soils 33
- 3.5 The Erosion Status of the Inxu River Catchment 35
- 3.6 Land Cover and Use 37
- 3.7 Chapter Summary 39

4 Methods 40
4.1 Selection of Monitoring Points 40
4.2 Training Technicians 43
4.3 Suspended Sediment Concentration 44
4.3.1 Sample Collection 44
4.3.2 Sample Analysis 46
4.4 Discharge Measurements 48
4.4.1 Discharge Data Collection 48
4.4.2 Discharge Data Analysis 49
4.5 Suspended Sediment Flux 51
4.6 Suspended Sediment Yield 52
4.7 Sediment Source Areas 53
4.7.1 Database 54
4.7.2 Sub-Catchment Contribution 56
4.7.3 Catchment Characteristics 57
4.8 Chapter Summary 58
5 Results 59
5.1 Measured Suspended Sediment Contribution Results 59
5.1.1 Suspended Sediment Yield of the Inxu River Catchment 59
5.1.2 Sub-Catchment Sediment Contribution 65
5.2 Comparison with Previously Modelled Results 70
5.2.1 Sediment Yield 70
5.2.2 Suspended Sediment Source Areas 71
5.3 Catchment Characteristics and Processes Results 76
5.4 Chapter Summary 79
6 Discussion 80
6.1 The Suspended Sediment Contribution of The Inxu River Catchment 80
6.2 The Relative Suspended Sediment Contribution of The Major Inxu River Sub-Catchments 84
6.3 Sediment Source Areas 85
6.3.1 Soils 85
6.3.2 Land Cover and Use 86
6.3.3 Gully Erosion 87
6.3.4 Sheet Erosion 89
6.3.5 Comparing Previously Modelled Results with Measured Suspended Sediment Data. 91
6.4 Limitations and Future Research 91
6.4.1 Data Collection Techniques 91

6.4.2 Measurement of Sediment Flux 93
6.4.3 The Identification of Sediment Source Types 95
6.4.4 Interpretation of results 96
6.5 Chapter Summary 98
7 Conclusion 100
7.1.1 Key Findings 100
7.1.2 Recommendations 102
8 References 103
9 Appendices 109
Appendix 1: Citizen-Based Technician Training Material. 110
The Competency Test 110
CHECKLIST for Training and Contracting of Service Providers 111
Safety Guidelines 113
Training Material for Sample Collection 115
Appendix 2: Turbidity-SSC Relationships 126
Appendix 3: Site-Specific Cross-Sections, Manning's Values and Rating Curves 129

List of Figures

Figure 3.1: Inxu River Catchment locality and the quaternary catchments of the proposed Lalini Dam. 27
Figure 3.2: Location of rain gauges across the Inxu River Catchment........ 28
Figure 3.3: Hourly rainfall for rain gauge A and B........ 29
Figure 3.4: Hourly rainfall for rain gauge C and D 30
Figure 3.5: Inxu River Catchment topography based on slope class. 32
Figure 3.6: Geology Map of the Inxu River Catchment 33
Figure 3.7: Inxu River Catchment broad soil types (Le Roux *et al.*, 2015). 34
Figure 3.8: Sediment yield results (Le Roux *et al.*, 2015) 36
Figure 3.9: Land cover Map for the Inxu River Catchment (National Land Cover, 2014)........ 38
Figure 4.1: Inxu River Catchment suspended sediment flux monitoring points. 42
Figure 4.2: Depth-integrating sampling pole with a sample bottle attached 45
Figure 4.3: An example of a rating curve developed from HEC-RAS and calibrated with measured water depth and discharge 50
Figure 5.1: Q-SSC relationship for the Inxu River Catchment at the seasonal scale 60
Figure 5.2: Q-SSC relationship and sediment load during the 27 July 2016 snow event from the Inxu River Catchment Outlet. 62
Figure 5.3: Q-SSC relationship and sediment load during the 05-19 November 2016 flood event from the Inxu River Catchment Outlet. 62
Figure 5.4: Q-SSC relationship and sediment load during the 12-21 January flood event from the Inxu River Catchment Outlet. 63
Figure 5.5: Q-SSC relationship and sediment load during the 16 February - 07 March 2017 flood event from the Inxu River Catchment Outlet. 63
Figure 5.6: Proportion of sediment contributed by high and low flow from the Inxu River Catchment between 01 May 2016 and 30 April 2017........ 64
Figure 5.7: High frequency suspended sediment flux from all sub-catchments (21 October 2017 – 11 January 2017)........ 65
Figure 5.8: The Suspend Sediment Flux of the Ncolosi, River Sub-catchment during the 06-21 November 2016 Flood Event 66
Figure 5.9: The Suspend Sediment Flux of the Qwakele River Sub-catchment during the 06-21 November 2016 Flood Event 66
Figure 5.10: The Suspend Sediment Flux of the Ngxaza River Sub-catchment during the 06-21 November 2016 Flood Event 67
Figure 5.11: Suspended Sediment Contribution from each Sub-Catchment (21 October 2016 – 12 January 2017)........ 68
Figure 5.12: Relative suspended sediment contribution from the major Inxu Sub-catchments (November 2016 – May 2017). 69
Figure 5.13: Sub-catchment Sediment Contribution based on the Monthly SS Flux indicating Sediment Provenance in the Inxu River Catchment. 73
Figure 5.14: Modelled Sediment Yield from Sheet and Gully Erosion for the Quaternary Catchments of the Inxu River (Le Roux *et al.*, 2015)........ 73
Figure 5.15: Inxu River Catchment Sheet Erosion Map (based on USLE Factors). 74
Figure 5.16: Inxu River Sub-catchment Gullied Area Map........ 75
Figure 5.17: Gully extent on slope class, soil type and land cover and use........ 76
Figure 9.1: Turbidity-SSC relationship of the Inxu River Catchment 126
Figure 9.2: Turbidity-SSC relationship of the Ngxaza River Catchment........ 126

Figure 9.3: Turbidity-SSC relationship of the Ncolosi River Catchment 127
Figure 9.4: Turbidity-SSC relationship of the Qwakele River Catchment 127
Figure 9.5: Turbidity-SSC relationship of the Umnga River Catchment... 128
Figure 9.6: Cross-section and discharge parameters for the Umnga River monitoring point........... 129
Figure 9.7: Rating curve for the Umnga River monitoring point 129
Figure 9.8: Cross-section and discharge parameters for the Ngxaza River monitoring point........... 130
Figure 9.9: Rating curve0 for the Ngxaza River monitoring point 130
Figure 9.10: Cross-section and discharge parameters for the Qwakele River monitoring point 131
Figure 9.11: Rating curve for the Qwakele River monitoring point.. 131
Figure 9.12: Cross-section and discharge parameters for the Ncolosi River monitoring point 132
Figure 9.13: Rating curve for the Ncolosi River monitoring point.. 132
Figure 9.14: Cross-section and discharge parameters for the Inxu Outlet monitoring point 133
Figure 9.15: Rating curve for the Inxu Outlet monitoring point... 133

List of Tables

Table 3.1: Summary of Rainfall Data on 27 May 2016 - 07 May 2017 from Rain Gauges Across the Inxu River Catchment. 31
Table 4.1: Prioritisation system for establishing the monitoring network in the Inxu River Catchment for high priority sub-catchments (refer to Figure 4.1 for the location of point numbers). 41
Table.4.2: The number of samples from each monitoring point 46
Table 4.3: Database for the identification of potential sediment source areas in the Inxu River Catchment.. 54
Table 5.1: The Extrapolated, relative suspended sediment yield for each sub-catchment 70
Table 5.2: Sediment Yield output - Measured vs Modelled Data (Le Roux et al., 2015)..................... 71
Table 5.3: Summary of the Inxu River Sub-Catchment Characteristics... 77
Table 9.1: Checklist for training and contracting of service providers (To protect the privacy of the technicians, personal details have been replaced with a tick) 112

1 Introduction

This section provides the motivation behind conducting this study, the study aims and objectives and an outline of the thesis.

1.1 Problem Statement

The excessive supply and accumulation of suspended sediment leads to the degradation of fluvial systems such as rivers and dams. Interest in suspended sediment has been driven by its transportation capabilities which enable it to transport nutrients that support biological life, but also transport pollutants and pathogens (Collins *et al.,* 2017). Moreover, the excessive increase in suspended sediment due to soil erosion processes affects water quality negatively, reduces light penetration, damages aquatic habitats (Martínez-Carreras *et al.,* 2010; Sherriff *et al.,* 2016) and, if not managed, may lead to channel and harbour siltation (Rovira and Batalla, 2006) as well as dam sedimentation (Martínez-Carreras *et al.,* 2010; Rovira and Batalla, 2006). Therefore, excessive accumulation of suspended sediment may lead to the degradation of important water resources such as dams and rivers (Martínez-Carreras *et al*, 2010). For the sake of protecting these resources, sources of suspended sediment need to be managed.

Management of suspended sediment should be catchment-wide and catchment specific to account for the variability and context of soil erosion processes that produce sediment. A critical step to managing suspended sediment effectively is to gain knowledge of suspended sediment dynamics over various spatial and temporal scales (Collins and Walling, 2004; Gao, 2008). Fundamental to this knowledge is the quantity of sediment that is produced by the catchment, the provenance of this sediment and how both the quantity and sources change over space and time (Gao, 2008; Evrard *et al.,* 2011; Sherriff *et al.,* 2016). Such information will support decision-making and planning (Bannatyne *et al.,* 2017) and will ensure relevant strategies for suspended sediment management are designed and implemented (Walling *et al.*, 2008). According to Sergeant *et al.* (2012) effective management also requires baseline information that answers questions and meets objectives for sediment management. Sediment management should be established at the desired spatial and temporal scales.

Obtaining this information requires scientifically rigorous methods for assessing suspended sediment and these methods need to account for spatial and temporal variability (Gao, 2008). Generally, methods that can be used are restricted by the availability of data and its quality, available resources, the spatial and temporal resolution as well as limited funding (Martínez-Carreras *et al.*, 2010; Bannatyne *et al.,* 2017). The use of tools that are simple and cost effective is encouraged (Rowntree *et al.,* 2017), especially in poorly developed areas (Bannatyne *et al.,* 2017). Methods such as sediment flux monitoring are effective for quantifying suspended sediment and identifying the spatial distribution of sediment sources (Bannatyne *et al.,* 2017). Citizen-based monitoring, which was used in this research, is a cost effective and effective method of obtaining high resolution sediment flux data that is otherwise unavailable to scientists (Tulloch *et al.,* 2013). This method is effective in determining sediment fluxes from different tributaries in a catchment and thus identifying sediment source areas in the catchment, but supporting data are required to understand sediment processes in the catchment. Desktop studies using Geographic Information Systems and modelling can be useful in identifying critical factors that contribute to sediment processes and insight on sediment sources in the catchment (Collins and Walling, 2004), accounting for variability in both space and time (Bhuttarai and Dutta, 2007).

1.2 Study Context

The Department of Water and Sanitation (DWS) plans to construct two multipurpose dams along the Tsitsa River with the aim of improving the socio-economic status of the Eastern Cape (DWS, 2014). The proposed dams include the 490 million m^3 multipurpose Ntabelanga Dam and approximately 20 km downstream from it will be the 232.5 million m^3 Lalini Dam for hydropower (DWS, 2014; van Tol *et al.*, 2014). These dams are to operate as an integrated scheme to provide potable water, water for irrigation and electricity from the hydropower plants (DWS, 2014; van Tol *et al.*, 2014).

The catchment in which these proposed dams are located has highly dispersive soils which are subject to gully erosion (Le Roux *et al.,* 2015; van Tol *et al.,* 2014). The area is prone to high erosion rates which have been exacerbated by overgrazing (Le Roux *et al.,* 2015; van Tol *et al.,* 2014). These high levels of soil loss have raised concerns about the longevity of the proposed dams (Le Roux *et al.*, 2015). DWAF (2005) recommended that the area should be rehabilitated so that siltation is reduced. As a result, the Department of Environmental Affairs (DEA) has established a catchment wide rehabilitation project, the Ntabelanga Lalini Environmental Infrastructure Project. This project is supported by scientific research that elucidates sediment processes and source areas. There is lack of knowledge of suspended sediment dynamics in the Tsitsa River Catchment. Therefore, there is a need to quantify and identify suspended sediment yield and sources, respectively, in order to inform decisions on prioritisation and identification of management needs in the catchment.

Sediment studies have been conducted in the Upper Tsitsa River Catchment (Bannatyne, 2017), but there is limited knowledge of the sediment processes that are at play in the Middle Tsistsa River Catchment and how these processes will influence the Lalini Dam. The Inxu River is the largest tributary of the Tsitsa River and lies between the two dams, having a direct influence on the downstream Lalini Dam. Erosion models for the Mzimvubu River Catchment have already identified part of the Inxu River Catchment as highly erodible (Le Roux *et al.,* 2015). Gullies directly linked to the river have been identified as the primary source of sediment for the Tsitsa River Catchment (Le Roux and Sumner, 2012) and the Inxu River Catchment possesses many of these gullies. Van Tol *et al.* (2004) have identified sediment as one of the environmental aspects that will impact the dams negatively and that it should be subject to long-term monitoring. This research will provide base flow information for sediment yield and indicate potential sediment sources areas for the Inxu River Catchment.

1.3 Aim and Objectives

The aim of this study was to determine the suspended sediment contribution of the Inxu Tributary to the Tsitsa River and identify the main sediment source areas within the Inxu River Catchment as a guide to rehabilitation priorities. It has the following objectives:

1. Determine the suspended sediment contribution of the Inxu River Catchment to the main Tsitsa River.
2. Determine the relative contribution of the major Inxu River Sub-catchments to the suspended sediment of the Inxu River.
3. Compare previously modelled results with measured suspended sediment data.
4. Identify the factors that affect the sediment contribution from the major sub-catchments and the potential source areas for suspended sediment.

1.4 Thesis Structure

Following this introduction, the literature review gives insight into the nature of suspended sediment (processes behind the transportation and delivery of sediment in the catchment as well as sediment sources), the need to manage suspended sediment as well as methods of assessing suspended sediment, focussing on sediment flux monitoring and desktop techniques. This will justify why suspended sediment yields and sources should be determined for catchment management, highlighting areas where knowledge of sediment dynamics are limited.

The study area will give insight into the geographic setting where this study took place. This will include the location, climate, topography, geology and soils, land cover and use, as well as existing knowledge on soil erosion and sediment yield in the Inxu River Catchment from previous studies.

The methods section will explain data collection and analysis procedures and tools that were used to meet this study's objectives. Citizen-based sediment flux monitoring was used to determine suspended sediment contribution at catchment and sub-catchment scales on 01 May 2016 - 30 April 2017 and was also used to determine sediment provenances. Desktop studies were used to support and give deeper understanding of factors determining potential sediment sources within each sub-catchment.

Results are divided into suspended sediment contribution and yields as well as sediment sources within Inxu River Sub-catchments. The discussion explains the phenomena behind what was observed in the results and the conclusion provides the outcome of this study. Recommendations have been made based on the outcome of this study.

2 Literature Review

The following chapter introduces the nature of suspended sediment, why it is important to manage it and methods for assessing suspended sediment. Emphasis is placed on spatial and temporal variability and heterogeneity which explains the importance of understanding and managing suspended sediment.

2.1 Introduction

Suspended sediment is the sediment particle size that is transported the most (Nadal-Romero *et al.,* 2008a) in the river and can best represent sediment dynamics and erosion processes at the various temporal and spatial scales (Rovira and Batalla, 2006). Suspended sediment influences water quality, biological life and the sustainability of water resources (Martínez-Carreras *et al.,* 2010). However, excess amounts of sediment deposited and accumulated by water resources may lead to the degradation of those resources (Carter *et al.,* 2003; Walling, 2005; Sherriff *et al.,* 2015; Sherriff *et al.,* 2016). Therefore, there is a need to manage suspended sediment (Martínez-Carreras *et al.*, 2010). Fundamental to managing suspended sediment is establishing the quantity of sediment that is transported by rivers and identifying sources for suspended sediment in the catchment (Walling, 2005; Sherriff *et al.,* 2016). Moreover, methods used to assess suspended sediment should be catchment-wide and catchment-specific to account for spatial and temporal variability and the context of the catchment (Le Roux *et al.,* 2015).

The purpose of this literature review is to provide insight into suspended sediment dynamics; the importance of quantifying suspended sediment and determining its sources; and the methods used to assess suspended sediment. The review discusses the importance of suspended sediment and the role it plays in water resources, why excessive supply of suspended sediment needs to be managed for catchment rehabilitation and what needs to be understood about suspended sediment as this informs how it should be assessed. Understanding sediment dynamics is explained through soil erosion and sediment connectivity, emphasising the interdependent and integrated nature of soil erosion factors and catchment systems across spatial and temporal scales. Therefore, methods of assessing suspended sediment should account for context as well as variability across space and time. Methods for sediment sourcing are distinguished by direct and indirect methods and emphasis is placed on hysteretic relationships, sediment flux monitoring and desktop techniques.

2.2 The Importance of Suspended Sediment

Suspended sediment is comprised of the sediment particles in water that are usually 0.63 µm or less in size (Horowitz *et al.,* 1990; Navratil *et al.,* 2012; Collins *et al.,* 2017). Globally, they exceed the quantity of solutes transported in fluvial systems by a factor of 3.5 (Nadal-Romero *et al.,* 2008a); bedload normally constitutes a very small proportion of the sediment transported by these systems (Hooke, 2003; Nadal-Romero *et al.,* 2008a). Suspended sediment is, therefore, critical in assessing sediment dynamics in fluvial systems (Walling, 2005). Suspended sediment is important for the ecological functioning (Sherriff *et al.,* 2016) and sustainability of fluvial environments (Navratil *et al.,* 2012), but the excessive supply of suspended sediment in fluvial systems leads to their degradation (Carter *et al.,* 2003; Walling, 2005; Sherriff *et al.,* 2015; Sherriff *et al.,* 2016).

Suspended sediment is responsible for moderating biochemical fluxes in fluvial systems, such that it adjusts biochemical processes and biological productivity, playing a critical role in water quality and biological life (Navratil *et al.,* 2012). Nutrients bind easily with suspended sediment particles (Bábek *et al.,* 2015), hence suspended sediment particles are responsible for nutrient transportation to living organisms in fluvial systems. However, they are also good vectors for contaminants such as heavy metals, phosphorus, pathogens (Carter *et al.,* 2003; Walling, 2005; Rovira and Batalla, 2006; Martínez-Carreras *et al.,* 2010), pesticides and polychlorinated biphenyls (PCBs) (Walling, 2005). Interest in suspended sediment has been driven by these transportation capabilities and their influence on water quality (Collins *et al.,* 2017) which may be detrimental when excessive quantities of sediment are deposited in the channel (Carter *et al.,* 2003; Walling, 2005; Sherriff *et al.,* 2015; Sherriff *et al.,* 2016).

Excessive supply, deposition and accumulation of suspended sediment in fluvial systems poses a threat to water quality and aquatic systems by increasing turbidity through reducing light penetration, destroying or altering habitats (Navratil *et al.,* 2012) for spawning fish and benthic species (Sherriff *et al.,* 2015), may bioaccumulate on organisms (Evrard *et al.,* 2011), clogging fish gills (Martínez-Carreras *et al.,* 2010) and may be a health hazard when consumed (Evrard *et al.,* 2011). Once accumulated in fluvial systems, it may lead to their degradation through eutrophication (Navratil *et al.,* 2012), channel and harbour siltation (Rovira and Batalla, 2006) and dam sedimentation (Rovira and Batalla, 2006; Martínez-Carreras *et al.,* 2010). This has implications on operational capacity (Aksoy and Kavvas, 2005) and longevity of dams (Walling, 2005; Martínez-Carreras *et al.,* 2010), water treatment costs for drinking water and the maintenance of water resources such as dams and reservoirs (Collins *et al.,* 2017). Interest in suspended sediment has grown due to the impact of suspended sediment on water quality, biological life, the sustainability of water resources such as dams (Martínez-Carreras *et al.,* 2010) as well as the socio-economic capital (van der Waal *et al.,* 2015). For the sake of protecting these resources, suspended sediment should be managed (Gao, 2008).

2.3 Managing Suspended Sediment

Restoration is regarded to be an essential strategy for preserving natural recourses and protecting aquatic biodiversity from loss and degradation of river systems (Gao, 2008). South Africa is no exception as water resource protection is regarded highly, coupled with appropriate water use (DWA, 2013a). The South African Department of Water and Sanitation identified sediment as an important catchment component to monitor in light of restoration efforts (DWA, 2013a).

Most restoration strategies concentrate on sediment because the components of the river are connected to sediment and its processes (Gao, 2008). A crucial step for restoration and catchment management efforts involves developing knowledge of how much suspended sediment is transported in a catchment and how that changes over time (Gao, 2008). Such information will help establish, assess, interpret and model sediment budgets and yields, and identify secondary sources that could remobilise sediment that is already stored in sinks (Collins and Walling, 2004). Knowledge of suspended sediment quantities, therefore, can assist managers in prioritising strategies for sediment management between sub-catchments but will give limited insight on the processes that control how sediment is produced (Walling, 2005; Sherriff *et al.,* 2016). Since sediment sources influence soil loss processes, effective catchment management of suspended sediment requires sediment sources to be identified (Walling, 2005; Sherriff *et al.,* 2016).

The identification of sediment sources will aid in the design of area and process specific interventions (Le Roux *et al.,* 2015). These intervention strategies will deal with physical features and processes in the catchment that produce the highest quantity of suspended sediment (Walling, 2005) and will help managers to prioritise areas that show the most vulnerability to erosion (Xu *et al.,* 2009). This should successfully control the quantity of suspended sediment that is produced (Collins and Walling, 2004; Walling, 2005; Walling *et al.,* 2008) as interventions will target primary sources of suspended sediment (Rowntree *et al.,* 2017). An integrated catchment management approach can be achieved from knowledge generated from sediment flux and sediment sources as they will provide information on the processes behind soil loss, areas that are vulnerable to high erosion rates and the extent of erosion and sediment supply in the catchment (Sherriff *et al.,* 2015). Methods that are used to determine suspended sediment quantities and sources require knowledge of the processes that are responsible for sediment fluxes in the catchment (Gao, 2008).

2.4 Soil Erosion

Suspended sediment is produced through soil erosion processes (Jain and Kothyari, 2000; Nadal-Romero *et al.,* 2008b; Nadal-Romero and Regüés, 2010) with water as the main erosion agent (Collins and Owens, 2006, Le Roux *et al.,* 2007). Soil erosion is a natural process that involves the removal of soil particles from their place of origin, followed by transportation and deposition in a new site (Merritt *et al.,* 2003; Gordon *et al.,* 2004; Aksoy and Kavvas, 2005; Collins and Owens, 2006). The amount of soil that is lost through the erosion process is a function of climate, topography, soil, vegetation cover as well as land use and management factors (Laker, 2004; Aksoy and Kavvas, 2005; Le Roux *et al.,* 2007).

According to Aksoy and Kavvas (2005), climatic conditions and seasonal variability are closely linked to rainfall-runoff erosivity and vegetation cover. In general, semi-arid areas are vulnerable to erosion because they are sparsely vegetated, causing easily erodible soils where high concentrations of sediment are detached by rainfall and runoff. Humid areas, on the other hand, are densely vegetated, protecting them from high erosion rates. Therefore, under natural conditions, soil loss increases with increasing aridity (Rovira and Batalla, 2006; Sherriff *et al.,* 2016).

Rainfall characteristics influence detachment processes and the extent of erosion, indicating the erosivity of rain (Nel and Sumner, 2007). Raindrop velocity and rainfall intensity influence the soil splash rate as soil aggregates are broken down due to raindrop impact (Fox and Bryan, 2000). The extent of erosion due to rainfall depends on the amount, intensity, the size distribution of the raindrops as well as the wind inclination and speed (Nel and Sumner, 2007). The amount of erosion over time as a consequence of rainfall erosivity depends on rainfall intensity, depth and seasonality (Nadal-Romero and Regüés, 2010). Rain impact on the hillslope leads to interrill erosion but interrill erosion rates increase with increasing runoff velocity (Fox and Bryan, 2000). There is a close link between runoff and erosion rates compared to rainfall, but runoff is related to rainfall events (Compton and Maake, 2007).

Runoff and flow characteristics influence detachment and transportation processes (Fox and Bryan, 2000). Flow characteristics include the type (infiltration or saturated overland flow as well as storm or base flow), magnitude, depth, and velocity (Nadal-Romero and Regüés, 2010). The amount of sediment that is transported by flow depends on its ability to carry and transport sediment that is available (Rovira and Batalla, 2006; Nadal-Romero *et al.*, 2008b). This is known as the carrying capacity of flow (Gordon *et al.,* 2004). As flow velocity increases, flow gains more energy and is able to transport more sediment and larger sediment particles (Jain and Kothyari, 2000; Gordon *et al.,* 2004; Aksoy and Kavvas, 2005; Lefrançois *et al.,* 2007; Bracken *et al.,* 2015). As a result, when measuring soil loss, the observation of floods is critical as floods can carry large quantities of sediment (Rovira and Batalla, 2006; Nadal-Romero *et al.*, 2008b) – flood characteristics include flood frequency, magnitude and duration (Nadal-Romero and Regüés, 2010). Once flow loses its transport capacity, usually as a result of reduction in flow or the increase in sediment supply, coarse materials are deposited first, and finer material travels longer distances (Gordon *et al.*, 2004; Jain and Kothyari, 2000).

Runoff erosivity can be observed both on the hillslope and in the channel (Merritt *et al.,* 2003). On the hillslope, runoff either occurs as unconcentrated flow that results in sheet erosion or follows preferred pathways that result in rill and gully erosion (Aksoy and Kavvas, 2005, Le Roux *et al.*, 2007; Merritt *et al.*, 2003; Vrieling 2006). Over time, the sediment eroded on the hillslope is deposited into the channel (Merritt *et al.,* 2003; Bracken *et al.,* 2015). In the channel, sediment is eroded from the stream bed and the stream bank (Merritt *et al.,* 2003; Aksoy and Kavvas, 2005). The impact of rainfall and runoff erosivity can be curbed by vegetation cover (Laker, 2004) and limited by soil erodibility (Fox and Bryan, 2000).

Soil erodibility refers to the resistance of sediment against detachment and transportation, largely determined by the soil's stability against dispersion and disaggregation (Laker, 2004). Soil particle size, structure and chemistry influence the erodibility of soils. These depend on soil type, which in turn is highly dependent on the parent lithology (Laker, 2004). Easily erodible soils can be transported by low peak floods (Nadal-Romero *et al.,* 2008a). The presence of vegetation increases organic matter in the soils, thus reducing soil erodibility (Laker, 2004).

According to Laker (2004), vegetation cover is an erosion factor that reduces soil loss; its efficiency in reducing soil erosion depends on the type of vegetation. Grass, for example, has a root system that enables the soil to be resistant against erosion (Laker, 2004; Vargas-Luna *et al.,* 2015), a dense vegetation canopy that intercepts rainfall, reducing rainfall erosivity, a dense basal vegetation cover to reduce the amount and velocity of flow, increasing surface roughness and reducing runoff erosivity (Vargas-Luna *et al.,* 2015). The effects of topographic factors such as slope gradient on soil erosion are buffered by slope roughness (Fox and Bryan, 2000).

Topographical factors include slope characteristics such as length, form and gradients, upslope contributing area and slope curvature (Kakembo *et al.,* 2009). It is globally accepted that the degree of erosion increases with slope gradient due to increased kinetic energy and shear stress (Fox and Bryan, 2000; Laker, 2004). This enables runoff to have a greater detachment and transportation capacity (Fox and Bryan, 2000). However, in South Africa, the relationship is not simple (Kakembo *et al.,* 2009; Laker, 2004; Le Roux and Sumner, 2012). For example, Kakembo *et al.* (2009) found that gullies in the Ngqushwa District prefer to initiate on concave lower hillslopes with a gentle gradient, while Le Roux and Sumner (2012) found a similar phenomenon in the Tsitsa River Catchment and that the gullies tend to expand into midslopes.

The land use and management factors are associated with anthropogenic activity (Laker, 2004). For example, livestock farming practises have a potential to exacerbate erosion due to overgrazing and cattle tramping (Rovira and Batalla, 2006; Le Roux and Sumner, 2012; van Tol *et al.,* 2014; Sherriff *et al.,* 2015) and dirt roads increase flow paths that enhance gully erosion (Laker, 2004). Agriculture is often associated with high erosion rates (Laker, 2004; Sherriff *et al.,* 2015). In catchments that are dominated by agricultural activities, tillage often results in bare soils which leaves soils erodible (Laker, 2004) and vulnerable to rainfall-runoff erosivity (Sherriff *et al.,* 2015). Other agricultural activities include artificial methods that increase runoff erosivity by making channels wider, deeper or straighter (Sherriff *et al.,* 2016). Additionally, such activities encourage deposition by reducing base flows (Sherriff *et al.,* 2016). Land management practises are encouraged to find ways to reduce soil erosion (Laker, 2004).

Soil erosion factors are interdependent, operating as an integrated system at various spatial and temporal scales (Nadal-Romero and Regüés, 2010). At the catchment scale, erosion processes occur over the hillslope, between the hillslope and the channel and within the channel, illustrating connectivity (Bracken *et al.,* 2015). Connectivity will be explained through the lens of sediment since sediment is the material of interest in this study.

2.5 Sediment Dynamics

Connectivity describes the integrated transfer of sediment from a source to a sink zone transported by an agent at various spatial and temporal scales (Bracken *et al.,* 2015; Fryirs *et al.,* 2007). Sediment source zones are areas where sediment is prepared and made available for transportation, while sink zones are areas where sediment deposition and storage occur until sediment is remobilised (Bracken *et al.,* 2015; Fryirs *et al.,* 2007). Once sediment is made available at a source, an agent such as water transports the sediment to a sink. Water transports sediment from all sources connected to its path to a sink zone (Bracken *et al.,* 2015). The supply of sediment from source to sink zones will depend on the spatial configuration of these zones and is hydrologically controlled (Long and Pavelsky, 2013; Bracken *et al.,* 2015).

The spatial configuration of source and sink zones effectively indicates landscape features that either enhance or disrupt sediment connectivity such that they will affect lateral, longitudinal and vertical linkages of sediment flow (Fryirs *et al.,* 2007). According to Fryirs *et al.* (2007), vertical linkages are concerned with the relationship between water and sediment occurs at the surface to sub-surface levels of the channel. These are influenced by the texture of sediment and the sediment transportation regime, which are governed by surface and sub-surface flows, groundwater, slope hydrology and sediment characteristics. For example, when the surface layer is composed of coarse material in relation to the bed material, finer sediment particles tend to be “protected” underneath this layer, preventing them from being eroded until the layer is removed (Gordon *et al.,* 2004). This phenomenon is known as bed armouring and acts as a blanket which disrupts connectivity that occurs over vertical linkages.

Longitudinal linkages reflect the trunk-tributary relationships – how different forms of sediment are transported by the channel to downstream areas. Features such as woody debris and bedrock steps often introduce a local base level as they lower the local slope of the bed, trapping sediment from upstream areas and behaving as local barriers in the channel. Other barriers include dams and reservoirs which decrease the amount and the frequency at which sediment is delivered further downstream and constrains water recharge (Long and Pavelsky, 2013).

Lateral linkages show the relationship between the hillslope and the channel network – how sediment that is derived from the hillslope is transported through the channel and how frequently that occurs, as well as how the frequency of inundation and the magnitude of overbank events affect the relationship between the channel and floodplains. On the hillslope, features such as disconnected gullies (which are explained in Section 2.7), fans and alluvial pockets of floodplain act as buffers as they withhold and delay sediment that is derived from the hillslope from being transported to the channel. Features such as connected gullies will efficiently deliver sediment to the channel (Le Roux and Sumner, 2012; van der Waal, 2014; Rowntree *et al.,* 2017).

Coupling is the property in fluvial systems that describes the efficiency with which sediment is transported between source and sink zones (Bracken *et al.,* 2015). Decoupling, therefore, is the property that limits the transfer of sediment between these zones (Fryirs *et al.,* 2007). According to Fryirs *et al.* (2007), decoupling effects occur as buffers, barriers and blankets. Buffers decouple lateral and longitudinal linkages, barriers decouple longitudinal linkages and blankets decouple vertical linkages. For a medium to be able to efficiently deliver sediment from the hillslope to the channel, the medium must exert forces that will overcome decoupling effects. These forces are known as the breaching capacity (Fryirs *et al.,* 2007), which is important for detachment (Bracken *et al.,* 2015). Additionally, the medium must have sufficient transport capacity (Bracken *et al.,* 2015). The distance at which sediment is transported is directly proportional to the velocity and the energy of the medium and is inversely proportional to particle size (Bracken *et al.,* 2015). Hence suspended sediment is the most transported sediment particle in a fluvial system (Nadal-Romero *et al.,* 2008a) and can best represent sediment fluxes and yield as well as sediment transport processes in the catchment (Walling, 2005).

Both transport and breaching capacities of a medium depend on the magnitude and frequency of events and their effects on detachment, transportation and deposition of sediment will vary across different spatial and temporal scales (Fryirs *et al.,* 2007; Bracken *et al.,* 2015). The relationship between flow characteristics and suspended sediment concentration can be used to illustrate these sediment dynamics over various temporal scales (Nadal-Romero *et al.,* 2008a; Nadal-Romero *et al.,* 2008b). This relationship is seldom homogenous over an event and is best described by the hysteretic relationship between suspended sediment concentration and discharge over time (Rovira and Batalla, 2006; Nadal-Romero *et al.,* 2008b; Sherriff *et al.,* 2016). Clockwise and anti-clockwise hysteresis are the most commonly observed types of hysteretic relationships (Nadal-Romero *et al.,* 2008b). Clockwise hysteresis occurs when the suspended sediment concentration peak precedes discharge peak, showing a progressive decline of sediment that is available during an event (Nadal-Romero *et al.,* 2008b); while the opposite is true for anti-clockwise hysteresis (Rovira and Batalla, 2006; Lefrançois *et al.,* 2007; Nadal-Romero *et al.,* 2008b; Sherriff *et al.,* 2016). Rovira and Batalla (2006) argue that trends for suspended dynamics can be observed at the event, seasonal and annual scales and that these dynamics change, primarily, between clockwise and anticlockwise hysteretic loops over the different temporal scales.

At the event scale, sediment transport depends on flood frequency, duration and magnitude, as well as the availability of suspended sediment. High magnitude, low frequency events have a greater capacity to overcome resistance from blankets, barriers and buffers, increasing all linkages to the extent that large quantities of sediment from both hillslope and channel are transported in areas that are further downstream (Fryirs *et al.,* 2007). For example, in their research in the Vuvu River Catchment, South Africa, van der Waal *et al.* (2015) found that sediment from distal sources of the catchment was transported during flow events which are infrequent but have high magnitude. During such events, connectivity is high across various spatial scales (Fryirs *et al.,* 2007) and can be observed at the event scale (Bracken *et al.,* 2015). The lag time between events indicates the arrival of sediment that is derived from catchment wide sources (Bracken *et al.,* 2015).

In their research in the Lower Tordera River Catchment in Spain, Rovira and Batalla (2006) explained that changes in hysteresis occur as a cycle that illustrates sediment preparation and sediment exhaustion phases at the seasonal scale. This has been observed in South African rivers that are located on the eastern seaboard of Southern Africa (Grenfell and Ellery, 2009).

In the Umfolozi River in Kwa-Zulu Natal, Grenfell and Ellery (2009) found that during the dry season, a combination of two sediment preparation activities occurs simultaneously. Sediment was accumulated in the catchment during the dry season through low seasonal discharge as the discharge had limited sediment transport capacity. Low magnitude, high frequency events lack the capacity to transport huge amounts of sediment from the hillslopes and the channel (Fryirs *et al.,* 2007), so at the catchment scale small amount of sediment are transported over short distances over short periods (Nadal-Romero and Regüés, 2010; Bracken *et al.,* 2015). Such events may show low sediment connectivity at large spatial scales (Fryirs *et al.,* 2007) but also illustrate the accumulation, redistribution and storage of sediment along the path (Nadal-Romero and Regüés, 2010) over a long period of time (Bracken *et al.,* 2015). In another sediment preparation activity, sediment availability on the slopes increased because of the reduction in vegetation cover during the dry season. Therefore, during the sediment preparation phase, there is limited variability in sediment and discharge patterns (Nadal-Romero and Regüés, 2010) and there was little deposition of sediment downstream of the channel, consequently sediment yield was very low.

This sediment that was prepared during the dry season was readily available for sediment transportation at the beginning of the wet (Rovira and Batalla, 2006). During this phase, large quantities of sediment were deposited downstream, due to a high upstream sediment yield. Over time, suspended sediment in the system was depleted as the dry season approached and the sediment exhaustion phase began. Rovira and Batalla (2006), and Nadal-Romeo and Regüés (2010) found that, due to the prevalence of floods during the wet season, sediment and discharge were highly variable, and that clockwise hysteresis dominated during this season. Rovira and Batalla (2006) acknowledged that deviations from patterns that are observed at the seasonal scale happen due to flash floods that occur during the dry season. Additionally, they observed that, at the annual scale, flood frequency as well as catchment-based conditions such as land use and climate determine the variability in suspended sediment concentration and flux.

Sediment connectivity helps us to understand the interdependent relationship between the structural component of the landscape (landscape geometry) and the erosion processes and anthropogenic factors in a system (the system being the catchment, hillslope or stream) that govern sediment flux (Zebaleta *et al.*, 2007). Sediment flux is defined as the amount of sediment per unit volume or per unit time (Bracken *et al.,* 2015). Its transportation and deposition depend on hydrological control. Sediment flux that is observed locally demonstrates (dis)connectivity that occurs at different spatial and temporal scales (Fryirs *et al.,* 2007; Bracken *et al.,* 2015). At the spatial scale, the effectiveness and intensity of transportation and delivery of sediment depends on topographic factors while the variability in processes that trigger activity depends on seasonal climatic conditions at the temporal scale (Nadal-Romero and Regüés, 2010). Factors, therefore, interact at various spatial and temporal scales (Nadal-Romero and Regüés, 2010).

2.6 Sediment Sources

In order to better understand the processes behind sediment flux, it is important to identify sediment sources (Walling, 2005; Sherriff *et al.,* 2016). Since the suspended sediment flux that is transported in a catchment represents sediment from different locations and sources from the catchment (Walling, 2005) and within the channel (Carter *et al.,* 2003), suspended sediment sources can be identified according to their spatial location as well as the source type (Carter *et al.,* 2003; Collins and Walling, 2004).

2.6.1 Sediment Source Provenance

The spatial distribution of suspended sediment sources can be determined by identifying the location of sources across the catchment, sediment source areas (Collins and Walling, 2004). Sediment source areas are also known as sediment provenances (Rowntree *et al.,* 2017). Sediment provenance is usually determined through the relative sediment contribution by tributaries to the trunk (Collins *et al.,* 2017) as well as the use of spatial features such as geology (Collins *et al.,* 2017; Rowntree *et al.,* 2017). In other words, sediment source provenance informs the manager about the areas where rehabilitation strategies should be targeted.

For example, Compton and Maake (2007) found two dominant geochemical groups, the Drakensberg Group basalts which form hard bedrock that will not be easily eroded, and the Karoo Supergroup sedimentary rocks which are easily erodible soils compared to basalts and were the source of high erosion rates in the Orange River. Similarly, van der Waal *et al.* (2015) and Rowntree *et al.* (2017) found that areas dominated by sedimentary derived soils were areas of high erosion rates compared to areas dominated by igneous soils. Therefore, rehabilitation in these areas would be targeted at areas where certain geochemical and mineralogical properties are found (Compton and Maake, 2007).

2.6.2 Sediment Source Type

Sediment source types are the features in the catchment that enhance erosion processes, sediment generation and connectivity. These are features such as top- and subsoils (Rowntree *et al.,* 2017), bank, gullies or sheet erosion, road runoff as well as land use types (Rowntree *et al.,* 2017). Therefore, sediment source types inform managers on what rehabilitation strategies need to address in the catchment.

Rills and gullies occur as concentrated pathways for water but the difference between the two is that rills are pathways that are small enough to be removed through cultivation methods, whereas gullies cannot (Aksoy and Kavvas, 2005). Gullies either enhance lateral linkages when they supply the channel with sediment at the base of the hillslope, or act as buffers that trap sediment in a depositional area on the hillslope (Le Roux and Sumner, 2012).

According to Zabaleta *et al.* (2007), land use strongly influences sediment availability. According to Sherriff *et al.* (2015), agricultural activities are closely linked with arable farming practises such as seed bed preparation and soil redistribution achieved through mechanical means, bare farm lands and controlled traffic farming (tramlines) down the slope. These efforts leave bare soils vulnerable to rainfall-runoff erosivity and high erosion rates. Overgrazing disturbs the soils structure making soils easily eroded, cattle trampling causes compaction creating erosion pathways (Sherriff *et al.,* 2015) and loss of channel banks (Lefrançois *et al.,* 2007). Agricultural practises are therefore important sediment sources (Sherriff *et al.,* 2015, Sherriff *et al.,* 2016).

Different sources enhance erosion at different spatial and temporal scales, thus methods that are used for sediment assessment should account for variability. To date, it has been difficult to measure the relative dominance of each of these factors for suspended sediment dynamics as they behave according to the context of their environment (Nadal-Romero *et al.*, 2008a). Therefore, it is important to interpret these factors and their influence in the context they occur (Nadal-Romero *et al.*, 2008a). Furthermore, methods that are used in understanding suspended sediment dynamics should account for this variability (Gao, 2008).

2.7 Assessing Suspended Sediment

The following section presents an overview of methods that are used to assess suspended sediment, as well as detailed descriptions of hysteretic loops, suspended sediment flux monitoring as well as desktop techniques as they are methods of interest in this study.

2.7.1 Overview

Since suspended sediment sources are influenced by the interplay of various processes across spatial and temporal scales, Collins and Walling (2004) argue that the challenge with obtaining representative data can be overcome if measures for assessing suspended sediment are conducted over various spatial and temporal scales. Temporal coverage should ensure that all events that are responsible for sediment transport and the subsequent sediment fluxes and yields are accounted for; spatial coverage should ensure that all sediment sources are covered as this will influence decision making and the design of strategies for sediment management (Bannatyne *et al.,* 2017). Although, practically, measuring all possible sediment sources is unrealistic, a variety of methods can be used to obtain data at the required resolutions (Gao, 2008). The choice should be based on meeting research or management objectives and needs (Gao, 2008; Lindenmayer and Likens, 2010; Sergeant *et al.,* 2012; Tulloch *et al.,* 2013).

There are various methods that can be used to assess suspended sediment. Methods include vulnerability indices, hysteretic loops, and sediment fingerprint methods, soil erosion plots, erosion pins, other sediment tracers, monitoring sediment flux (Collins and Walling, 2004), the use of turbidity as a surrogate for suspended sediment (Gao, 2008) as well as desktop techniques such as remote sensing (Collins and Walling, 2004; Walling, 2005), modelling and GIS (Jain and Kothyari, 2000; Bhuttarai and Dutta, 2007). General challenges facing these methods includes the reliability on complimentary information that is gathered, especially concerning sediment sources and their contribution to sediment flux since sediment processes are interlinked across various spatial and temporal scales (Collins and Walling, 2004). Thus, the use of combined procedures is very important (Collins and Walling, 2004; Walling, 2005). In addition*, a priori* assumptions must be made concerning the likely primary sources, and possible uncertainties lie on whether or not these are the true primary sources (Walling, 2005). Generally, there are practical and logical sampling constraints that are difficult to overcome due to the spatial and temporal variability of suspended sediment sources and processes that are at play (Walling, 2005; Martínez-Carreras *et al.*, 2010). Lastly, financial and resource limitations prevent covering the wide range in spatial and temporal scale that is required, especially for monitoring purposes (Martínez-Carreras *et al.*, 2010).

2.7.2 Hysteretic Loops

Hysteretic loops, described above as the relationship between suspended sediment concentration (SSC) and discharge (Q), can be used to indicate sediment provenances (Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b) and how they vary across space and time (Nadal-Romero *et al.,* 2008b). They also provide insight on the processes of sediment availability and delivery (Sherriff *et al.,* 2016) (as illustrated in section 2.6) and so they illustrate sediment dynamics (Lefrançois *et al.,* 2007).

Clockwise hysteresis is characterised by a SSC peak that precedes the Q peak during an event and the progressive decline in SSC as Q peaks (Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b). This is caused by a rapid sediment response from a small catchment area, sediment supply from steep slopes that are near the main channel or the arrival of sediment limited discharge from upland forested areas that would contribute to the progressive decline is SSC at seasonal scale (Nadal-Romero *et al.,* 2008b). Therefore, clockwise hysteresis sediment is derived from local areas that occur in or within close proximity to the channel (Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b) or from areas that are close to the monitoring point (Lefrançois *et al.,* 2007; Nadal-Romero *et al.,* 2008b).

Anti-clockwise hysteresis is characterised by a SSC peak following the Q peak and an increase in suspended sediment after Q peaks (Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b). This is a consequence of the arrival of sediment from distal areas of the catchment or channel processes that occur at late stages of a flood event such as bank erosion (Lefrançois *et al.,* 2007). Bank erosion would occur following sufficient saturation of the channel bank during the early stages of the flood event that result in bank collapse (Lefrançois *et al.,* 2007). Lefrançois *et al.* (2007) found that the rate of bank erosion increased due to bank damage from cattle tramping. Anti-clockwise hysteresis indicates distal and catchment wide sources as well as delayed channel processes (Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b).

2.7.3 Sediment Flux Monitoring

Monitoring involves in situ measurement of suspended sediment at the outlet of each tributary of interest in the catchment river network (Gao, 2008). Repeated measurement over extended periods of time is considered valuable as it provides base flow information for investigating system response to disturbances and the consequent structural and process based changes, identifying trends and anomalies, interrogating hypotheses, exploring new ideas, developing models (Lindenmayer and Likens, 2010), guiding planning, management (Conrad and Hilchey*,* 2011) and policy development in decision-making and evaluating actions and interventions (Sergeant *et al.,* 2012). The accuracy of the data that are collected depends on the quality of data collection and how representative the data are (Gao, 2008). To understand suspended sediment dynamics, for reasons explained above, representative data requires data collection over various temporal and spatial scales (Collins and Walling, 2004; Gao, 2008).

Monitoring is very effective for measuring suspended sediment flux and concentration (Gao, 2008). It can give information on sediment provenances (Evrard *et al.,* 2011) based on tributary contributions (Collins and Walling, 2004), but it is difficult to discriminate sediment source types (Gao, 2008), as explained in section 2.6.

Sediment flux monitoring has been used for many years to achieve various purposes that include investigating sediment dynamics, measuring the degree of soil erosion and investigating the effect of sediment sources (Gao, 2008). Many monitoring attempts are limited as they lack access to ongoing funding (Lindenmayer and Likens, 2010) and practical resources, such as the difficulty of collecting samples manually over a flood event, often limit the achievement of the monitoring method (Walling, 2005). Obtaining short or long-term data for suspended sediment flux such as discharge and suspended sediment concentration is a challenge that often limits the availability of data and its quality (Bannatyne *et al.,* 2017). Data requirements and human and financial resources limit the choice of the method used to gather data (Bannatyne *et al.,* 2017) and what can be achieved (Walling, 2005), including the spatial and temporal coverage (Bannatyne *et al.,* 2017).

Sediment samples can be collected by automated or manual techniques (Gao, 2008). Automated Pumping Samplers (APS) collect point samples automatically using a pump system to draw samples from a channel (Gao, 2008). For long term monitoring (Gordon *et al.,* 2004), APS are typically installed on gauging stations (where discharge data are also collected) that are usually situated at catchment outlets (Evrard *et al.,* 2011). This limits the accurate determination of the spatial distribution of sediment sources and sediment erosion processes. APS often use a calendar-based sampling frequency which often miss significant sediment transport events (Evrard *et al.,* 2011; Bannatyne *et al.,* 2017). To overcome this, APS can use thresholds determined from specific triggers such as turbidity (Evrard *et al.,* 2011), stream velocity or water depth values (Gao, 2008) to determine the sampling frequency during events (Evrard *et al.,* 2011). Additionally, APS operate with a limited number of sample bottles (Gao, 2008). They also run the risk of missing important events if sample bottles are not replaced timeously (Gao, 2008; Gordon *et al.,* 2004). According to Bannatyne *et al.* (2017), the high purchase and maintenance costs of APSs, in addition to the risk of vandalism and theft of equipment, discourage the use of such equipment in areas like South Africa (Bannatyne *et al.,* 2017). Catchment management efforts should use simple and cost-effective tools (Rowntree *et al.,* 2017), which could, potentially, be achieved through citizen-based monitoring efforts.

Citizen-based monitoring is one of the ways in which common limitations for monitoring, such as spatial and temporal coverage as well as human capital, can be overcome (Bannatyne *et al.,* 2017; Tulloch *et al.,* 2013). Local members of the community collect sediment samples during catchment-wide, unpredictable flood events, as well as during base flow conditions which provide continuous sediment flux observations (Bannatyne *et al.,* 2017). This method, therefore, is valuable in obtaining data that is otherwise inaccessible to a researcher (or expert) (Tulloch *et al.,* 2013). Moreover, this method is useful for obtaining large volumes of data at wide spatial scales and fine temporal resolutions (Hochachka *et al.,* 2012) and has potential to fill gaps from incomplete and inadequate data that is necessary for understanding systems and phenomena (Conrad and Hilchey*,* 2011).

Common issues that are raised with citizen-based monitoring techniques are quality assurance, credibility, comparability and completeness as information is collected by people that are not experts in the field (Conrad and Hilchey,2011) as well as keeping participants interested (Conrad and Hilchey*,* 2011). One of the ways in which Bannatyne *et al.* (2017) overcame this issue was by using smartphones to collect real time data and frequent visits and constant evaluation of participants. Furthermore, Bannatyne *et al.* (2017) were involved in a community-based restoration project where one of the mandates was to improve livelihoods of local people. This enabled them to provide financial incentives to participants.

Gao (2008) encourages the use of a variety of techniques to assess sediment in order to overcome limitations, especially those of monitoring techniques. Turbidity can be used as a surrogate for suspended sediment concentration (Zabaleta *et al.,* 2007; Gao, 2008). Turbidity can be accurately sensed at low values since low suspended sediment concentration (SSC) values are associated with an error when SSC is determined by means of gravimetric analysis. Bannatyne *et al.* (2017), made similar observations using the evaporation method, and the turbidity-SSC relationship was used to overcome the measurement error associated with low SSC values.

Using this method, it is assumed that the relationship between turbidity and SSC is linear, clear and unique (Gao, 2008) and that the physical properties of suspended sediment such as their size and shape remain constant (Zabaleta *et al.,* 2007). However, Zabaleta *et al.* (2007) argue that the Turbidity-SSC relationship is not linear because different discharges carry different sediment particles. As a result, scatter is introduced in the Turbidity-SSC relationship through the influence of various sources, from heterogeneous soils or the effects of land use. The relationship is time and site specific and can be used only if adequate relationships are determined.

2.7.4 Desktop Techniques

In this study, the term “desktop technique” has been used as an umbrella term that refers to mapping, Geographic Information Systems (GIS), remote sensing and modelling.

2.7.4.1 Mapping

Mapping is an effective way of representing sediment source types and provenances as it provides information on the spatial distribution of landscape features and processes that influence sediment erosion (Collins and Walling, 2004). These include maps showing the spatial distribution of gullies, areas in the catchment that have bare soils (Collins and Walling, 2004) and sediment yield maps (Le Roux *et al.,* 2015). Limitations to mapping are its subjectivity and include the technical skills, time and the difficulty in displaying temporal variability from a single map (Collins and Walling, 2004). GIS, remote sensing and modelling enable the interaction of data from different temporal scales.

2.7.4.2 Geographic Information Systems

Geographic Information Systems (GIS) is a computer-based approach that facilitates how spatially referenced data are captured, managed, manipulated, analysed and displayed, and how a spatially referenced phenomenon is analysed (Goodchild and Longley, 1999; Chang, 2012) in order to solve a problem and answer management questions (Goodchild and Longley, 1999). In terms of assessing sediment, GIS is a valuable tool for assembling data on the soil erosion factors and interacting with these factors at different spatial and temporal scales (Bhuttarai and Dutta, 2007). It is used to support the processing of data inputs for various soil erosion factors (Gassman, 2007) which can be data intensive (Jain and Kothyari, 2000; Bhuttarai and Dutta, 2007). It quantifies the heterogeneity in these factors as they influence drainage and topographic characteristics and facilitates how factors such as slope and soil type are discretized into small grids of homogeneity (Jain and Kothyari, 2000; Bhuttarai and Dutta, 2007) and divide the catchment into hillslope and channel components (Bhuttarai and Dutta, 2007). This has assisted the estimation of sediment yield and soil erosion as it can be coupled with models (Jain and Kothyari, 2000; Bhuttarai and Dutta, 2007) and remote sensing techniques (Smith and Pain, 2009).

2.7.4.3 Remote Sensing

Remote sensing is a useful and reliable tool for visualising and analysing geomorphic changes over vast spatial and temporal scales through the analysis of aerial photographs (Kakembo and Rowntree, 2003; Collins and Walling, 2004; Smith and Pain, 2009). It can be very useful in gathering information in areas that are inaccessible and when field data collection is expensive (Gordon *et al.,* 2004) and providing evidence of erosion incidents (Walling, 2005). Remotely sensed imagery can be captured using airborne sensors and satellites (Collins and Walling, 2004; Gordon *et al.,* 2004; Smith and Pain, 2009; Le Roux *et al.,* 2015).

Airborne systems offer high resolution data (Smith and Pain, 2009) which is useful for observing erosion features (Le Roux *et al.,* 2015) and making local scale observations (Collins and Walling, 2004). Kakembo and Rowntree (2003) used images collected from airborne sensors to identify, quantitatively record and map vegetation cover, land use and erosion types across the landscape of the Ngqushwa District, South Africa. Although Kakembo and Rowntree (2003) were able to use successive aerial photographs that were taken in 1938, 1954, 1965, 1975 and 1988 for their study, generally, airborne imagery does not offer the repeatable data over long temporal periods (Le Roux *et al.,* 2015) and over large spatial scales that satellite images do (Collins and Walling, 2004; Le Roux *et al.,* 2015).

From a general perspective, Vrieling (2006) claims that remotely sensed images are difficult to use to detect small erosion features such as small gullies since most remotely sensed images have a resolution between ten meters and a kilometre. Le Roux and Sumner (2012) overcame this issue when they digitized gullies using SPOT imagery in the effort of mapping gully erosion in the Tsitsa River Catchment. SPOT 5 is satellite imagery that is panchromatic sharpened at 2.5 m resolution, therefore it offers “high resolution air photo-like quality” (Le Roux and Sumner, 2012: 442) which is useful for gully mapping. Additionally, it was available on various dates in 2008 to digitise gullies. Through using SPOT 5, they were able to identify two types of gullies, namely connected and disconnected gullies. Le Roux *et al.* (2015) developed this further by mapping gullies for the Mzimvubu River Catchment (where the Tsitsa River Catchment lies), identifying active and non-active gullies and further categorising gullies into gully depth classes, active and non-active as well as connected, partially connected, potentially connected and disconnected. This helped them to estimate sediment yield for the Mzimvubu River Catchment at quaternary catchment scale through modelling techniques.

Suspended sediment has been monitored using Landsat TM, which is the most used satellite data in geomorphology and soil loss studies at large, according to Collins and Walling (2004). Landsat TM has been used for assessing individual tributary suspended sediment loads (Collins and Walling, 2004). In large catchments, such as the Amazon, satellite images from MODIS have been used to estimate suspended sediment concentration using the spectral reflectance as well as algorithms for calculation (Espinoza Villar *et al.,* 2013).

In South Africa, according to Le Roux *et al.* (2008), remote sensing has been used in conjunction with Geographic Information Systems to investigate soil degradation management through modelling. This research, funded by the Institute of Soil Climate and Water of the Agricultural Research Commission, has produced the Erosion Susceptibility Map and the Predicted Water Erosion Map. These maps have integrated various maps and satellite images and have made use of erosion models such as the Universal Soil Loss Equation (USLE) and the Revised Soil Loss Equation (RUSLE) (Le Roux *et al.,* 2008). However, these data sets lack comparison and validation with actual field data and do not account for temporal and spatial variability (Le Roux *et al.,* 2008). This is because they are based on single-date imagery, while erosion processes vary at different scales, and are produced from very coarse images of 1 km resolution so they can identify the most vulnerable areas at regional scale.

2.7.4.4 Sediment Modelling

Sediment modelling provides a platform for interrogating the interplay of the physical attributes contributing to the movement of sediment by using mathematical equations and simulating various scenarios pertaining to sediment processes (Gao, 2008). It enables the estimation of sediment yield to be performed consistently and quantitatively at various spatial and temporal scales (Bhattarai and Dutta, 2007). Modelling has been used as an alternative method for assessing sediment erosion and has been used to identify catchment sediment sources as well as the processes of mobilisation and sediment delivery (Collins and Walling, 2004; Walling, 2005).

In addition to accounting for spatial and temporal variability (Bhattarai and Dutta, 2007), modelling is a method attractive to catchment managers because it allows for the simulation of alternative scenarios (Gao, 2008). A limitation to both the extent of scale and the cost behind modelling is the availability of data (Merritt *et al.,* 2003). Moreover, the degree of accuracy depends on the richness of information that is contributed to run the model (Gao, 2008; van Zijl *et al.*, 2013). This refers to both the quality and the quantity of data. Van Zijl *et al.* (2013) suggests that increasing the information that is provided to support models will improve the accuracy of the model output and the map that is created. Therefore, the quality and quantity of data influences the success for the model to simulate sediment processes realistically (Chen and Mackay, 2004).

It is difficult for models to account for all possible and realistic processes concerning sediment erosion that occurs in a catchment (Xu *et al.,* 2009) and, as a result, models are continuously being improved (Merritt *et al.,* 2003). The growing need for the management of erosion at the catchment scale, as well as the advancement of modelling technologies and expertise, has led to the improvement of process-based sediment modelling over the years, but there is no perfect model (Merritt *et al.,* 2003). Advancing technology has accelerated the capabilities of models to simulate sediment processes realistically and has enabled models to be coupled with other GIS (Merritt *et al.,* 2003) platforms such as ArcMap and Quantum GIS, in the case of the Soil and Water Assessment tool (Le Roux *et al.,* 2015). Coupling models with GIS allows enables flexibility in manipulating, organising and representing data and its attributes (Chen and Mackay; 2004; Xu *et al.,* 2009).

The choice of model should be informed by the ease of model application and the model components, hardware and software requirements, input data requirements including the temporal and spatial scale, the form of the data (sediment yield vs sediment load, for example), as well as the accuracy, precision and validity of data, assumptions and output (Merritt *et al.*, 2003). Moreover, choice of the model that is used depend on the objectives or the questions that need to be answered, in conjunction with the characteristics of the catchment to which these questions need to be addressed (Merritt *et al.*, 2003). There is a diversity of models to choose from and, according to Merritt *et al.* (2003), models differ in complexity, data requirements for calibration and validation as well as the processes that are considered.

Models are classified based on the processes that are simulated, the algorithms the model uses to describe these processes and the data dependence. Fundamental to modelling sediment erosion, models need to be able to simulate surface runoff and transportation processes that are at play in the catchment (Xu *et al.,* 2009). This has led to the development of process-based models (Merritt *et al.*, 2003). The efficiency to which process-based models simulate sediment erosion depends on how hydrologic processes are represented and how the catchment is described (Xu *et al.,* 2009). Process based hydrological models should capture both hillslope and instream processes (Gao, 2008) and account for the spatial and temporal variability of sedimentological and hydrological factors (Jain and Kothyari, 2000). There are two kinds of models that are used to present this variability of sediment processes, namely lumped models, distributed models (Gao, 2008) and semi-distributed models which are a hybrid of the two.

An example of a semi-distributed model is the Soil and Water Assessment Tool (SWAT) (Gassman, 2007; Xu *et al.,* 2009; Arnold *et al.,* 2012a; Arnold *et al.,* 2012b; Le Roux *et al.,* 2013; Le Roux *et al.,* 2015). SWAT simulates sediment, water and chemical fluxes within a variety of spatial conditions (Gassman, 2007; Xu *et al.,* 2009; Arnold *et al.,* 2012a; Arnold *et al.,* 2012b; Le Roux *et al.,* 2013; Le Roux *et al.,* 2015). Its distributed nature enables a catchment that is divided into sub-catchment to be further divided into grid cells of homogeneous combinations (Chen and Mackay, 2004; Arnold *et al.,* 2012a). These are unique of slope, land use and soils and are known as Hydrologic Response Units (HRU) (Gassman, 2007; Xu *et al.,* 2009; Arnold *et al.,* 2012a; Arnold *et al.,* 2012b; Le Roux *et al.,* 2013; Le Roux *et al.,* 2015). As a lumped model, results of each HRU are added together (or lumped together) to provide fluxes for each sub-catchment (Chen and Mackay, 2004; Xu *et al.,* 2009; Le Roux *et al.,* 2013). The SWAT model can be used to model the impact of land management in a complex catchment (Gassman, 2007; Gao, 2008; Xu *et al.,* 2009; Arnold *et al.,* 2012a; Arnold *et al.,* 2012b; Le Roux *et al.,* 2013; Le Roux *et al.,* 2015) because the division of a catchment into homogeneous segments permits the differentiation of conditions within a catchment to be accounted for (Le Roux *et al.*, 2015).

Le Roux *et al.* (2015) used the SWAT model on an ArcGIS interface to investigate the sediment contribution from sheet and rill erosion when they modelled sediment yield in the Mzimvubu River Catchment, within which the present-day study area of interest lies. A well-known issue regarding the SWAT model is under- or overestimation of sediment yield. Both Chen and Mackay (2004) and Le Roux *et al.* (2013) found that the issue is related to the model's inability to account for landscape connectivity. Since all the results from each HRU are lumped to produce sediment yield values for each sub-catchment, SWAT ignores transfer boundaries and assumes that all the sediment that is generated from each HRU reaches the channel. Consequently, landscape disconnectivity is misrepresented as SWAT ignores sink zones, and the effects of deposition on sediment transport processes that exist between an HRU and the channel. This leads to over-estimation of sediment yield. Landscape connectivity is also misrepresented as inputs from sediment sources such as gullies are overlooked (Le Roux *et al.,* 2013; Le Roux *et al.,* 2015). SWAT estimates sediment yield from sheet and rill erosion, thus underestimating sediment contribution from gully erosion (Le Roux *et al.,* 2015).

Le Roux *et al.* (2015) overcame these limitations by integrating the SWAT model with a gully erosion model that they developed. The gully erosion model was based on the gullies that were digitized using SPOT 5 imagery and their subsequent categories (as explained previously). Gully volumes and erosion rates were used to estimate sediment yield. Their research lacked sufficient field data validation and comparison purposes (Le Roux *et al.*, 2008; Le Roux *et al.*, 2015). There is a need to generate field data on sediment yield as well as validating the contribution of the gullies which were the predicted primary sources of sediment in the Mzimvubu River Catchment. Generally, conclusions drawn from these methods is always theoretical as they are based on prediction (Walling, 2005). Thus, it is important to validate modelled data with techniques such as ground truthing and monitoring (Gordon *et al.*, 2004)

2.8 Conclusion

The management of suspended sediment requires sediment quantities to be determined but effective catchment management should include the identification of sediment sources. To do so, suspended sediment dynamics need to be understood. Suspended sediment dynamics can be understood through the lens of sediment connectivity as it illustrates the interdependence of the structural features of the landscape and processes that affect the sediment cascade across variety of space and time. This indicates the transportation of sediment fluxes as well as different sediment sources.

Citizen based sediment flux monitoring and desktop techniques complement each other by overcoming limitations of spatial and temporal resolutions as well as the investigation of suspended sediment flux and the identification of sediment sources in the study area of interest. Previous erosion models have identified areas of the present-day study as vulnerable to high erosion rates, but sediment yield values need to be supported with measured data and sediment sources need to be identified.

2.9 Chapter Summary

Suspended sediment is the most transported particle of sediment. Therefore, the excessive deposition of suspended sediment into water resources, it is important to manage suspended sediment. Critical to the management of suspended sediment is knowledge to the quantity of sediment that is eroded and the provenance of that sediment. This requires knowledge of erosion processes: the detachment, transportation and deposition of sediment.

One of the ways in which erosion processes can be understood is through sediment (dis)connectivity. Sediment (dis)connectivity describes the ease (or the difficulty) of which sediment is transferred between source to sink zones, illustrating the interdependent relationship between the structural component of the landscape (landscape geometry), the erosion processes and anthropogenic factors in a system (the system being the catchment, hillslope or stream). All these components govern sediment flux as they influence soil erosion factors such as rainfall-runoff erosivity, soil erodibility, slope as well as land cover and use. Additionally, suspended sediment flux that is transported in a catchment represents sediment from different locations and sources from the catchment and within the channel. Suspended sediment sources, therefore, can be identified according to their spatial location (the sediment provenance – areas where rehabilitation should be implemented such as geology or land use) and by type (features or processes that rehabilitation should target such as gullies).

The interaction of erosion factors differs across various temporal and spatial scales; therefore, the assessment of suspended sediment should account for spatial and temporal variability. Temporal coverage should ensure that all events that are responsible for sediment transport and the subsequent sediment fluxes and yields are accounted for. Spatial coverage should ensure that all sediment sources are covered as this will influence decision making and the design of strategies for sediment management. There are various methods that can be used to assess suspended sediment and the choice should be based on meeting the objectives for the management of sediment. Methods include the use of citizen-based sediment flux monitoring, analysis of hysteretic loops and desktop studies, all of which can be combined to investigate sediment fluxes and sediment provenances.

Previous erosion studies identified the catchment of interest to have high erosion rate, be vulnerable to gully erosion and contribute high concentrations of suspended sediment to the Tsitsa River. As a result, knowledge of suspended sediment quantities and sources is required if sediment is to be managed in the Tsitsa River.

3 Study Area

The following section provides a description of the catchment in terms of its locality, climate and hydrology, topography, land cover and use, geology and soils, and erosion status for the Inxu River Catchment. This information is used to divide the catchment into the sub-catchments of interest.

3.1 Location

The Inxu River is a tributary of the Tsitsa River, which is itself a main tributary of the Mzimvubu. It is situated between 31^{o}13’39.30” South and 27^{o}56’09.31” on the far West; 31^{o}14’45.81 South and 28^{o}43’52.93” on the far East. The Mzimvubu River is located in the far east of the Eastern Cape and falls under the Tsitsikamma to Mzimvubu Water Management Area 12 (DWA, 2013). The Mzimvubu River is one of the few remaining major rivers in South Africa that has not yet been developed to its full potential in terms of water resource infrastructure (DWA, 2014). It presents opportunities for the development of the economic and social status of the Eastern Cape, one of the least developed and poorest provinces of South Africa (DWA, 2014). The Mzimvubu River has high environmental status and tourism potential and has potential for rainfed and irrigation agriculture as well as afforestation (van Tol *et al.*, 2014). This forms part of the motivation behind the proposed Ntabelanga and Lalini Dam Catchments along the Tsitsa River (van Tol *et al.*, 2014).

The catchment of the Tsitsa River supports the main towns of Maclear and Ugie (Base *et al.*, 2007) and small towns such as Tsolo (van Tol *et al.*, 2014) and Qumbu (Figure 3.1). District municipalities in the area include Joe Gqabi and OR Tambo (DWA, 2014). The Tsitsa River Catchment comprises quaternary catchments T35A-M, as delineated by DWS. This study takes interest in the effective Lalini Dam Catchment (T35E-L) and particularly the Inxu River Catchment (T35F-H and J). The confluence of the Inxu Tributary with the Tsitsa lies between the proposed Ntabelanga and Lalini Dams. With a catchment area of 1 632 km^2, the Inxu River Catchment is the biggest sub-catchment draining towards the Lalini Dam (68% of the Lalini Dam catchment area).

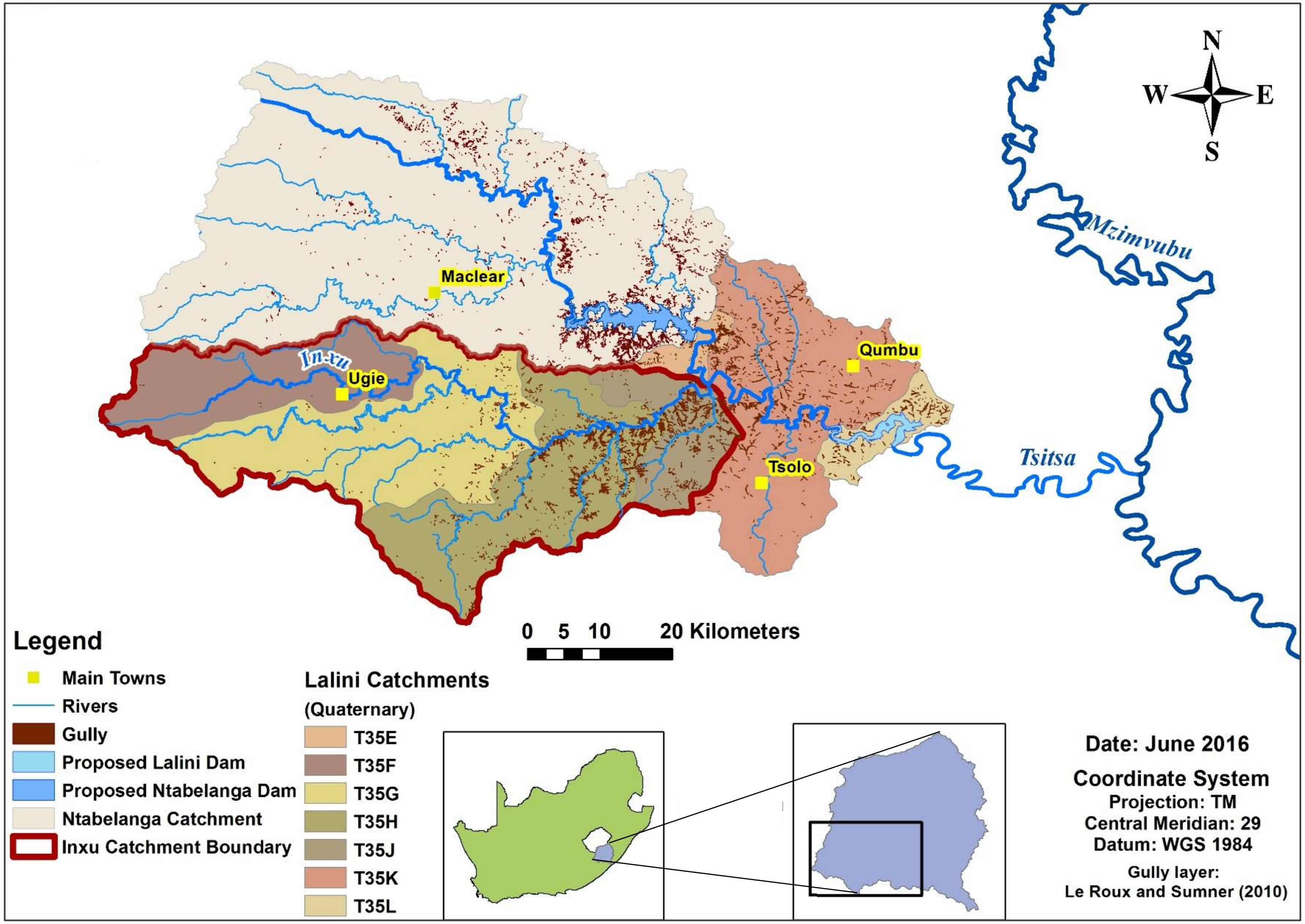


Figure 3.1: Inxu River Catchment locality and the quaternary catchments of the proposed Lalini Dam.

3.2 Climate and Hydrology

The Tsitsa River Catchment is situated in a temperate-subtropical area (Base *et al.,* 2007). It has distinct seasonal rainfall which is received mostly during the summer (van Tol *et al.,* 2014) and particularly between the months of November to March (Base *et al.,* 2007). It has high peak flow and permanent baseflow (van Tol *et al.,* 2014). The nearest DWS rain gauges with long term data are at the Mtata Dam, approximately 2 km to the south of the Inxu River Catchment, straight-line distance. The data showed that Mtata Dam received a mean annual precipitation (MAP) of 670 mm in 1954 – 2014 (Drewitt, 2015). The rain gauge at Maclear is approximately 17 km to the north of the Inxu River Catchment, straight-line distance, had an average of 823.7 mm between 1978 and 2012, ranging between 502 and 1143 mm (Moore, 2016). Figure 3.2 shows the locations of the rain gauges that were installed across the Inxu River Catchment during the period of study, 27 May 2016 – 07 May 2017. Figures 3.3-4 show the hourly rainfall from each rain gauge during this period while table 3.1 provides a summary of the amount of rainfall recorded by each rain gauge. The number of events (n) when rainfall was greater than 10 mm per hour is also shown in the table as this indicates rainfall erosivity (Moore, 2016).

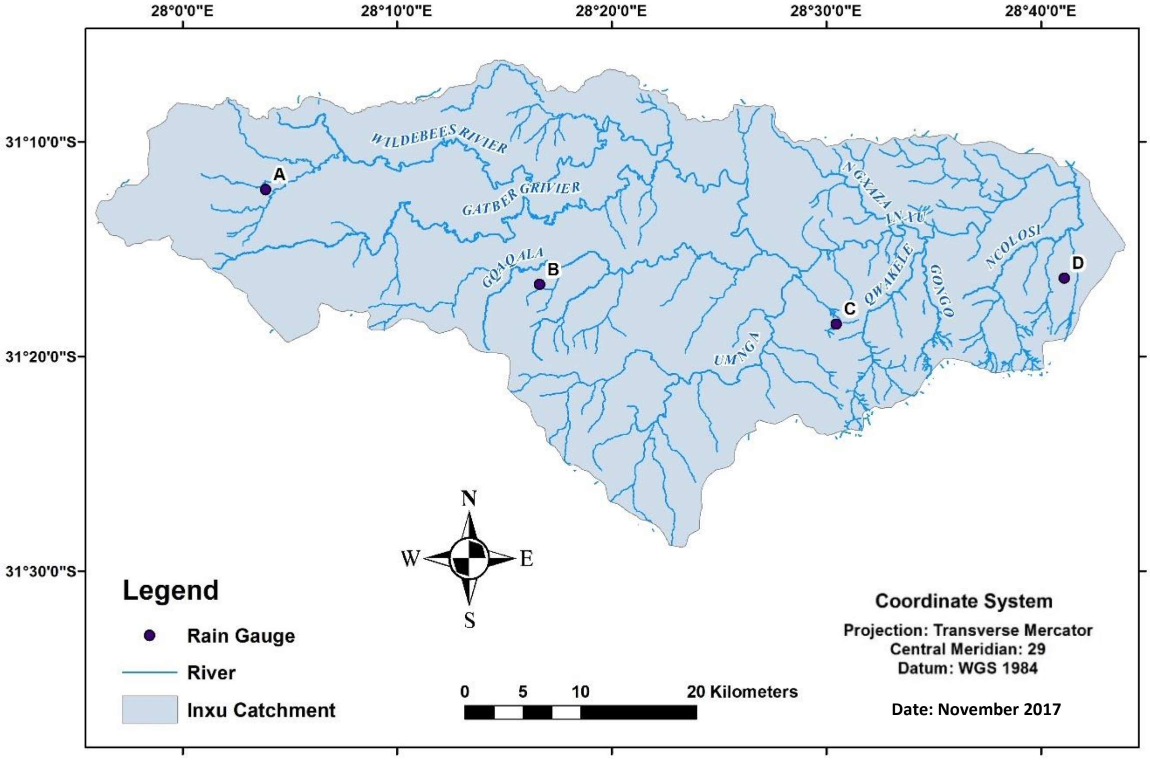


Figure 3.2: Location of rain gauges across the Inxu River Catchment

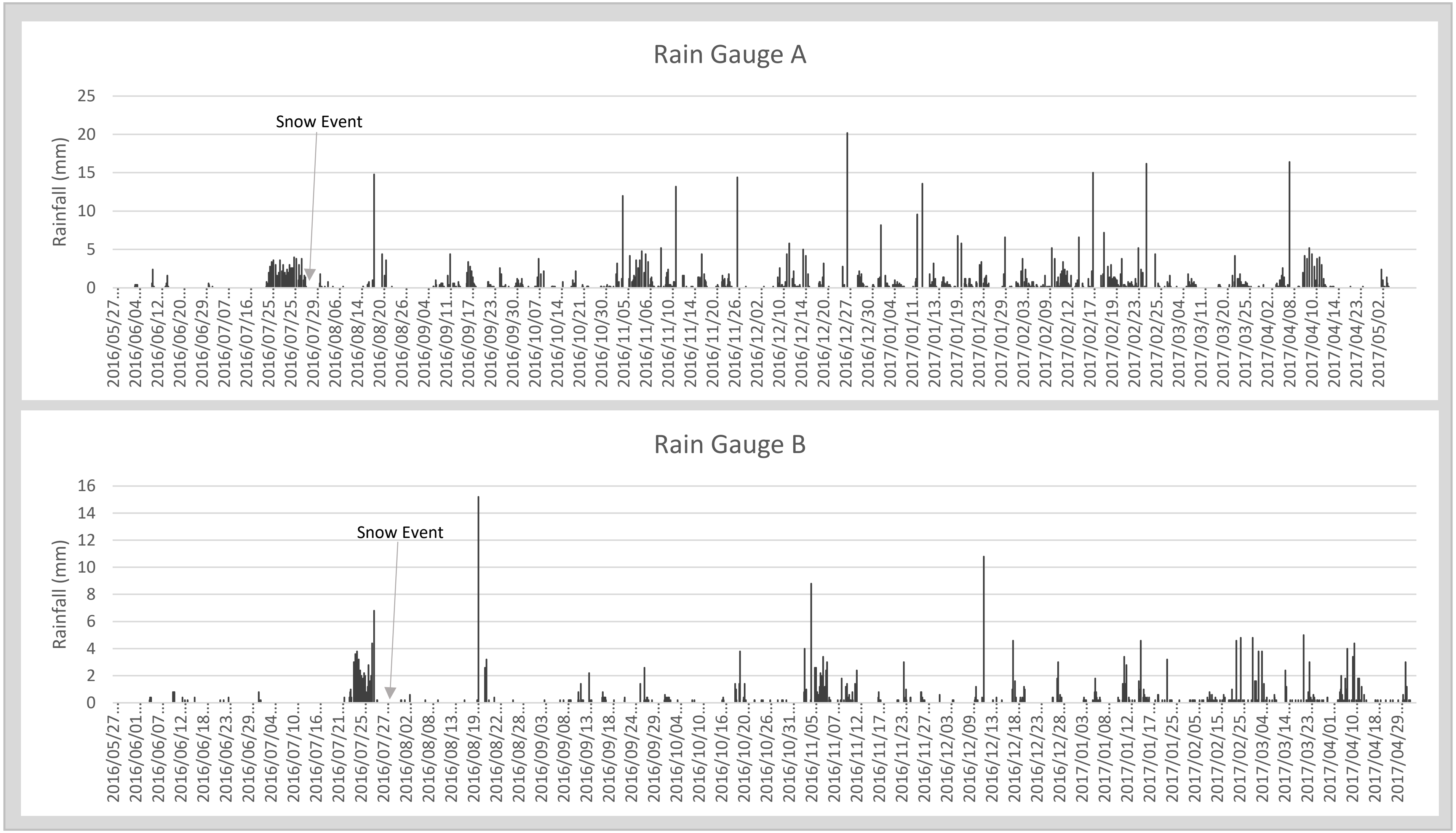


Figure 3.3: Hourly rainfall for rain gauge A and B

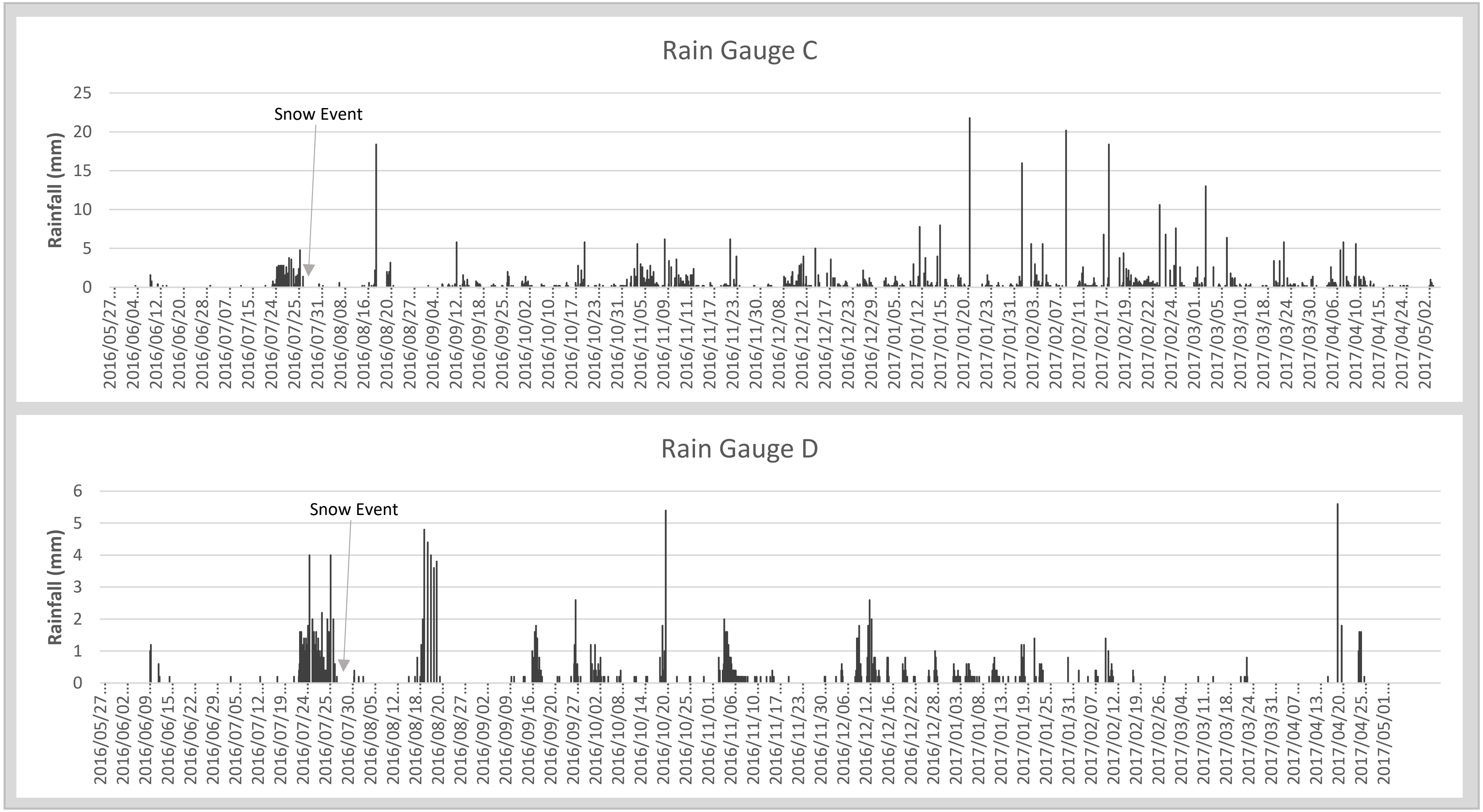


Figure 3.4: Hourly rainfall for rain gauge C and D

Table 3.1: Summary of Rainfall Data on 27 May 2016 - 07 May 2017 from Rain Gauges Across the Inxu River Catchment.

Rain Gauge	Total Rainfall, mm	n ≥ 10 mm	Possible error present in measurement (see reasons for error in the text below)
A	788	9	No
B	350	2	Yes
C	680	7	No
D	214	0	Yes

During the period of study, the Inxu River Catchment received 508 mm of rainfall, which was below average year rainfall based on long-term data from both the Mtata and Maclear rain gauges (670 mm and 824 mm respectively) and indicates a dryer than usual hydrological year for this catchment. In her study of the area of the Tsitsa River Catchment that is upstream of the Tsitsa's confluence with the Inxu River, Moore (2016) noted that below average rainfall during this period was influenced by the 2015/2016 El Niño-Southern Oscillation (ENSO) event. The decrease in rainfall over the study area could be associated with the El Niño event as the El Niño event (the warming of surface temperature) (WMO, 2014).

A snow event that occurred around 27 July 2016. According to Munica and Rutherford (2006) snow can be expected in the upper catchment as snow falls regularly in areas of high altitude on the Drakensberg Mountain, where this catchment lies. Snow may occur less frequently in the lower catchment, when compared to the upper catchment.

Rainfall in the Inxu River Catchment followed a downward trend from the upstream to downstream direction. Most of the rain was received in the head-water areas of the Inxu River, measured by rain gauge A, and the least rainfall near the outlet, measured by rain gauge D. Though the rain gauges were installed on similar altitude, the variation in rainfall recorded by each rain gauge may be influenced by topographic variability as rain gauges A and C were installed at mountain tops and had higher rainfall compared to rain gauges B and D which were situated at the foot of the mountain.

Variation may have also occurred as a consequence of issues that were found in rain gauges B and D. On 15 January 2017, the pole that rain gauge B rests on was found to be tilted. The pole was straightened after the observation. On 05 May 2017, rain gauge D was found to be blocked by a spider web and dust. Rainfall may have not been recorded correctly for an unknown period for these rain gauges since the time when the rain gauges were last checked.

3.3 Topography

According to Base *et al.* (2007), the catchment of the Tsitsa River is situated on the south-eastern slopes of the Great Escarpment, with an altitude range of 783-2700 m asl. Its landscape is dominated by plateaux and hills, where headwaters are made up of steep slopes and floodplains are narrow. The Inxu River Catchment has two escarpments, one in the headwater areas and one separating the upper and the lower Inxu River Catchment (Figure 3.5). As a result, the Inxu River Catchment has a mix of steep and gentle slopes. The head waters are dominated by steep slopes draining towards gentle slopes in the mid-section, and again, steep slopes draining into gentle slopes towards the outlet of the Inxu River.

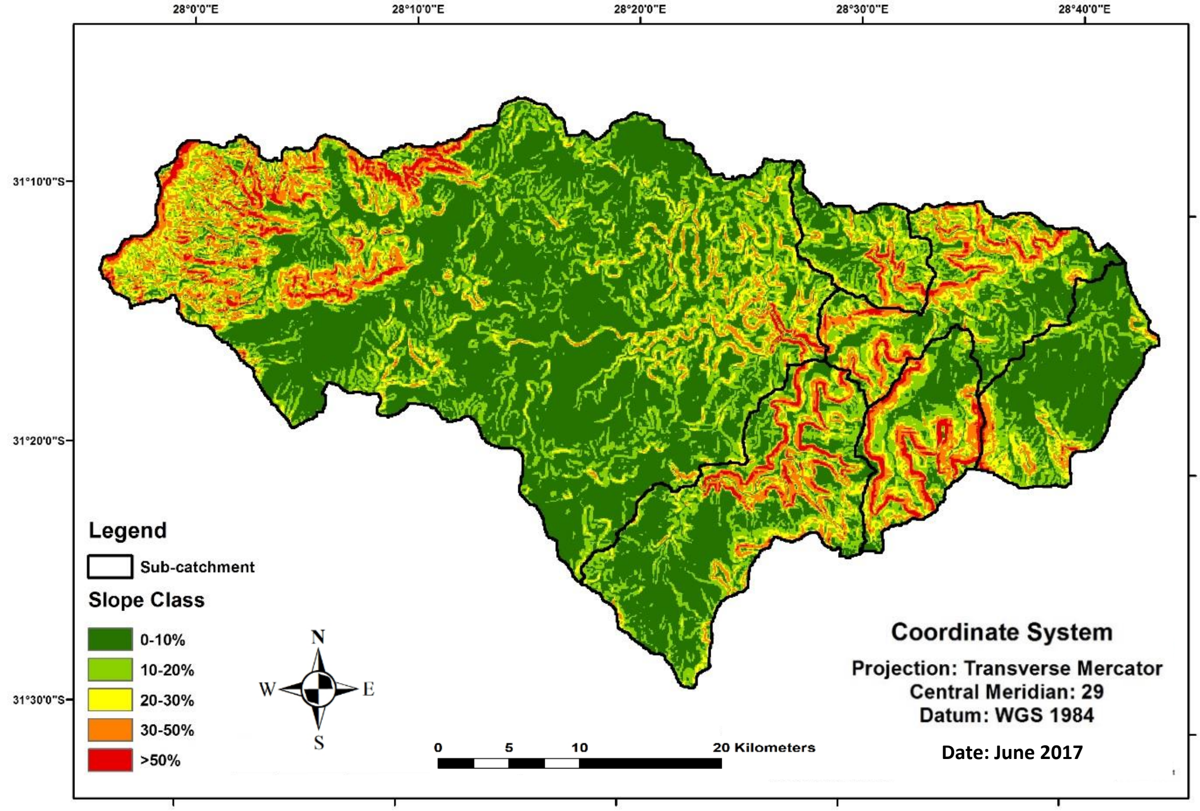


Figure 3.5: Inxu River Catchment topography based on slope class.

3.4 Geology and Soils

The Tsitsa River Catchment is characterised by Triassic sediments of the Karoo Supergroup (Base *et al.,* 2007) (Figure 3.7). These comprise sandstone and mudstone of the Elliot, Molteno, and Tarkastad (Beaufort Group) Formations, with layers of siltstone and carboniferous shales (Base *et al.,* 2007). They are intruded by sills and dykes of Jurassic dolerite that has aquiclude properties, making it more resistant to erosion relative to the hosting Karoo lithology. Fine-grained sandstone and siltstone of the Clarens Formation form the uppermost Triassic Formation, overlain by Jurassic Drakensberg basaltic lava (Le Roux *et al.,* 2015).

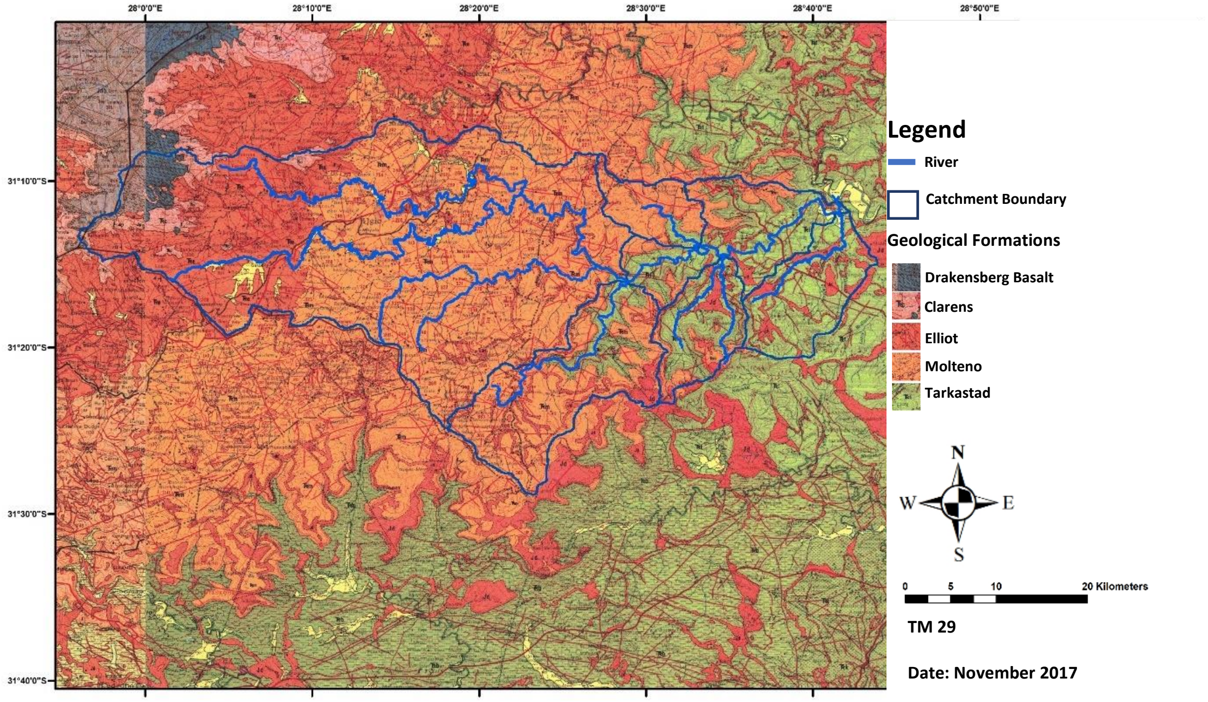


Figure 3.6: Geology Map of the Inxu River Catchment

According to Land Type Survey Staff (1972-2006), the most prevalant and broad land types for the Inxu River Catchment include A, D, E and F land types. Of these land types, the Db and Fa soils are the most erodible (Land Type Survey Staff, 1972-2006; van Tol *et al.,* 2014); van Tol *et al.* (2014) found Ab soils in the Tsitsa River Catchment were in areas of high erosion (Figure 3.8).

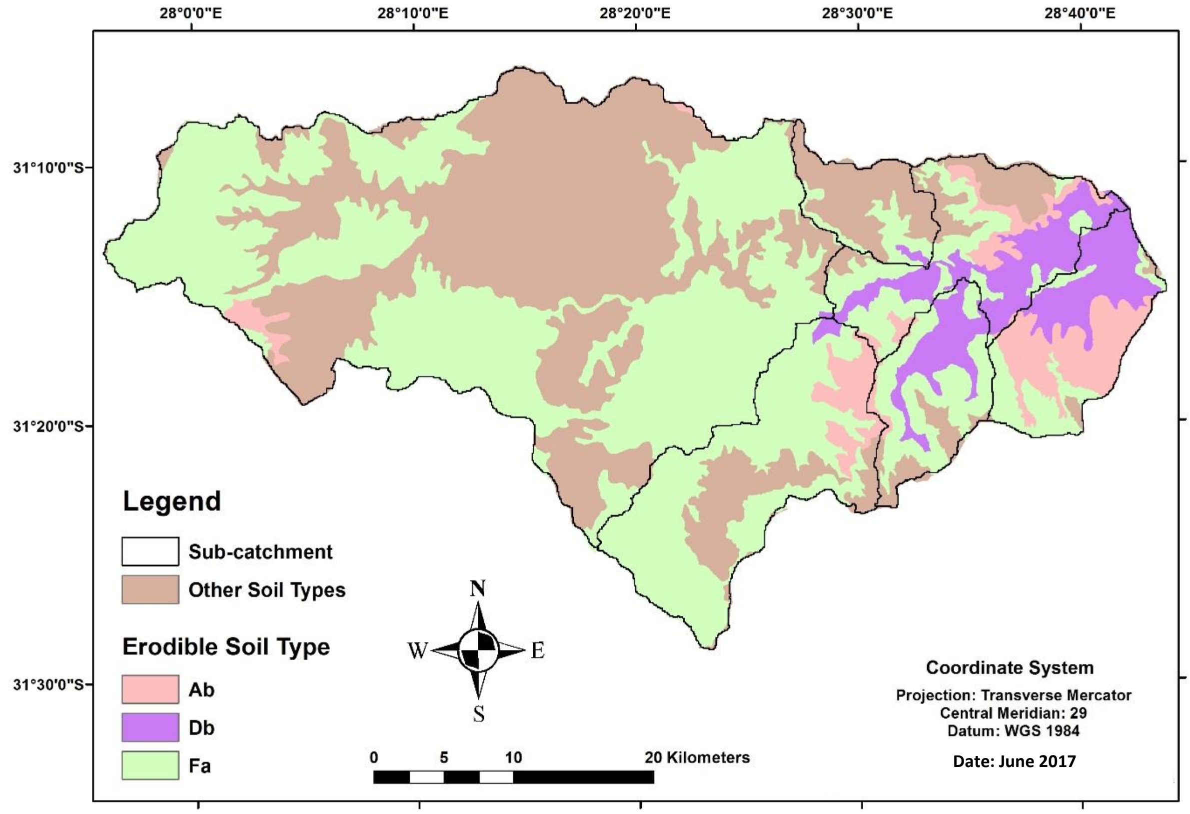


Figure 3.7: Inxu River Catchment broad soil types (Le Roux *et al.*, 2015).

Below is a description of the erodible land types, according to Land Type Survey Staff (1972-2006) and van Tol *et al.* (2014).

A-land types are soils that are suitable for crop production and irrigation. They contain freely drained red and yellow dystrophic and mesotrophic soils. This suggests that they do not remain saturated for extended periods; therefore, they are not easily erodible. However, van Tol *et al.* (2014) found that some of the areas where Ab soils that were found across the Tsitsa River Catchment were on old cultivated land which was vulnerable to high erosion rates due to the disruption of soil structure from cultivation and removal of natural vegetation.

D-land types are dominated by duplex soils. They are characterised by contrasting A and B horizons with significantly finer soils found in the B horizon. In other words, they have a marked difference from top to sub-surface soils in terms of soil structure, texture and consistence, due to the increase in clay content from surface to sub-surface soils (Le Roux and Sumner, 2012). Duplex soils are highly erodible soils because the clay soils are rich in sodium which gives them a dispersive nature. These dispersive soils result in surface crusting which reduces infiltration and increases runoff (Fey *et* *al.,*2010) and have a high propensity for tunnel erosion and piping (Le Roux and Sumner, 2012). According to Le Roux and Sumner (2012), where duplex soils are found, a permeable horizon overlies an impermeable one. Once the permeable horizon is saturated, water moves as sub-surface flow, forming tunnels and pipes. Once the roof of the tunnel collapses, gullies occur. Duplex soils have a shallow topsoil which limits agricultural productivity (van Tol *et al.,* 2014).

F-land types are shallow, often representing young landscapes, and occur on relatively steep slopes. The combination of shallow depth and steep slopes prevent crop production on Fa soils and increases their susceptibility to erosion. Due to these conditions, these soils are easily erodible and are subject to weathering.

3.5 The Erosion Status of the Inxu River Catchment

The Elliot and Tarkastad Formations have been associated with the highly erodible duplex soils that have widespread gully erosion (Le Roux *et al.,* 2015). Previously, erosion potential (Le Roux *et al.,* 2008) and sediment yield (Le Roux *et al.,* 2015) have been modelled at national and regional scale, respectively. According to Le Roux *et al.* (2008), large parts of the Tsitsa River Catchment have the highest erosion potential in the country, being classified as extremely high. Gullies are prevalent where erosion has been classified as extremely high.

Le Roux *et al.* (2015) simulated sediment yield for the Mzimvubu River Catchment for 2008-2012 using the SWAT Model (which simulates sheet-rill erosion) as well as the Gully Model (which was developed during their study to simulate gully erosion). When the gully and SWAT models were integrated, results indicated that the quaternary catchment T35J had the third largest sediment yield in the Mzimvubu River Catchment, which came up to 20.4 t/ha/yr (Le Roux *et al.,* 2015) (Figure 3.9). Additionally, their results showed that sediment yield decreases in the upstream direction and most of the sediment is contributed by the gullies, when compared to sheet-rill erosion.

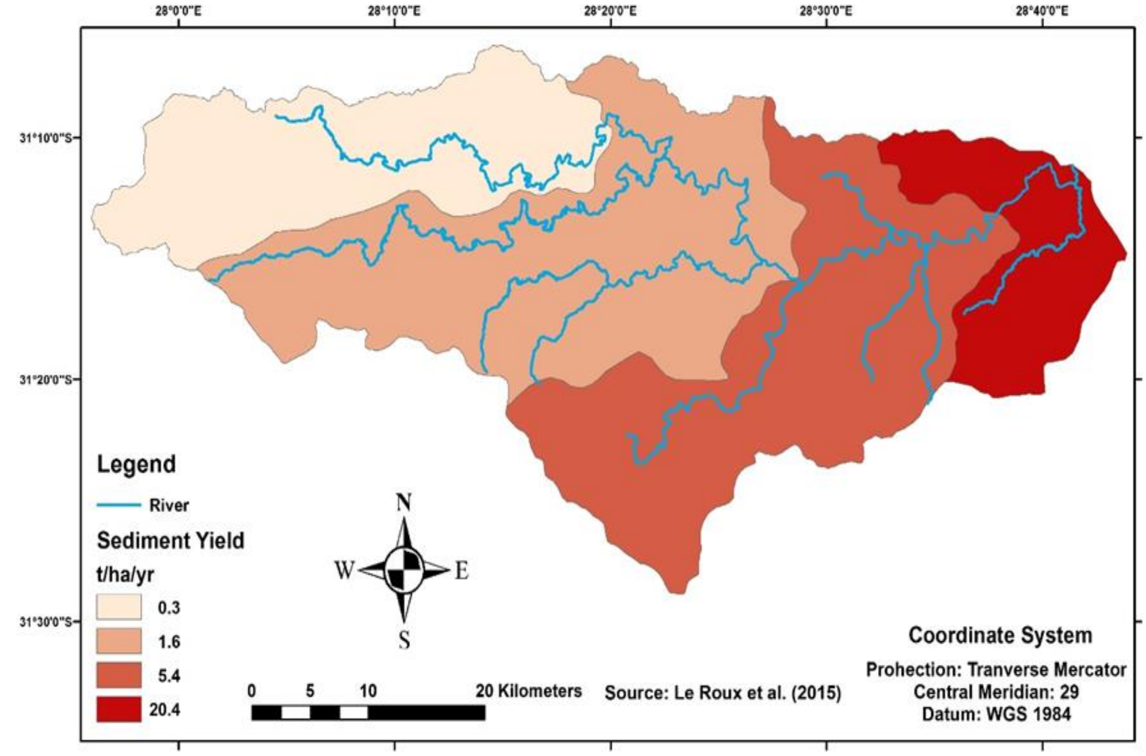


Figure 3.8: Sediment yield results (Le Roux *et al.*, 2015)

3.6 Land Cover and Use

National Land Cover (2012) reveals that the Inxu River Catchment vegetation is made up of, largely, grassland and, to a lesser extent, thicket (Figure 3.6). The Land Cover Map reveals that large wetlands dominate the upper catchment. This is also where most plantations are situated. The upper catchment is also used for commercial farming. The lower catchment is dominated by densely settled rural homelands under the communal tenure system where most of the land is used for subsistence farming. A small area of the catchment downstream is used for plantations. Sand mining was observed during the dry season in the rivers of the lower catchment.

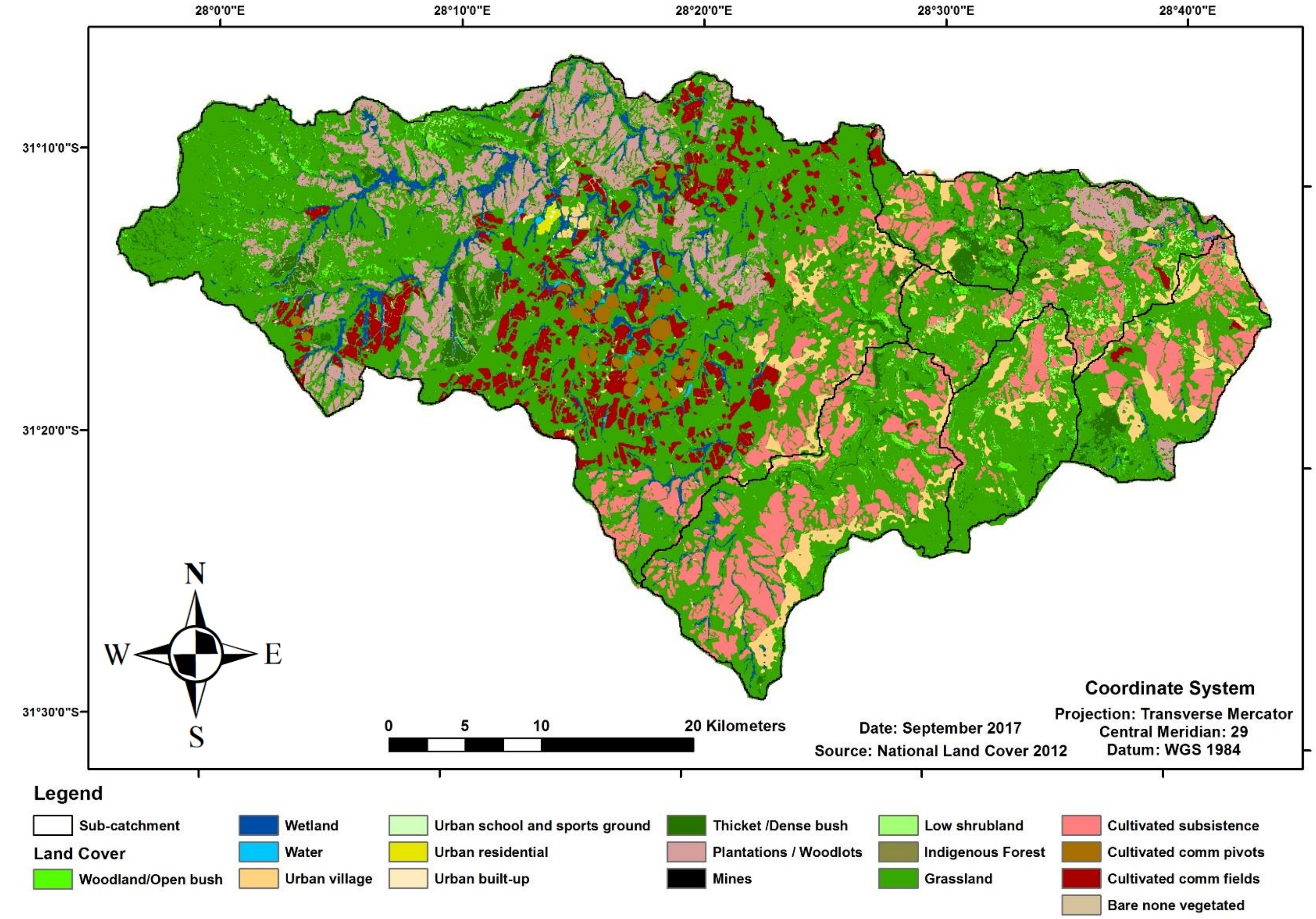


Figure 3.9: Land cover Map for the Inxu River Catchment (National Land Cover, 2014)

3.7 Chapter Summary

The Inxu River is a tributary of the Tsitsa River, a major river of the Mzimvubu River Catchment in the far east of the Eastern Cape. The Inxu River Catchment is the biggest sub-catchment of the Tsitsa, has high erosion rates and is heavily gullied.

During the period of study, the Inxu River Catchment received rainfall that was below the MAP, as derived from the 1954 – 2014 rainfall data, obtained from the Umtata Dam rain gauge. This study signified a dry hydrological year which could have been caused by the 2016/2017 ENSO event. Additionally, headwater areas of the catchment received heavier or more frequent rains while the lower area received a smaller amount, although this variation is related to topographic variability. The Inxu River Catchment has two escarpments, one in the headwater area and the other separating the upper and lower catchment.

The upper catchment is used for commercial faming and plantation forestry while the lower catchment is used for subsistence farming in areas under communal tenure systems. The vegetation of the Inxu River Catchment is predominantly grassland, with small areas of thicket. The soils in the catchment are primarily derived from sandstone and mudstone from the Tarkastad, Elliot and Molteno Formations. They are dominated by erodible soils. Shallow, easily weathered soils are found on the steep slopes. Duplex soils, which contain highly dispersive clay soils, are found in the lower catchment on lower slopes.

4 Methods

This chapter outlines the procedures that were followed to determine suspended sediment yield for the Inxu River Catchment, the suspended sediment contribution from the sub-catchments, as well as the identification of sediment sources. This was achieved by describing the process that was followed in selecting monitoring sites (4.1), sediment sample collection and analysis (4.2), discharge data collection and analysis (4.3), the two-step method followed to assess the amount of sediment from each site (4.4) and sediment sourcing (4.5).

4.1 Selection of Monitoring Points

Suspended sediment from the Inxu River Catchment Outlet has been monitored since December 2015 from ongoing sediment studies (Bannatyne *et al.,* 2017). This study observed suspended sediment dynamics between 01 May 2016 and 30 April 2017, following the establishment of additional monitoring points across the Inxu River Catchment between 1-5 May 2016 that were based on major sub-catchments of the Inxu River. The selection of monitoring points between the upper and lower Inxu River Catchment was based on land use and major sub-catchment and catchment size. Further selection (Table 4.1) was based on the geology, land cover and use, gully prevalence and erosion potential (Le Roux *et al.,* 2008), as well as the proximity and accessibility of the tributary to the residents (referred to as technicians) who were employed to collect suspended sediment samples. The monitoring point where a technician collected the sediment samples could not be more than 500 m from the home of that technician. Further motivation for the selection of sampling points included preliminary suspended sediment contribution studies that were conducted in the catchment on 23 January 2016.

Table 4.1: Prioritisation system for establishing the monitoring network in the Inxu River Catchment for high priority sub-catchments (refer to Figure 4.1 for the location of point numbers).

Site Number	River	Catchment area (km^2)	Geology	Land Use	Land Cover	Gully Prevalence	Erosion Potential (Le Roux *et al.*, 2008)	Proximity to Monitoring Point	Preliminary Results
1	**Umnga**	213	Tarkastad Formation and the upper area is dominated by the Molteno Formation	Rural Residential, Subsistence Farming.	Predominantly Grassland and some areas of Thicket and Woodland.	Medium	High	< 500 m from sampling point	Preliminary results = 382 NTU.
2	**Inxu Upstream**	973	Molteno and Elliot Formations, Drakensberg Basalts	Urban Residential, Commercial farming, Forest Plantation	Dominated by Grassland and Wetlands, cropland and forest plantations	Medium	Moderate	< 500 m from sampling point	Preliminary results = 80 NTU.
3	**Ngxaza**	59	Tarkastad Formation and the upstream area is dominated by the Molteno Formation.	Rural Residential, Subsistence Farming.	Forest, Woodland and Grassland.	Low	High	< 500 m from sampling point	Preliminary results = 1760 NTU.
4	**Qwakele**	89	Tarkastad in the lower regions, some areas with the Molteno Formation in the upper region; dolerite intrusions	Rural Residential, Subsistence Farming	Grassland	High	High	< 500 m from sampling point	Preliminary results = 870 NTU.
5	**Ncolosi**	114	Overlain with alluvium close to the outlet, dominated by Tarkastad Formation; dolerite intrusions	Rural Residential, Subsistence Farming.	Grassland, a few Wetlands and some Wood Plantation	High	Moderate	< 500 m from sampling point	No preliminary results
6	**Inxu (Description for the area near the outlet)**	1632	Tarkastad Formation and some alluvium deposits.	The area near the outlet is dominated by Rural Residential and some Subsistence Farming activities.	The area near the outlet is dominated by Grassland	Medium	Low	Already existing technician < 500 m from sampling point	No preliminary results

Financial resources and logistical limitations restricted monitoring to five sites established across the Inxu River Catchment in addition to the Inxu River Catchment Outlet monitoring point. This study, therefore, had a total of six monitoring sites in the Inxu River Catchment (Figure 4.1).

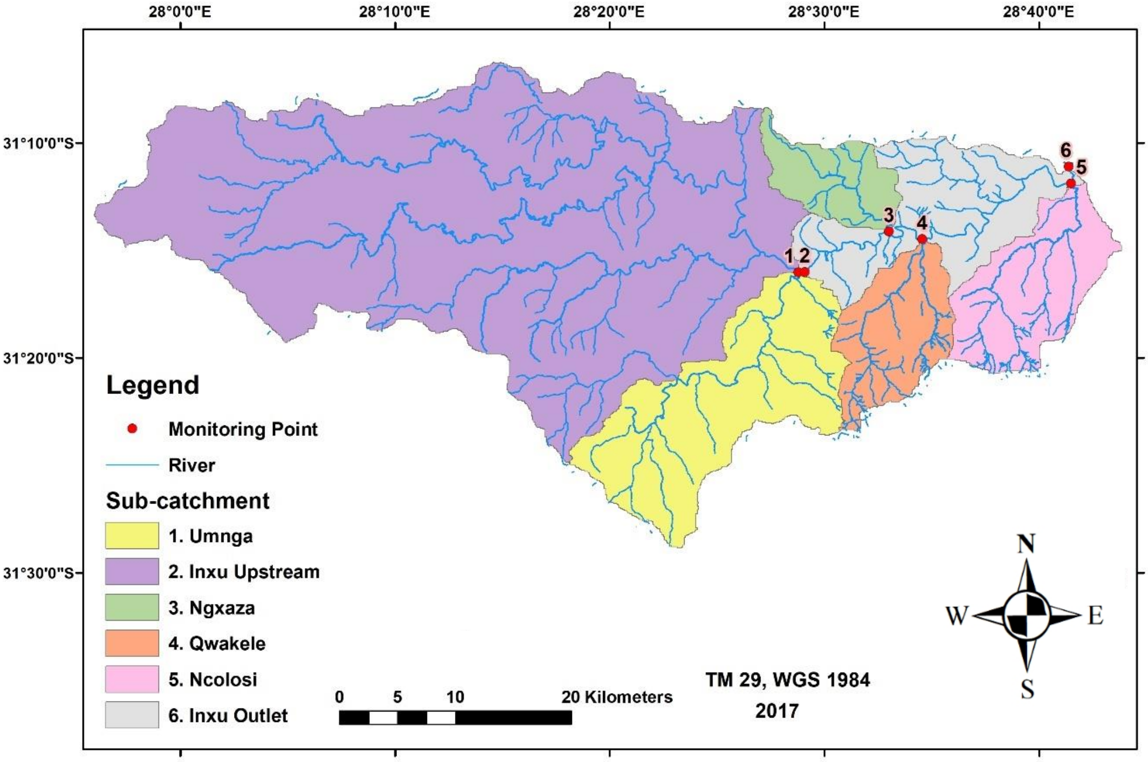


Figure 4.1: Inxu River Catchment suspended sediment flux monitoring points.

To determine the suspended sediment contribution from the Inxu to the Tsitsa River (objective 1), samples were collected at the Inxu River Catchment Outlet (sampling point 6). To determine the quantity of suspended sediment that is generated by the major Inxu River Sub-catchments individually (objective 2), the same sampling strategies and analysis were applied for monitoring points established near the outlets of the Umnga (1), Ngxaza (3), Qwakele (4) and Ncolosi (5) sub-catchments, as well as one monitoring point at the most upstream point along the Inxu River (2).

The furthest monitoring point upstream of the Inxu River (referred to as Inxu Upstream) was situated downstream of the Umnga and Inxu confluence due to the non-availability of technicians upstream of the confluence. Preliminary sampling showed that very little sediment was contributed by the upper Inxu River Catchment, upstream of the Umnga River. The upper catchment is dominated by grassland, croplands, commercial forestry and has large wetlands that trap sediment. The upper Inxu monitoring point is, therefore, comprised of sediment from Umnga, Gqaqala, Gatberg and Wildebees major tributaries. The load carried by the upper Inxu River was to be calculated as the difference between the loads carried by the Inxu and Umnga Rivers.

4.2 Training Technicians

The citizen-based sediment flux monitoring technique that was used in this research was the prescribed monitoring method devised by Bannatyne *et al.* (2017). Technicians who were responsible for collecting sediment samples were employed from August 2016 to November 2016, after consultation with traditional leaders. The chief who had jurisdiction over the monitoring area of interest allocated headmen to recommend people in their communities who met basic requirements to be considered as technicians. Basic requirements included unemployment and availability, ease of mobility to and from the monitoring site and, given that the form was written in English, the technician needed ability to read and understand instruction in English.

Recommended candidates were tested for their ability to:

1. Count and write numbers when they began to count from 15 and end at 20;
2. Calculate time intervals;
3. Count the total number of samples that would have been collected during the time interval in point 2 above.

These were critical skills for the job. After explaining the terms and conditions of the job to successful candidates, equipment that was needed to collect samples (explained in the following section) along with details of attribute data to be collected for each sample (Appendix 1) was provided and training was conducted.

Training involved teaching data collection methods and demonstrating safety measures to be observed while collecting a sample. This included the use of life-jackets, how to record attribute data for each sample using the Open Data Kit (ODK) application on the smartphone that was provided to the technician, as well as the time and the method used for collecting sediment samples. The efficiency of each technician was ensured by performing several demonstrations:

Training day

- The process of collecting samples was demonstrated away from the sampling point while the technician was being introduced to the method;
- Another demonstration was performed at the designated sampling point where the technician was required to collect several samples.

Post-Training Evaluation

- For further evaluation, technicians were required to demonstrate how they had been collecting samples during the field trips in November 2016 and February 2017.

4.3 Suspended Sediment Concentration

The following sub-sections will describe the procedures that were followed to collect and analyse suspended sediment (SS) samples.

4.3.1 Sample Collection

Although suspended sediment (SS) samples have been collected from December 2015 at the Inxu River Outlet, this study made use of the samples that were collected from 01 May 2016 up to 30 April 2017, to give a full year of data. Suspended sediment samples from the Inxu River Sub-catchments were collected from 19 September 2016. The sampling strategy that was used in this research was the prescribed monitoring method devised by Bannatyne *et al.* (2017).

Samples were collected by technicians at a sub-daily time-step over base flow conditions and twenty times over a flood event. Technicians were encouraged to observe the water level of the river throughout the day as their trigger for flood samples was a rapid rise in water level. The technician collected flood samples when the water level rose and fell over time. Since flood events transport a major amount of sediment (Gordon *et al.,* 2004), the purpose of the sampling frequency used during flood events was to ensure that changes in suspended sediment concentration over the rising and the falling limb of the stream hydrograph were captured, and hysteretic effects were accounted for. Fewer samples are needed during base flow conditions as sample concentrations are less variable (Gordon *et al.,* 2004). As a result, calendar (for base flow conditions) and event based (for flood events) sampling strategies were applied to improve the level at which data was representative. Furthermore, three replicated samples were collected on Thursday mornings from all sampling points to measure sediment concentration for samples that contain low concentrations of sediment.

In addition to the samples that were collected by the technicians, the researcher also collected point samples once a month during field trips using the same technique. Point samples were collected in areas where there was good mixing of sediment. Discharge measurements were also taken (4.4.1). Field trips by the researcher tended to occur during base flow conditions as floods were short-lived events.

All samples were collected using a hand-held isokinetic depth-integrating sampler of 400 mL capacity, attached to a pole (Gordon *et al.* 2004). The pole was lowered into the water with the nozzle facing the direction of oncoming water (Figure 4.2).

Figure 4.2: Depth-integrating sampling pole with a sample bottle attached

According to Gordon *et al.* (2004), the design of an isokinetic depth-integrated sampler allows for the velocity at which a sample was collected to be the same as the velocity of the stream. This would best imitate the sediment load for each stream as the amount of suspended sediment entering through the nozzle is the same as the amount of sediment that is transported by water over time. This was accounted for as the sampling pole was lowered and raised through the water column, which also provided continuous extraction of the sample. As a result, a depth integrated sample was collected over the vertical, as it accounted for the different velocities and sediment concentrations with changes in depth. Water purification pills (17 mg Sodium dichloroisocynurate - NaDCC) were added to the sample immediately after it had been collected to prevent changes in turbidity due to algae growth in the sediment sample prior to lab processes.

Attribute data for each sample was recorded by the technician at the site using the Open Data Kit application through a smartphone. Attribute data required technicians to make observations on the weather, rainfall intensity and snow, river level and its visual clarity, the location from which the sample was collected, and whether it was a base flow, flood and/or repeat sample. Global Positioning System tagged photos of the river were taken to support attribute data, while photographs of the sample(s) were also taken at the site at the time of sampling. Field notebooks were used to record the same attribute data as a backup.

Data collection for the Qwakele, Inxu Upstream and Umnga River monitoring points was inconsistent as technicians from those sites stopped collecting samples either for personal reasons or in pursuit of other interests. The searching and training of technicians was ongoing at these monitoring points until the study reached its completion. As a result, fewer samples were collected from these monitoring points compared to the total number of samples collected from the Inxu River Catchment Outlet, Ncolosi and Ngxaza River monitoring points (Table 4.2). The technician from the Umnga River missed all the flood events.

Table.4.2: The number of samples from each monitoring point

Monitoring Site	Sampling Dates	Total Number of samples	Base flow Samples	Flood Samples
Inxu River Outlet	01/05/2015 – 03/05/ 2017	982	745	237
Ncolosi	20/09/2016 – 30/04/2017	527	476	51
Qwakele	20/09/2016 – 24/03/2017	264	165	99
Ngxaza	20/09/2016 – 02/05/2017	648	388	260
Inxu Upstream	21/09/2016 – 31/03/2017	164	142	22
Umnga	21/09/2016 – 02/05/2017	285	285	0

Due to the lack of consistency in sample collection from half the monitoring points, only SS samples that were collected over the same time periods were analysed in this study (for example, base flow samples that were collected in the afternoon on the same day from all monitoring points across the catchment). This amounted to a total of 61 samples from each site, collected over base flow conditions on 21 October 2016 – 12 January 2017 and flood events that occurred on 06-12 November 2016.

4.3.2 Sample Analysis

The following section explains the procedures for sample analysis for high suspended sediment concentrations and low suspended sediment concentrations.

4.3.2.1 High Suspended Sediment Concentrations

A preferred method to measure suspended sediment is the filtration method, as it is sensitive to the volume of sediment concentration, according to Gordon *et al.* (2004). However, Bannatyne *et al.* (2017), working in the Tsitsa River, found that sediment concentration results from the filtration method had low confidence: the particle sizes were finer than filter paper pore size, the process of transferring and filtering had high potential for inaccuracy, filter paper was at risk of cross-contamination while being dried, and the filtration method was unfavourable because it took extended periods of time to process samples. To overcome these issues, the evaporation method was used for measuring sediment concentration. Moreover, because this study is a continuation from on-going research, the evaporation method was used for SSC analysis for data comparability purposes.

Samples were left in the lab for a month for suspended sediment to settle at the bottom of the sampling bottle. The total weight of the bottle containing sediment and water was determined by weighing each sample to two decimal places. Clear water from the sample, which was in the upper 80% of the bottle, was decanted up to a level above the sediment using a suction system with a J-tube that is connected to a pump. The remaining water was evaporated in an oven at 60 ° C for 72 hours until the bottle and the sediment were dry. Once the sample bottle was dry (at which point it would contain only sediment), it was weighed to four decimal places. The difference between the full jar and the dried jar containing sediment gave the volume of water in the bottle (V_w). After the dried jar with sediment was weighed, sediment was washed from the sample bottle, and the bottle was oven dried and weighed empty to four decimal places. The difference between the empty jar and the dried jar with sediment gave the weight of the sediment in the bottle (w_{ss}). Suspended sediment concentration (SSC) was calculated as the ratio of V_w and w_{ss} (Equation 1).

$$SSC = \frac{w_{ss}}{V_w} \qquad \text{(Equation 1)}$$

Where SSC = Suspended sediment concentration (mg/L), w_{ss} =weight of suspended sediment (mg), V_w = Volume of the water in the bottle (L).

4.3.2.2 Low Suspended Sediment Concentrations

It was assumed that the higher the suspended sediment concentrations in water, the lower the transparency of water (Gordon *et al.,* 2004). Thus, turbidity was used as a surrogate to measure suspended sediment for samples with low SSC because low SSC, normally coincident with low discharge, does not make a large difference to the calculation of the total sediment yield (Gordon *et al.,* 2004). Bannatyne *et al.* (2017) also found an error in SSC measurements when samples that had a turbidity measurement below 200 NTU were processed through evaporation.

Turbidity is the optical property that influences how water absorbs or scatters light; hence it is the measure of how much light is transmitted by water (Gordon *et al.,* 2004). Turbidity is, however, affected by the physical properties of suspended sediment such as particle size, and water characteristics such as water colour (Gordon *et al.,* 2004; Nadal-Romero and Regüés, 2010). Therefore, the relationship between turbidity and suspended sediment is complex and varies depending on the influence of sediment and water properties (Nadal-Romero and Regüés, 2010). According to Zabaleta *et al.* (2007), the relationship is site – and, to some degree, time – specific, which is why it is important to observe the relationship for each site individually.

Using the Thursday morning replicate samples, as well as every tenth base flow sample, the relationship between turbidity and measured suspended sediment concentrations was used to develop a Turbidity-SSC standard curve for each site. This standard curve was used to infer suspended sediment concentration for samples whose turbidity was below 200 NTU, contained low quantities of suspended sediment (Zabaleta *et al.,* 2007) and therefore could not be processed through the evaporation method. The turbidity readings were taken using a UTech TN-100 Turbidity Meter.

Bannatyne *et al.* (2017) showed that dissolved solutes in the Inxu River were not a significant component of the load, so electronic conductivity was not measured for each sample from the Inxu River Sub-catchments. Following the measurement of turbidity from the chosen base flow samples and the replicate samples, suspended sediment concentration was determined through the outlined evaporation method. (Results for the Turbidity-SSC relationships for each site are shown in Appendix 2).

4.4 Discharge Measurements

The following section describes the procedure that was followed to collect and analyse discharge measurements from all monitoring points across the Inxu River Catchment.

4.4.1 Discharge Data Collection

At each monitoring point, Solinst pressure transducers (referred to as level loggers) were installed to capture continuous data on changes water depth above the level logger at 20-minute intervals. They were installed on exposed bedrock that remained under water during base flow conditions. Barometric data from a barometer that was installed near the Inxu River Catchment Outlet was used to compensate the levels measured by the level logger for changes in air pressure.

Cross-sections of the channel where the level loggers were installed and where floods were intended to be measured were surveyed to provide the information required to estimate discharge using the slope-area method. The slope-area method is commonly used to indirectly estimate discharge at various water levels through Manning's equation (Equation 2) as it best describes surface flow (Gordon *et al.,* 2004). Site-specific cross-sections as well as Manning's values are provided in Appendix 3.

$$Q = \frac{1}{n} A. R^{2/3}. S^{1/2} \qquad \textit{Equation 2}$$

Where Q *= Discharge (*m^3s^{-1}*),* n*= Manning's Roughness Coefficient,* A*= Cross-Sectional Area (*m^2*),* R*= Hydraulic radius (m) and* S*= Slope.*

The slope was measured by surveying a traverse where the surface and the bed slopes were parallel. Manning's Roughness Coefficient values were estimated as suggested by Gordon *et al.* (2004: 102). Discharge (Q) was manually measured at one fixed cross section per site, in areas that had uniform flow conditions, using the velocity-area method. The channel width perpendicular to the flow was divided into 20 sub-sections where the water depth was measured. The product of the total width and the average depth gave the cross-sectional area (A). At the vertical of each of these sub-sections where depth was measured, the velocity ($\bar{v}$) was measured using a Marsh McBirney current meter to determine the average velocity for the water column in the sub-section. When the water depth was less than 0.5 m, the velocity was measured at 60% of the depth. When the water depth was 0.5 m and greater, the velocity was measured at 20, 60 and 80 % of the depth.

Floats, in the form of oranges and lemons, were used as an alternative method to determine velocity when river conditions were unfavourable, that is when the river was flowing fast, and/or the water level was high. It was assumed that an orange or a lemon would best represent stream velocity since their densities (~1.02 g/mL) are similar to the density of water (1 g/mL). Moreover, they are not easily disturbed by wind. Floats were launched towards both banks and the middle of the channel and the time it took for each float to traverse downstream over a straight reach of 50 m, with uniform flow conditions, was measured. The average velocity of the channel was determined through the time recorded for all floats over the 50 m reach. The water level was marked using photographs and channel features such as exposed rocks on the channel bank. These were then marked on the surveyed cross-sections in order to determine the cross-sectional area.

Discharge, in the slope-area method, is the product of the cross-sectional area and the average velocity (Equation 3). Manual discharge measurements provided instantaneous discharge data that was collected an over the wet season (November 2016 – March 2017).

$$Q = \bar{v}A \qquad \textit{Equation 3}$$

Where Q = *Discharge* (m^3s^{-1}), $\bar{v}$ = *Velocity* ($m.s^{-1}$) *and* A = *Cross-Sectional Area* (m^2).

At the same time as discharge was measured, the time and the water depth over the level logger were recorded as these were used to validate the compensated water depth readings from the level logger and calibrate rating curves.

4.4.2 Discharge Data Analysis

Discharge for different water depths was estimated using Manning's equation and the stage-discharge relationship for each site. The stage-discharge relationship for each site was expressed as a rating curve. Site-specific rating curves were developed using HEC-RAS software, a computer-based program that simulates the hydraulic characteristics of water flow. Rating curves were developed from the Manning's values as the following data inputs were required by HEC-RAS;

1. Surveyed Cross-section;
2. Manning's roughness values for the right- and left-hand-banks as well as the channel;
3. Slope.

Rating curves developed from HEC-RAS were calibrated with the measured water depth over the level logger and discharge. Results for each site can be seen in Appendix 3 together with the cross-sections and Manning's values for each site. The relationship between discharge and water depth is expressed in Equation 4 and an example of this relationship in mathematical and graphical form is shown in Figure 4.3.

$$D = aQ^b \qquad \textit{Equation 4}$$

Where D= Depth (m), Q= Discharge (m^3s^{-1}) and a, b= empirically derived coefficient and exponent, respectively.

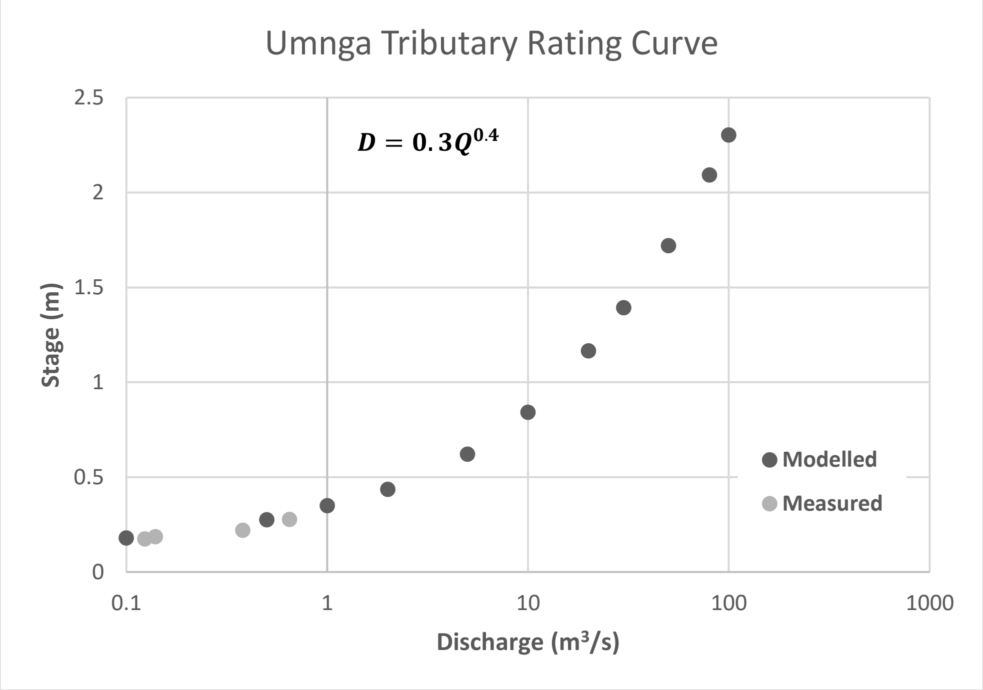


Figure 4.3: An example of a rating curve developed from HEC-RAS and calibrated with measured water depth and discharge

Discharges at different water depths above the level logger were determined through the rating curve developed for each site. Discharges for the upper Inxu (Inxu Upstream) monitoring point were not determined due to instrument error. An error in water depth compensation from the level logger was observed when water levels were either smaller than they were expected, or negative. This was validated by the manually measured water depth above the level logger. A diagnostic test, requested by the Solinst Software Support, could not be performed on the level logger, as it had already been installed in another river for other research and was currently inaccessible due to elevated water depth. However, a diagnostic test was performed on the Barometer and confirmed that the issue was with the level logger and not the Barometer.

A flow duration curve was used to distinguish events of high sediment transport, flood events. According to Gordon *et al.* (2004), flow duration curves show the percentage of time to which a certain discharge is exceeded. A discharge of 20 m^3/s was exceeded 20% of the time at the Inxu River Catchment Outlet. Therefore, flood events at this site were defined as events whose discharge exceeded 20 m^3/s ($Q > 20\ m^3/s$).

Sample collection by technicians was not consistent between monitoring points in terms of timing and frequency. Only one flood event was observed across all sub-catchments. Therefore, flow duration curves were not used for sub-catchments to distinguish events of high sediment transport.

4.5 Suspended Sediment Flux

Instantaneous sediment load, referred to as sediment flux (SSFlux), was used to measure the contribution of suspended sediment by a catchment at a given moment in time. Sediment flux is a product of suspended sediment concentration (SSC) and discharge (Q) (Equation 5).

$$SSFlux = Q.SSC \qquad \text{Equation 5}$$

Where SSFlux = Instantaneous Sediment Load (mg/L), Q = Discharge (L/s) and SSC =Suspended Sediment Concentration (g/L).

Suspended sediment flux was calculated using the sample sediment concentration and the discharge of the river, estimated from the rating curve (Section 4.3.2) at the time the sediment sample was collected by the technician. The time at which a sample was collected, as well as the interval between samples, was not always coincident with the level logger measured water depth. The average discharge between the measured water depth before and after the sample was collected was used as the discharge reading for the sample. At sub-catchment scale, the total SSFlux was used to measure the suspended sediment (SS) contribution generated by major sub-catchments individually.

The following calculations of sediment flux were made.

a. High frequency (at least twice daily) SSFlux was expected from the SS samples that were collected by technicians. Due to the lack of consistency in sample collection, SSFlux was determined from SS samples that were collected for all sites over the same period, as explained in 4.3.1. Even so, sediment sampling by the technicians was considered as high frequency compared to a monthly sampling resolution. Furthermore, since the discharges for the upper Inxu monitoring point could not be determined due to instrument error, SSFlux based on samples that were collected by the technician from this monitoring point could not be determined. Therefore, the comparison of SS contribution from each sub-catchment at high frequency was performed only for the Ncolosi, Qwakele, Ngxaza and Umnga River monitoring points.

b. Monthly-time scale comparison of SS contribution was performed for all sub-catchments since SSFlux could be determined for the upper Inxu site using the manually measured discharges and point samples collected by the researcher.

4.6 Suspended Sediment Yield

Suspended sediment yield for the Inxu River Catchment was determined based on the measured SSFlux using the sediment yield flux at the Inxu River Catchment Outlet monitoring point between 01 May 2016 and 30 April 2017. This value was compared to the yield values presented by Le Roux *et al.* (2015); sediment yield for the Inxu River Catchment was determined from the quaternary catchment estimates given by Le Roux *et al.* (2015).

The sediment contribution of the entire Inxu River Catchment was determined from the sediment flux measured at the Inxu River Catchment Outlet monitoring point between 01 May 2016 - 30 April 2017. Sediment flux estimates needed to compensate for the period between each sample (Equation 6) so that the sediment yield reflects the specific period when sediment was transported. The total sediment flux for the period 01 May 2016 - 30 April 2017 was calculated as the sum of these discreet flux estimates.

$$Load = \frac{SSFn+SSFn-1}{2}.t \qquad \text{Equation 6}$$

$Where\ Load\ (tons),\ SSF = Suspended\ Sediment\ Flux\ (mg/s)\ t = time\ interval\ (s),\ n = event$

Sediment yield is the mass of sediment that is lost or transported out of the catchment per unit area of the catchment (Chen and Mackay, 2004; Gordon *et al.,* 2004). For this reason, suspended sediment yield (SSY) (Equation 7) for the Inxu River Catchment was determined by observing the time compensated suspended sediment flux per catchment area (ha) over the 2016-2017 hydrological year.

$$SSY \ = \ \sum Load/A \qquad \text{Equation 7}$$

$Where\ SSY = Suspended\ Sediment\ Yield\ (t/ha/yr),\ Load\ (t)\ and\ A = Catchment\ Area\ (ha)$

The integrated sheet-rill and gully erosion model (Le Roux *et al.,* 2015) produced sediment yield at quaternary catchment scale. Equation 8 shows how the sediment yield from the Inxu River Quaternary Catchments (Q) (T35 F, G, H and J) was converted to a sediment yield of the Inxu River Catchment (SSY_I).

$$SSY_I = \sum (SSY_Q \,.\, A_q)/A_I \qquad \text{Equation 8}$$

Where SSY = Suspended Sediment Yield (t/ha/yr), A = Catchment Area (ha), I = Inxu, Q = Quaternary Catchment

Modelled data was compared with the monthly data measured by the researcher. Both studies were conducted at the sub-catchment scale. Monthly data was preferable as it offered a higher spatial resolution, compared to the high frequency data collected by the technicians. The integrated sheet-rill and gully erosion model (Le Roux *et al.,* 2015) produced sediment yield values (in t/ha/yr) at quaternary catchment scale for the Inxu River Catchment, while the measured data produced sediment flux values (in t) for specific major sub-catchments of the Inxu River. Similar measuring units are required to compare results. To achieve this, suspended sediment yield for each of the measured sub-catchments was estimated from the product of the total sediment yield (TSSY), the proportion of sediment contributed by the sub-catchment ($SSFlux_{\%}$) and the total catchment area (A_{Inxu}), over the sub-catchment area (A_N) (Equation 9).

$$SSY_N = \frac{TSSY \,.\, SSFlux_{\%} \,.\, A_{Inxu}}{A_N}/100 \qquad \text{Equation 9}$$

Where SSY = Sub-catchment's Suspended Sediment Yield (t/ha/yr), TSSY= Total Suspended Sediment Yield of the Inxu River Catchment (t/km²/ha), $SSFlux_{\%}$ = Sub-catchment's SSFlux contribution (Converted to % contribution), A = Catchment Area (km²), N = Sub-catchment of Interest.

4.7 Sediment Source Areas

Sediment sources can be identified by their broad spatial distribution (provenance) and by type (Collins *et al.,* 2017; Rowntree *et al.*, 2017). Sediment source areas in this study were identified using a two-step method. The first step involved the catchment wide spatial distribution of main suspended sediment sources based on the suspended sediment contribution by sub-catchments of the Inxu River. The second step involved the identification of features of each sub-catchment that could explain the amount of sediment that each sub-catchment contributed. Through this step, comparisons of the common and contrasting features of the catchment were used to make inferences on the possible sources for suspended sediment.

4.7.1 Database

The following table (Table 4.3) describes the database used to support premises on potential sediment source areas in the Inxu River Catchment. Once the sub-catchments were delineated, suspended sediment contribution at sub-catchment scale was displayed. Maps of the erosion potential of the Inxu River Catchment, the gully and sheet erosion model output, gully extent for each sub-catchment, as well as slope class, soil type and land use were used to justify the premises made on why certain areas of the Inxu River Catchment produced more sediment than others. Details for each step are explained in Sections 4.7.2 and 4.7.3 for catchment delineation and spatial representation of suspended sediment sources based on catchment contribution, as well as the maps produced to observe catchment characteristics, respectively.

Table 4.3: Database for the identification of potential sediment source areas in the Inxu River Catchment

Input Data	Source	Purpose
1:50 000 Topographic River Network	National Geo-spatial Information (2013)	Catchment Delineation
90 m Resolution Hydrologically Correct SRTM DEM	United States Geological Survey	Catchment Delineation; Slope Class
Sub-Catchment Total SSFlux	Measured	Spatial Representation of Sub-Catchment Contribution
1:250 000 Land Type Inventories	Land Type Survey Staff (1972-2012)	Soil Properties
National Land Cover Map 2012	South African Institute of Biodiversity	Land Cover and Land Use Properties
May 2016 - May 2017 LandSat8	United States Geological Survey	Calculate NDVI to create the USLE c-factor
USLE K, R and LS factors from the Erosion Potential Map	Le Roux *et al.* (2008)	Model Erosion Potential based on Sheet Erosion
Gully and Sheet Erosion Model Output	Le Roux *et al.* (2015)	Compare Previously Modelled Results
Gully Location	Le Roux and Sumner. (2012)	Gully Extent Map

Sub-catchment delineation was conducted using the ArcGIS interface of the Soil and Water Assessment Tool (SWAT) as this step is automated (Le Roux *et al.,* 2015). SWAT is a semi-distributed, hydrological model that can simulate water, chemical and sediment yields from large, ungauged catchments (Arnold *et al.,* 2012a). It was not used for its full capabilities for three reasons.

1. **The measurement of sediment flux and yield took precedence over modelling for this study.** This study was developed as a continuation of sediment yield measurements for tributaries across the Tsitsa River Catchment. Following the identification of the Inxu River Catchment as a major sediment source area, a detailed analysis of sediment source areas of the Inxu River Catchment was required.
2. **Sediment yield for this catchment had already been modelled in the past using SWAT.** Results from the study showed that sheet-rill erosion, which is simulated by SWAT, was not the dominant erosion process for the Mzimvubu River Catchment, where the Inxu River is situated.
3. **SWAT disregarded other major source areas of suspended sediment.** SWAT is well known for its ability to divide sub-catchments into homogeneous units, known as Hydrologic Response Units (HRUs) based on slope, soil and land management characteristics. However, SWAT identified 1 492 HRUs for the Inxu River Catchment, which were difficult to analyse and would have crashed the software if simulation of sediment yield had proceeded. In the event where many HRUs are produced, SWAT allows users to reduce the number of HRUs through various options which include simulating yields though the dominant HRUs or the dominant characteristics of each sub-catchment. Although this step was useful in identifying dominant features of each sub-catchment such as the prevalence of grassland throughout the catchment, this step disregards major sediment sources such gullies and land use activities such as cultivation. For these reasons, up to this point for this study, the SWAT model was used only for its first step in preparing for simulation: catchment delineation up to the sub-catchment level.

SWAT divides a catchment into sub-catchments to create drainage attributes through the DEM and the river network (Arnold *et al.,* 2012; Le Roux *et al.,* 2015). Using the 90 m SRTM DEM and the 1:50 000 river network, SWAT divided the Inxu River Catchment into 23 sub-catchments. Geoprocessing techniques were used to combine sub-catchments from SWAT to divide the Inxu River Catchment into the five sub-catchments that were monitored during the period of study, namely the Ncolosi, Qwakele, Ngxaza, Umnga and Inxu Upstream.

4.7.2 Sub-Catchment Contribution

Sub-catchment contribution was determined from the measured and the modelled data. Both data-sets were compared.

4.7.2.1 Measured Contribution

Once the sub-catchments were delineated, total SSFlux for each sub-catchment based on the monthly data collected by the researcher was used to identify sediment source areas. As explained above, this data was chosen since it had SSFlux data from all monitoring points. It provided monthly suspended sediment contribution that had a bigger spatial coverage of the catchment, compared to high-frequency data. The determination of sediment flux for each sub-catchment is explained in the previous section (4.5). A map of the sub-catchment sediment contribution was produced to illustrate sediment provenance by major tributaries. This map was compared to the sediment yield map produced by Le Roux *et al.* (2015) to investigate whether similar sediment source areas were identified.

4.7.2.2 Modelled Contribution

Le Roux *et al.* (2015) modelled sediment yield for each quaternary catchment by integrating sheet-rill and gully erosion models. A summary of how sediment yield was derived from the model is provided in Section 4.6. The modelled sediment contribution from the quaternary catchments was provided as sediment yields, while the sediment contribution measured from the sub-catchments was provided as sediment flux.

To compare sediment contributions between the sub-catchment sediment yield maps from both measured and modelled data, measured SSFlux for the sub-catchments was used to infer sediment yield by using relative percentage sediment contribution for each sub-catchment. Equation 9 (Section 4.6) was used to infer sediment yield for each sub-catchment.

Sheet erosion potential was modelled using RUSLE factors following Le Roux *et al.* (2008). The soil erodibility (K), slope length and steepness (LS) as well as the rainfall-runoff erosivity factors were taken from their study. The rainfall-runoff erosivity factor (R) used by Le Roux *et al.* (2008) was not changed as it was assumed that similar spatial patterns for rainfall and runoff would be observed in the Inxu River Catchment during this period. Normalised Difference Vegetation Index (NDVI) from May 2016 - May 2017 was used to assign the cover management factor (C) values.

Multispectral Landsat 8 images captured monthly were loaded in ArcGIS. To calculate NDVI, image analysis properties were altered to 4 for the Red Band, and 5 for the Infrared band, as suggested by ArcGIS. Once NDVI was calculated for each image, average NDVI for May 2016 - May 2017 was calculated with a mosaic that was converted to a raster, whose pixel type was a 32-BIT Float. C-values were estimated using a regression equation with NDVI. The equations were as described by Le Roux *et al.* (2008).

Erosion potential was a product of the above-mentioned erosion factors (Equation 10).

$$A = R.K.LS.C \qquad \textit{(Equation 10)}$$

$\textit{Where } A = \textit{Annual Soil Loss (t/ha/yr); } R = \textit{Rainfall-Runoff Erosivity, } K = \textit{Soil Erodibility, } LS = \textit{Slope length and Steepness and } C = \textit{Vegetation Cover}$

4.7.3 Catchment Characteristics

The second step involved the comparison of sub-catchment characteristics to make predictions of potential sediment source areas within the major sub-catchments. Catchment characteristics that were observed are as follows;

1. Catchment Area;
2. Percentage sediment contribution based on monthly sediment load;
3. Total rainfall that was received from the rain-gauge nearest to the tributary;
4. Slope class;
5. Geology;
6. Erodible soil types;
7. Dominant land cover and use;
8. The area of the catchment that is gullied.

Rainfall, topography, land cover and use as well as soil properties are well known factors of soil erosion, usually associated with the Universal Soil Loss Equation (Le Roux *et al.,* 2007). Since Le Roux *et al.* (2015) had suggested that gullies indicated the dominant soil erosion process in the catchment, gully extent was measured using “Zonal Statistics as a table” on ArcMap to calculate the area of the sub-catchment that was gullied. The areas that were calculated from the Zonal Statistic table were added to the attribute table of the sub-catchment layer in ArcGIS.

Monthly suspended sediment contribution (as outlined in previous sections) was used to compare sub-catchment contribution because it had a better spatial coverage of the catchment, compared to high-frequency data. Justification for potential sediment source areas within each sub-catchment was based on similarities in these catchment features between the sub-catchments that contributed the most sediment.

4.8 Chapter Summary

The Inxu River Catchment has a total of six sampling points where sediment flux was monitored at the Inxu River Catchment Outlet and an upper Inxu River Catchment monitoring point, as well as four major sub-catchments. Pressure transducers were installed in all monitoring points to provide continuous water depth readings and cross sections were measured along the points. Discharge was measured manually monthly using the velocity area method at base flow conditions and floats during high flows. The slope area method was used to establish the stage-discharge relationship for each monitoring point. The stage-discharge relationship, derived through a rating curve, was used to estimate discharge throughout the study period for each monitoring point. Point samples were collected together with discharge measurements.

This project made use of citizen-based monitoring for suspended sediment sample collection. Citizen technicians (referred to as technicians) were expected to collect suspended sediment samples sub-daily during base flow conditions and 20 times during flood events. Sediment concentration for samples that had visibly low sediment (<200 NTU) was determined through turbidity while high sediment concentration was determined through the evaporation method.

Sediment flux from each monitoring point is the product of the suspended sediment concentration and discharge. Sediment yield was measured from sediment flux per catchment area per annum. The suspended sediment contribution of the Inxu River Catchment was determined through the sediment yield measured at the catchment outlet and results were compared with previously modelled sediment yield from Le Roux *et al.* (2015). The relative suspended sediment contribution from major sub-catchments was based on sediment loads from the Ncolosi, Qwakele, Ngxaza and Umnga Tributaries and the sediment inputs from the upper Inxu River Catchment were determined from a second monitoring point along the Inxu River. The second monitoring point was situated downstream of the Umnga River Outlet due to the scarcity of citizen available technicians upstream of the Umnga River Outlet.

Maps were used to identify sediment source areas based on suspended sediment contribution measured from major sub-catchments. The measured suspended sediment contribution map was compared to modelled sediment yield from sheet erosion (RUSLE) and sheet-gully erosion map from Le Roux *et al.* (2015). Factors such as rainfall, slope class, geology and soil type, land use as well as gully extent were used to investigate what affected sediment contribution at each sub-catchment.

5 Results

This chapter presents the results that were found in this study in order to determine the suspended sediment contribution of the Inxu Tributary to the Tsitsa River and identify the main sediment source areas within the Inxu River Catchment. The chapter is divided into three sections, in accordance to research objectives as follows,

- Measured suspended sediment contribution results which includes a section on the sediment contribution of the Inxu River to the Tsitsa River (objective 1) and a section on the relative sediment contribution of the Inxu River Sub-catchments to the Inxu River (Objective 2);
- A comparison of the sediment yield estimates and sediment provenance results from this study against results from previously modelled output (Objective 3); and
- Catchment characteristics and process results which assist in interpreting the main factors that affect sediment contribution from each sub-catchment (Objective 4).

5.1 Measured Suspended Sediment Contribution Results

This section presents results for the suspended sediment flux (SSF) and the suspended sediment yield (SSY) of the Inxu River Catchment, as well as the results for the relative suspended sediment (SS) contribution from each of the sub-catchments that were monitored.

5.1.1 Suspended Sediment Yield of the Inxu River Catchment

A total of 562 samples were collected from the Inxu River Catchment Outlet from 01 May 2016 – 30 April 2017 and were analysed to measure suspended sediment flux at the outlet and suspended sediment yield from the catchment. The suspended sediment flux relationships were used to provide information on possible sediment processes and sediment sources in the Inxu River Catchment.

5.1.1.1 Suspended Sediment Flux – Time Series Relationship

The Q-SSC hysteretic relationship can be used to understand dominant processes for suspended sediment over different time scales, that is at annual, seasonal, monthly and event scales (Lefrançois *et al.,* 2007; Rovira and Batalla, 2006). This study took place over one hydrological year, 01 May 2016 – 30 April 2017. Results are shown for the seasonal and event scales.

Figure 10 illustrates the relationship between Q-SSC at the seasonal scale. At this scale, the seasonal sediment dynamics can be observed for one wet season (November 2016 – April 2017). Clockwise or anti-clockwise hysteresis could not always be distinguished due to multiple Q-SSC peaks. Numbers on the graph indicate high sediment transport events whose discharge is above average.

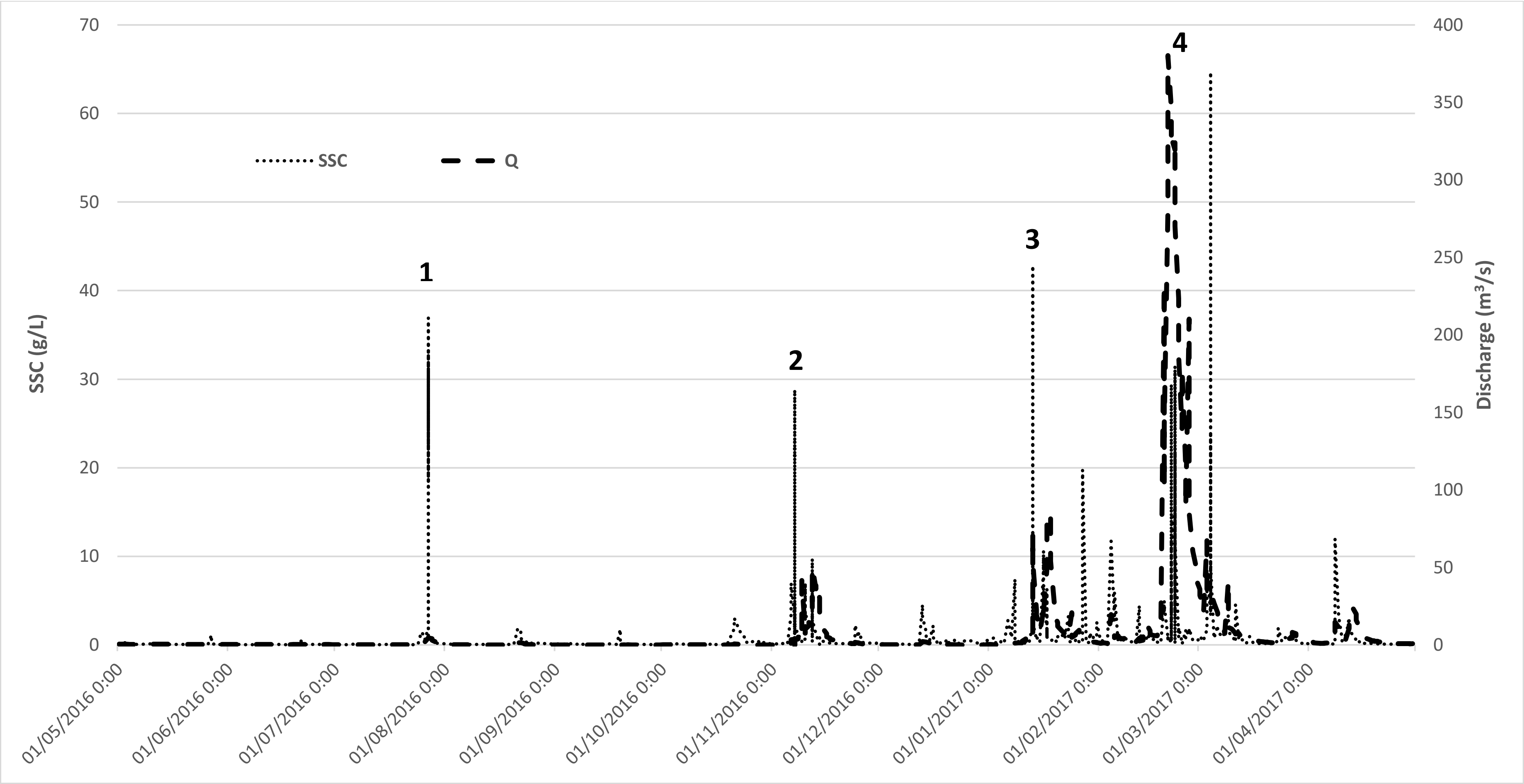


Figure 5.1: Q-SSC relationship for the Inxu River Catchment at the seasonal scale

At the seasonal scale (Figure 5.1), the Q-SSC relationship shows that sediment and discharge peaks occur at different times throughout the year. Sediment peaks that precede discharge peaks, with relatively small discharges and a longer time lag, are more prominent in the beginning of the wet season. For example, a maximum of 28 g/L of sediment was observed on 07 November and discharge peak was observed two days later at 40 m^3/s. By January and February, peaks have a short lag time, and some occur almost simultaneously. For example, on 13 January the sediment peak of 43 g/L preceded a discharge peak of 72 m^3/s and the peaks were only 8.5 hours apart. By the end of February and early in March, sediment peaks with smaller amplitudes were observed after discharge peaks. For example, the peak discharge of 371 m^3/s on 20 February was followed by a peak sediment of 29 g/L 18 hours later and a major sediment peak of 65 g/L 15 days later. Peaks that occurred simultaneously are also observed at this period in the year.

Base flow conditions were prominent throughout the year and persisted for almost a month between flood events. During base flow conditions, sediment concentrations were generally low but multiple sediment peaks occurred despite low flow conditions. Baseflow sediment peaks during the wet season, particularly between January and March, were higher than sediment peaks that occurred during the dry season, before the first flood event in November and after the last flood event in April.

Although base flow conditions were prominent, they transported low quantities of sediment. The Q-SSC relationship at the seasonal scale shows that large quantities of sediment were transported by flood events. There were 3 distinct flood events (labelled 2-4 on Figure 5.1) that contributed the most to the annual sediment yield, with one major flood event on 19-26 February 2017. Flood events were defined as having a distinct rising and falling limb and a discharge that was higher than average, $Q > 20$ m^3/s. An additional high sediment peak during low discharges was observed on 27 July 2016, associated with a snow event that occurred in the upper Inxu River Catchment.

Event scale sediment dynamics were observed for the main flood events, as marked in Figure 5.1. These are illustrated in Figures 5.2-5.5 where the Q-SSC relationship, together with the loads, are presented for each event. Clockwise or anti-clockwise hysteresis could not be distinguished since all flood events have multiple peaks. The dates for these high flow events are as follows

1) 27 July 2016;
2) 05-19 November 2016;
3) 12-21 January 2017;
4) 16 February-07 March 2017.

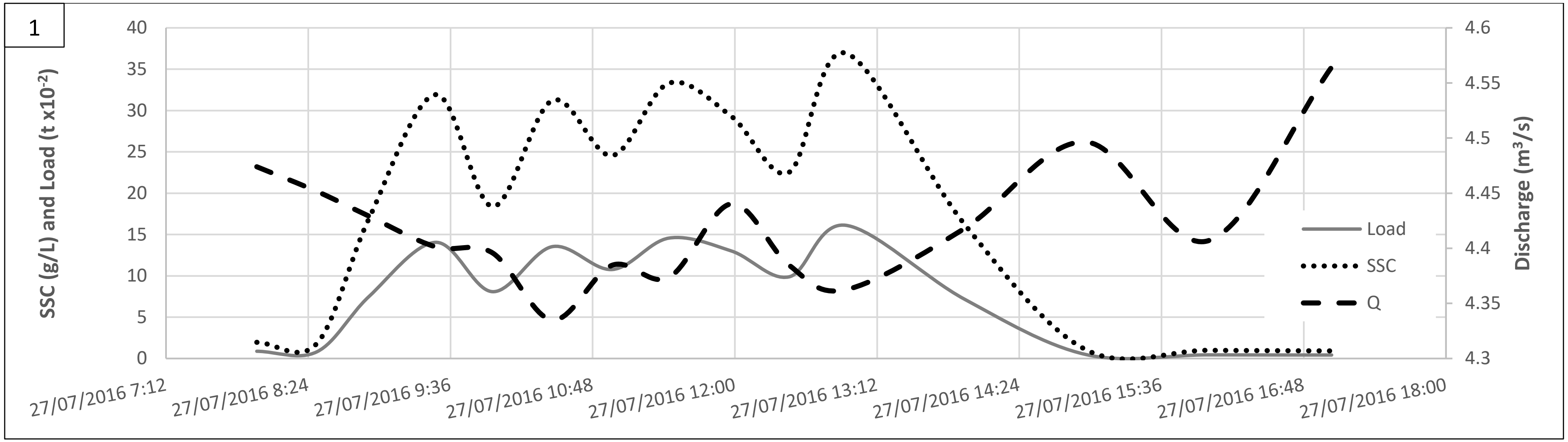


Figure 5.2: Q-SSC relationship and sediment load during the 27 July 2016 snow event from the Inxu River Catchment Outlet.

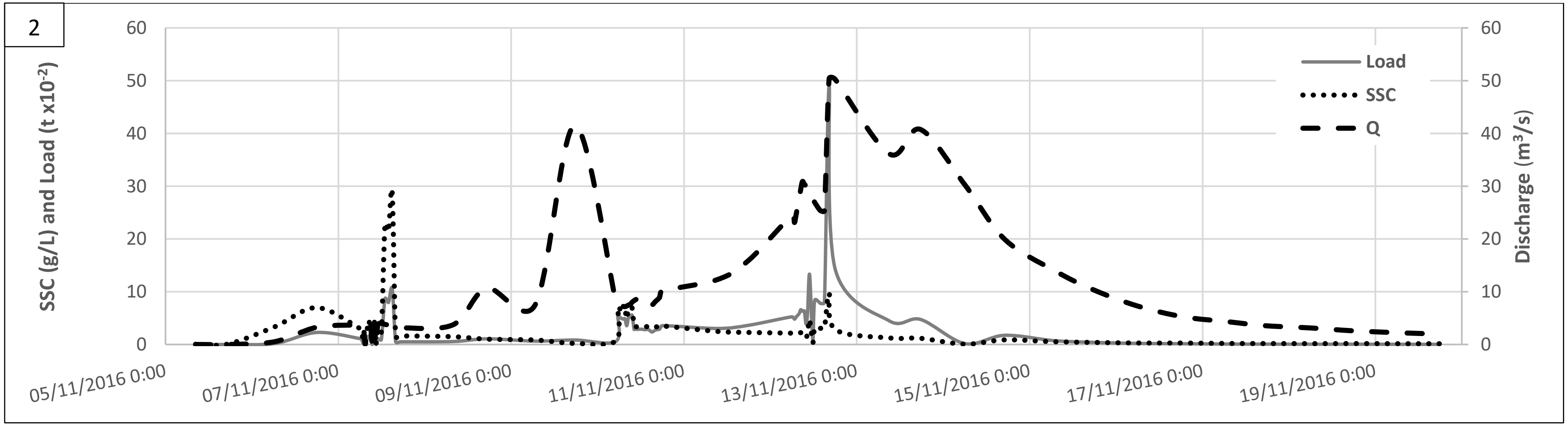


Figure 5.3: Q-SSC relationship and sediment load during the 05-19 November 2016 flood event from the Inxu River Catchment Outlet.

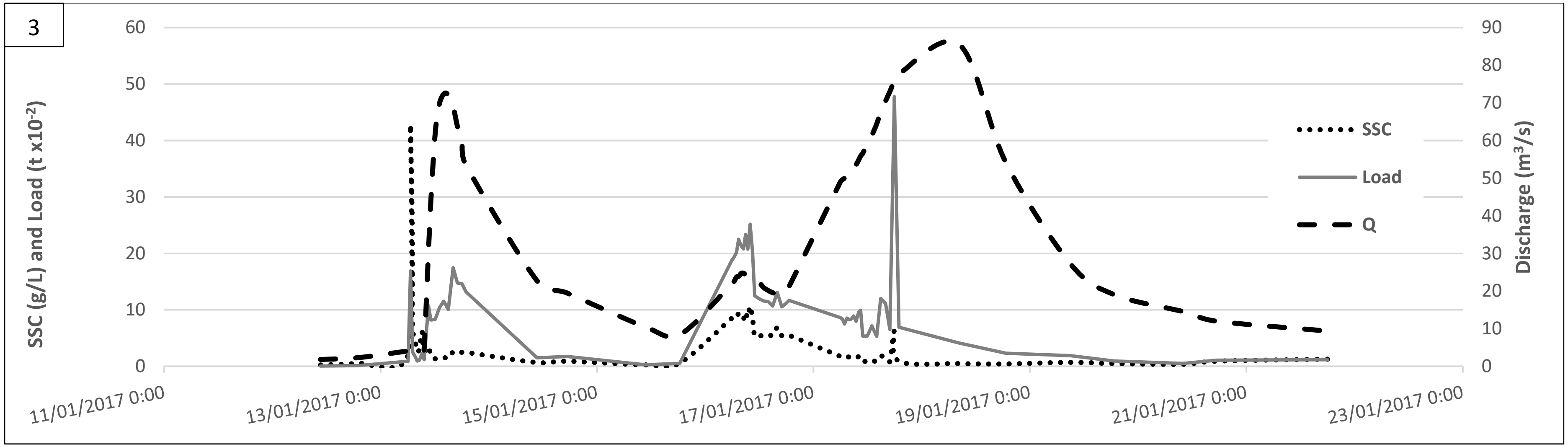


Figure 5.4: Q-SSC relationship and sediment load during the 12-21 January flood event from the Inxu River Catchment Outlet.

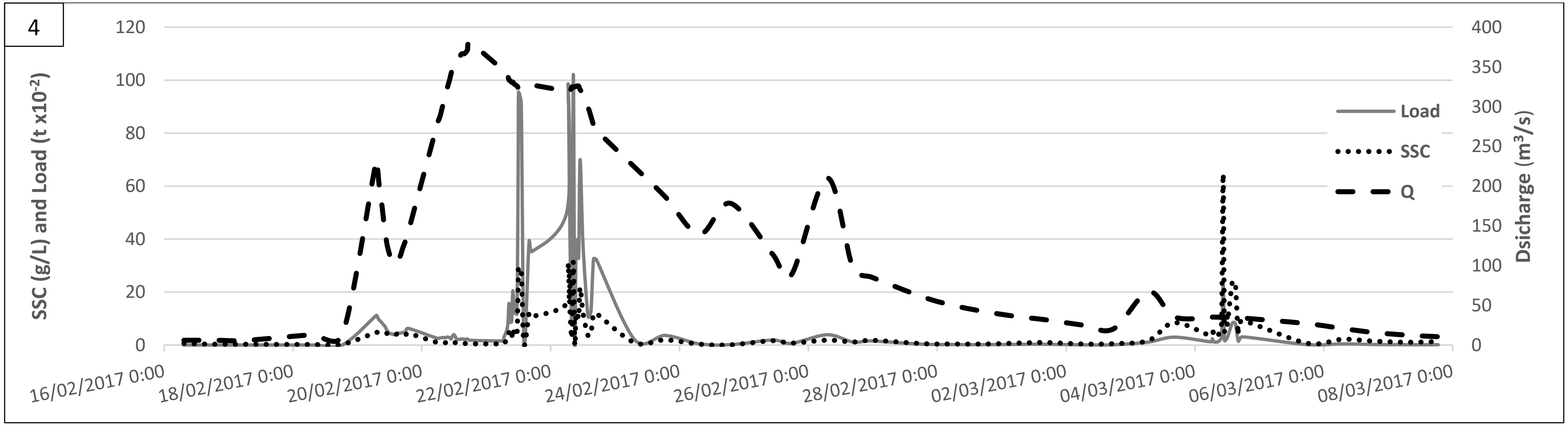


Figure 5.5: Q-SSC relationship and sediment load during the 16 February - 07 March 2017 flood event from the Inxu River Catchment Outlet.

The snow event transported the least sediment. Q was relatively constant, so SCC dominated the load relationship. The Q-SSC relationship for the snow event shows that this was a low discharge event characterised by multiple SSC and Q peaks, and SSC peaks that precede discharge peaks over short time lags. The load seems to follow the pattern of sediment concentration.

In November and January, the major sediment peaks preceded the peak discharge. In the flood event observed in 16 February – 07 March 2017, the major sediment peak occurred after the major flood peak. It is quite evident that each event had multiple sediment and discharge peaks and the amplitudes of the secondary sediment peaks were less than half of the major sediment peak. These peaks do not have a clear association with local discharge patterns as there is a mix between simultaneous peaks, sediment peaks that precede discharge peaks and sediment peaks that follow discharge peaks.

5.1.1.2 Suspended Sediment Yield

Sediment yield is the mass of sediment that is transported per unit area, usually measured at an annual rate (Bracken *et al.,* 2015). The sediment yield values from this section represent the total sediment, per hectare, that was transported out of the Inxu River Catchment from 01 May 2016 - 30 April 2017. The total load over this period was 882 874 t. This translates to a catchment yield of 5.5 t/ha/a.

Figure 5.6 shows the suspended sediment yield (SSY) results from the Inxu River Catchment Outlet are presented in terms of the total SSY that was measured, as well as identifying the proportion of sediment that is contributed by base flow and the major flood events as stipulated in Figure 5.1. 7% was contributed by low flows and 93% was from flood events (Figure 5.6).

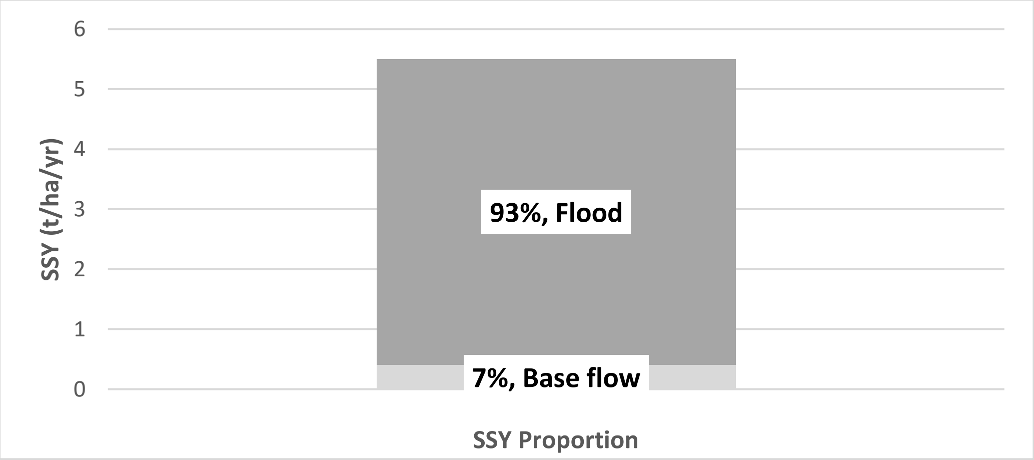


Figure 5.6: Proportion of sediment contributed by high and low flow from the Inxu River Catchment between 01 May 2016 and 30 April 2017.

5.1.2 Sub-Catchment Sediment Contribution

Results presented in this section are from the samples that were collected sub-daily and 20 times over a flood event by the technicians, and the samples that were collected monthly by the author. Since data from the pressure transducer at the Inxu Upstream monitoring site could not be obtained, discharges for the site could not be calculated, and thus, loads for Inxu Upstream could not be determined. As a result, high frequency data reveals sediment flux for the four major tributaries only (Ncolosi, Qwakele, Ngxaza and Umnga Tributaries). Monthly suspended sediment data, collected by the author, includes the upper catchment since discharge measurements from all sites were conducted manually. SS flux has been represented in the form of graphs and tables.

5.1.2.1 High Frequency Sediment Flux Monitoring

Suspended sediment (SS) samples were to be collected from each sub-catchment – by local technicians – twice daily during low flow conditions and 20 times during high flows. Due to the lack of consistency in sample collection by the technicians, only SS samples that were collected over the same time periods were analysed in this study. Most of the samples that were analysed were collected over base flow conditions and one flood event on 06-15 November 2016. SS flux results were observed for each of the monitored sub-catchments on 21 October 2016 – 12 January 2017. Figure 5.7 illustrates the sediment flux from all monitored sub-catchments.

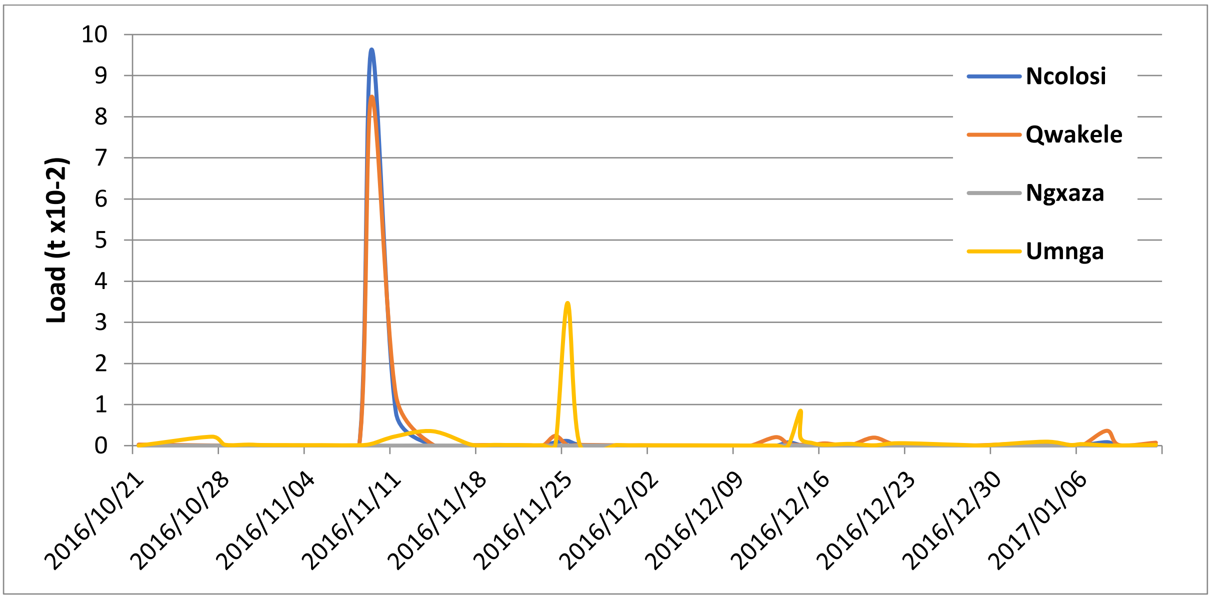


Figure 5.7: High frequency suspended sediment flux from all sub-catchments (21 October 2017 – 11 January 2017)

Between late October 2016 and early January 2017, most of the measured sediment was transported during the flood of 09-11 November 2016, mainly from the Ncolosi River Sub-catchment and, secondly, from the Qwakele River Sub-catchment. This was a period where flood events occurred across the catchment. The Ngxaza River Sub-catchment barely contributed, while the Umnga River

Sub-catchment made larger contributions at various times. Additionally, the Qwakele and Umnga River Sub-catchments contributed more sediment, compared to other sub-catchments, through the course of time.

Between 06-15 November 2016, with the exception of the Umnga River Sub-catchment, technicians across the lower Inxu River Sub-catchments collected flood samples based on observing a progressive rise in the water level, higher than base flow conditions. There was no other flood event whose sediment samples were collected across the stations. Figure 5.8-10 shows the suspended sediment flux from the flood event period of 06-15 November 2016.

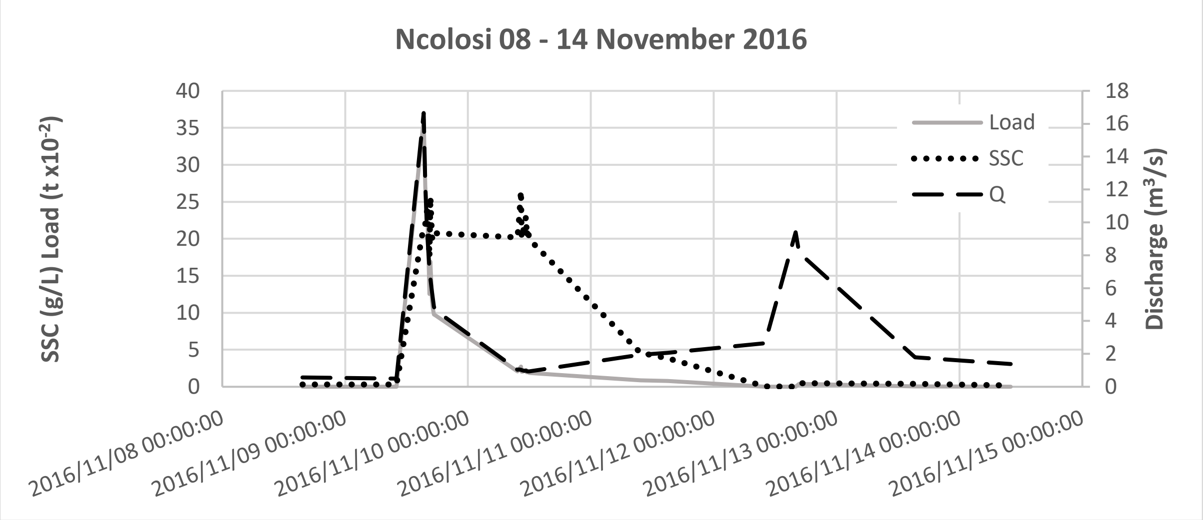


Figure 5.8: The Suspend Sediment Flux of the Ncolosi, River Sub-catchment during the 06-21 November 2016 Flood Event

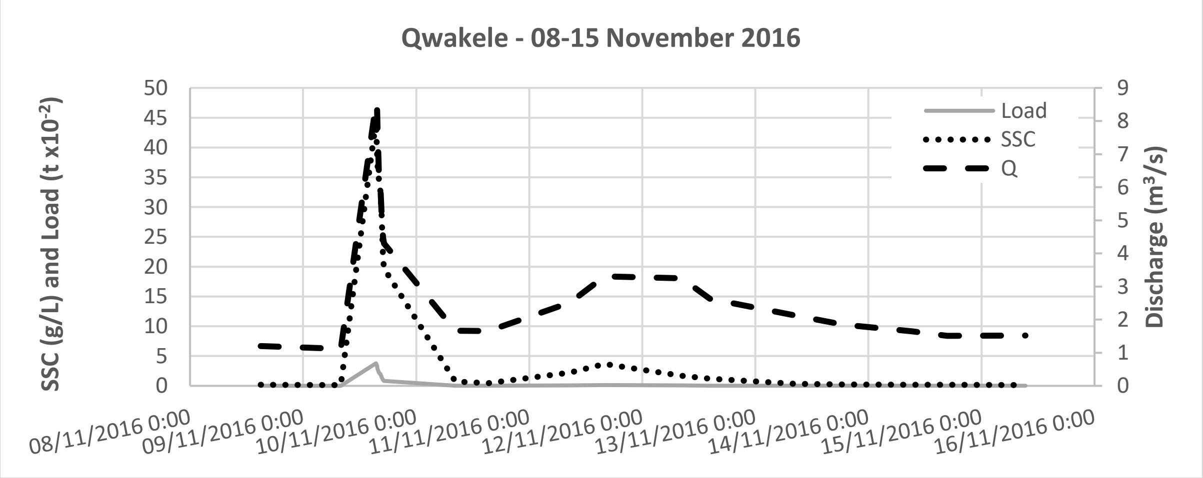


Figure 5.9: The Suspend Sediment Flux of the Qwakele River Sub-catchment during the 06-21 November 2016 Flood Event

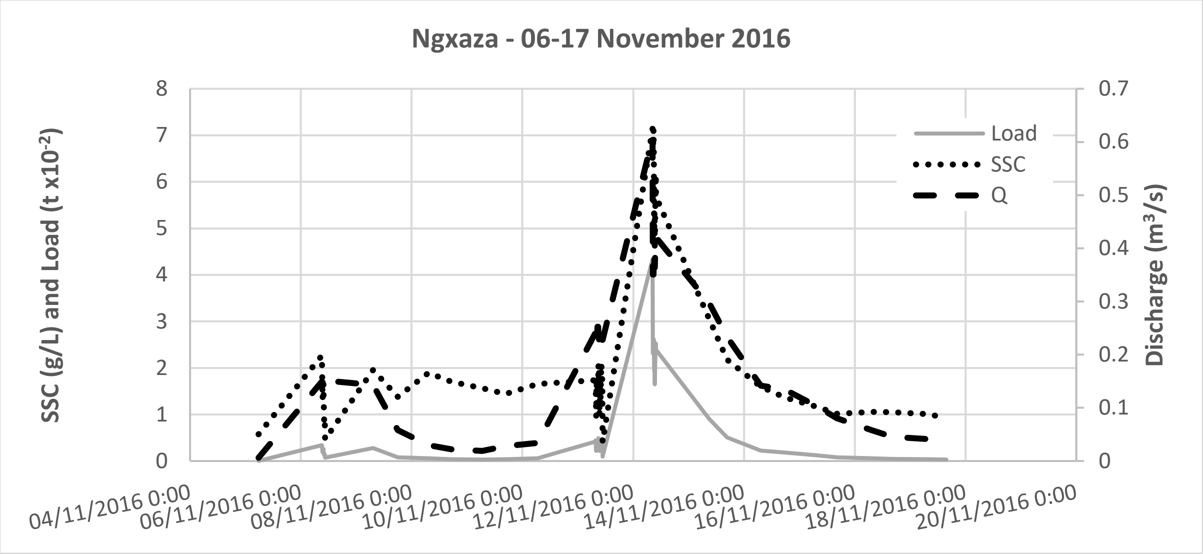


Figure 5.10: The Suspend Sediment Flux of the Ngxaza River Sub-catchment during the 06-21 November 2016 Flood Event

The Q-SSC relationship for this flood period indicates that discharge and sediment peaks occurred at the same period across all sub-catchments, particularly on 11 November 2016. Q-SSC peaks for all sub-catchments occurred simultaneously.

The Ncolosi and Qwakele River Sub-catchments contributed the same sediment load (2 t). The Ncolosi River Sub-catchment had the highest discharge peak (17 m^3/s) and two sediment peaks at 25 and 26 g/L. Peak SSC for the Ncolosi River Sub-catchment lasted longer than the discharge peak. Peak SSC for the Ncolosi River Sub-catchment lasted longer than the discharge peak. The Qwakele River Sub-catchment had the highest sediment peak (44 g/L) and a lower secondary sediment peak but a lower discharge peak (8 m^3/s) compared to the Ncolosi River Sub-catchment. The contribution made by the Ngxaza River Sub-catchment was very small (0.003 t) compared to the other catchments, even though its flood lasted longer, with two distinct discharge peaks and multiple sediment peaks.

Figure 5.11 shows the total measured sediment flux and sediment contribution from each of the monitored tributaries of the Inxu River Catchment from 21 October 2016 – 12 January 2017.

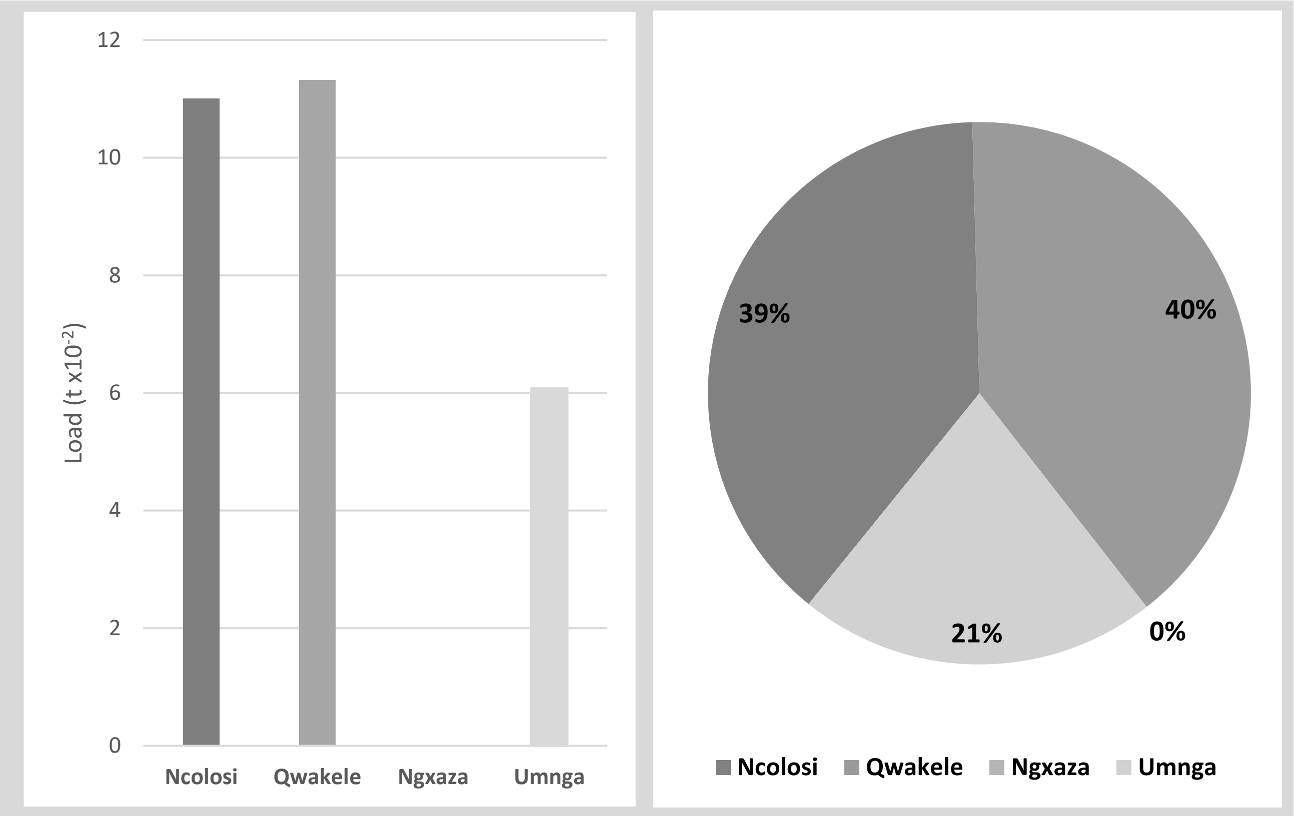
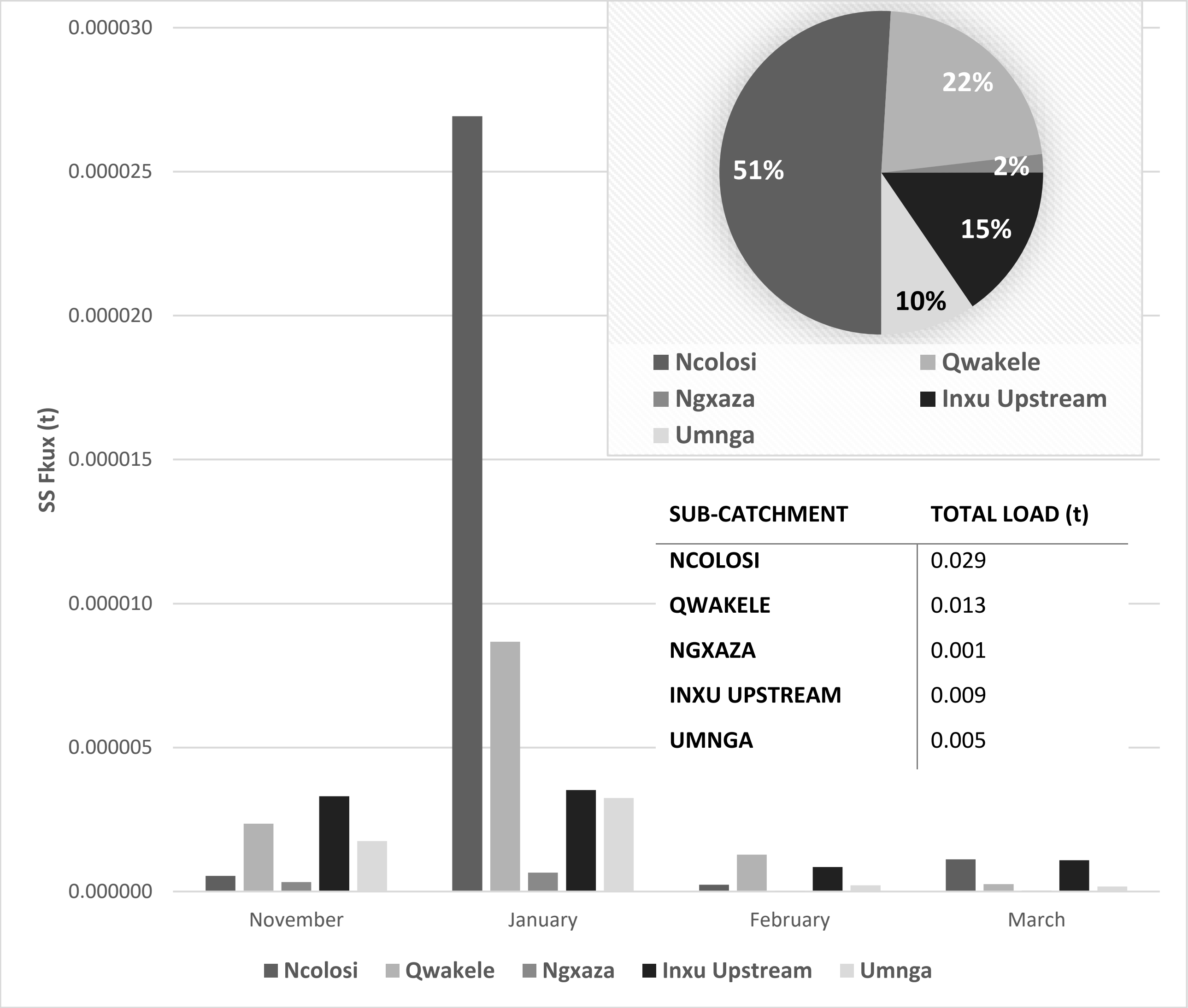


Figure 5.11: Suspended Sediment Contribution from each Sub-Catchment (21 October 2016 – 12 January 2017).

When assessing the sediment contribution of these sub-catchments relative to one another, sub-catchments that lie in the lower Inxu River-Catchment (Ncolosi, Qwakele and Ngxaza River Sub-catchments) contributed 79% of SS. During base flow conditions, most of the sediment came from the Qwakele River Sub-catchment followed by the Ncolosi River Sub-catchment in the lower Inxu. However, the difference between the contribution from these sub-catchments was small. The Ngxaza River Sub-catchment barely made any sediment contribution when compared to these sub-catchments while Umnga River, the only monitoring point that lies in the upper catchment, made a small contribution.

5.1.2.2 Monthly Sediment Flux Monitoring

Over the summer season, four field trips were taken between November 2016 – March 2017, during which Q measurements and point samples for SSC were collected from each monitored tributary. Figure 5.12 shows the total contribution from these tributaries over this period.



SUB-CATCHMENT	TOTAL LOAD (t)
NCOLOSI	0.029
QWAKELE	0.013
NGXAZA	0.001
INXU UPSTREAM	0.009
UMNGA	0.005

Figure 5.12: Relative suspended sediment contribution from the major Inxu Sub-catchments (November 2016 – May 2017).

At the seasonal scale, most of the sediment was contributed by the sub-catchments early in the summer season, November 2016 – January 2017 (Figure 5.12). At the monthly scale, it seemed as though the Ncolosi and Qwakele River Sub-catchments alternate every month on the highest sediment contribution. Most of the sediment that was contributed by the Ncolosi River was supplied in January, prior to the flood event that was observed at the Inxu River Outlet on 12-21 January (Figure 5.4).

The sediment contribution from the Inxu Upstream monitoring point was higher relative to monitored sub-catchments in November; however, overall, only 15% of the sediment was contributed by this area although it has a proportionally larger catchment area (Figure 5.12). The Ngxaza Tributary barely contributed sediment, which was the case with the high frequency suspended sediment flux monitoring.

Monthly data revealed that most of the sediment was contributed by the lower Inxu River Catchment (Figure 5.12). Relative to each other, 75% of the sediment came from the lower Inxu River Catchment which is made up of the Ncolosi, Qwakele and Ngxaza River Sub-catchments. The Ncolosi River Sub-catchment contributed the most sediment (0.0239 t, 51%) followed by the Qwakele River Sub-catchment (0.013 t, 22%). The Ngxaza River Sub-catchment barely made a contribution (0.001 t, 2%). The upper Inxu River Catchment is made up of the Inxu Upstream (0.009 t, 15%) and Umnga River (0.005 t, 10%) Sub-catchments which contributed 25% of the sediment. Table 5.1 provides the extrapolated suspended sediment yields, which were converted from tonnes to t/ha/yr based on the sediment yield calculated at the Inxu outlet and the area of the Inxu River Catchment, the relative percentage contribution and area of the sub-catchment (as explained in Section 4.6, Equation 9).

Table 5.1: The Extrapolated, relative suspended sediment yield for each sub-catchment

Sub-Catchment	Suspended Sediment Contribution (%)	Extrapolated Sediment Yield (t/ha/yr)
Ncolosi	51	40.2
Qwakele	22	22.1
Ngxaza	2	3.1
Umnga	10	4.2
Inxu Upstream	15	1.4

Though the percentage contribution of the upper Inxu River Catchment was relatively higher, sediment yield is inversely proportional to catchment area. As a result, when accounting for the catchment area, the upper Inxu contributed the least suspended sediment, relative to other sub-catchments (Table 5.1).

5.2 Comparison with Previously Modelled Results

This section presents a comparison between measured and modelled results for sediment yield and sediment source areas.

5.2.1 Sediment Yield

Sediment yield has been modelled for the Inxu River Catchment by Le Roux *et al.* (2015). Table 5.2 provides a summary of the differences between the modelled output for sediment yield and the measured data from this study.

Table 5.2: Sediment Yield output - Measured vs Modelled Data (Le Roux *et al.,* 2015)

Method	**Measured**	**Modelled Output** Le Roux *et al.,* 2015)
Study Period	2016-2017	2008-2012
Sub-catchment Delineation	Specific sub-catchments	Quaternary Catchments
Sediment Yield	5.5 t/ha/yr	7 t/ha/yr

Differences between the two data sets include the method used to determine sediment yield, how sub-catchments were delineated, as well as the period of study. In the model, sub-catchment delineation was based on the DWS quaternary catchments which divide the Inxu River Catchment into four areas. The measured sediment yield was based on data collected at the Inxu River Catchment Outlet while the modelled yield was averaged across the quaternary catchments to determine sediment yield for the Inxu River Catchment. However, at the catchment scale, suspended sediment was measured from specific major sub-catchments. The period of study for the measured sediment yield was one year while Le Roux *et al.* (2015) estimated sediment yield over a period of 4 years. The modelled sediment yield is greater than measured sediment yield by 1.5 t/ha/yr, 27% greater than the measured estimate.

5.2.2 Suspended Sediment Source Areas

Sediment sources are identified spatially (provenance) or by type (e.g. gullies and land use). This study identified sediment source areas through a two-step process.

The first step involved the measurement of the relative sediment contribution from each sub-catchment so as to identify which areas generate more sediment, have high erosion rates and should be prioritised for rehabilitation. The measured suspended sediment flux results were presented in Section 5.2. In this section, maps are used to show and compare the measured results and the modelled output from Le Roux *et al.* (2015) for sediment contribution at sub-catchment and quaternary catchment scale, respectively.

The second step was to identify the factors that affect the major contribution from the main sub-catchments by considering the similarities in the characteristics of each sub-catchment to give indications of which sediment source types are likely to cause high erosion rates in the Inxu River Catchment, primarily in those areas that generate a lot of sediment. Results are shown the form of maps and tables.

5.2.2.1 The Spatial Distribution of Sediment Sources by Contribution by Sub-catchment

The spatial distribution of the sediment sources was identified through measuring the contribution of sediment by the monitored sub-catchments. Figure 5.13 maps the provenance of the sediment from the Inxu River Catchment based on measured sub-catchment sediment contribution. The SS Yield values are based on the monthly SS Loads results measured by the author (Figure 5.12) because they have a greater spatial coverage compared to the high frequency SS results collected by the technicians. Although monthly and high-frequency data do not show the same results in terms of sub-catchment contribution, they both indicate that the likely major sediment inputs are from the Ncolosi and Qwakele River Sub-catchments.

The measured results from the sub-catchments were compared to previously modelled results which were also described spatially, although the Inxu River Catchment was divided into its quaternary catchments for the modelled output. Figure 5.14 is a map of the sediment contribution from each quaternary catchment of the Inxu River, according to Le Roux *et al.* (2015).

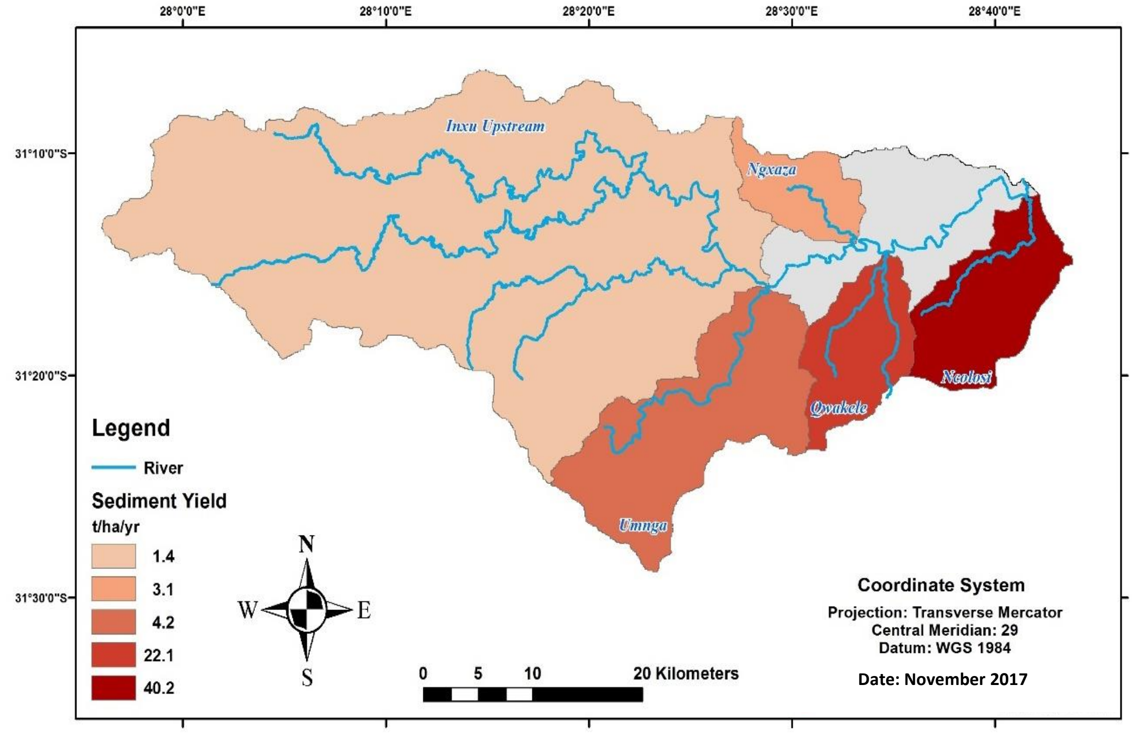


Figure 5.13: Sub-catchment Sediment Contribution based on the Monthly SS Flux indicating Sediment Provenance in the Inxu River Catchment.

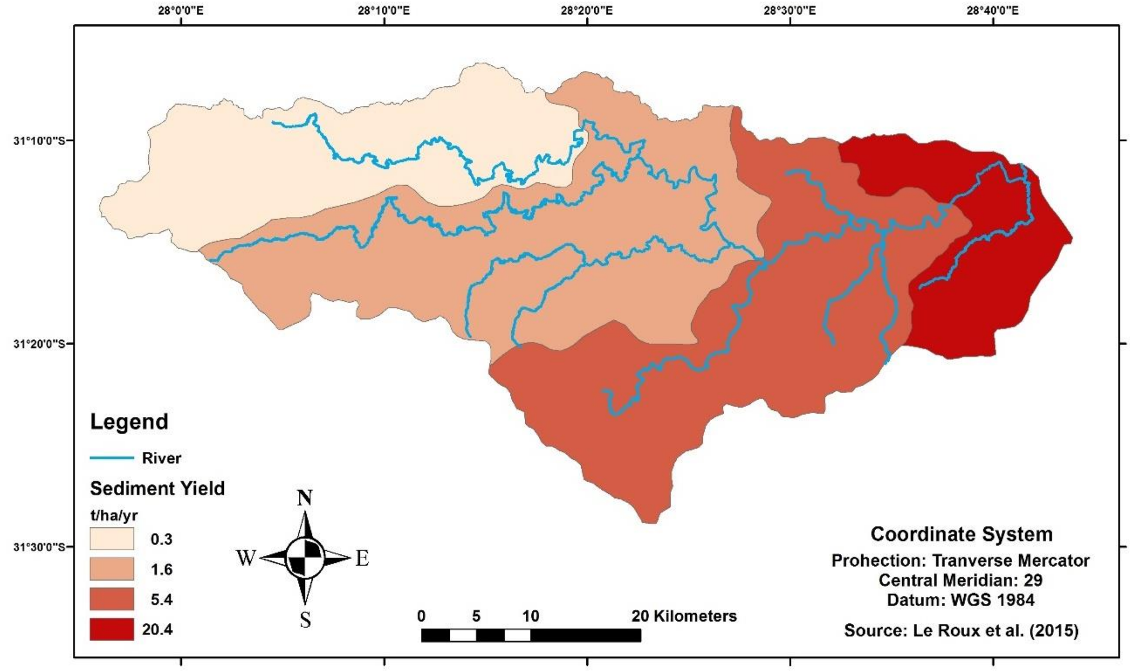


Figure 5.14: Modelled Sediment Yield from Sheet and Gully Erosion for the Quaternary Catchments of the Inxu River (Le Roux *et al.*, 2015).

In both the measured and the modelled data, most sediment was contributed by the lower region of the Inxu River Catchment. Measured data revealed that of the lower Inxu River Sub-catchments monitored in this study, the Ncolosi and Qwakele River Sub-catchments were the dominant contributors of sediment. These sub-catchments lie on the right-hand bank of the Inxu River and are next to each other. The Ncolosi River Catchment Outlet is approximately 1.42 km and the Qwakele River Catchment ~~is~~ 12.51 km from the Inxu River Outlet, straight-line distance

Similarities in terms of sediment provenance were found with the modelled results from Le Roux *et al.* (2015), as explained in chapter 3.6. Their results showed that sediment yield decreased as one travels upstream. Le Roux *et al.* (2015) also found that most of the sediment was from gully erosion compared to sheet erosion.

5.2.2.2 Sheet Erosion Mapping

The erosion potential map is based on sheet erosion and was modelled using USLE factors. This is based on rainfall erosivity, topography, soil erodibility and vegetation cover. The map in Figure 5.15 shows the spatial distribution of soil erosion potential in the Inxu River Catchment, based on the USLE factors. Erosion potential has been categorised into soil loss classes adopted from Le Roux *et al.* (2008).

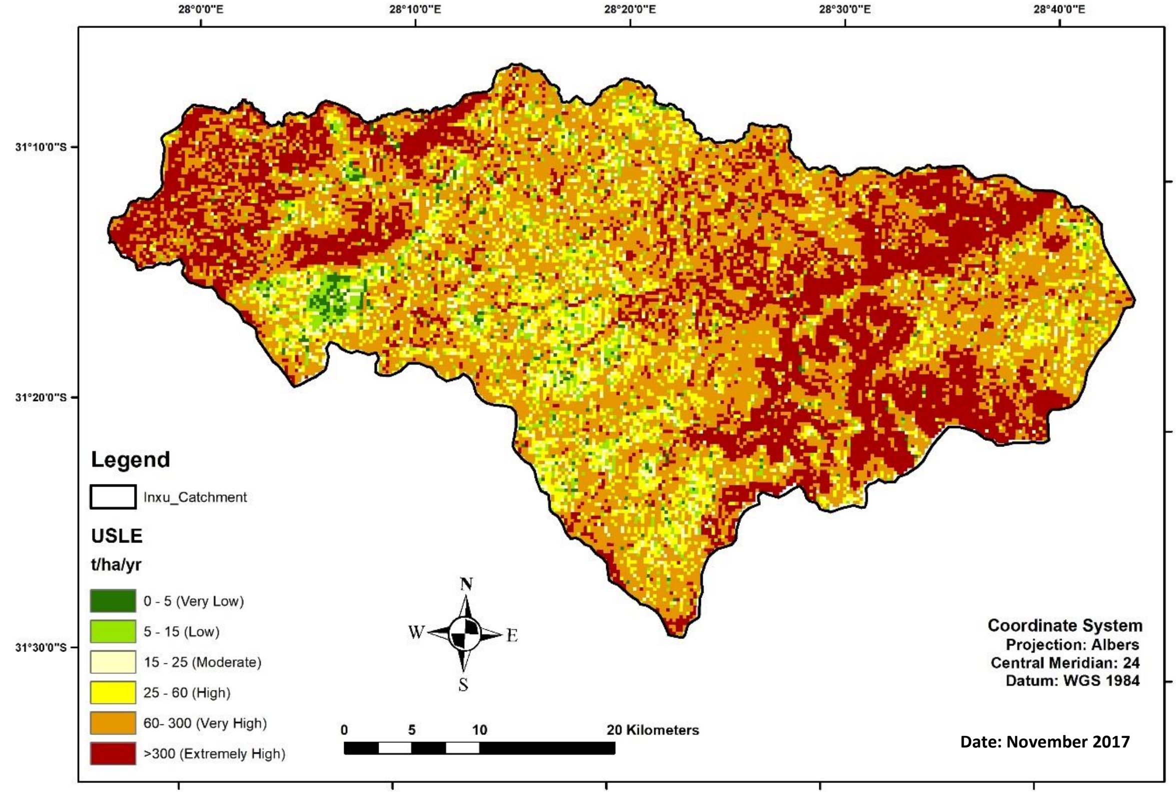


Figure 5.15: Inxu River Catchment Sheet Erosion Map (based on USLE Factors).

The Erosion Potential Map identified areas that were vulnerable to high erosion rates were closely linked to steep slopes. According to the erosion potential map, most of the erosion in the Inxu River Catchment would occur on steeply sloping areas of the catchment. These would have been areas of the upper Inxu River Catchment, Umnga, Qwakele, and Ngxaza River Sub-catchments as well as upper areas of the Ncolosi River Sub-catchment.

5.2.2.3 Gully Erosion

Le Roux *et al.* (2015) suggested that gullies showed higher potential for soil erosion in this catchment. Figure 5.16 is a map that shows the area of each monitored sub-catchment that is gullied.

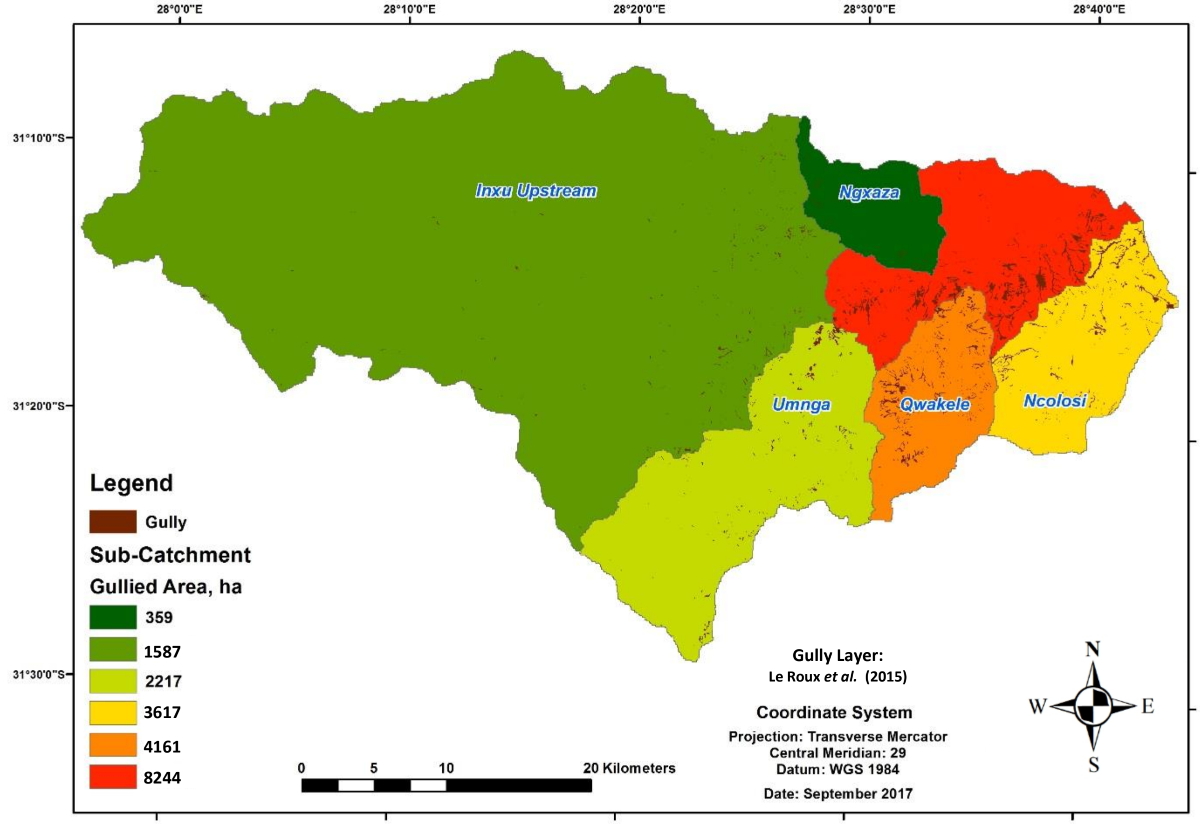


Figure 5.16: Inxu River Sub-catchment Gullied Area Map

The lower Inxu River Catchment was heavily gullied compared to the upper Inxu area. Of the monitored sub-catchments, the Qwakele River Sub-catchment was the most vulnerable to gully erosion followed by the Ncolosi, and upper Inxu. The Ngxaza River Sub-catchment had fewer gullies. The most gullied area of the Inxu River Catchment drains into the outlet of the catchment but was not monitored; it can be assumed to be a significant sediment source for the Inxu. Various factors were considered to explain the cause of gully erosion and the sediment that is generated by each sub-catchment. Gully extent on mapped topography, soil and land cover and use factors was calculated from the SWAT analysis to investigate the conditions under which gullies in the Inxu River Catchment tended to develop (Figure 5.17).

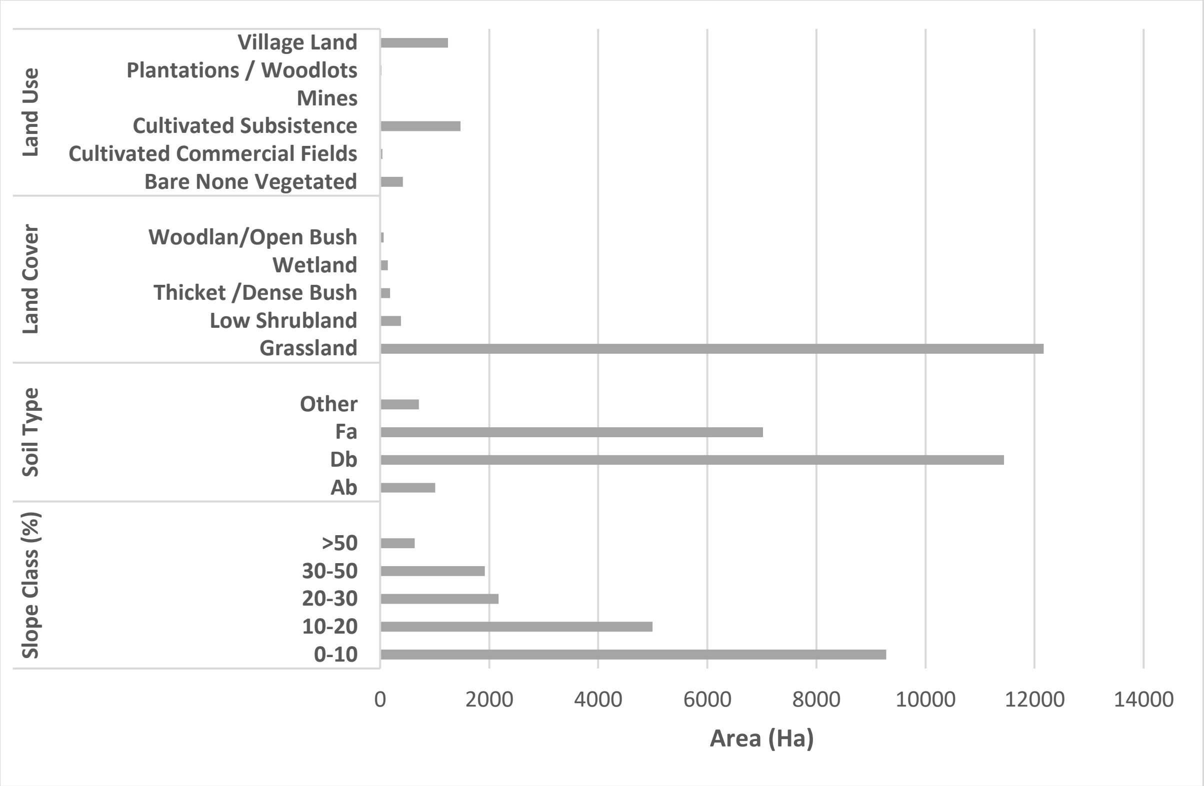


Figure 5.17: Gully extent on slope class, soil type and land cover and use

In the Inxu River Catchment, gullies tend to develop on gentle slopes of 0-10% and to a lesser extent on the 10-20% slopes, on Db soils and to a lesser extent on the Fa soils, mostly on grassland compared to other land cover classes as well as village land and subsistence farms. The land use class most prone to gullying is grassland; gullies are also found on village land ad cultivated subsistence farms.

5.3 Catchment Characteristics and Processes Results

Similarities and differences in the characteristics of each sub-catchment were considered to explain sediment generation and gully erosion. Differences between the characteristics of each sub-catchment makes each catchment unique but their similarities give indications of the possible drivers of soil erosion in this catchment. These characteristics are composed of land cover, topography, soil types, modelled outputs and measured data for sediment provenance and contribution. Table 5.3 gives a summary of the dominant factors for each of the monitored sub-catchments. Values for SS Flux are based on the monthly SS results measured by the author because they have a greater spatial coverage compared to the high frequency SS results collected by the technicians. Maps of the slope class, erodible soils as well as land cover and use, the map and graphs of the rainfall data can be found in the chapter 3.

Table 5.3: Summary of the Inxu River Sub-Catchment Characteristics

	Ncolosi	**Qwakele**	**Ngxaza**	**Inxu Upstream**	**Umnga**
Catchment Area, ha	11 394	8 945	5 880	97 938	21 332
Total Rainfall, mm	214*	680	680	788	680
Dominant Slope Class, %	0-10	30-50	0-10	0-50	20-50
Geology	Tarkastad, Dolerite	Tarkastad, Dolerite	Tarkastad, Molteno	Tarkastad (in Umnga), Molteno and Elliot, Basalts	Tarkastad, Molteno
Erodible Soil Type(s)	Duplex soils (Db), Freely drained soils (Ab)	Easily weathered (Fa), Duplex soils (Db)	Freely drained soils (Ab)	Easily weathering (Fa)	Easily weathered (Fa), Duplex soils (Db)
Dominant Land Cover and Use	Grassland, Subsistence farms, Rural residential areas, a few wetlands.	Grassland, Subsistence farms, Rural residential areas.	Cultivated Subsistence farms, Rural residential areas.	Grassland, Plantation, Commercial farms, Wetlands, Urban residential areas.	Grassland, Subsistence farms, Rural residential areas, a few wetlands
Gullied Area, ha	3 617	4 162	359	1 587	1 586
Gully Density, ha/ha	0.31	0.47	0.06	0.02	0.07
Monthly Sediment Contribution, %	51	22	2	15	10

*rain gauge was faulty

The sub-catchments that have the greatest sediment contribution differ in catchment size, dominant slopes, gullied area and some of the land cover. The Ncolosi River Sub-catchment has a bigger catchment area compared to the Qwakele River Catchment (the second biggest SS contributor) and is dominated by gentle slopes. Both sub-catchments were widely gullied and underlain by highly erodible duplex soils found particularly in the lower areas of each sub-catchment, underlain by the Tarkastad Formation. The Ncolosi River Sub-catchment also contains Ab soils which are suitable for subsistence farming activities as these soils are less easily eroded. These Ab soils occur in the upper areas of the Ncolosi River Sub-catchment.

In addition to Db soils, the Qwakele River Sub-catchment, which was the most gullied sub-catchment of those that were monitored, is dominated by easily weathered Fa soils. Fa soils are found on steep slopes and the Qwakele River Sub-catchment is dominated by these slopes. Field observations showed that gullies in this catchment were prominent on footslopes which were gently sloping. Like the

Ncolosi River Sub-catchment, duplex soils dominate in the lower Qwakele River but are mainly found on its gentle slopes. Both sub-catchments are dominated by grassland and the area is used for subsistence farming and dense rural residential areas. The Ncolosi River Sub-catchment has very few and small wetlands.

The Ngxaza, Umnga and upper Inxu River Sub-catchments provided the lowest sediment contribution during the study period. The area of the upper Inxu is more than half of the area of the Inxu River Catchment as a whole. Given this, the area has a wide variety in land use and cover, soils and slope classes. The town of Ugie and commercial farms are found in the area where Ab soils occur. The easily erodible Fa soils are also found in areas that are dominated by steep slopes. The upper Inxu is also dominated by wetlands.

The Umnga and the Qwakele River Sub-catchments have similar characteristics in terms of topography, soils as well as land cover and use, although the Umnga River has a bigger catchment area. The Umnga River Catchment is dominated by steep slopes with easily erodible Fa soils, but a small area of the lower catchment contains duplex soils. The Umnga River Sub-catchment is dominated by grasslands and the area is used for subsistence farming and contains densely populated rural residential areas. However, some areas of the upper Umnga River Sub-catchment have wetlands.

Ngxaza River is the smallest catchment. It barely made any sediment contribution and is the least gullied. Although it is dominated by freely drained soils, the lower areas of this catchment, where gentle slopes and gullies occur, are underlain by duplex soils. The area is populated by rural communities and is used for subsistence farming.

5.4 Chapter Summary

The Q-SSC relationship for the Inxu River Catchment demonstrated that the Inxu River Catchment follows the typical cycle for suspended sediment dynamics where sediment availability in the catchment is high at the beginning of the wet season (sediment preparation) and gradually decreases over time (sediment exhaustion). The sediment preparation phase is dominated by sediment peaks that precede discharge peaks, and the opposite is true for the sediment exhaustion phase. Sediment peaks that precede discharge peaks were prominent, suggesting that sediment is derived from areas that are in close proximity to the Inxu River Catchment Outlet. Multiple peaks, at the Inxu River Catchment scale, demonstrated the arrival of sediment from local and distal areas of the catchment and may indicate local processes that occurred in the late stages of the flood event.

At the catchment and sub-catchment scales, the Q-SSC relationship demonstrated that most of the sediment was transported during flood events. Results from the Inxu River Outlet suggested that the biggest flood event, which transported most of the sediment, was in February. High frequency sediment monitoring recorded only one flood event, in November, and monthly baseflow sediment flux monitoring found that, for these four sampling sites, most of the sediment was transported in January.

Both sediment flux monitoring temporal resolutions suggest that most of the sediment is contributed by the Ncolosi and Qwakele River Sub-catchments, both of which are situated in the lower Inxu River Catchment. Of the sub-catchments that were monitored in this study, the Qwakele River Sub-catchment was the most gullied catchment, followed by the Ncolosi River Sub-catchment. In both catchments, gullies occur predominantly in gently sloping areas. From Figure 5.16, it can be seen that the most gullied area of the Inxu River Catchment is near the catchment outlet but was not an area that was monitored.

In addition to widespread gullying, the catchments that contribute the most sediment are underlain by highly erodible soils and a land use cover of subsistence farming and high density rural residential areas.

Sediment provenance based on sub-catchment contribution in this study is similar to previously modelled output by Le Roux *et al.* (2015). The sheet-rill erosion model shows different sediment source areas compared to measured data and gully erosion.

6 Discussion

This chapter interprets the sediment dynamics that were investigated in this research based on the findings presented above. The structure of the chapter is based on the objectives listed in Chapter 1 and demonstrates how research questions for this study have been answered. Limitations for this research are stated at the end of the chapter.

6.1 The Suspended Sediment Contribution of The Inxu River Catchment

Suspended sediment is the most transported sediment particle in fluvial systems (Nadal-Romero *et al.,* 2008a). Investigating the dynamics behind suspended sediment flux, therefore, gives insight on key erosion processes that are at play in the catchment and indicates how (dis)connected a system is (Bracken *et al.,* 2015). Suspended sediment is a key indicator of sediment transport and delivery processes that are at play at different temporal and spatial scales (Rovira and Batalla, 2006; Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b; Nadal-Romero and Regüés, 2010). Thus, investigating suspended sediment requires knowledge of sediment dynamics at all possible scales (Collins and Walling, 2004).

In this study, the Q-SSC hysteretic relationship was used to investigate the variability of suspended sediment flux over the seasonal and event scales and determine how sediment flux was affected by sources at various spatial scales. The shape of the Q-SSC relationship demonstrates sediment transportation and delivery processes (Rovira and Batalla, 2006) at different spatial and temporal scales and is interpreted through the lag time between sediment and discharge peaks (Lefrançois *et al.,* 2007). The distribution of sediment peaks depends on the availability of erodible sediment in the channel and the capacity of the event to transport the available sediment (Rovira and Batala, 2006; Lefrançois *et al.,* 2007).

A single hydrological year was investigated in this study. Consequently, the Q-SSC relationships were limited to observing a single wet season and event scale observations that were within this season. At the seasonal scale, the Q-SSC relationship showed that sediment and discharge peaks of different amplitude and duration occurred at different times throughout the year (Figure 5.1). The seasonal scale can be divided into the wet and the dry seasons (Nadal-Romero and Regüés, 2010). The Inxu River Catchment receives summer rainfall, hence the wet season was observed between November and February. The dry season was characterised by low base flow conditions, and sediment concentrations were generally low and steady. However, prior to the beginning of the wet season, a short duration snow event occurred in July 2016. The wet season was characterised by variable discharge peaks as flood frequency and duration increased, thus sediment response was highly variable. Furthermore, base flow conditions were elevated compared to the dry season and the sediment response associated with these base flows were higher and more variable. Elevated base flow conditions in the wet season had low but highly variable sediment peaks due to the increased energy of discharge which enabled more sediment to be transported, an increased sediment supply in the channel from the floods and the arrival of sediment from other sources.

Base flow conditions are high frequency, low magnitude events (Bracken *et al.,* 2015). They have a low transportation capacity; thus, deposition would be high during these conditions. As a result, base flow conditions transported low volumes of suspended sediment over short distances (Bracken *et al.,* 2015), storing sediment along the path (Nadal-Romero and Regüés, 2010). Therefore, base flow conditions did not contribute much to the sediment load, even though they were prominent throughout the year. Base flow conditions assisted in accumulating sediment in the channel, increasing the sediment stock and availability prior to the wet season which has high magnitude, flood events.

High concentrations of suspended sediment transported at the beginning of flood events were prominent at the beginning of the wet season. Hence the Q-SSC relationships at this stage of the wet season were dominated by sediment peaks that preceded relatively smaller discharge peaks with a longer lag time. As the wet season progressed, the mass of sediment transport could be related directly to the magnitude of flood events – the bigger the flood event, the larger the quantities of suspended sediment were transported. The end of the wet season saw the depletion of suspended sediment as smaller and fewer sediment peaks were observed.

The Q-SSC relationship at the seasonal scale revealed that the Inxu River Catchment went through a similar suspended sediment dynamic cycle as the Mfolozi River in South Africa (Grefell and Ellery, 2009) and the Tordera River in Spain (Rovira and Batalla, 2006). This was in terms of the sediment preparation and exhaustion phases of suspended sediment dynamics, shown by the increased sediment transport, stock and availability during the dry – and the beginning of the wet – season and the depletion of sediment at the end of the wet season. Event scale observations are useful in determining the processes that govern these sediment flux patterns and infer possible sediment sources based on the shape of the Q-SSC relationship (Rovira and Batalla, 2006; Nadal-Romeo and Regüés, 2010).

At the event scale, the Q-SSC relationship for the Inxu River Catchment was used to analyse events of high sediment transport. These were made up of three floods and one snowmelt event which was catchment-wide (see figures 3.3 and 3.4). The Q-SSC relationship for the snow event was composed of a low discharge-high SSC event, relative to the floods, characterised by temporarily variable SSC and Q peaks that resulted in a multiple-peak hysteretic relationship. Due to the multiple peaks, sediment sources during the event could not be determined easily. Furthermore, there was minimal variability in the load and it is not clear whether the event is dominated by sediment or transport processes.

Sediment transport processes related to snowmelt are not well documented in the South African context as only certain areas experience snow events and snow does not remain frozen for extended periods. When snow melts, discharge increases and can transport higher quantities of sediment. The snowmelt process is slow, hence low discharge levels that had variability were observed during the snow event (Figure 5.2). Moreover, snow falls gently on the soil surface therefore snow erosivity is minimal. Soil loss, therefore, relies heavily on entraining lose particles. The snowmelt event occurred in the dry season, when sediment stock is high and vegetation cover is low, availing large quantities to be transported by this event.

Floods have a high transportation capacity which enables them to carry high suspended sediment concentrations over long distances, increasing sediment loads further downstream (Rovira and Batalla, 2006). This is why 93% of the sediment yield was related to floods. The magnitude of floods influences the mass of sediment that is transported. Over the wet season, the general trend was that the greater the magnitude of the flood, the higher the sediment load. Hence the largest flood event (16 February – 07 March 2017) transported the most sediment.

During the first flood events of the wet season (November and January), the major sediment peak preceded the discharge peak. Sediment peaks that precede discharge peaks can indicate sediment inputs from local areas or sources (Rovira and Batalla, 2006; Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b). This sediment is usually associated with the channel through various processes. Sediment may have accumulated in the channel during base flow conditions, increasing the quantity of sediment that is available to be remobilised by flood events. In addition to remobilising sediment that was deposited in the channel, floods also transport sediment from the channel banks. Local sources for suspended sediment associated with channel banks include connected gullies which deposit sediment directly into the channel. Tributaries near the monitoring point on the Inxu River, such as the Ncolosi and Qwakele River Sub-catchments, as well as activities that disturb the banks and channel beds, are considered as local sources for suspended sediment (Lefrançois *et al.,* 2007). In the Inxu River Catchment, it was observed that cattle trampling on the banks and other activities such as sand mining could be associated with the channel erosion. Sand mining is quite prevalent during the dry season. It could have accounted for SSC peaks during baseflows in the dry seasons but may have not been a significant sediment source during the wet season. Vegetation cover increases during the wet, summer season, creating opportunities for cattle grazing that result in increased cattle trampling. Cattle trampling leads to the destruction of channel banks (Lefrançois *et al.,* 2007).

In the flood event observed in February to March, the major sediment peak occurs after the major flood peak. Sediment peaks that follow discharge peaks indicate the arrival of sediment from distal, catchment wide sources such as tributaries, hillslope and land use activities that occur in the upper catchment or delayed channel processes such as bank collapse (Lefrançois *et al.,* 2007). These peaks may also be associated with spatial rainfall patterns. Rainfall data from various areas of the catchment (Figure 3.3 and 3.4) showed that the upper area often experienced heavy, and in some instances, erosive rainfall prior to a flood event or discharge peak, measured at the catchment outlet.

Each event had multiple sediment and discharge peaks, and the amplitudes of the secondary sediment peaks were not more than half the amplitude of the major sediment peak. These peaks did not have a clear association with local discharge patterns. They indicate the depletion of sediment during a flood event, delayed soil loss processes that occurred locally, sediment that arrived from distal areas of the catchment, and may be related to rainfall variability across the catchment. Local processes would include recently deposited sediment on the channel from low flows and saturated channel banks, and local sources include nearby gullies and areas disturbed by land use activities. Distal sources would include tributaries, hillslopes and other erosion-prone land use areas across the catchment.

Field observations were not conducted to support the above-mentioned hypotheses. However, given that high flow events transported most of the sediment, rainfall and high flow events from sub-catchments had a strong link with secondary sediment peaks as well as the multiple peak patterns associated with distal sources. Generally, flood events from all tributaries could have occurred at least a day before sediment and discharge peaks were observed at the Inxu River Catchment Outlet, as observed in the rainfall data (Figure 3.3 and 3.4).

Sediment loads associated with the Q-SSC relationships showed different stages where the load was dominated by either sedimentological or hydrological processes. Since most flood events showed that sediment is derived from local sources, the loads in the Inxu River Catchment may be derived from erodible soils from lower catchment slopes, sediment inputs from the catchment of nearby tributaries (the Ncolosi and Qwakele Tributaries in the case of the Inxu River) as well as a sediment sources, such as gullies, that enhance lateral linkages and connectivity in the catchment.

6.2 The Relative Suspended Sediment Contribution of The Major Inxu River Sub-Catchments

The suspended sediment contribution from the major sub-catchments from both high-frequency and monthly sampling resolution was observed in terms of sediment flux at different temporal scales. To compare sediment contribution from each sub-catchment, suspended sediment flux was observed over periods where sediment samples were collected at all monitoring points.

High frequency sampling was inconsistent and irregular, therefore trends for suspended sediment flux for each site were not clear. The data was dominated by baseline samples and one flood event period. Over base flow conditions, the Qwakele and Umnga River Sub-catchments contributed the most sediment. The Umnga Sub-catchment often had higher loads throughout the observed period for the high frequency data. Because the catchment of the Umnga is relatively large, it is possible that baseline samples were collected ahead of or following flood peaks. Therefore, higher SSC would have been available for transportation at the beginning of the flood or would have been recently delivered at the tail end of a flood. Rainfall data from Rain Gauge C (Figure 3.5) suggests that both cases may be true as increased rainfall before or after the samples were collected would have elevated discharge levels. This hypothesis would need to be supported with flood data. Due to the lack of flood sediment data, processes that govern the mass of sediment that was contributed by these two sub-catchments could not be determined.

Most of the sediment was transported on 08-12 November 2016 by the Ncolosi and Qwakele River Sub-catchments. The Ncolosi River Sub-catchment had higher discharges and a sustained sediment supply, relative to other sub-catchments. The Qwakele River Sub-catchment had a short lived, high sediment concentration that declined during the latter part of the flood.

The Q-SSC relationships that were observed from all sites over the flood events showed that sediment and discharge peaks occurred simultaneously. These peaks indicated that the sediment transport processes from all sites were not restricted during the event (Lefrançois *et al.,* 2007). In other words, discharge had sufficient carrying capacity to transport the available suspended sediment. Moreover, sediment loads did not have a distinct and single driver since both Q and SSC peaks occurred simultaneously. Given that this was the only flood event period that was monitored across all sub-catchments, it was difficult to tell whether sediment from these catchments was from local or distal sources. Secondary peaks may occur due to delayed channel processes, the arrival of sediment from other tributaries within the sub-catchment or may be linked to channel disturbance (Lefrançois *et al.,* 2007) but there is no data to support these hypotheses. Due to these limitations, it was difficult to determine dominant sediment processes and sources for suspended sediment within the sub-catchments using Q-SSC relationships.

Monthly sediment samples offered a better spatial and temporal resolution as the sediment contribution from all sub-catchments could be observed between November 2016 and March 2017; but all of the data was collected over base flow conditions. Monthly sediment flux suggested that the period of high sediment transport was in January 2017 and most of the sediment was transported by the Ncolosi River Sub-catchment. The seasonal trends from the Inxu River Outlet (Figure 5.1) support these findings as higher base flow levels were observed during this period of the wet season and higher concentrations of sediment were transported during this period, compared to base flows that occurred over the dry season.

Both sampling frequencies identified similar sediment source areas at the catchment scale: most of the sediment was contributed by the lower Inxu River Catchment. This was supported by the observations made from the Q-SSC relationships at the Inxu River Catchment Outlet (section 5.1.1), showing that sediment sources were located near the catchment outlet. However, monthly data singled out the Ncolosi River Catchment as a major sediment source area. The Ncolosi River Sub-catchment was situated at close proximity to the Inxu River Outlet. The Qwakele River Sub-catchment also contributed significant masses of sediment, followed by smaller volumes from the Umnga and the upper Inxu River Catchment. Both sampling frequencies also agreed that the Ngxaza River Sub-catchment (also situated in the lower catchment) barely contributed sediment.

6.3 Sediment Source Areas

Investigating similarities and differences in the factors that affect sediment contribution enabled the identification of both sediment source areas as well as the dominant sediment processes in the Inxu River Catchment. Sub-catchment contribution identified the lower Inxu River Catchment as the area that contributed the most sediment. Within this area, the Ncolosi River Sub-catchment contributed the most sediment followed by the Qwakele River Sub-catchment. Common features of these catchments include soil type, land use and widespread gullying.

6.3.1 Soils

High sediment yield was expected and observed in areas whose soils were derived from the Tarkastad Formation. The Tarkastad Formation has a high prevalence of duplex soils (Db soil type) compared to other Formations (Laker, 2004). Duplex soils are highly erodible (van Tol *et al.,* 2010) and dominate gentle slopes of the lower Inxu River Catchment along the channel, particularly the lower Qwakele River and Ncolosi River Sub-catchments and to a lesser extent the lower Umnga and Ngxaza River Sub-catchments. Van Tol *et al.* (2014) expected high sediment yield in the site of the proposed Ntabelanga Dam due to duplex soils.

Van der Waal *et al.* (2015) and Rowntree *et al.* (2017) found that areas underlain by mudstone in the Vuvu Catchment (a catchment that is similar to the Inxu River Catchment in terms of rainfall, size, components of the geology and land use) were dominant sediment source areas due to high soil erosion rates. The Tarkastad Formation was found in the lower Inxu, and the Elliot and Molteno Formations dominated the upper Inxu.

The Molteno Formation is dominated by soils that are more resistant to erosion and are preferable for land productivity. Erodible soils in the Molteno Formation are the Fa soils which are found on steep slopes. Though the upper Catchment contains soils from the Elliot Formation, these erodible soils may be trapped by wetlands in the upper Inxu River, reducing sediment input from the upper Inxu River, and hence causing the lower sediment loads.

6.3.2 Land Cover and Use

Erosion is expected to occur at a high rate in areas where soils are frequently disturbed (Le Roux and Sumner, 2012) and van Tol *et al.* (2014) found that sediment yield was higher in areas where land use practices were inappropriate. Le Roux and Sumner (2012) found that grassland in the Tsitsa River Catchment, which is the dominant land cover in the area, was susceptible to erosion when degraded.

Overgrazing, cattle trampling, and dense rural populations have played a role in accelerating soil erosion and the consequent land degradation in the Tsitsa River Catchment (van Tol *et al.,* 2014) and other areas of the Mzimvubu River Catchment (Rowntree *et al.,* 2017; van der Waal *et al.,* 2017). The Inxu River Catchment shows evidence of the consequences of this as land use in the Inxu River Catchment differs between the upper and the lower catchment (Figure 3.6).

The upper Inxu River Catchment is where minimal erosion occurred. In this area, the land is used for commercial farming and forest plantations. Wetlands, which trap sediment, dominate in this part of the catchment. Furthermore, it was observed that this area was not densely populated, compared to the lower catchment.

The lower catchment has high erosion rates. This part of the catchment is densely populated, has village land and has small subsistence farms. The Ncolosi and Umnga River Sub-catchments contain more subsistence farms and village land than the Qwakele and Ngxaza River Sub-catchments. The difference between Ncolosi and Umnga Rivers is that Umnga is underlain by soils from the Molteno Formation which are more able to sustain land productivity compared to the soils from the Tarkastad and Elliot Formations, found in the Ncolosi River Sub-catchment, which are highly erodible. Further erosion may occur in areas where degraded grassland is found. From a land use perspective, erosion in the Ncolosi River Sub-catchment is likely to be exacerbated more than other areas of the Inxu River Catchment due to the soils.

Village land systems are often densely populated by people who live in a rural setting and impoverished conditions (van der Waal, 2014). In his research in the Vuvu River Catchment, van der Waal (2014) found that intensive use of resources was closely related to dense populations on village land.

Like other parts of the Eastern Cape, the region where the Inxu River Catchment lies is known to have exacerbated erosion due to cultivation followed by abandonment, frequent burning as well as on-going grazing pressure (van der Waal, 2014). Kakembo and Rowntree (2003) found a strong relationship between land use change, especially within village land, and gully initiation and intensification in the Peddie District. In the Peddie case, it was closely related to abandoned cultivated land. Factors that have led to the abandonment of cultivated land include the introduction of grants and the increase of pension payments. This provided alternative livelihoods, reducing people's dependence on subsistence farming practices. Furthermore, periodic droughts have discouraged cultivation as droughts have reduced farming productivity and exacerbated erosion rates. The current study was conducted over a moderately dry period. Erosion may have been exacerbated during this period due to low vegetation cover. However, the effects of land use change, climate change and erosion rates were not the focus of this study and have not been investigated. In the Tsitsa River Catchment, van Tol *et al.* (2014) found that areas where productive soils were found, Ab soils, tended to be vulnerable to high erosion rates as old abandoned cultivated land were found on these soils.

In addition to abandoned cultivated land, overgrazing, cattle trampling, and frequent burning have led to high erosion rates in the area and have resulted in the development of erosion features (van der Waal, 2014) such as river incision (Lefrançois *et al.,* 2007) and gullies (Kakembo and Rowntree, 2003).

6.3.3 Gully Erosion

Gully initiation and development are affected by rainfall and hydraulics such as those of critical shear stress, soils and geology, vegetation cover and type, land use, as well as topographic factors (Kakembo *et al.,* 2009) while the variability of gully location occurs because of landscape heterogeneity (Le Roux and Sumner, 2012). None of the above-mentioned factors supersedes the other (Kakembo *et al.,* 2009); however, Le Roux and Sumner (2012) found that topography, soil and land use factors were the main drivers for gully initiation and development in the Tsitsa River Catchment, which the Inxu River Catchment is part of. For this reason, gully extent on topography, soil and land cover and use factors was calculated to investigate the conditions under which gullies in the Inxu River Catchment tended to develop (Figure 5.17). In the Inxu River Catchment, gullies tend to develop on gentle slopes, Db and Fa soils, grassland, village land and subsistence farms.

Le Roux and Sumner (2012) conducted studies on the factors that controlled gully development in the Tsitsa River Catchment, where they compared connected and disconnected gullies. Connected gullies were regarded as gullies whose mouth drained into the river channel, increasing sediment inputs and lateral linkages, and therefore connectivity in the catchment. Disconnected gullies, on the other hand, were those whose mouth did not reach the channel, thus sediment would remain on the hillslopes for long periods. They acted as buffers on the hillslopes, reducing lateral linkages and sediment inputs to the channel, and therefore reducing connectivity in the catchment.

Le Roux and Sumner (2012) found that gullies in the Tsitsa River Catchment occurred, mainly, in areas where the slope gradient was gentle (less than 10^0), areas that had a large critical drainage area and a concave slope curvature as flow would concentrate on preferred pathways. Concave slopes were common on foot slopes and valley bottoms (Kakembo *et al.,* 2009). Furthermore, these gentle slopes had a high topographic wetness index, meaning that soils would become easily erodible because of increased saturation (Kakembo *et al.,* 2009; Le Roux and Sumner, 2012). These conditions were critical for gully initiation in this area and connected gullies were found mainly under these conditions. Furthermore, these gullies were prevalent on the mudstones from the Tarkastad Formation. Table 5.3 shows that most gullies occurred on duplex soils (Db) which are notorious on the Tarkastad Formation.

Disconnected gullies, on the other hand, tended to develop on steeper slopes (Le Roux and Sumner, 2012). However, due to the decrease in the critical drainage area required for gully initiation, gully erosion was limited on steep slopes and less prevalent at the Tsitsa River Catchment scale. The development of disconnected gullies on steep slopes was promoted by the shallow soils that occur on steep slopes in this catchment, the soils from the Fa soil type. Furthermore, steep slopes were less vulnerable to gully erosion since land use activities such as ploughing are not likely to occur on steep slopes, compared to gentle slopes.

Generally, most gullies were found on village land and subsistence farms. Gully development was prevalent in cultivated areas (Le Roux and Sumner, 2012) due to the removal of vegetation that is replaced by cultivation techniques that disrupt the soil structure (van Tol *et al.,* 2014). Le Roux and Sumner (2012) also found that degraded grassland areas were vulnerable to gully erosion as most gullies were found on grassland. Areas that contained shrublands were vulnerable to erosion as shrublands reduced vegetation cover, exposing the stones and fine sediments (Boardman *et al.,* 2003). This increased runoff and made the surface vulnerable to rainfall-runoff erosivity (Fox and Bryan, 2000).

The Qwakele River Sub-catchment had the largest area that was gullied of the sub-catchments that were monitored and was one of the catchments that contributed the most sediment. The topography of this catchment is mainly steep and footslopes, which are gently sloping, are found in the lower catchment. Furthermore, duplex soils on gentle slopes, associated with the Tarkastad Formation, and shallow soils on the steep slopes, are found in this catchment. This catchment, therefore, is dominated by conditions that promote both connected and disconnected gullies, which is the likely reason why it had most gullies compared to other catchments. Given that the area is dominated by steep slopes and shallow soils, it is likely that most gullies in this catchment are disconnected. With disconnected gullies, sediment remains on the hillslopes for extended periods. Connected gullies, which are probably fewer than disconnected gullies in this catchment, would occur mainly on footslopes where the slope gradient was gentle, and the slope curvature was concave all the way up into the mid-slopes. This was confirmed by field observations.

The catchment of the Ncolosi Tributary, which was the other catchment that produced the most sediment, was predominantly gentle and was dominated by duplex soils of the Tarkastad Formation, and some areas where soils from the Elliot Formation could be found. The Ncolosi River Sub-catchment, therefore, contributed a lot of sediment because most of the gullies that occurred in this area were likely to be connected gullies. Thus, the catchment contributed more sediment because it is more connected compared to other sub-catchments that were monitored in this study. Furthermore, erosion was expected to be higher in the Ncolosi River Sub-catchment due to the land use that was found on the erodible soils, as explained in Section 6.3.2.

Gullies in the Ngxaza River Sub-catchment were also found on gentle slopes and duplex soils. However, the area was very small, hence this catchment barely made any contribution compared to other sub-catchments. Gullies in the Umnga River Sub-catchment were also fewer compare to the Ncolosi and Qwakele River Sub-catchments. However, they occurred on similar topographic features as the Qwakele River Sub-catchment, meaning that most of the gullies in this area could be disconnected, compared to connected gullies. The upper Inxu River Catchment had both steep and gentle slopes, as well as the Fa soils but did not suffer from gully erosion to the extent that the lower catchment did. Furthermore, most of the upper Inxu River is dominated by stable soils found on the Molteno Formation and sediment is potentially trapped by wetlands in this area.

6.3.4 Sheet Erosion

Sediment yield from sheet erosion was modelled using USLE factors (Figure 5.15). This model also identified areas in the lower catchment as being vulnerable to erosion. However, the model identified areas where steep slopes occurred to be the areas where most erosion occurred. Results from USLE suggested that the Qwakele River Sub-catchment, one of the areas that contributed the most sediment, was vulnerable to sheet erosion due to the steep slopes. So was the Umnga and Ngxaza River Sub-catchments. However, the model suggested that, since the Ncolosi River Sub-catchment did not show high vulnerability to sheet erosion, the Ncolosi River Sub-catchment was not a major sediment source, which is contrary to measured data. Since the USLE model is selective on catchment features that are highly erodible, the model would not have been a reliable technique to use to investigate sediment source areas.

One difficulty with the application of the USLE equation to simulate erosion in South Africa is that the South African landscape is very heterogeneous (Laker, 2004). Thus, dominant soil loss factors differ across the landscape. The USLE model can be an effective model to use in areas where topographic factors such as slope drive sediment processes (Le Roux *et al.,* 2007). The USLE relies on the assumption that erosion increases with increasing slope (Le Roux *et al.,* 2007). However, that was not the case for the Inxu River Catchment, and other areas in South Africa (Kakembo *et al.,* 2009; Laker, 2004; Le Roux and Sumner, 2012). Dominant erosion processes in the Inxu and Tsitsa River Catchments (Le Roux and Sumner, 2012) as well as the Sneeuberg, Great Karoo (Boardman *et al.,* 2003) and the Peddie district (Kakembo *et al.,* 2009) occurred on gentle slopes. Moreover, in the case of the Inxu River Catchment, the main drivers of soil erosion are soil erodibility, land cover and land use, in addition to topographic factors.

In areas where the dominant erosion process is gully erosion, as in the case of the Inxu, Tsitsa and Mzimvubu River Catchments, as well as the Peddie district (Kakembo *et al.,* 2009), sediment yield values derived from sheet erosion underestimate sediment inputs from gully erosion and misrepresent sediment yield, erosion processes and catchment connectivity. According to Merritt *et al.* (2003), de Vente *et al.* (2008) and Le Roux *et al.* (2015), very few studies consider other forms of erosion such as gully erosion, channel erosion and mass movement, the effects of deposition and spatial patterns of sediment delivery. Moreover, these few sediment transport models often require high data inputs (de Vente *et al.,* 2008).

The limited ability for USLE to identify areas that are vulnerable to other forms of erosion emphasises the importance of measured data for calibration and validation of models (Jain and Kothyari, 2000; Merritt *et al.,* 2003; Chen and Mackay, 2004; Gassman, 2007; Gao, 2008; Xu *et al.,* 2009; Arnold *et al.,* 2012a; Arnold *et al.,* 2012b; Le Roux *et al.,* 2013; van Zijl *et al.*, 2013; Le Roux *et al.,* 2015) as relying on the modelled results would have resulted in the identification of fewer sediment source areas at the sub-catchment scale, poor identification of a secondary sediment process and the underestimation of the influence of gentle slopes, dispersive soils and gully erosion.

6.3.5 Comparing Previously Modelled Results with Measured Suspended Sediment Data.

Previous studied have shown that areas of the Inxu River Catchment have the biggest erosion potential at a national scale (Le Roux *et al.,* (2008). Le Roux *et al.* (2015) identified the lower Inxu River Catchment as one of the areas that contribute the most sediment in the Mzimvubu River Catchment, which is the regional scale, and previous suspended sediment concentration studies showed that the Inxu River Catchment contributes the most sediment to the Tsitsa River, at the Tsitsa River Catchment scale (Bannatyne *et al.,* 2017).

Le Roux *et al.* (2015) estimated that the Inxu River Catchment produced 7 t/ha/yr on 2008-2012; while the current study measured 5.5 t/ha/yr over the 2016-2017 hydrological year. With a difference of 1.5 t/ha/yr, the previously modelled sediment yield results are not far from the measured sediment yield, even though the studies were not conducted over the same period and do not have the same temporal and spatial resolution.

In the model, sub-catchment delineation was based on the DWS quaternary catchments which divided the Inxu River Catchment into four areas. The measured data was collected from specific major sub-catchments. Le Roux *et al.* (2015) estimated sediment yield over a period of 4 years before measured data from this study was available. The current study was conducted over a period when rainfall was below average, while the study period for modelled data occurred during above and below average rainfall (Drewitt, 2015).

Both studies produced similar sediment yield values at the catchment and the sub-catchment scale and identified similar sediment source areas across the Inxu River Catchment based on the sediment contribution from sub-catchments that was collected monthly. Le Roux *et al.* (2015) stated that their modelled output lacked measured data that would validate their findings, which was what the current study served to do. The current study confirms that the model developed by Le Roux *et al.* (2015) is a reliable model for determining sediment yield and sediment provenances in the Mzimvubu River Catchment.

6.4 Limitations and Future Research

Conclusions drawn from this study are within the following limitations.

6.4.1 Data Collection Techniques

The researcher used a calendar-based technique to collect suspended sediment samples from sub-catchments. Samples were collected monthly and the calendar-based data set was collected over base flow conditions. Major sediment transport events may occur between sampling periods and, given the length of time between sampling periods over the wet season, it is not surprising that all the major sediment transport events were missed (Evrard *et al.,* 2011; Bannatyne *et al.,* 2017). As a result, critical sediment processes were misrepresented, and temporal variability was not accounted for.

The analysis of observations from the high frequency data were limited to samples that were collected over similar time periods. This was limited to 21 October 2016 – 12 January 2017. This was, a smaller sample period compared to the monthly data. Again, most of the sediment samples were collected over base flow conditions.

Sediment loads during the sampled base flow conditions were very small and would not have given true values for sediment yield. High flow events from high frequency data were misrepresented and major sediment transport events such as the February-March 2017 flood event that was observed at the Inxu River Catchment Outlet, were missed.

In terms of identifying sediment sources, calendar-based data and high frequency data were in agreement with the lower catchment contributing the most sediment; calendar-based data and modelled data identified similar sediment source areas between sub-catchments.

Bannatyne (2017) investigated the effectiveness of the citizen-based monitoring method that was used to collect suspended sediment samples. Key findings from her study which are relevant to this study are as follows.

a) The method was effective for catchments whose area is greater than and equal to the area of the Inxu River. Most flood occurred overnight in the Tsitsa River Catchment, thus most flood events would have been missed since it was dangerous for technicians to collect samples at that time. Therefore, this method was effective in measuring suspended sediment concentrations over flood events and flood peaks that occur during daylight. In Bannatyne's study, discharge data revealed that the period of flood sediment sampling did not coincide with the highest flood discharge because it occurred during the at night. This was the case for all flood events that were observed. Therefore, sediment transport and sediment yield may have been miss-represented and under-estimated.

   For large rivers the flood duration is long, thus there were opportunities for collecting samples over the falling limb of the stream hydrograph. In small catchments, however, the duration of a flood is short, therefore it is easier to miss floods not only because they occur at night but also that they may occur rapidly during the day. An analysis of catchment hydrology would be useful in determining flood peak duration and flood frequency at each monitoring point. This could improve sampling frequency in small catchments.

To account for flood peaks that occur over night, the use of Automatic Pumping Samplers (APS) could have been explored. However, APS are at risk of risk of vandalism and theft and are expensive. Bannatyne (2017) found that employing local technicians was cheaper than the purchase and maintenance cost of APS.

b) The efficiency of this method depends on human attributes. This includes personality, ability and availability. In the case of the Inxu River Catchment, sample collection was inconsistent as technicians who were responsible for collecting samples lived in areas where they could not monitor the river level well and missed flood events, were involved with other activities, lost interest or had other work opportunities. Other reasons included taking care of sick members of the family and bereavement. Other people in the area who were capable of collecting samples were not interested, were not available due to other engagements or their availability was limited by cultural norms. A common issue at the sub-catchment scale was that there were few people that actually live on the area. In some parts of the catchment, most of the houses were left unoccupied.

c) The quality of the data depended on the analysis of SSC samples in the laboratory. Bannatyne *et al.* (2017) found that issues such as dysfunctional ovens and balances that required frequent calibration led to a drift from the true value of SSC. Furthermore, human error was introduced in instances where attention to detail was limited.

6.4.2 Measurement of Sediment Flux

The following sections brings forth the limitations of sediment flux calculations at the catchment and sub-catchment scales.

7.5.2.1 The Inxu River Catchment scale

Patterns for suspended sediment flux were observed over a single hydrological year. This limited observations for sediment flux and sediment transport processes to one wet season and the high sediment transport events that occurred over the specific period. Rovira and Batalla (2006), Zabaleta *et al.* (2007) and Grenfell and Ellery (2009) observed patterns for suspended sediment transport over longer periods of time which enabled them to conduct observations at the event, seasonal and interannual scales. Rovira and Batalla (2006) and Zabaleta *et al.* (2007) conducted studies over 3 years while Grenfell and Ellery (2009) used 6 years-worth of turbidity data to make interannual observations.

For the current study, conclusions on patterns for suspended sediment dynamics could be improved by observing the Q-SSC hysteretic relationships over an extended monitoring period to account for sediment response over different climatic conditions, that is over wet and dry years. Additionally, a wider variety of temporal resolutions could be observed such as annual, seasonal, monthly and event scales.

Monitoring at the Inxu River Catchment Outlet had begun in December 2015 but for the purpose of comparing sediment observed at the outlet to that observed at the sub-catchments for which suspended sediment flux was observed only for 01 May 2016 - 30 April 2017, the analysis was restricted to that time period. An analysis of the full Inxu Outlet data set from December 2015 is recommended. Monitoring at the Inxu River Catchment Outlet will continue for the 2017-2018 hydrological year, so these data can also be included. Thereafter the continuance of sediment flux monitoring will be contingent on the availability of funds.

7.5.2.2 Sub-catchment Scale

Sediment flux monitoring could only be sustained at the sub-catchment scale from 01 May 2016 - 30 April 2017 due to funding constraints. Thus, issues that were faced with sample collection at the Inxu River Sub-catchment scale cannot be improved for the monitored sub-catchments going forward. Primary issues with data collection at the sub-catchment scale included inconsistency in sampling by technicians such that Q-SSC relationships could not be observed at various scale for each sub-catchment; the pressure transducer at the Upstream Inxu monitoring point was faulty, thus available data from high-frequency sampling could not be used as discharges could not be determined. Moreover, only 45 samples were received from this monitoring point due to the unavailability of people from the area who could be responsible for collecting samples at high frequency. Including this site in the analysis would have further limited the number of events that could have been analysed for assessing the relative suspended sediment contribution from sub-catchments.

For this study, the use of high-frequency and monthly sediment flux monitoring was beneficial as both methods could overcome each other’s limitations to a certain degree. Monthly data offered a coarse temporal sampling resolution but provided observations for a longer time span and a wider spatial scale compared to high-frequency sampling. High frequency data offered a finer sampling resolution and could account for base flow and, to some degree, flood event observations within the sub-catchments, while monthly data only accounted for base flow conditions. Base flow conditions do not transport a lot of sediment and do not reflect well the sediment processes behind sediment transport in a catchment. Confidence in the conclusions about the relative sediment contribution of sub-catchments would have been strengthened by observing flood events.

Due to the lack of data and consistency in data collection across the sub-catchment monitoring sites from high-frequency sampling, fewer events could be observed; only one flood period was accounted for. The flood events that were observed in November 2016 could not determine which sub-catchment contributed the most sediment between the Ncolosi and Qwakele River Sub-catchments. However, these observations could be strengthened by increasing the number of flood events that were observed and having a wider temporal range so that seasonal and event-based patterns can be observed. Furthermore, the flood events that were observed did not provide sufficient information on sediment processes at the sub-catchment scale. A longer time span was needed to observe patterns in sediment processes and to strengthen conclusions on sediment source areas within each sub-catchment. Additionally, suspended sediment samples were not collected in the Umnga River Sub-catchment during the November flood event, thus sediment dynamics over flood events from this area could not be determined well. Though high magnitude events tend to be infrequent (Fryirs *et al.,* 2007), they transport the most sediment and provide a better estimation of sediment yield.

6.4.3 The Identification of Sediment Source Types

This study has successfully demonstrated how the use of suspended sediment flux monitoring and desktop techniques could be used to identify sediment source areas based on the analysis of the factors that affect sub-catchment sediment contribution. It has led to the identification of gully erosion as the dominant soils erosion process. However, sediment flux monitoring at the catchment outlet and desktop studies can only be used to infer sediment source types because they do not measure the actual sediment contribution from the gullies (Collins and Walling, 2004; Gao, 2008).

Sediment tracing techniques such as the fingerprint method could be used to verify sediment sources that were identified in this study: that is, whether gullies are the dominant sediment source and what the effects of land use change are. A close look at the effects of land use change on the rates of soil loss requires further investigation and an in-depth analysis as it may be a dominant driver for high erosion rates in the lower Inxu River Catchment.

The fingerprint method is a well-accepted sediment tracing technique used for determining the sources of the sediment that is delivered to downstream areas of a catchment (Evrard *et al.,* 2011; Guzmán *et al.,* 2013; van der Waal *et al.,* 2015). It provides a catchment-wide and integrated representation (Rowntree *et al.,* 2017) of sediment sources and catchment connectivity (van der Waal, 2014). The method discriminates sources by comparing unique properties observed from the sediment that is received downstream to those that match the properties of source from upstream areas (Guzmán *et al.,* 2013).

Source discrimination is based on the already existing physical and chemical properties of soils such as geochemistry, mineral and magnetic properties (Collins *et al.,* 2017; Walling, 2005), cosmogenic radionuclides, fallout radionuclides (Collins *et al.,* 2017), isotopic ratios and bulk stable isotopes, biomarkers, soil enzymes, pollen, particle size and colour (Collins *et al.,* 2017). As a result, there are a variety of fingerprint tracing techniques (Collins *et al.,* 2017) and each tracer that is used must be able to robustly distinguish sources in a given catchment (Walling, 2005; Collins *et al.,* 2017; Rowntree *et al.,* 2017). The tracer that is chosen should be measurable and representative, and tracer properties must be conserved throughout the sediment cascade (Guzmán *et al.,* 2013; Collins *et al.,* 2017).

There may be opportunities for colour tracing in the Inxu River Catchment as soils appeared to have different colours (yellowish-white, red, brown, purple, black) across the catchment. The feasibility of colour tracing has not been determined.

Other sediment tracing techniques can be used to investigate sediment delivery and the rate of erosion at various spatial and temporal scales as they offer insight on the timing of the detachment of sediment, the distance travelled as well as the rate of transportation (Parsons *et al.,* 1993). Tracing techniques could be used to investigate the level of connectivity and validate modelled erosion rates and predictions of the longevity of the Lalini Dam.

6.4.4 Interpretation of results

The interpretation of results concerning gully erosion was further limited by the following;

The gullies that were mapped in this study were not classified into connected and disconnected, or further divided into classes such as active and non-active as well as connected, partially connected, potentially connected and disconnected gullies, as was done by Le Roux *et al.* (2015). As a result, the relative proportions of connected and disconnected gullies are unknown. Geoprocessing selection tools from ArcGIS could have been used to measure the density of gullies that were directly connected to rivers, when the gully and river network layers were overlapped.

Classification of gullies would have provided evidence and a better justification as to why the Qwakele River Sub-catchment was highly gullied but produced similar quantities of sediment as the Ncolosi River Sub-catchment. For this study, justification for this is limited to the dominant topographic and soil factors of the two catchments. It is likely that the Qwakele River Sub-catchment is dominated by disconnected gullies rather than connected gullies. The landscape of this catchment is dominated by steep slopes (where disconnected gullies are likely to form) where erosion is promoted by shallow soils, compared to gentle slopes (where connected gullies are likely to form) which were dominated by dispersive soils in the lower catchment.

The slopes of the Ncolosi River Sub-catchment are predominantly gentle, and the soils are mainly dispersive and hence a greater likelihood of connected gullies, higher sediment inputs into the channel and higher connectivity in the Ncolosi River Sub-catchment. Higher connectivity due to increased lateral linkages would increase sediment yield in this catchment.

Measured data revealed that most of the sediment from the Inxu River Catchment is derived from the lower areas of the Inxu River Catchment and that sediment sources are likely to be situated near the Inxu River Catchment Outlet. However, it was difficult to distinguish, confidently, which sub-catchment contributed the most sediment between the Ncolosi and the Qwakele River Sub-catchments. Measured data are inconclusive at this scale. Moreover, these catchments are different, and their characteristics demonstrate that both catchments are areas that are vulnerable to erosion in the Inxu River Catchment. A detailed analysis of sediment contribution and sediment sources is needed to assist decision making for prioritisation between the two sub-catchments.

<u>The interpretation of results did not account for the following;</u>

1. Deposition, residence time, remobilisation and rate of entrainment. These affect the efficacy of processes that deliver sediment from sub-catchments and the rate at which sediment derived from the Inxu River Catchment could fill the proposed Lalini Dam along the Tsitsa River. This was not the scope of the study. However, sediment delivery models and tracing methods could be used to investigate these factors. Additional monitoring points along the trunk, between sub-catchments that are monitored, could be used to investigate sediment delivery rates.

2. Wetland health. Some of the wetlands may be degraded and not able to provide ecosystem services such as trapping sediment for extended periods. Therefore, they may not act as buffers which disconnect lateral linkages between hillslopes and the channel in all areas of the catchment. This may be the case in the Ncolosi River Sub-catchments as this was the area that produces the most sediment. Wetland health should be determined in the Inxu River Catchment as the health of wetlands that occur in the lower Inxu River may be threatened by gullies.

6.5 Chapter Summary

In the 2016-2017 hydrological year, the Inxu River Catchment produced 5.5 t/ha/yr and, as expected, most of the sediment was transported during flood events, and a snowmelt event. The Q-SSC relationships showed that in this period sediment dynamics in the Inxu River Catchment had gone through the typical cycle of sediment preparation prior to the wet season and sediment depletion at the end of the season. Similar patterns were observed for most flood events as there was more sediment at the beginning of the event, with sediment depletion occurring throughout the event and at the end of the season when the sediment peak was delayed. From the Q-SSC relationships observed at the event scale, sediment peaks that preceded discharge peaks, as well as secondary sediment peaks, indicated that most of the sediment came from local processes and sources which included erodible soils that are derived from the hillslopes, available soils from the channel, sediment inputs from nearby tributaries (the Ncolosi and Qwakele Tributaries in the case of the Inxu River) as well as a sediment sources that enhance lateral linkages and connectivity in the catchment.

Sub-catchment sediment contribution further supported these findings. The sub-catchments that contributed the most sediment were the Ncolosi and Qwakele River Sub-catchments. Both sub-catchments were situated in the lower catchment and close to the outlet. Moreover, connected gullies were thought to be the main source of sediment. Gully distribution was related to soil properties, topography, as well as land cover and land use activities.

The Ncolosi River Sub-catchment contributed the most sediment because it was a highly connected catchment and erosion was further exacerbated in this sub-catchment due to land cover as well as land use change. Though the Qwakele River Sub-catchment had more gullies, most of the gullies were likely to be disconnected gullies due to steep slopes and shallow soils which dominate this sub-catchment. Consequently, the Qwakele River Sub-catchment is less connected, compared to the Ncolosi River Sub-catchment, and would, therefore, contribute less sediment.

The soil and topographic conditions required for gully erosion were more prominent in the Ncolosi and Qwakele River Sub-catchments than those that were found in the Ngxaza and Umnga River Sub-catchments, which is why the latter contributed less sediment compared to the former. Though the upper Inxu River was a large area compared to the Lower Inxu River, the upper Inxu River Catchment was not as vulnerable to erosion as its counterpart, due to stable soils and landscape features such as wetlands that would trap sediment, decreasing sediment connectivity in this part of the catchment.

Measured data from this study supported the Erosion Model developed by Le Roux *et al.* (2015) as a reliable model for determining sediment yield and provenance in the Mzimvubu River Catchment. Both techniques had similar sediment yield values and identified similar sediment source areas.

Furthermore, both studies identified gully erosion as the dominant soil erosion process in the Inxu River Catchment.

Since the USLE Map identified different sediment source areas compared to the measured data, the map did not identify dominant sediment processes as well as dominant sediment source areas at the sub-catchment scale. Therefore, in the context of this catchment, and for serving the purpose of this study, the USLE model would not have been a reliable technique.

7 Conclusion

The purpose of this research was to determine suspended sediment yield and provenance of the Inxu River Catchment and sub-catchments. This was achieved by determining the suspended sediment contribution of the Inxu River Catchment to the Tsitsa River, determining the relative contribution of the major Inxu River Sub-catchments to the suspended sediment of the Inxu River, identifying the factors that affect the sediment contribution from the major sub-catchments and the potential source areas for suspended sediment and comparing previously modelled results with measured suspended sediment data from this study. Citizen-based sediment flux monitoring and desktop techniques were used to generate the required data. Key findings from this chapter are as follows.

7.1.1 Key Findings

- In terms of sediment contribution, the Inxu River Catchment contributed 5.5 t/ha/yr of suspended sediment in 01 May 2016 - 30 April 2017. Most of the sediment (93%) was transported by flood events, as expected (Gordon *et al.,* 2004; Rovira and Batalla, 2006; Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Gao, 2008; Nadal-Romero *et al.,* 2008b; Nadal-Romero and Regüés, 2010). Flood events had a lower frequency compared to base flow conditions; however, floods were events of high magnitude and, therefore, could transport large quantities of sediment.

- Sediment transport patterns were observed at the seasonal and event scales. At the seasonal scale, suspended sediment dynamics in the Inxu River Catchment follow the typical cycle of sediment preparation in the dry season and sediment exhaustion in the wet season. Deviations from this pattern occurred in the 2016 dry season as a snowmelt event transported large quantities of sediment, though less than that transported by flood events during the wet season. At the event scale, in most cases the pattern of sediment and discharge peaks suggested that most of the sediment was produced in areas close to the catchment outlet (Rovira and Batalla, 2006; Lefrançois *et al.,* 2007; Zabaleta *et al.,* 2007; Nadal-Romero *et al.,* 2008b). This includes the channel, connected gullies, nearby tributaries, as well as nearby hillslopes. Land use activities that took place close near the channel may have also generated more sediment that was supplied to the channel (Lefrançois *et al.,* 2007). This was confirmed by the measured contribution from the sub-catchments.
- Sub-catchment contribution suggested that the area that produces the most sediment across the catchment is the lower Inxu River Catchment. Within this area, the Ncolosi and Qwakele River Sub-catchments contributed the most sediment. Both sub-catchments are close to the Inxu River Catchment Outlet, especially the Ncolosi River Sub-catchment, which contributed

the most sediment. Key similarities in both catchments suggest that gully erosion is the dominant erosion process in the Inxu River Catchment. The following observations were similar to Le Roux and Sumner (2012)'s study on the factors that control connected and disconnected gully formation in the Tsitsa River Catchment.

  - In terms of topography, gullies initiate and develop on gentle slopes and concave shaped footslopes (Kakembo *et al.,* 2009).
  - In terms of soils, gullies were found mainly on the Tarkastad Formation. This Formation is highly erodible as it supports duplex soils on the gentle slopes, as well as shallow, easily erodible soils on steep slopes.
  - The lower Inxu River Catchment is dominated by degraded grassland; therefore, it was unsurprise that gullies would dominate this land cover. But in addition to grasslands, areas with shrubland were also vulnerable to gully erosion, but to a lesser extent.
  - Erosion processes were exacerbated by land use practices such as those associated with abandoned cultivated land, cattle trampling, overgrazing and dense rural populations. However, there is a need to further investigate the effects of land use change in this catchment.

Therefore, topography, soil, and land cover and use were important erosion factors (Kakembo *et al.,* 2009; Le Roux and Sumner, 2012) in the Inxu River Catchment.

- The measured sediment yield from this study and the modelled sediment yield from Le Roux *et al.* (2015) were similar at both catchment and sub-catchment scales. Both studies identified similar sediment source areas and the dominant soil erosion processes. The measured data from this study validated the modelled data. It supports the viability of the model and its application to determine areas of high erosion in the Mzimvubu River Catchment, which should be targeted for rehabilitation.
- Furthermore, since both measured and modelled output identified similar sediment source areas and dominant soil erosion processes in this catchment, in addition to similar sediment yields, it highlights the importance of developing context-based models as they can better simulate sediment processes in a catchment. Most erosion models emphasise sheet-rill erosion, and only a few model gully erosion at regional scales. By integrating gully and sheet erosion models, Le Roux *et al.* (2015) were able to produce a model that better represents erosion processes that occur in the context of the catchment.
- Coupling Citizen based monitoring and desktop studies were effective in determining sediment yield and identifying sediment sources. However, the determination of sediment transport processes could be improved by increasing the temporal scale (Rovira and Batalla, 2006, Zabaleta *et al.,* 2007; Grenfell and Ellery, 2009).s This would improve the confidence in

determining various sediment responses over wet and dry years and how that changes over seasonal, monthly and event scales.

- The information gained from this study can facilitate decision making by catchment managers. It is useful to the Department of Environmental Affairs - Natural Resource Management as it will assist in identifying and designing appropriate strategies for managing suspended sediment within the Inxu River Catchment. The following recommendations were made.

7.1.2 Recommendations

- The Inxu River Catchment should be prioritised for rehabilitation as sediment produces in this catchment directly contributes to the proposed Lalini Dam. Within the Inxu River Catchment, priority areas lie within the lower catchment, particularly the T35 J, where the Ncolosi River Sub-catchment and the area that was not monitored – but was highly gullied and drained directly into the Inxu River Catchment – lie.
- Rehabilitation should target areas in the catchment where soils from the Tarkastad Formation can be found, especially where these soils occur on gentle slopes and are prone to gully erosion.
- Rehabilitation strategies should focus on trapping sediment, stabilising gullies, and improving vegetation cover.
- The effects of land use change on gully intensification should be investigated so that appropriate interventions could be utilised. Alternative land use practices should be designed where current activities occur on gentle slopes that occur on the Tarkastad Formation.
- Sediment flux monitoring in this area should be continued in this catchment
    - to identify long term trends and anomalies, especially in those of climate change;
    - to investigate how the catchment has responded to rehabilitation efforts and to evaluate the efficiency and effectiveness of these efforts;
    - to guide management and policy development;
    - to improve socio-economic development.

This study has demonstrated the value of context-based catchment management and the importance of accounting for spatial and temporal variability when investigating suspended sediment dynamics.

8 References

Aksoy, H. and Kavvas, M.L. 2005. A review of hillslope and watershed scale erosion and sediment transport models. *Catena*, *64*(2): 247-271.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B. and Neitsch, S.L. 2012a. Soil and Water Assessment tool: Input and output documentation. Texas: Texas Water Resource Institute.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., van Liew, M.W. and Kannan, N. 2012b. SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4): 1491-1508.

Bábek, O., Grygar, T.M., Faměra, M., Hron, K., Nováková, T. and Sedláček, J. 2015. Geochemical background in polluted river sediments: how to separate the effects of sediment provenance and grain size with statistical rigour? *Catena*, *135*: 240-253.

Bannatyne, L.J. 2017. Developing a Citizen Technician Based Approach to Suspended Sediment Monitoring in the Tsitsa River Catchment, Eastern Cape, South Africa. MSc Thesis, Rhodes University, South Africa.

Bannatyne, L.J., Rowntree, K.M., van der Waal, B.W. and **Nyamela, N.** 2017. Design and implementation of a citizen technician-based suspended sediment monitoring network: Lessons from the Tsitsa Catchment, South Africa. *Water SA*, *43*(3): 365-377.[2]

Base, F., Helmschrot, H. and Flugel, W. 2007. The impact of land use change on the hydrological dynamic of the semi-arid Tsitsa catchment in South Africa. *Global Change Issues in Developing and Emerging Countries: Proceedings of the 2nd Göttingen GIS and Remote Sensing Days 2006, 4th to 6th October, Göttingen, Germany.* 4: 257.

Bhattarai, R. and Dutta, D. 2007. Estimation of soil erosion and sediment yield using GIS at catchment scale. *Water Resources Management*, *21*(10): 1635-1647.

Boardman, J., Parsons, A.J., Holland, R., Holmes, P.J. and Washington, R. 2003. Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa. *Catena, 50:* 165-184.

Bracken, L.J., Turnbull, L., Wainwright, J. and Bogaart, P. 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms, 40*(2): 177-188.

Carter, J., Owens, P.N., Walling, D.E. and Leeks, G.J. 2003. Fingerprinting suspended sediment sources in a large urban river system. *Science of the Total Environment, 314*: 513-534.

Chang, K. 2012. Introduction to GIS. McGraw-Hill: New York.

---

[2] This paper resulted from the Bannatyne's Master of Science project 2017 for which I was a Secondary Investigator. My main role in production of this paper was the production of maps, assistance in data collection and revision of initial and final drafts. Bannatyne was the main author for the work and did most of the analysis, under the guidance of Professor Rowntree and Dr van der Waal who contributed substantially to the experimental design and collection of field data and assisted with editing the manuscript.

Chen, E. and Mackay, D.S. 2004. Effects of distribution-based parameter aggregation on a spatially distributed agricultural nonpoint source pollution model. *Journal of Hydrology, 295*(1): 211-224.

Collins, A.J and Owens, P.N. 2006. Chapter 1. Introduction to soil erosion and sediment redistribution in river catchments: measurement, modeling and management in the 21st century. *In* Owens, P. N. and Collins, A. J. *Soil Erosion and Sediment Redistribution in River Catchments: Measurement, Modeling and Management.* Cambridge: CAB International. p. 3-9.

Collins, A. L. and Walling, D. E. 2004. Documenting Catchment Suspended sediment sources: problems, approaches and prospects. *Progress in Physical Geography*, *28*(2): 159-196.

Collins A L, Pulley S, Foster I D L, Gellis, A, Porto P, Horowitz A J. 2017. Sediment source fingerprinting for informing catchment management: methodological approaches, problems and uncertainty – a review of the current state of knowledge. *Journal of Environmental Management, 194:* 86-108.

Compton, J.S. and Maake, L. 2007. Source of the suspended load of the upper Orange River, South Africa. *South African Journal of Geology*, *110*(2-3): 339-348.

Conrad, C.C. and Hilchey, K.G. 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment*, *176*(1): 273-291.

De Vente, J., Poesen, J., Verstraeten, G., van Rompaey, A and Govers, G. 2008. Spatially distributed modelling of soil erosion and sediment yield at regional scales in Spain. *Global and Planetary Change, 60*: 393–415.

Drewitt, J. 2015. Rainfall Variability and Implications for Agriculture in the Tsitsa Catchment, Eastern Cape, South Africa. Unpublished Honours Project, Rhodes University, South Africa.

Espinoza Villar, R., Martinez, J., Le Texier, M., Guyot, J., Fraizy, P., Meneses, P.R. and Oliveira, E.D. 2013. A study of sediment transport in the Madeira River, Brazil, using MODIS remote-sensing images. *Journal of South American Earth Sciences, 44*: 45-54.

Evrard, O., Navratil, O., Ayrault, S., Ahmadi, M., Némery, J., Legout, C., Lefèvre, I., Poirel, A., Bonté, P. and Esteves, M. 2011. Combining suspended sediment monitoring and fingerprinting to determine the spatial origin of fine sediment in a mountainous river catchment. *Earth Surface Processes and Landforms*, *36*(8): 1072-1089.

Fey, M., Hughes, J., Lambrechts, J. and Dohse, T. 2010. Chapter 2. The Soil Groups: Distribution, Properties, Classification, Genesis and Use. *In* Fey, M. *Soil of South Africa: Their Distribution, Properties, Classifiction, Use and Environmental Significance.* Cambridge: Cambridge University Press.

Fox, D.M. and Bryan, R.B. 2000. The relationship of soil loss by interrill erosion to slope gradient. *Catena*, *38*(3): 211-222.

Fryirs, K.A., Brierley, G.J., Preston, N.J. and Kasai, M. 2007. Buffers, barriers and blankets: the (dis) connectivity of catchment-scale sediment cascades. *Catena, 70*(1): 49-67.

Gao, P. 2008. Understanding watershed suspended sediment transport. *Progress in Physical Geography, 32*(3): 243-263.

Goodchild, M.F. and Longley, P.A. 1999. The future of GIS and spatial analysis. *Geographical Information Systems*, *1*: 567-580.

Gordon, N. D., McMahon, T. A., Finlayson, B. L., Gippel, C. J. and Nathan, R. J. 2004. Stream Hydrology: An Introduction for Ecologists. (2e). England: John Wiley & Sons, Ltd.

Grenfell, S. and Ellery, W. 2009. Hydrology, sediment transport dynamics and geomorphology of a variable flow river: the Mfolozi River, South Africa. *Water SA, 35*(3): 271-282.

Guzmán, G., Quinton, J.N., Nearing, M.A., Mabit, L. and Gómez, J.A. 2013. Sediment tracers in water erosion studies: current approaches and challenges. *Journal of Soils and Sediments*, *13*(4): 816-833.

Hochachka, W.M., Fink, D., Hutchinson, R.A., Sheldon, D., Wong, W.K. and Kelling, S. 2012. Data-intensive science applied to broad-scale citizen science. *Trends in Ecology & Evolution*, *27*(2): 130-137.

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology, 56*(1): 79-94.

Horowitz, A.J., Rinella, F.A., Lamothe, P., Miller, T.L., Edwards, T.K., Roche, R.L. and Rickert, D.A. 1990. Variations in suspended sediment and associated trace element concentrations in selected riverine cross sections. *Environmental Science & Technology, 24*(9): 1313-1320.

Jain, M.K. and Kothyari, U.C. 2000. Estimation of soil erosion and sediment yield using GIS. *Hydrological Sciences Journal, 45*(5): 771-786.

Kakembo, V. and Rowntree, K. 2003. The relationship between land use and soil erosion in the communal lands near Peddie Town, Eastern Cape, South Africa. *Land Degradation & Development, 14*(1): 39-49.

Kakembo, V., Xanga, W.W. and Rowntree, K. 2009. Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa. *Geomorphology*, *110*(3): 188-194.

Land Type Survey Staff. 1972-2006. Land types of South Africa: Digital map (1:250 000 scale) and soil inventory datases. ARC-Institute for Soil, Climate and Water, Pretoria.

Lefrançois, J., Grimaldi, C., Gascuel-Odoux, C. and Gilliet, N. 2007. Suspended sediment and discharge relationships to identify bank degradation as a main sediment source on small agricultural catchments. *Hydrological Processes, 21*(21): 2923-2933.

Le Roux, J.J. and Sumner, P. 2012. Factors controlling gully development: comparing continuous and discontinuous gullies. *Land Degradation and Development, 23*: 440-449.

Le Roux, J.J., Morgenthal, T., Malherbe, J., Pretorius, D. and Sumner, P. 2008. Water erosion prediction at a national scale for South Africa. *Water SA, 34*(3): 305-314.

Le Roux, J.J., Newby, T. and Sumner, P. 2007. Monitoring soil erosion in South Africa at a regional scale: review and recommendations. *South African Journal of Science, 103*(7-8): 329-335.

Le Roux, J.J., Sumner, P.D., Lorentz, S.A. and Germishuyse, T. 2013. Connectivity aspects in sediment migration modelling using the Soil and Water Assessment Tool. *Geosciences*, *3*(1): 1-12.

Le Roux, J.J., Barker, C.H., Weepener, H.L., van der Berg, E. and Pretorious, S.N. 2015. Sediment Yield Modelling in the Mzimvubu River Catchment. Water Research Commission. Pretoria

Lindenmayer, D.B. and Likens, G.E. 2010. The science and application of ecological monitoring. *Biological Conservation, 143*(6): 1317-1328.

Long, C.M. and Pavelsky, T.M. 2013. Remote sensing of suspended sediment concentration and hydrologic connectivity in a complex wetland environment. *Remote Sensing of Environment*, *129*: 197-209.

Martínez-Carreras, N., Krein, A., Udelhoven, T., Gallart, F., Iffly, J.F., Hoffmann, L., Pfister, L. and Walling, D.E. 2010. A rapid spectral-reflectance-based fingerprinting approach for documenting suspended sediment sources during storm runoff events. *Journal of Soils and Sediments, 10*(3): 400-413.

Merritt, W.S., Letcher, R.A. and Jakeman, A.J. 2003. A review of erosion and sediment transport models. *Environmental Modelling & Software*, *18*(8): 761-799.

Moore, N. 2016. Rainfall Erosivity in the Tsitsa Catchment, Eastern Cape, South Africa. Unpublished Honours Project, Rhodes University, South Africa.

Nadal-Romero, E. and Regüés, D. 2010. *Geomorphological dynamics of sub-humid mountain badland areas - weathering, hydrological and suspended sediment transport processes: A case study in the Araguás catchment (Central Pyrenees) and implications for altered hydroclimatic regimes.* Sage Publications, Ltd.

Nadal-Romero, E., Latron, J., Martí-Bono, C. and Regüés, D. 2008a. Temporal distribution of suspended sediment transport in a humid Mediterranean badland area: The Araguás catchment, Central Pyrenees. *Geomorphology, 97*(3–4): 601-616.

Nadal-Romero, E., Regüés, D. and Latron, J. 2008b. Relationships among rainfall, runoff, and suspended sediment in a small catchment with badlands. *Catena, 74*(2): 127-136.

Department of Environmental Affairs (DEA). 2012. National Land Cover 2012.

Navratil, O., Evrard, O., Esteves, M., Legout, C., Ayrault, S., Némery, J., Mate-Marin, A., Ahmadi, M., Lefèvre, I. and Poirel, A. 2012. Temporal variability of suspended sediment sources in an alpine catchment combining river/rainfall monitoring and sediment fingerprinting. *Earth Surface Processes and Landforms, 37*(8): 828-846.

Nel, W. and Sumner, P.D. 2007. Intensity, energy and erosivity attributes of rainstorms in the KwaZulu-Natal Drakensberg, South Africa. *South African Journal of Science*, *103*(9-10), 398-402.

Parsons, A.J., Wainwright, J. and Abrahams, A.D. 1993. Tracing sediment movement in interrill overland flow on a semi-arid grassland hillslope using magnetic susceptibility. *Earth Surface Processes and Landforms,* 18(8): 721-732.

Republic of South Africa. 2013a. Department of Water Affairs. *National Water Resource Strategy: Water for an Equitable and Sustainable Future.* Pretoria: Government Printer.

Republic of South Africa. 2013b. Department of Water Affairs (DWA). *National Water Resource Strategy: Perspectives Per Water Management Area (Annexure A)*. Pretoria: Government Printer.

Republic of South Africa. Department of Water Affairs (DWA). 2014. *Mzimvubu Water Project: Background Information Document*. Pretoria: Government Printer.

Republic of South Africa. 2005. Department of Water Affairs and Forestry (DWAF). *Mzimvubu River Basin: Water Utilization Opportunities*. Pretoria: Government Printer

Republic of South Africa. Department of Water and Sanitation (DWS). Nd. Mzimvubu Water Project. [Online]. Available: https://www.dwa.gov.za/mzimvubu/. 7 May 2016.

Rovira, A. and Batalla, R.J. 2006. Temporal distribution of suspended sediment transport in a Mediterranean basin: The Lower Tordera (NE SPAIN). *Geomorphology, 79*(1): 58-71.

Rowntree, K.M., van der Waal, B.W. and Pulley, S. 2017. Magnetic susceptibility as a simple tracer for fluvial sediment source ascription during storm events. *Journal of Environmental Management, 194*: 54-62

Sergeant, C.J., Moynahan, B.J. and Johnson, W.F. 2012. Practical advice for implementing long-term ecosystem monitoring. *Journal of Applied Ecology*, *49*(5): 969-973.

Sherriff, S.C., Rowan, J.S., Melland, A.R., Jordan, P., Fenton, O. and O hUallachain, D.O. 2015. Investigating suspended sediment dynamics in contrasting agricultural catchments using ex situ turbidity-based suspended sediment monitoring. *Hydrology and Earth System Sciences*, *19*:3349-3363.

Sherriff, S.C., Rowan, J.S., Fenton, O., Jordan, P., Melland, A.R., Mellander, P. and Huallachain, D.O. 2016. Storm Event Suspended Sediment-Discharge Hysteresis and Controls in Agricultural Watersheds: Implications for Watershed Scale Sediment Management. *Environmental Science & Technology, 50*(4): 1769-1778.

Smith, M. and Pain, C. 2009. Applications of remote sensing in geomorphology. *Progress in Physical Geography, 33*(4): 568-582.

South African Weather Service. 2018. How does ENSO affect South Africa? [Online]. Available: http://www.weathersa.co.za/learning/climate-questions/35-how-does-enso-affect-south-africa [2018/05/31].

Tulloch, A.I.T., Possingham, H.P., Joseph, L.N., Szabo, J. and Martin, T.G. 2013. Realising the full potential of citizen science monitoring programs. *Biological Conservation, 165*: 128-138.

Van der Waal B.W. 2014. Sediment connectivity in the upper Thina catchment, Eastern Cape, South Africa. Unpublished PhD thesis, Rhodes University, South Africa.

Van de Waal, B. W., Rowntree K. M. and Pulley S. 2015. Flood bench chronology and sediment source tracing in the upper Thina catchment, South Africa: the role of transformed landscape connectivity. *Journal Soils and Sediments, 15*: 2398-2411.

Van Tol, J., Akpan, W., Kanuka, G., Ngesi, S. and Lange, D. 2014. Soil Erosion and Dam Dividends: Science Facts and Rural 'Fiction' around Ntabelanga Dam, Eastern Cape, South Africa. *South African Geographical Journal,* 169-181.

Van Zijl, G.M., Le Roux, P.A. and Turner, D.P. 2013. Disaggregation of land types using terrain analysis, expert knowledge and GIS methods. *South African Journal of Plant and Soil, 30*(3): 123-129.

Vargas-Luna, A., Crosato, A. and Uijttewaal, W.S. 2015. Effects of vegetation on flow and sediment transport: comparative analyses and validation of predicting models. *Earth Surface Processes and Landforms*, *40*(2): 157-176.

Vrieling, A. 2006. Satellite remote sensing for water erosion assessment: A review. *Catena,* 65(1): 2-18.

Walling, D. E. 2005. Tracing suspended sediment sources in catchments and river systems. *Science of The Total Environment,* 344(1–3): 159-184.

Walling, D., Collins, A. and Stroud, R. 2008. Tracing suspended sediment and particulate phosphorus sources in catchments. *Journal of Hydrology,* 350(3): 274-289.

World Meteorological Organization (WMO) 2014. *El Niño Southern Oscillation.* Switzerland: WMO.

Zabaleta, A., Martínez, M., Uriarte, J.A. and Antigüedad, I. 2007. Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque Country. *Catena, 71*(1): 179-190.

9 Appendices

Appendix 1: Citizen Based Technician Training Material……………………………………………….…………110

The Competency Test……………………………………………………………………………….………………………110

Checklist for training and contracting service providers…………………………………………….…………..111

Safety Guidelines……………………………………………………………………………………………………...…..113

Training Material for Sample Collection…………………………………………………………………………..…..115

Appendix 2: Turbidity-SSC Relationships……………………………………………………………………………126

Appendix 3: Site-Specific Cross-Sections along with Manning's Values……………………………….…………129

Appendix 1: Citizen-Based Technician Training Material.

The following section gives the information that was presented to and required from the technicians that were employed. This includes the test, the terms and conditions of employment and the instruction book on how to collect samples.

The Competency Test

Prior to employment, candidate technicians were required to answer these questions. Successful candidates were chosen based on the researcher's satisfaction with the answer.

1. Label these bottles in sequence:

2. a) The time is ten o clock in the morning (10h00). You must go to the river and fill a bottle every 20 minutes until two in the afternoon (14h00). Take the first sample now (10h00). What times must you take the other samples?

10h00
10h20
10h40

b) How many bottles will you need? ☐

CHECKLIST for Training and Contracting of Service Providers

1) Explain that
    a) The job is from now till 30 April 2017 extended if it is still raining.
    b) The job is EVERY DAY including weekends, public holidays, Christmas, New Year's Day.
    c) Baseline sampling is twice a day, flood sampling is 20 samples, one every 10 minutes or whatever.
    d) FLOOD sampling is the most important
    e) They MUST stick to those times.
    f) When they send the information, we will be able to see when and where they are taking the sample.
    g) The phone will tell us where the sample is taken. If the GPS is not turned on, then that will not count as a sample.
    h) There is only ONE contracted sampler per site, but more people can do the training so that there can be a back-up.
    i) If they are sick or away they must get another person to do the work but that THEY must pay them and make sure that the job is done properly.
    j) The rate is PER SAMPLE: no sample no pay.
    k) If the weather or river is too bad to sample, then fill in everything else on the form and make sure the photos show WHY there is no sample.
    l) The phone, life jacket, crates, etc. belong to RU. They **must** be given back at the end.
    m) If they don't have a bank account then the money will be transferred to the post office, or an ATM
    n) They must open a bank account within a month.
    o) It would be great if they will send an SMS when their river is flooding
2) Do safety training and sign off
3) Do sampling training
4) Take a photo of their ID
5) Take a photo of their proof of bank account details.
6) Measure their chest for rain jacket.
7) Get shoe size.
8) Go through the MOU and get two signed copies and initial every page

Table 9.1: Checklist for training and contracting of service providers (To protect the privacy of the technicians, personal details have been replaced with a tick)

Station	Intro	Safety training and SIGN	Sampling training	Photo of ID	Photo of account details	Chest size	Shoe size	MOU signed
Ncolosi	✓	✓	✓	✓	✓	✓	✓	✓
Qwakele	✓	✓	✓	✓	✓	✓	✓	✓
Ngxaza	✓	✓	✓	✓	✓	✓	✓	✓
Inxu Upstream	✓	✓	✓	✓	✓	✓	✓	✓

Safety Guidelines

DO A SAFETY CHECK EVERY TIME YOU GO TO THE RIVER

Remember that **YOU** are responsible for your own safety!!

First answer these questions:

Have you been drinking alcohol? Even one or two beers?

DO NOT GO TO THE RIVER IF YOU HAVE BEEN DRINKING ALCOHOL

Is there a child or a baby with you?

DO NOT GO TO THE RIVER IF THERE IS A CHILD OR A BABY WITH YOU

Look at the river bank and the river and answer these questions:

- **Is it dark?**
- **Is it raining very hard?**
- **Is the river flowing very high or very fast?**
- **Is the riverbank washing away?**
- **Is the riverbank slippery?**

If you answer "YES" to any of these questions it may be unsafe to go to the river bank. It may be better to sample from the bridge.

KEEP CHECKING WHILE YOU WORK

Think about where you have seen the water rising to before and how fast it rises. Is the place where you are going to sample safe if the water rises quickly?

Think about what you will do if the water does rise quickly. Plan where you will go to get above the flood water.

Always face upstream while you are sampling, especially during floods, so that you can see if trees or other things are coming down the river towards you.

Check if the river is rising. Pick out two or three special rocks or other features in the river and on the bank. Check them to see if the water gets higher while you are sampling.

If it is getting higher, check often to make sure that the water is not washing away the bank under the place where you are standing.

Look out for insects and snakes that might be trying to get away from the water.

PERSONAL SAFETY

Do not take samples at night.

Always tell someone when you are going to the river, and when you expect to be back. Better yet ask a friend to watch while you work.

ALWAYS WEAR YOUR LIFE JACKET with the strings properly tied. Know where the whistle is and how to take it out quickly so that you can summon help with it.

NEVER tie yourself to something with a rope whilst you are taking samples – this is **extremely** dangerous.

Do not wear loose shoes or slops/flipflops that might make you trip and fall into the river.

Keep your equipment away from the edge of the water while you are working so that you don't trip over it and fall into the river. Also make sure it is higher up the bank in case the river rises.

Do not enter the water to take a sample.

Do not try to cross flood barriers like retaining walls and levees or sandbags

Do not walk or wade near flood waters where the ground may be unstable

Stay away from low level bridges, storm drains and side channels

Stay away from damaged powerlines, sewer pipes and other constructions - and report them to the authorities

If you are sampling from a bridge, watch out for traffic. Never lean over the rails unless you are standing firmly with good hand/foot holds.

If at any time you feel unsafe, stop sampling and leave the site at once. Your safety is more important than the data!

IF YOU FALL IN THE RIVER

If the water is shallow (below your knees) and slow, you can stand up and walk out. Call or whistle for help. Stay calm, face up-stream and take small steps sideways to the bank, moving your feet carefully to avoid tripping or slipping on the river bed.

If the water is deep or fast, lie on your back with your feet up and facing downstream. This is "survival swimming". Get your whistle out and blow it hard to attract attention. Even if you can't swim, your life jacket will keep you afloat.

NEVER try to stand up in deep moving water. Your feet can easily be caught between rocks and you may drown. Do not stop using the Survival Swimming Position because you are getting bumped. It is better to get a few bruises than get caught on the river bed.

Keep your head up so that you can see where you are going, see waves coming in time to take a breath, and push off rocks with your feet.

Use your arms to steer or to slow you down while moving to the side of the river to get out. When you see a place to get out of the river, use your arms to get to the side.

IF YOU SEE SOMEONE ELSE FALL IN THE RIVER DO NOT jump in to help someone who has fallen in the river. Rather call for other people to help and try to find a rope to throw (DO NOT tie it to yourself) or a long stick to reach them with so that you can pull them to shore.

I, the undersigned, confirm that I have read and understood these safety guidelines and that they have been explained to me in English and isiXhosa.

Name…………………………………………………………………………ID number……………………………………………………
Date…………………………………………………………………………..Signed…………………………………………………………….
Witness……………………………………………………………………..Witness…………………………………………………………

Training Material for Sample Collection

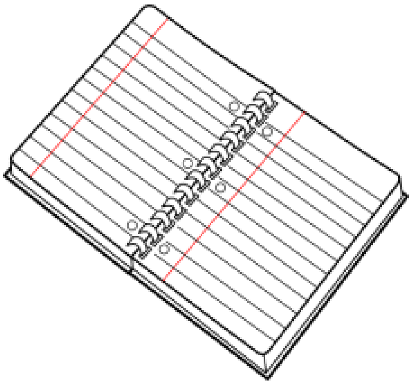
Baseline Sampling

You must do Baseline Sampling twice every day:

- **Once in the morning between 05h00 and 11h00, and**
- **Once in the afternoon between 14h00 and 19h00**

This training will show you how to:

- **Start ODK on your phone**
- **Fill a blank form**
- Take a photo
- Do a safety check
- Record your location
- Take and record your water sample
- **Save the form on your phone**
- **Edit the form**
- **Send the form to Rhodes University**



Remember: Your smartphone is the key to recording and sending your data every day, and your notebook is there as a backup.

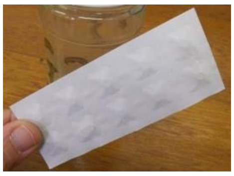
Problem? Call or message Nosi (0617995984) Or Namso (0810034625)

Equipment check

Before you begin, check that you have:

- ✓ Your life jacket
- ✓ Your sample pole
- ✓ Your fully-charged phone sealed INSIDE its water proof pouch
- ✓ Your notebook, pencil, and permanent marker
- ✓ A packet of chlorine pills
- ✓ Enough sample jars and lids

NOTE!! Never take the chlorine pill out of the packet until just before you use it!!

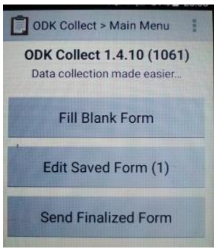


Now you're good to go!!

Let’s get started

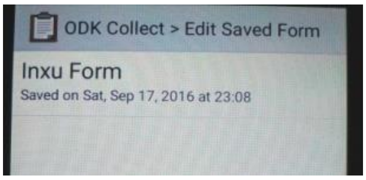
Turn on your phone and press the ODK Collect App

1. **Choose** Fill Blank Form **then**
2. **Select** the form you need …



ODK Collect > Main Menu

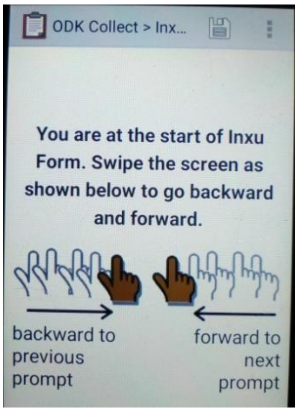
ODK Collect 1.4.10 (1061)
Data collection made easier...



ODK Collect > Edit Saved Form

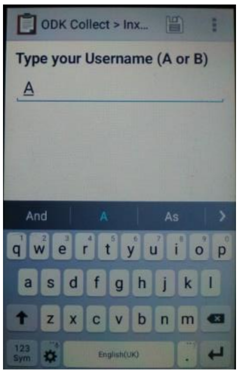
Inxu Form
Saved on Sat, Sep 17, 2016 at 23:08

3. swipe **to get started**
4. **Fill** in your **Username** (who you are)



ODK Collect > Inx...

You are at the start of Inxu Form. Swipe the screen as shown below to go backward and forward.



ODK Collect > Inx...

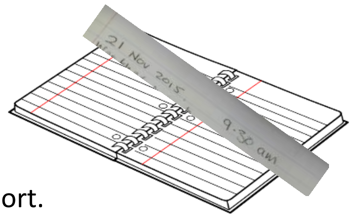
Type your Username (A or B)

A

A: the person employed

B: the assistant

Write the **date** and **time** (and **your name if you are the assistant)** in your notebook.



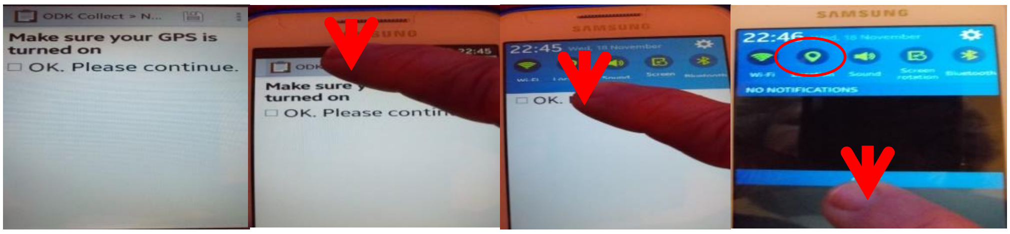
Now you are ready to make a weather report.

First make a weather report

You need to go **outside** your house to make a weather report so that:

- The GPS can work
- You can notice if it’s raining or snowing

Make sure your GPS is turned on:

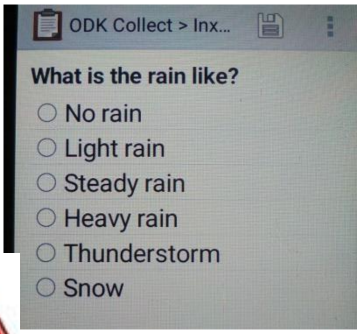


ODK Collect > N...

Make sure your GPS is turned on

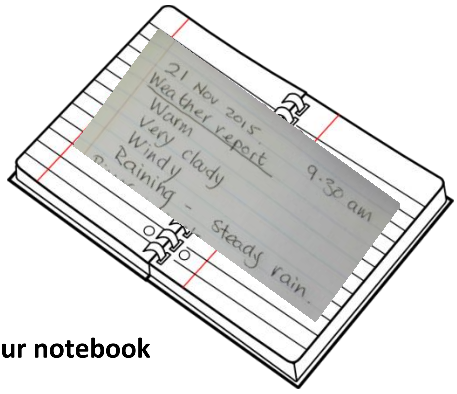
☐ OK. Please continue.

Answer all the question about the weather:



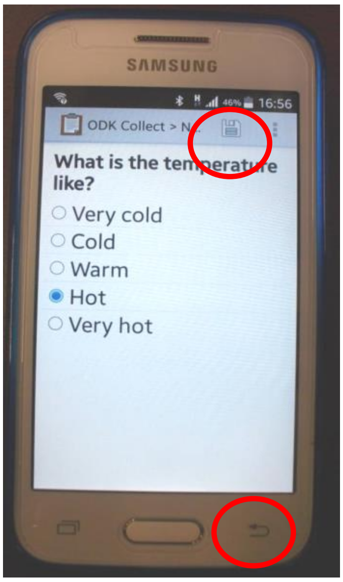
What is the rain like?

- ○ No rain
- ○ Light rain
- ○ Steady rain
- ○ Heavy rain
- ○ Thunderstorm
- ○ Snow



Also write these observations in your notebook

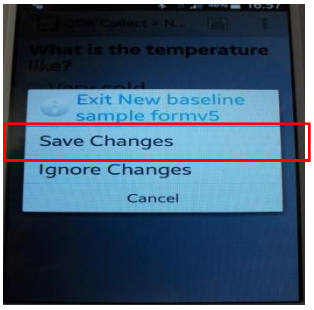
Let's take a moment to find out what to do if you want to stop working with the form.



What is the temperature like?

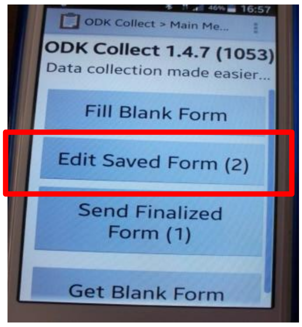
- ○ Very cold
- ○ Cold
- ○ Warm
- ● Hot
- ○ Very hot

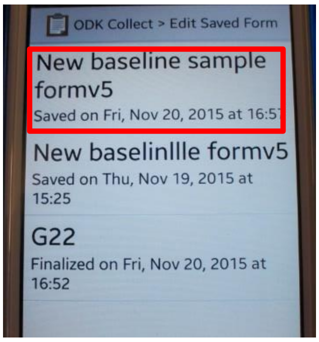
First save using this button



You can save the changes

Then exit using this button

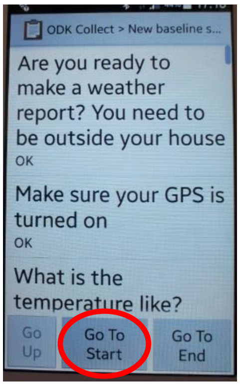




New baseline sample formv5
Saved on Fri, Nov 20, 2015 at 16:5

New baselinllle formv5
Saved on Thu, Nov 19, 2015 at 15:25

G22
Finalized on Fri, Nov 20, 2015 at 16:52



Are you ready to make a weather report? You need to be outside your house
OK

Make sure your GPS is turned on
OK

What is the temperature like?

and edit when you're ready **Select the form you want to complete** **and start at the**
beginning

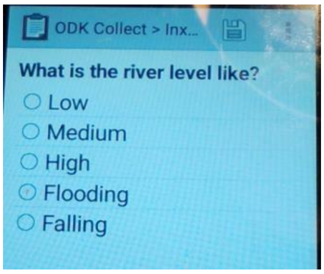
HINT!! If there is more than one saved form, check the TIME and DATE to get the right one.

OK, let's go.

Make a river report

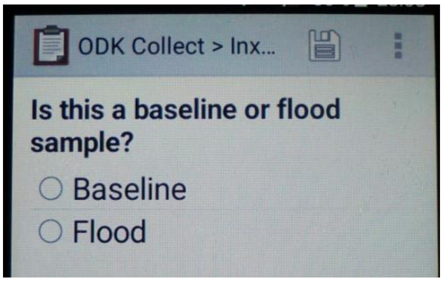
Go to where you can see the river, but don't go all the way to the bank yet.

Notice what the river level is like now and compared with last time. Is this a flood or baseline? How clear or muddy is the water? Write in your notebook, too.



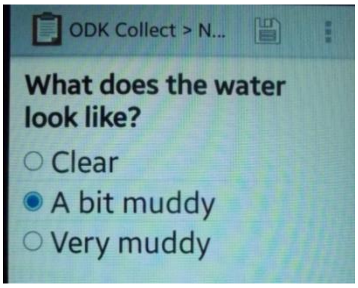
What is the river level like?

○ Low
○ Medium
○ High
○ Flooding
○ Falling



Is this a baseline or flood sample?

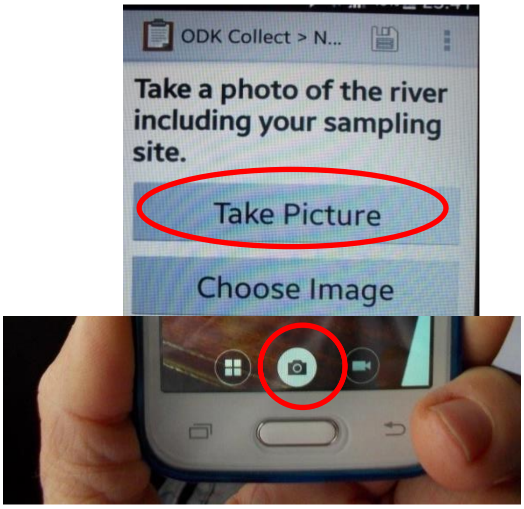
○ Baseline
○ Flood



What does the water look like?

○ Clear
● A bit muddy
○ Very muddy

Take a photo of the river including your sampling site. ALWAYS go to the exact same spot so that we can compare your photos over time. Hold the phone still while you take a picture.



Take a photo of the river including your sampling site.

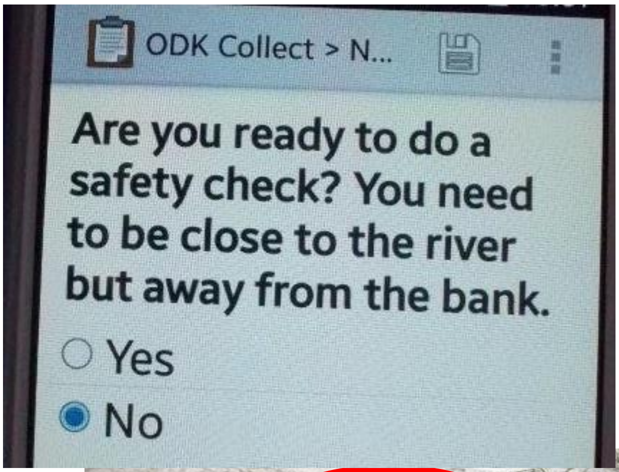
REMEMBER!! Whenever you take a photo, the phone records the date, the time, and the place where you took it. It is VERY important to take a photo.

Also write your river report in your notebook


21 Nov 2015 9.30 am
Weather report
Warm
Very cloudy
Windy
Raining - steady rain.
River report
Rising, a bit muddy

Do a safety check

Rivers are always changing. The river might start to flood since you took your last sample, even if it did not rain where you are. Before you go close to the bank or bridge to take a sample you **MUST** do a safety check every time.



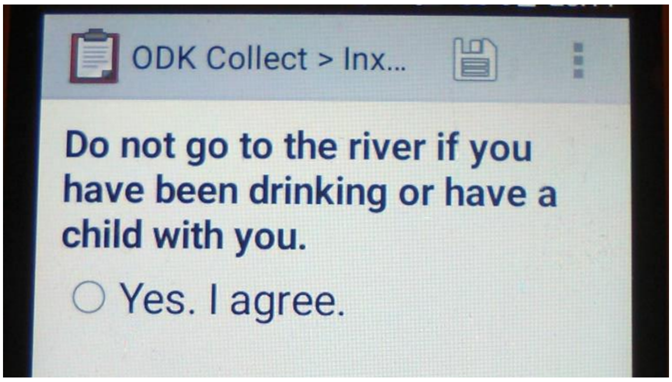
Are you ready to do a safety check? You need to be close to the river but away from the bank.

○ Yes

● No

It is very dangerous to go to the river if you have been drinking alcohol. Even a little alcohol (one or two beers) can cause you to be clumsy and fall, or to forget to take proper precautions when you are close to the river.

If you are looking after a small child or a baby, you must not take them to the river with you while you work. You cannot supervise a child while you are busy with your phone and taking samples.



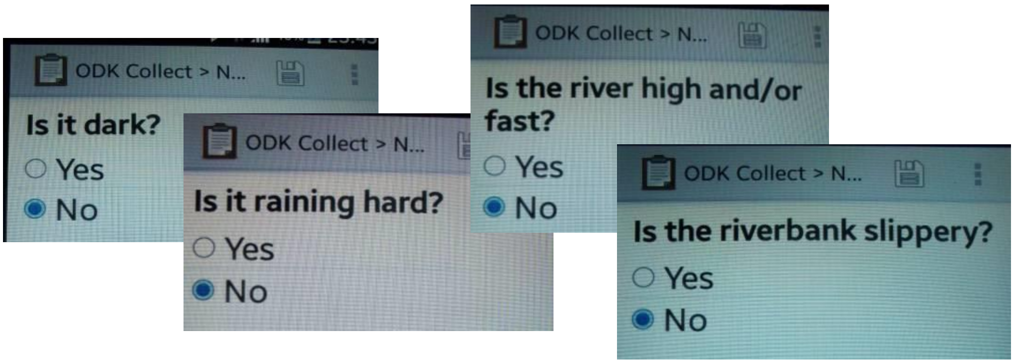
Do not go to the river if you have been drinking or have a child with you.

○ Yes. I agree.

It may be unsafe to go to the river bank to take a sample if

- it is dark, or
- it is raining very hard, or
- the river is running very high and/or fast or
- the riverbank is washing away or slippery

If you answer any of these safety questions “Yes” it may be safer to sample from the bridge instead of the bank.



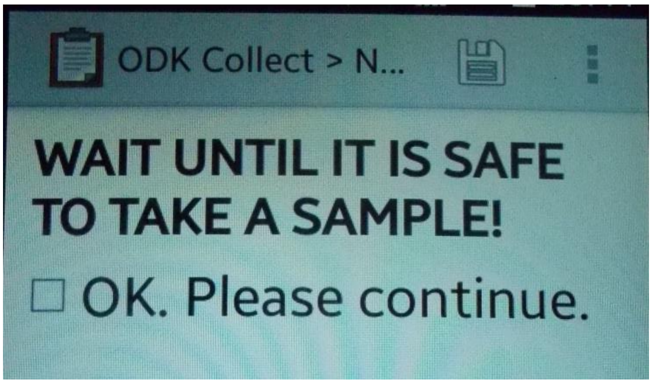
Is it dark?
○ Yes
● No

Is it raining hard?
○ Yes
● No

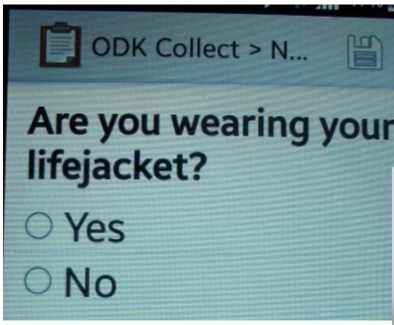
Is the river high and/or fast?
○ Yes
● No

Is the riverbank slippery?
○ Yes
● No

If the water is close to the bridge or over the road, you may be swept away by the flood. **DO NOT** attempt to take a sample until the level has dropped and it is safe to approach the bridge or bank.



WAIT UNTIL IT IS SAFE TO TAKE A SAMPLE!
☐ OK. Please continue.

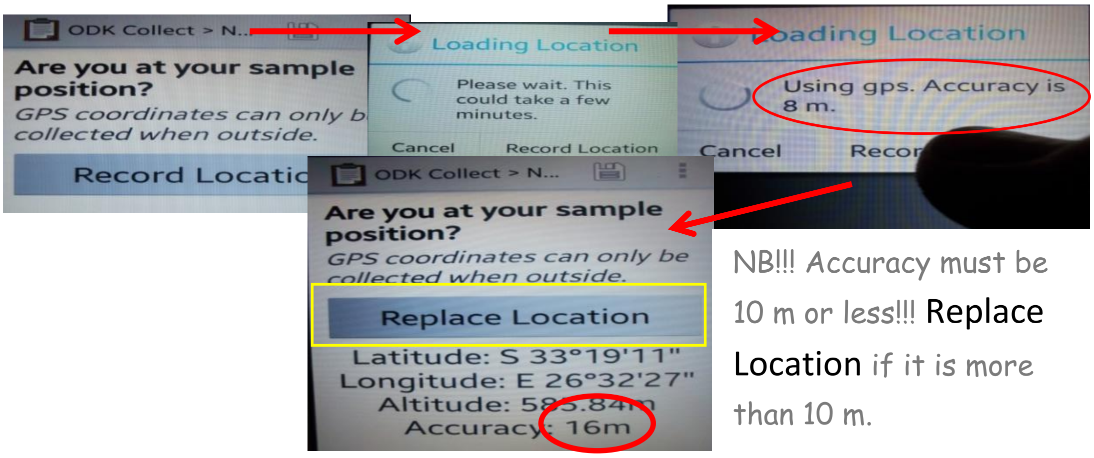


Are you wearing your lifejacket?
○ Yes
○ No

Now that you have checked that the river bank or the bridge is a safe place to sample from, let’s make sure YOU are safe!! Make sure you are wearing your **life jacket!!**

Record your sampling location

Now you can go to the place on the river bank where you will take your sample. Take a GPS reading to make sure you are in the right place.


ODK Collect > N...

Are you at your sample position?

GPS coordinates can only b collected when outside.

Loading Location

Please wait. This could take a few minutes.

oading Location

Using gps. Accuracy is 8 m.

ODK Collect > N...

Are you at your sample position?

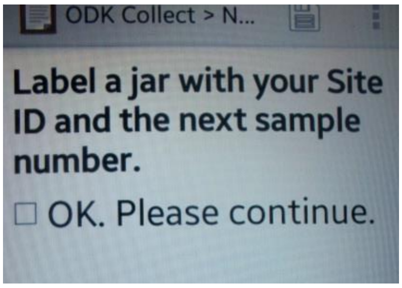
GPS coordinates can only be collected when outside.

Latitude: S 33°19'11"
Longitude: E 26°32'27"
Altitude: 585.84m
Accuracy: 16m

NB!!! Accuracy must be 10 m or less!!! Replace Location if it is more than 10 m.

Take and record your water sample

First you must clearly label the jar and **write the number down in your notebook**

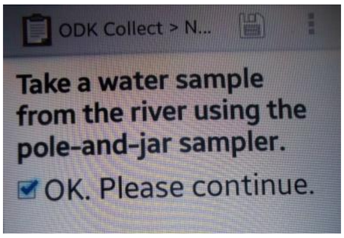

ODK Collect > N...

Label a jar with your Site ID and the next sample number.

☐ OK. Please continue.

Then you must firmly screw the jar into the top of the sampling pole

Now you're ready to take a water sample.


ODK Collect > N...

Take a water sample from the river using the pole-and-jar sampler.

☑ OK. Please continue.

Lower the sampler into the water

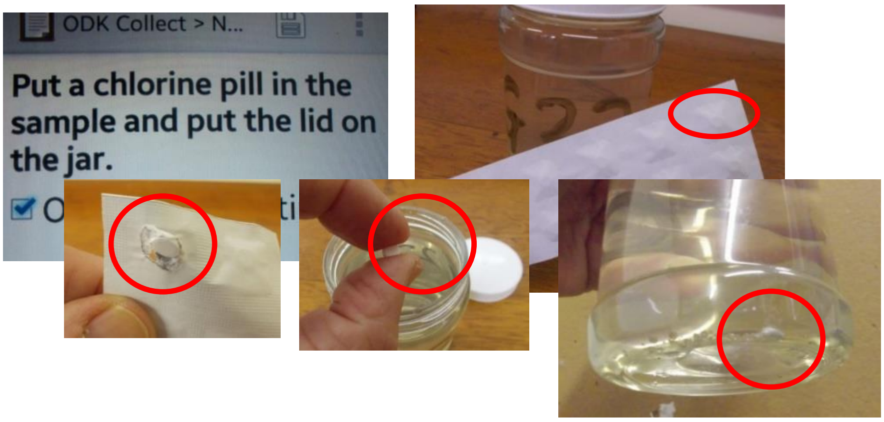
Make sure the pipe is facing upstream with the water flowing towards it

Lower the sampler far under water but do not touch the bottom

Keep the tube pointing upwards when you lift the sampler out so that you don’t spill!!

Keep the tube pointing upwards when you unscrew the jar. Don’t squeeze too hard!

Put a chlorine pill in the sample to stop the water going green.

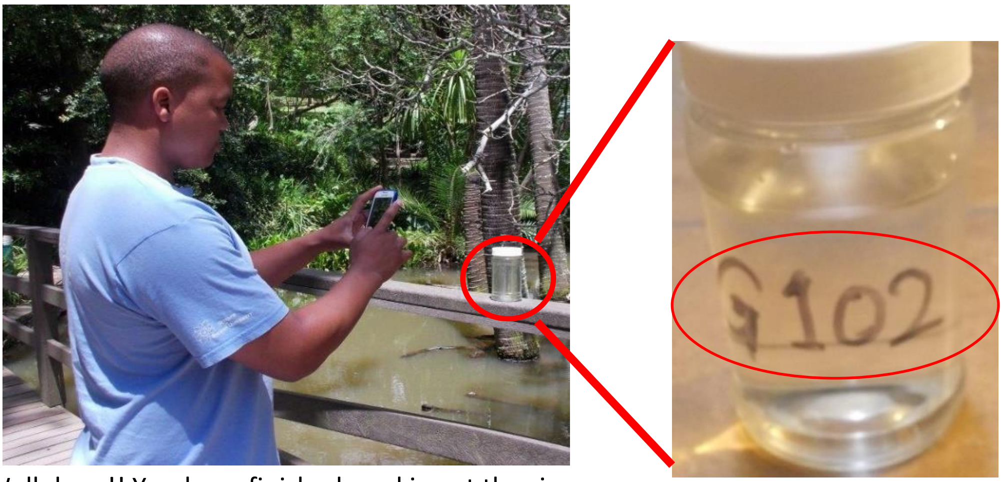

ODK Collect > N...

Put a chlorine pill in the sample and put the lid on the jar.

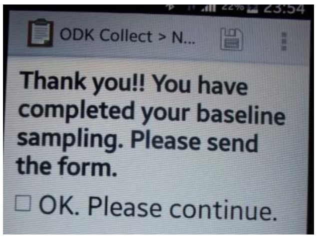
Then put the lid on firmly.

<u>**Take a photo of your sample.**</u>

IT IS VERY IMPORTANT TO SEE THE LABEL IN THE PHOTO!!



Well done!! You have finished working at the river.


ODK Collect > N...

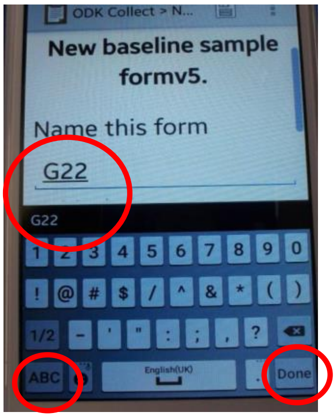
Thank you!! You have completed your baseline sampling. Please send the form.

☐ OK. Please continue.

Finally, you must **save the form and send it.**

Save the form on your phone

Name this form **the same as the sample number**


ODK Collect > N...

New baseline sample formv5.

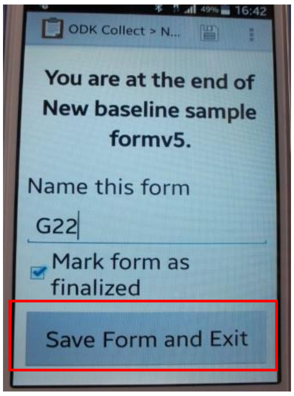
Name this form

G22

Use this button to get letters or numbers

Use this button when you are done

Now you can save Form and Exit



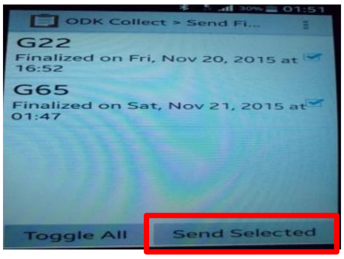
You are at the end of New baseline sample formv5.

Name this form

G22

☑ Mark form as finalized

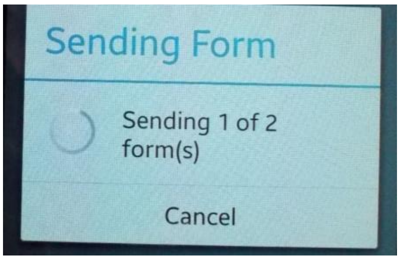
and Send Selected **form**



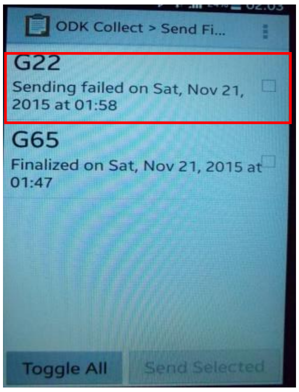
G22
Finalized on Fri, Nov 20, 2015 at 16:52 ☑

G65
Finalized on Sat, Nov 21, 2015 at 01:47 ☑

You can send the form straight away, or when you are back in the network.



Sending 1 of 2 form(s)



G22
Sending failed on Sat, Nov 21, 2015 at 01:58 ☐

G65
Finalized on Sat, Nov 21, 2015 at 01:47 ☐

If the form fails to send, check that you have data on your phone, and check that you have signal. TRY AGAIN!!

When you get home, put all your things away and store the sample in the crate in a cool, dark place.

PUT YOUR CELLPHONE ON CHARGE!!!

Appendix 2: Turbidity-SSC Relationships

The following section give the Turbidity-SSC relationships that were determined for each site.

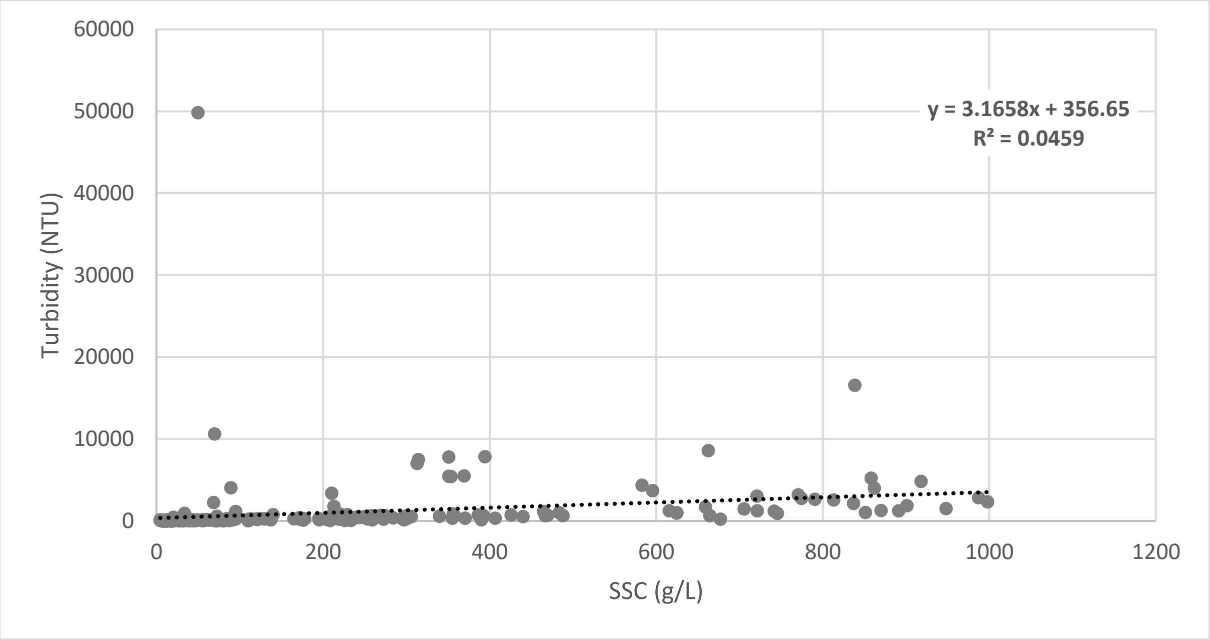


Figure 9.1: Turbidity-SSC relationship of the Inxu River Catchment

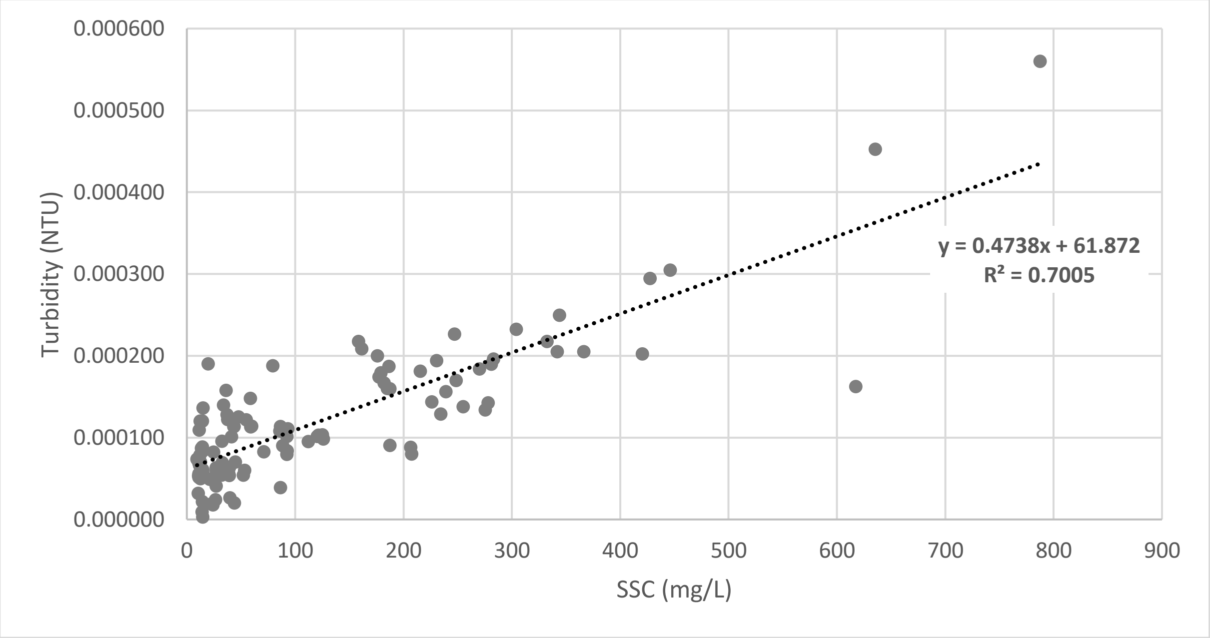


Figure 9.2: Turbidity-SSC relationship of the Ngxaza River Catchment

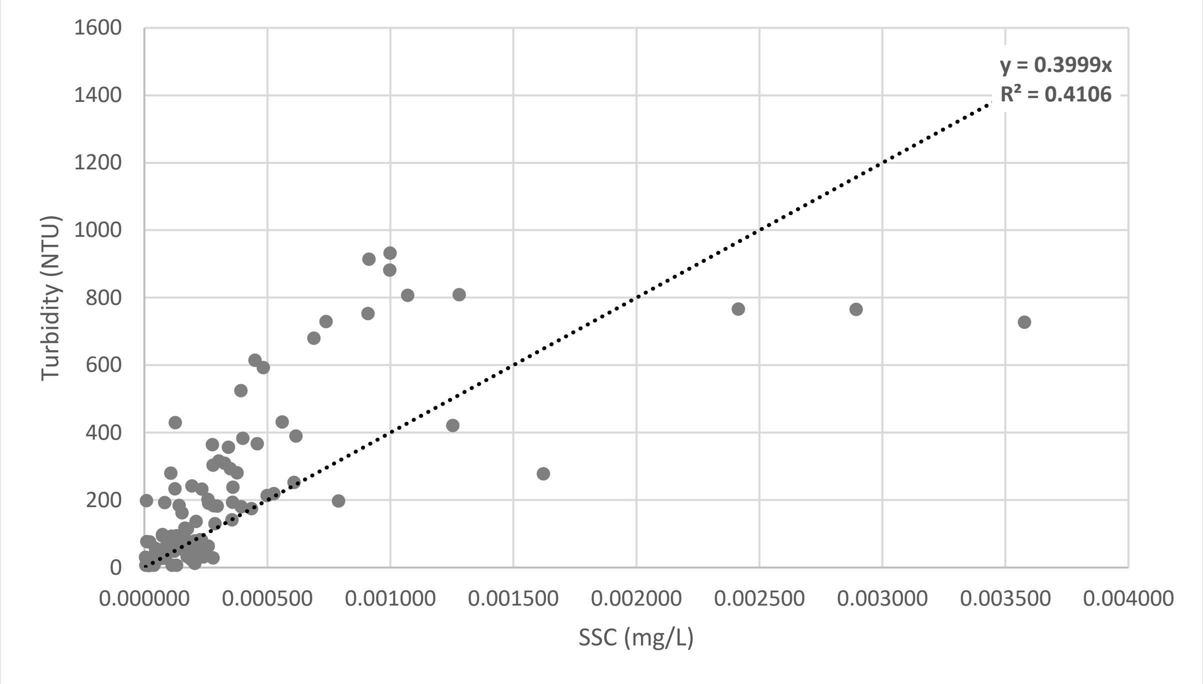


Figure 9.3: Turbidity-SSC relationship of the Ncolosi River Catchment

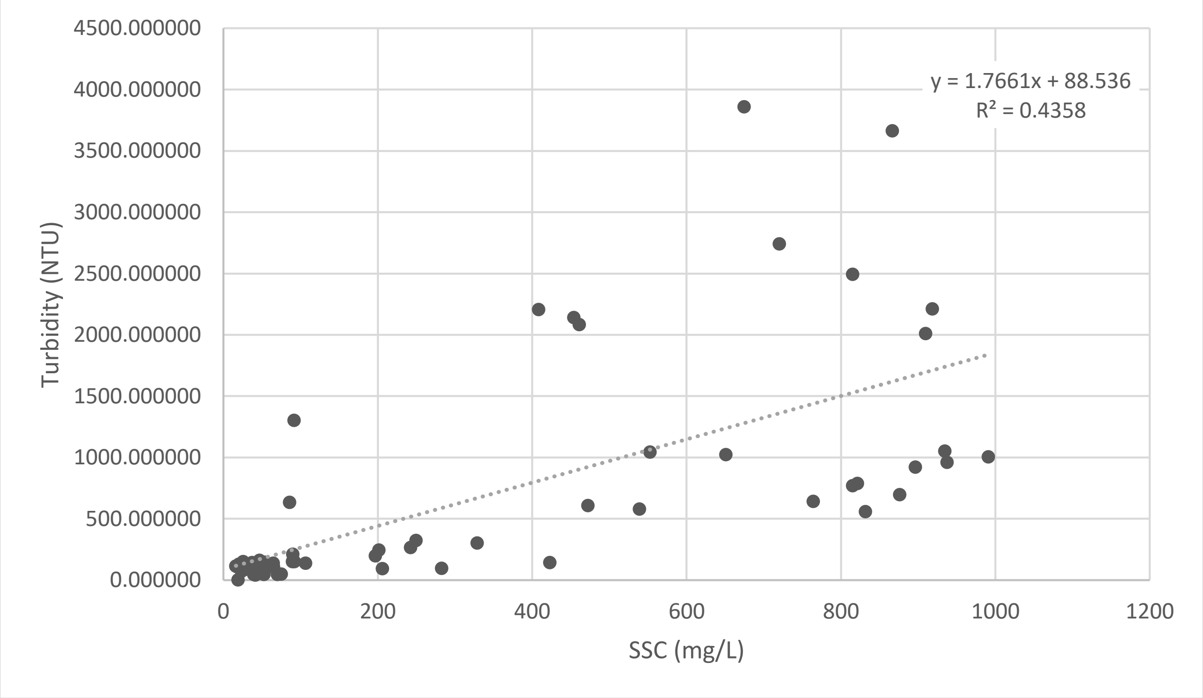


Figure 9.4: Turbidity-SSC relationship of the Qwakele River Catchment

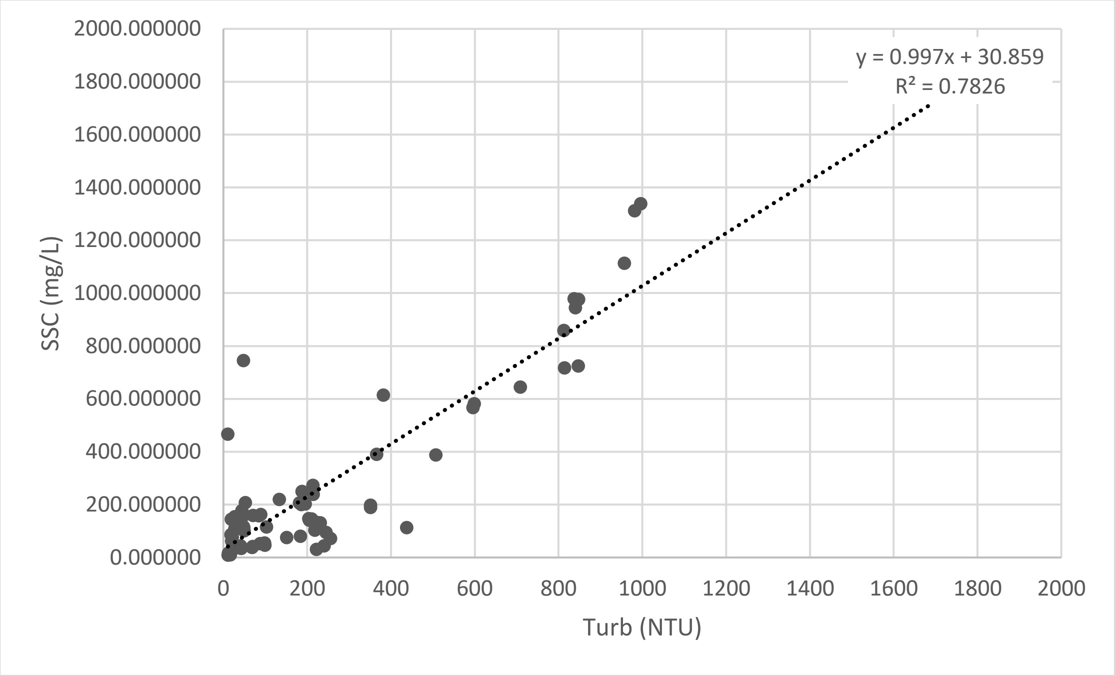


Figure 9.5: Turbidity-SSC relationship of the Umnga River Catchment

Appendix 3: Site-Specific Cross-Sections, Manning's Values and Rating Curves

The following section provides information for the site-specific parameters that were required to indirectly estimate discharge using Manning's equation.

Monitoring point: Umnga

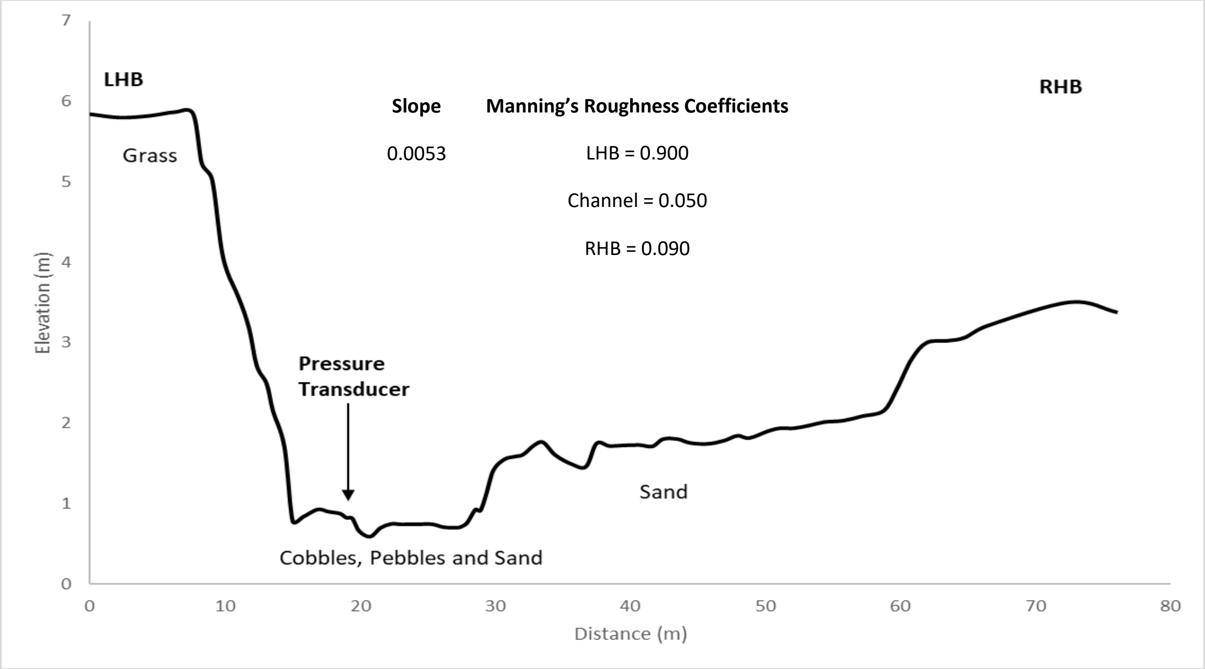


Figure 9.6: Cross-section and discharge parameters for the Umnga River monitoring point

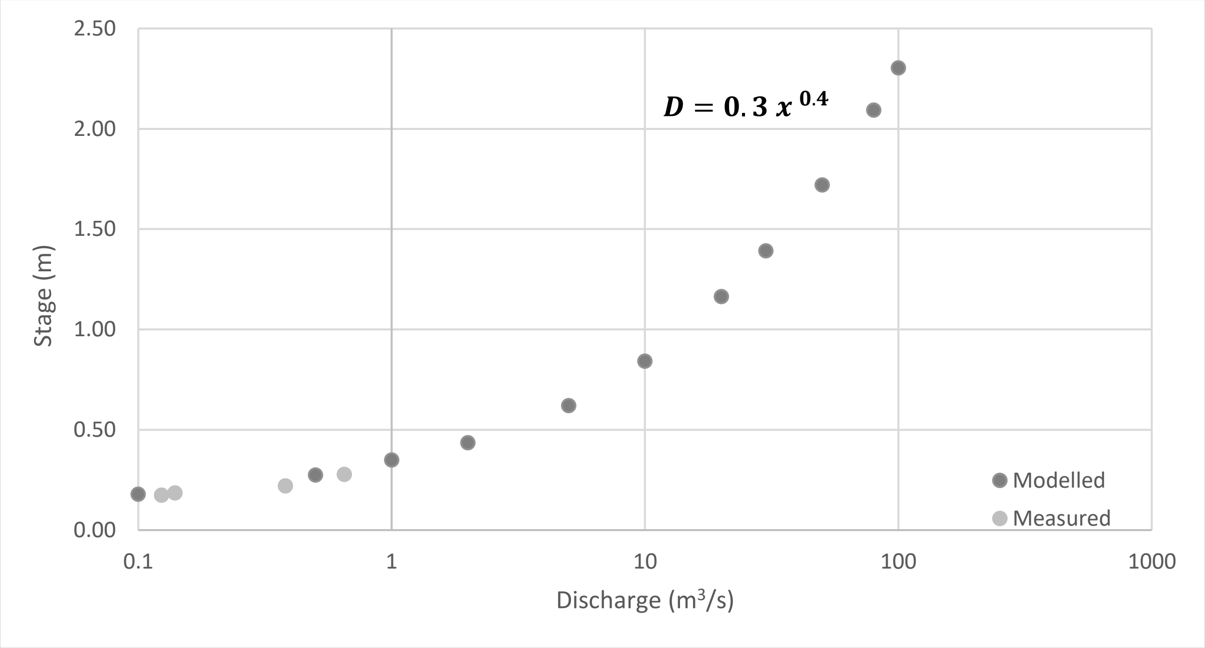


Figure 9.7: Rating curve for the Umnga River monitoring point

Monitoring Point: Ngxaza

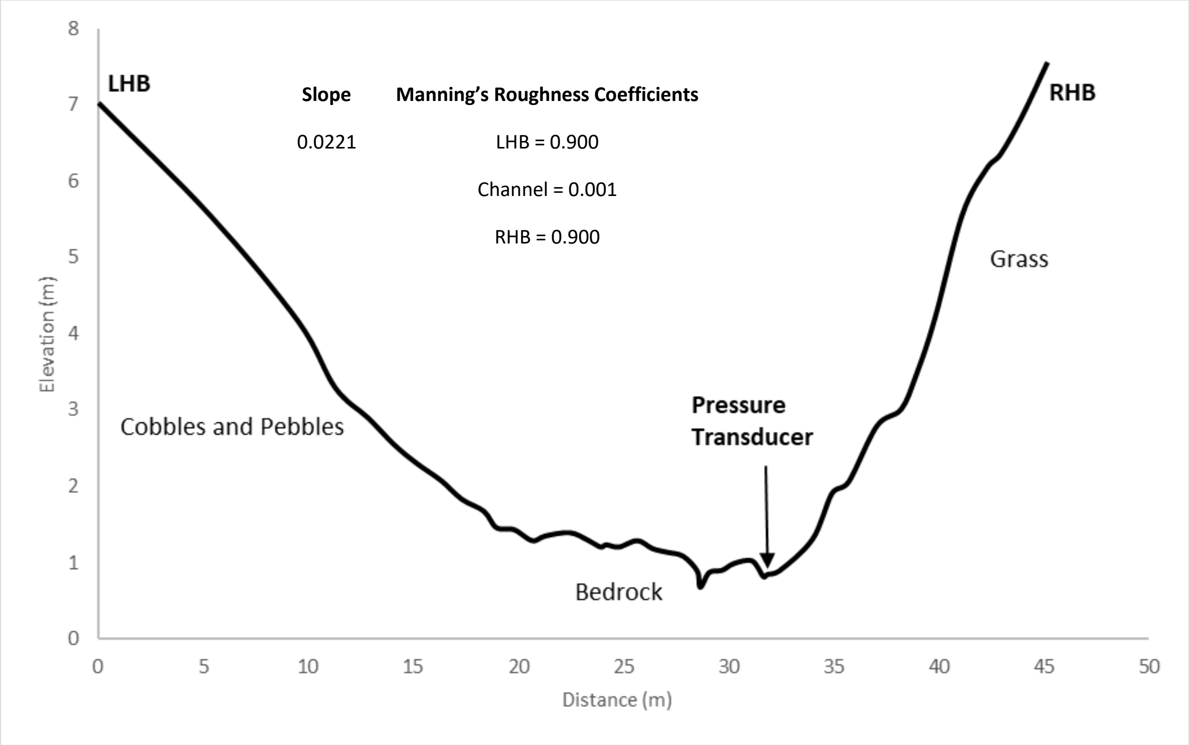


Figure 9.8: Cross-section and discharge parameters for the Ngxaza River monitoring point

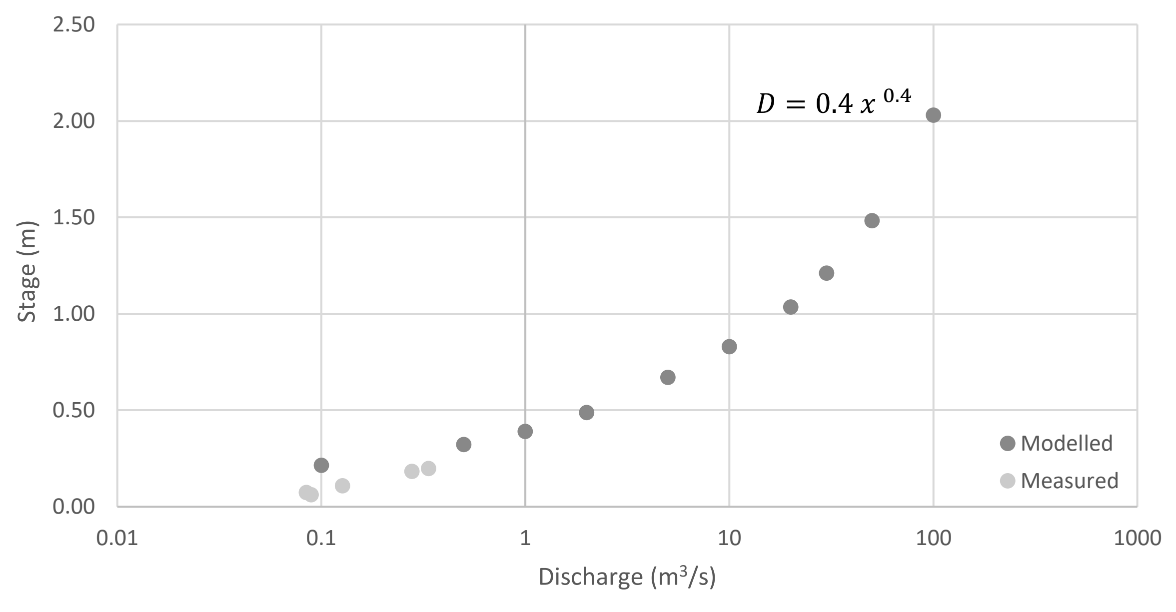


Figure 9.9: Rating curve0 for the Ngxaza River monitoring point

Monitoring Point: Qwakele

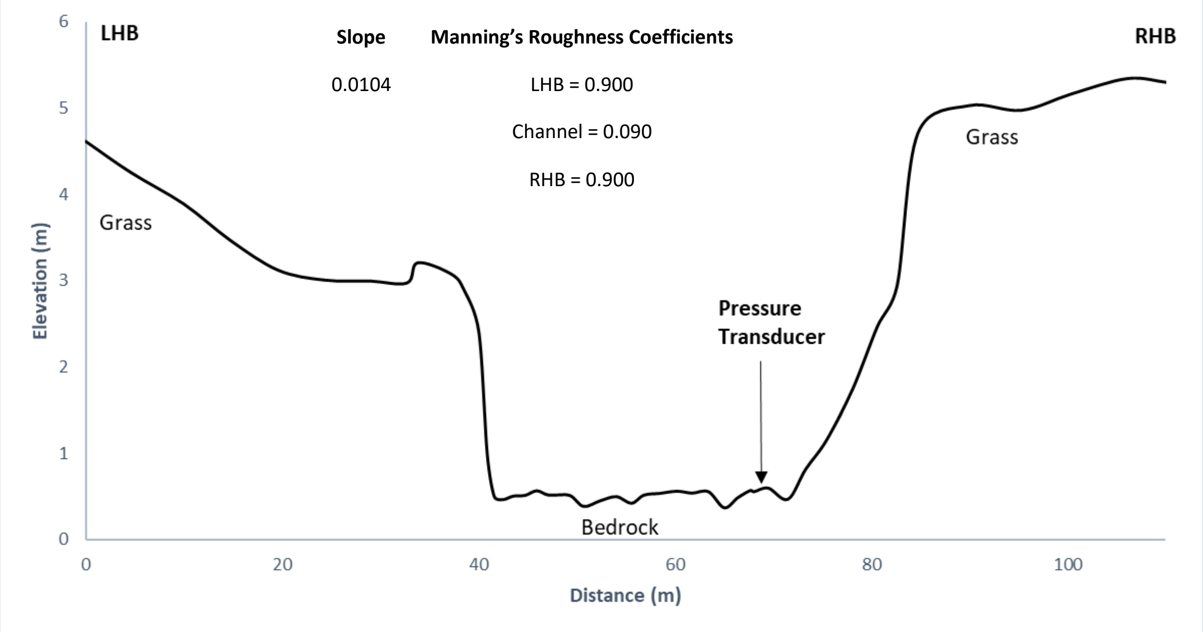


Figure 9.10: Cross-section and discharge parameters for the Qwakele River monitoring point

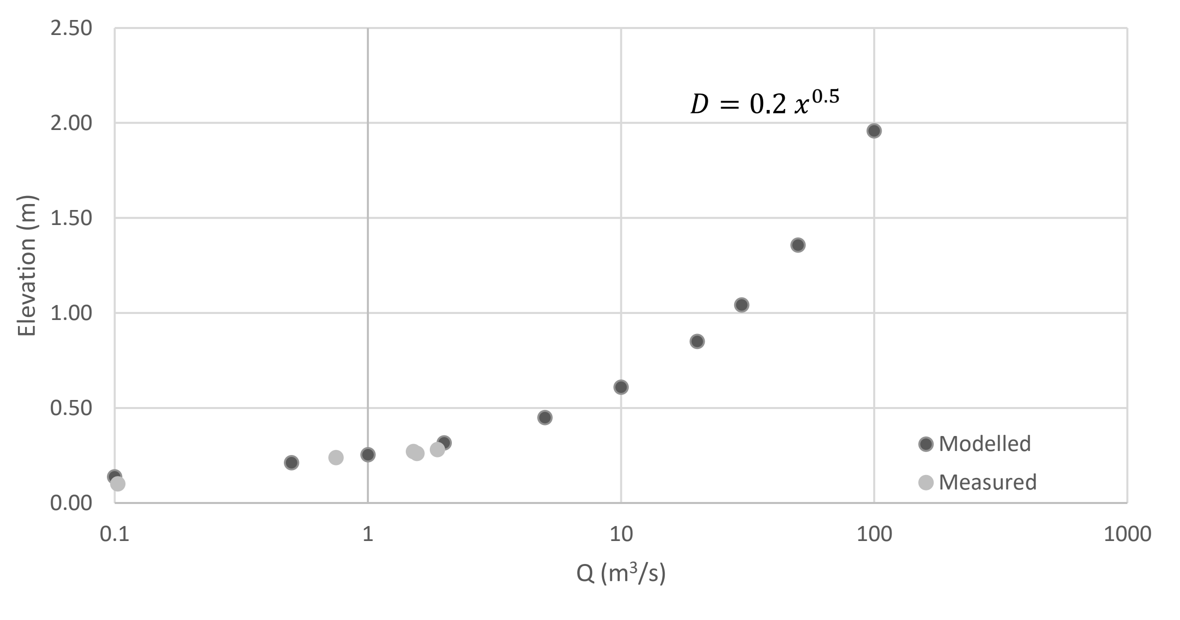


Figure 9.11: Rating curve for the Qwakele River monitoring point

Monitoring Point: Ncolosi

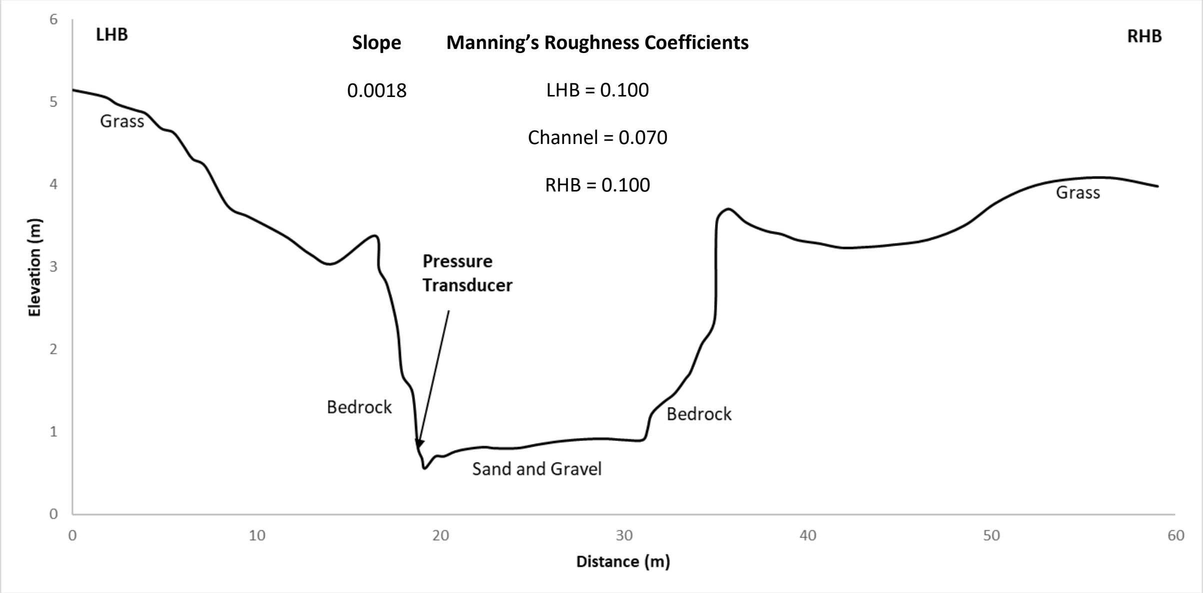


Figure 9.12: Cross-section and discharge parameters for the Ncolosi River monitoring point

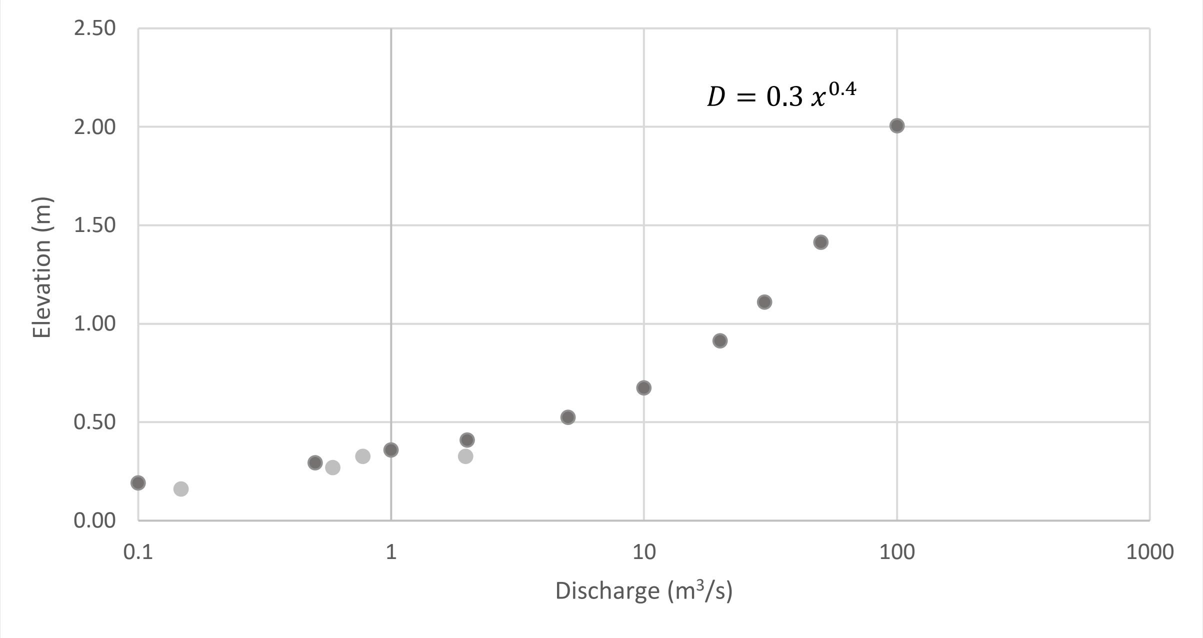


Figure 9.13: Rating curve for the Ncolosi River monitoring point

Monitoring Pont: Inxu Outlet

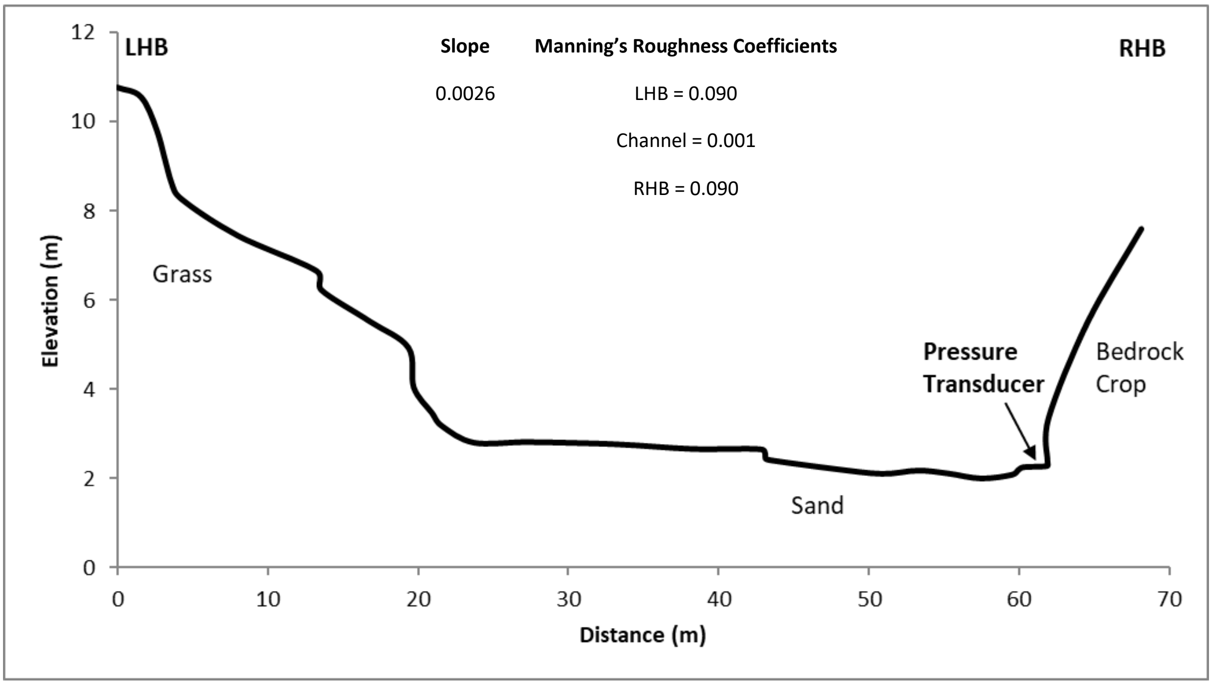


Figure 9.14: Cross-section and discharge parameters for the Inxu Outlet monitoring point

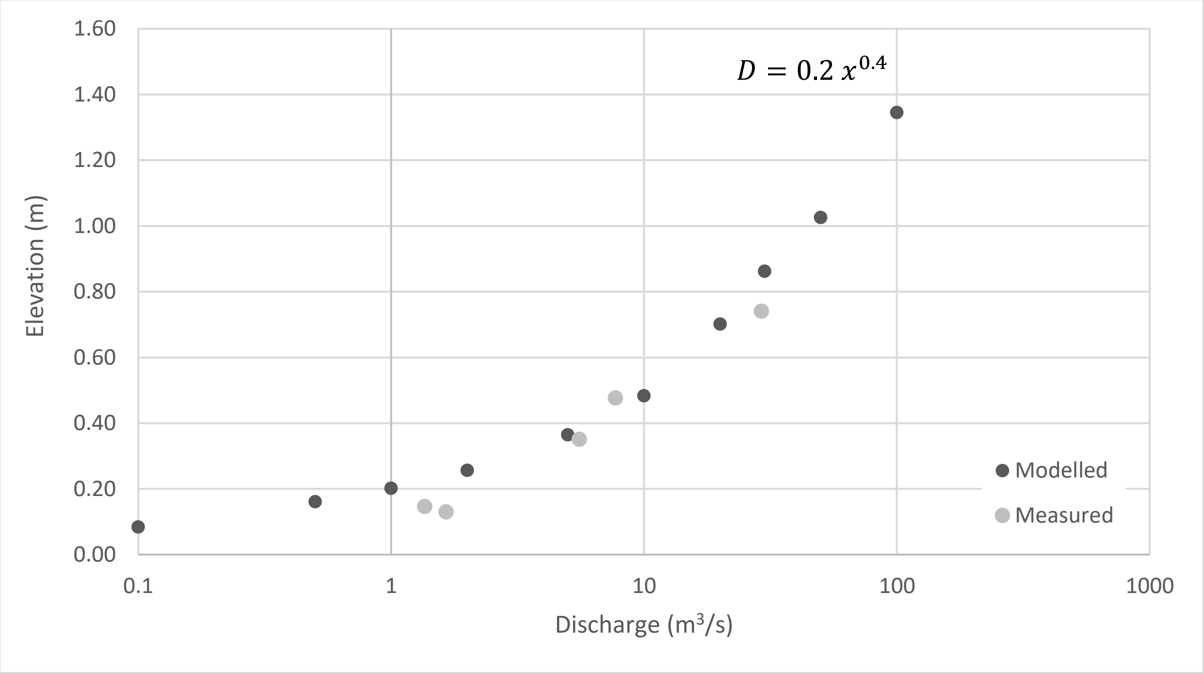


Figure 9.15: Rating curve for the Inxu Outlet monitoring point