

**The implications of the uncertainty
associated with suspended sediment load and yield estimates
for catchment management decision-making
in data and resource-scarce regions**

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Abstract

The research described here focuses on the uncertainties intrinsic to a citizen science-based approach to directly measuring suspended sediment concentration (SSC) in a remote, data scarce area. The research took place in the rural, largely undeveloped Tsitsa River catchment in the Eastern Cape Province of South Africa and has relevance to other parts of the world where similar biophysical and socio-economic challenges to determining suspended sediment loads (SSLs) and yields (SSYs) are found. The upper parts of the Tsitsa River catchment are characterised by private and commercial land ownership, with little evidence of land degradation. Communal land tenure characterises the lower and middle catchment, where dispersive duplex soils support degraded grasslands typified by water-related erosion processes, evidenced by widespread sheet, rill, and particularly gully erosion.

The study was prompted by the Department of Water and Sanitation's (DWS) 2014 plans to build two large dams in the middle to lower parts of the catchment, and by the Department of Fisheries, Forestry, Environment's (DFFE) concurrent launch of sustainable land management interventions in the same area (i.e. The Tsitsa Project). DWS and DFFE required measured SSL and SSY estimates to inform dam siltation rates, and to prioritise further interventions, respectively. The candidate designed, established, and oversaw the implementation of an SSC sampling and analysis programme (the focus of her Master's research). The research described in this thesis used the resulting SSC data and aimed to investigate the uncertainty associated with SSL/SSY estimates, and to consider the implications for catchment management decision-making in this and other remote and resource-scarce regions.

The study aim was achieved through four objectives: Objectives 1 and 2 identified and assessed the uncertainty associated with input SSC data and SSL and SSY estimates. The estimated SSLs/SSYs were compared between sub-catchments, and with published measured and modelled SSLs/SSYs. Objectives 3 and 4 critically evaluated the methods used to collect SSC samples, calculate discharge, undertake laboratory analysis, and estimate SSLs/SSYs.

The study area was 500 km distant from Rhodes University. Proximity to the site of those undertaking the monitoring was a key factor in responding to variable conditions and thereby constraining epistemic and natural uncertainty. Local residents, here referred to as citizen technicians, collected flood-focused river water samples which were analysed in a laboratory to provide SSC (mg L^{-1}) data. Data analysis covered the period from 1 December 2015 to 31 May 2019, although sampling continued until March 2023. Time-weighted mean concentration was used to estimate daily SSL (t day^{-1}) from instantaneous SSC and discharge. Annual SSL was estimated using a ratio estimator, as weak SSC/discharge relationships precluded the use of sediment rating curves.

SSC data was found to be representative of target high discharges for the periods that sites were sampled: The citizen technicians sampled SSC for >80% of the time that their site was active and > 78% of target high flows were typically sampled giving <20%CV variability for high SSC samples. However, sampling from the riverbank may not have been representative of channel cross-section SSC: the associated uncertainty is unknown, and further research is required to confirm assumptions that suspended sediment originates mainly from washload and is distributed homogeneously across river channels in South Africa.

SSL and SSY estimates both require input of discharge data. Secondary discharge data ($\text{m}^3 \text{s}^{-1}$) were received from two DWS gauges and, in nine previously ungauged sub-catchments, from stage data collected and calculated by other researchers as part of wider biophysical surveying for the Tsitsa Project.

Hydrological variability is a major component of natural uncertainty in SSL/SSY estimation, encompassing the variable hydrological responses of a catchment to long term flood and drought cycles, seasonal rainfall trends, antecedent conditions, and individual rainfall events. Although low flows dominated throughout the project period, the Tsitsa River and its tributaries were found to be flashy, with high seasonal and annual variability contributing to natural uncertainty.

Measuring flood discharges is recognised even in established national-level monitoring programmes to be challenging: In this study, limited funding coupled with the remote study area resulted in few, mainly dry-season multi-purpose field visits that allowed few, mainly low-discharge measurements. These in turn resulted in stage/discharge rating curves with a potentially significant but unknown error, particularly for high flows.

Hence, the most significant source of input data epistemic uncertainty was found to be associated not with the novel CT-sampling approach to SSC data, but with the measurement and calculation of the discharge data.

Annual SSYs ranged from $15 \text{ t km}^{-2} \text{ yr}^{-1}$ for Hlankomo (2016) to $1443 \text{ t km}^{-2} \text{ yr}^{-1}$ for Inxu (2018), i.e., within the $94 \text{ t km}^{-2} \text{ yr}^{-1}$ to $1509 \text{ t km}^{-2} \text{ yr}^{-1}$ estimated from reservoir studies for the Eastern Cape region. Mean SSY estimated for the entire $\sim 4900 \text{ km}^2$ Tsitsa River catchment ($111 \text{ t km}^{-2} \text{ yr}^{-1}$) was at the low end of this range, and $\sim 22\%$ of published mean SSY estimated using an uncalibrated model. Mean sub-catchment SSYs from this study were comparable to those estimated from specific reservoir studies, but uncalibrated modelled estimates were typically one to two orders of magnitude higher than rates found here. The error associated with the measured SSLs and SSYs was not quantifiable, but a relative

assessment of SSL/SSY uncertainty at each site was made, using criteria such as sampling coverage and record length.

Comparisons between sub-catchments showed that mean SSY increased downstream, probably due to the combination of dispersive soils, communal land management practices, and prevalent gullies in the middle and lower Tsitsa River catchment. However there was no clear relationship between SSY and catchment area.

It was concluded that project resources were disproportionately allocated towards collecting and analysing water samples with low SSC which comprised the majority of samples but which contributed a negligible amount to estimated SSLs/SSYs. Stratifying daily load data showed that sampling only in the wet season, or only the high flows, would have an insignificant effect on SSL/SSY precision. Decimation of daily SSL showed that sampling could be reduced to three days per week in the larger catchments. These strategies would substantially reduce both sampling and analysis costs, allowing greater temporal and/or spatial coverage. However, socio-economic circumstances in the Tsitsa River catchment mean that the resulting loss of income could lead to citizen technicians seeking other employment, severely disrupting the sampling programme. Instead, it is suggested that citizen technicians should be trained to substitute or supplement low flow samples with turbidity measurements and appropriate site-specific calibration strategies, in order to reduce sample numbers and allow improvements in laboratory analysis. Where practical, SSC sampling sites should be located near functional gauging weirs to reduce the uncertainty associated with measured discharge. In ungauged catchments, funding and equipment should be directed towards more frequently and more accurately measuring high flows to improve the accuracy of stage-discharge rating curves, although the challenge of being present for high flows, and of working safely in medium to high flows and of non-uniform channels with changing bedforms would persist.

This study has shown, for the first time, that an innovative, locally-appropriate SSC sampling and analysis strategy can result in precise SSC data, confirming that it can be adapted for use in other resource-scarce regions, with benefits not only for natural resource managers and scientists, but also for people living in the study area. These data allow, again for the first time, the calibration and verification of South African sediment yield models, as well as further research into sub-catchment scale sediment/discharge relationships, for example through events and seasons. They provide a foundation for investigations into key hydrological and geomorphological processes that impact catchment management decision-making in the Tsitsa River and similar catchments. These include amongst others the location and

prioritisation of land management initiatives and of water resources infrastructure design and management.

Complementary research is required regarding the potential heterogeneity of sediment characteristics throughout channel cross-sections, the volume and rate of movement of the sand-sized particles that form much of the bedload in the Tsitsa River catchment, and the spatial and temporal dynamics of sub-catchment sediment sources.

Keywords

Suspended sediment loads and yields; Data uncertainty; Citizen Science; Manual suspended sediment sampling; R-B Index; Tsitsa River catchment South Africa; Water resources management

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Acronyms and abbreviations

DALRRD	(South African) Department of Agriculture, Land Reform, & Rural Development
DFFE	(South African) Department of Forestry, Fisheries, and Environment
DoA	(South African) Department of Agriculture
DWS	(South African) Department of Water and Sanitation
EC	Electrical conductivity
GIS	Geographic information system
GPS	Global positioning system
HEC-RAS	Hydrologic Engineering Center's River Analysis System
h ₀	Zero level in a discharge calculation
HRU	Hydrological Response Unit
ISO	International Standards Organisation
MAE	Mean Absolute Error
MSE	Mean Square Error
MUSLE	Modified Universal Soil Loss Equation
NLEIP	Ntabelanga and Lalini Ecological Infrastructure Project
ntu	nephelometric turbidity unit
OBIA	Object based image analysis
ODK	Open Data Kit
R-B index	Richards-Baker Flashiness Index
RSA	Republic of South Africa
RSA	(Republic of) South Africa
RU	Rhodes University
RUSLE	Revised Universal Soil Loss Equation
SA	South Africa
SD	Standard deviation

SDR	Sediment delivery ratio
SS	Suspended sediment
SSC	Suspended sediment concentration
SSL	Suspended sediment load
SSY	Suspended sediment yield
SSYM	Suspended sediment yield model
SWAT	Soil and Water Assessment Tool
TDS	Total dissolved solids
TE	Trap efficiency
TWMC	Time-weighted mean concentration
USA	United States of America
USLE	Universal Soil Loss Equation
WQSED	Water Quality and Sediment Model
WRC	(South African) Water Research Commission

Appendices

NB. Appendices were submitted electronically and were not included in this manuscript.

Appendix 1: Evidence candidate's involvement with fieldwork

Appendix 2: Discharge monitoring and data calculation for previously ungauged catchments

Appendix 3: Percentage discharge exceedance calculations (MS Excel)

Appendix 4: Total dissolved solids calculations (MS Excel)

Appendix 5: Triple sample precision analysis example (MS Excel)

Appendix 6: Sampling coverage of high flows (MS Excel)

Appendix 7: SSC/turbidity regressions and error analysis example (MS Excel)

Appendix 8: Time-weighted mean concentration calculations (MS Excel)

Appendix 9: Bannatyne et al. (2022) Published paper

Appendix 10: Suspended sediment concentration/discharge regressions (MS Excel)

Appendix 11 Suspended sediment load calculation example (MS Excel)

Appendix 12: Daily load decimation and stratification example (MS Excel)

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What we call data are inference-laden signifiers of natural phenomena to which we have incomplete access.

(Oreskes et al., 1994)

“The unfortunate truth is that in many cases we lack the resources to explore the science and/or understand the process, we just want to be able to provide reasonably good estimates. The truth is that if we actually had the right amount of resource (money and personnel) we wouldn't need rating curves at all; we'd just sample all the time and all the events”. (Art Horowitz, Pers. Comm.)

You are so deeply missed, Art.

Declaration

“I have read and adhered to the Rhodes University plagiarism policy. All of the work presented in this thesis is my own. I have not included ideas, phrases, passages or illustrations from another person’s work without acknowledging their authorship.

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Ethical Clearance

The application for ethical clearance for this research project was reviewed by the Science Faculty Ethics Committee and approved without conditions.

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1 Study context

1.1 Soil erosion, land degradation, and dam sedimentation in South Africa

Soil erosion is a natural phenomenon which is increasing globally, largely due to anthropogenic activity (Bridges & Oldeman, 1999; Lal, 2001; Syvitski, 2003; Foster & Boardman, 2018). Borelli et al. (2017) estimated a global average soil erosion rate of $280 \text{ t km}^{-2} \text{ yr}^{-1}$ for 2001, with a 2.5% increase by 2012. Excess soil erosion and associated suspended sediment (SS) loads (SSL) and SS yields (SSY) negatively impact aquatic ecosystems, water resources infrastructure, and agricultural potential (Gordon et al., 2013).

Soil erosion and dam sedimentation are recognised landscape and water resources management issues in South Africa, where Le Roux et al. (2008) predicted that water erosion rates ranged between $500 \text{ t km}^{-2} \text{ yr}^{-1}$ and $>15000 \text{ t km}^{-2} \text{ yr}^{-1}$ for much of the country. In many parts of South Africa, land degradation through water erosion processes is predicted to increase due to climate change. This has negative implications for commercial agriculture, national food and water security, and rural livelihoods dependent on communal grazing and ecological goods and services (Le Roux et al., 2015; Itzkin et al., 2021). The rural poor are the most reliant on the land where they live, yet they are often the most vulnerable and the least empowered to manage the negative effects of soil erosion and associated land degradation, and will be particularly affected by the resulting loss of productivity (Itzkin et al., 2021).

In South Africa, water supply and demand are intensively managed and most rivers other than those in the Mzimvubu catchment in the Eastern Cape Province have been impounded (Van Vuuren, 2012 p4). However, approximately 25% of South African dams have lost 10 - 30% of their storage to siltation, whilst Welbedacht Dam in Free State Province lost approximately 87% of its capacity in 20 years (Msadala et al., 2010; Le Roux, 2018). Closer to the Tsitsa River catchment, Mt Fletcher Dam in the neighbouring Thina catchment (**Figure 1-1**) has lost 70% of its storage capacity since 2008 (Rowntree et al., 2012), while the Collywobbles Weir (a storage reservoir for a hydroelectric scheme on the Mbashe River in the Eastern Cape) has lost over 90% of its original 9 million m^3 storage capacity (Matthews, 2008).



Figure 1-1: Google Earth map showing the location of Mount Fletcher Dam and the Collywobbles Weir in relation to the proposed Ntabelanga Dam and nearby towns and cities.

Despite this, the research described in this thesis is the first large-scale (e.g., quaternary catchment), medium term (e.g., > 2 years) suspended sediment sampling (SS) programme that could provide insight into soil erosion and sediment transport rates to be carried out in southern Africa since the 1980s (**Chapter 4** describes previous studies).

1.2 Landscape and water resources governance and management in South Africa

SS data provide a means to determine the baseline and trajectory of catchment erosion rates, for use as an input to management decisions that aim to reduce land degradation and protect water resources (Owens et al., 2005; Horowitz, 2008; Talebizadeh et al., 2010; Vanmaercke et al., 2014; Meissner et al., 2017). The generation and analysis of such data should be funded by entities that undertake catchment management decision-making. South Africa has a complex catchment management framework that is occupied by multiple agencies and actors, across all levels of governance and civil society, including traditional authorities in former homeland areas (Itzkin et al., 2021). A brief overview of the institutional and legislative framework that supports catchment management in South Africa is given here as context for the requirement for and sources of funding of SS data in South Africa.

Protecting and managing the environment to support sustainable development, and the pursuit of equity and redress, provide the foundation of the post-apartheid South African legislative and institutional framework, and drive catchment management decision-making in South Africa (Barnard et al., 2003; Sowman & Brown, 2006). Communities, scientists and practitioners are all expected to play an active role in landscape and water resources management, in contrast to the pre-1994 emphasis on engineering solutions (DWAF, 2003).

South Africa's national environmental policies, legislation and strategies are aligned to global development and environmental management trends, and are intended to improve the lives of individuals through the National Development Plan (RSA, 2021). South Africa is a signatory to global agreements which aim to ensure sustainable social and economic development, climate change mitigation and resilience, and the protection and management of natural resources such as land, biodiversity, and water. These global agreements include:

- 1995 United Nations Convention to Combat Desertification, which obliged the Government of South Africa to develop a National Action Plan to combat desertification,
- 2010 United Nations Convention on Biological Diversity (the Aichi Agreement) which obliged South Africa to achieve 20 biodiversity targets by 2020,
- 2015 Sustainable Development Goals, with 17 goals to be achieved by 2030, and the
- 2019 UN Decade on Ecosystem Restoration 2021 – 2030.

There is a raft of national and provincial legislation that is intended to protect and develop natural resources and to promote socio-economic development. All tiers of government, from local to national, are required to undertake the development of a hierarchy of five-year Integrated Development Plans that are aligned with the Constitution and embody the national policy imperatives of sustainable socio-economic development (Sowman & Brown, 2006; Ruwanza & Shackleton, 2016). In the former “homelands¹” such as the Transkei, traditional leadership structures add a further hierarchical dimension to governance and land management (Cockburn et al., 2018).

The actions of South African government institutions are mandated by specific legislation. Institutionally, the statutory management of landscape and water resources in South Africa falls

¹ A homeland was an area reserved for black South Africans who were restricted from residing in “white” areas under the Apartheid regime (Rowntree et al., 2018).

largely (but not exclusively) within the mandates of the Department of Agriculture, Land Reform, & Rural Development (DALRRD); Department of Fisheries, Forestry and the Environment²: (DFFE); and Department of Water and Sanitation (DWS)³.

Significantly, land use is managed and monitored (sometimes cooperatively) by DALRRD and DFFE, but the direct mandate of DWS regarding water resources management is spatially constrained by riparian water course boundaries and seasonal wetland boundaries. Nevertheless, the National Water Act (Act No. 36 of 1998) tasks DWS with setting up Catchment Management Agencies and the consultative development of Catchment Management Strategies.

Research funding is mainly provided by WRC, DoA, DWS, and DFFE. For example, the research described in this thesis was funded by DFFE. The research and monitoring associated with soil erosion rates and risks, SSY model development and estimation, and gully development, growth and sediment contributions that are reviewed in **Chapter 4.5** were mainly commissioned and funded by DWS through the Water Research Commission (WRC), and/or Department of Agriculture (DoA) Directorate Land Use and Soil Management, and/or DFFE: Environmental Programmes – Natural Resource Management Operational Support and Planning, reflecting their need for data and information for management decision-making.

1.3 Research motivation: The need for measured suspended sediment data in the Tsitsa River catchment

In 2014 DWS indicated their intention to construct the Ntabelanga and Lalini dams on the Tsitsa River for bulk water supply and power generation, as part of the broader Mzimvubu Water Project (van Tol et al., 2014)⁴. At the same time, DFFE initiated the Tsitsa Project⁵, funding multi-disciplinary research and implementation for community-focussed sustainable land management, and hillslope rehabilitation in support of rural livelihoods and climate change resilience (Cockburn et al., 2018; Itzkin et al., 2021; Weaver et al., 2023).

² At that time: Department of Environmental Affairs (DEA), later Department of Environmental Affairs, Fisheries and Forestry (DEFF), and now Department of Fisheries, Forestry, and the Environment (DFFE)

³ At that time: Department of Water Affairs (DWA), later the Department of Human Settlement, Water and Sanitation, and now the Department of Water and Sanitation (DWS).

⁴ Still at the planning stage as of 15 02 2024

⁵ Then the Ntabelanga and Lalini Environmental Infrastructure Project (NLEIP)

Uncalibrated modelled estimates of SSY in some parts of the Eastern Cape in South Africa exceed 2100 t km⁻² yr⁻¹, i.e., they are among the highest in the world (Baade et al., 2012; Vanmaercke et al., 2014; Le Roux et al., 2015). Soil erosion mapping and SSY modelling (discussed in detail in **Chapter 4.5.2**) that had been carried out at sub-catchment scale for the Mzimvubu River catchment indicated that surface water erosion was pervasive, and SSYs in the Tsitsa River catchment were high in comparison with other similar African catchments (Vanmaercke et al., 2014; Le Roux et al., 2015). Estimates of SSY averaged 500 t km⁻² yr⁻¹ for the catchment as a whole, but ranged from 100 t km⁻² yr⁻¹ in the headwaters near the Drakensberg escarpment, to 2250 t km⁻² yr⁻¹ in the highly gullied sub-catchments in the mid-Tsitsa River catchment (Le Roux et al., 2015).

Very few measured SSC data were available for the Tsitsa River catchment prior to the inception of SSC sampling programme on which this research is based (Bannatyne, 2018). Although a very limited number of grab samples were collected by Le Roux et al. (2015), their modelled SSY estimates were neither calibrated nor verified, and were inherently uncertain, leading to a recommendation for an SSC sampling programme (Le Roux et al., 2015). In response to this recommendation, a citizen technician based SSC sampling programme and associated laboratory sampling protocol was designed, implemented, and evaluated by the author in 2015 as the focus of her MSc research. This work is recapped in **Chapter 5.2** to **5.5** with further detail regarding field work in **Appendix 1**. Discharge monitoring sites in the previously ungauged sub-catchments were also selected at this time by the author, although the discharge data collection and discharge calculations were carried out at these and other sites by researchers who were undertaking the biophysical surveying of the Tsitsa River catchment as part of the wider Tsitsa Project. The discharge measurement and analysis methodologies are included as **Appendix 2**.

The overarching aim of the author's MSc research was to develop a relatively low-cost, basic, easily administered, locally appropriate SSC sampling and analysis approach. Spatially, the SSC sampling programme sought to monitor as many sub-catchments as the budget would allow, to represent the range and variability of the roughly east-west trending anthropogenic and biophysical influences on soil erosion and transport, and to provide data that would allow comparison with existing modelled SSYs (Bannatyne et al., 2017). Temporally, sub-daily timestep, flood-focused monitoring was required to collect SSC data representative of seasonal and catchment-specific sediment transport conditions, particularly the high flows that are known to transport the majority of sediment (Horowitz, 2013).

Although the SSC sampling programme design was informed by general recommendations (Msadala et al., 2010), it was limited by several factors, including the 500 km distance from Rhodes University to the Tsitsa River catchment; the prevailing socio-economic and biophysical conditions in the catchment; and, importantly, the restricted fieldwork budget available (Bannatyne et al., 2017). An instrumented approach was precluded by the high cost of importing and maintaining equipment; by the lack of appropriate, secure installation sites and of electrical infrastructure, and by the number of sub-catchments that needed to be monitored.

It was impractical to ensure sufficient continuous researcher presence to sample sediment during the unpredictable high flows throughout the sub-catchments, or to rely on voluntary sampling to provide consistent, protocol-compliant SSC data in an area typified by unemployment and rural poverty (Bannatyne et al., 2017). The solution was to train and employ local residents as citizen technicians to take SSC samples. This approach, suggested by Msadala et al. (2010), had been implemented on a small scale in the neighbouring Thina catchment (Pulley & Rowntree, 2016), and satisfied the DFFE's funding requirement for job creation. However, the significant challenge of ensuring sampling compliance and data quality control in several distant sub-catchments was coupled with concerns regarding the management of and support to citizen technicians (Bannatyne et al., 2017). Software-enabled smartphones were therefore used to support communication, data reporting and compliance-checking.

The author's MSc thesis (Bannatyne, 2018) critically evaluated the design of the SSC sampling programme, and investigated the efficiency and effectiveness of the first six months of citizen technician-based SS sampling at four sites, the proficiency of the laboratory analysis methods, and the accuracy of the resulting SSC data (Bannatyne, 2018). Early findings were summarised in a paper (Bannatyne et al., 2017). SSLs and SSYs were not estimated as part of that research. However, the MSc research left the following questions unanswered:

- What are the measured SSLs and SSYs in the Tsitsa River catchment?
- What is the uncertainty associated with CT-based measured SSC and with the SSLs/SSYs derived from them?
- How does data and resource scarcity influence the spatiotemporal design of direct SS sampling programmes, and how does this affect the degree of uncertainty associated with measured SSLs/SSYs?
- What are the implications of this for catchment management decision-making and further scientific research in inaccessible, ungauged catchments where resources are scarce?

1.4 This study

1.4.1 Aim and objectives

One aim and four objectives were identified from the research gaps described above:

Aim: to investigate the implications of the uncertainty in SSC data gathered by citizen technicians for catchment management decision-making in inaccessible, ungauged catchments with limited resources.

Objective 1: Identify, and assess where feasible, sources of uncertainty associated with the input SSC data in terms of its spatiotemporal coverage and data quality.

Objective 2: Estimate the project period measured SSLs and SSYs for each sub-catchment with, where feasible, an assessment of the sources and extent of the uncertainty in the estimate.

Objective 3: Investigate the effect of stratifying and decimating daily SSC data on the precision of SSL/SSY estimates.

Objective 4: Evaluate the current approach to SS monitoring and SSL/SSY estimation and suggest modifications to the sampling programme to reduce uncertainty in yield estimation in inaccessible and ungauged catchments where resources are limited.

This thesis describes the original research undertaken to estimate sub-catchment SSLs/SSYs, investigate the associated uncertainty, and consider the implications for sampling programme design, catchment management decision-making, and further research. This study used the SSC data collected using the CT-based, flood focused direct sampling programme undertaken from mid-December 2015

to 1 June 2019 in the Tsitsa River catchment, Eastern Cape Province, South Africa. Initially envisioned as a 10 year programme, data collection continued until 31 March 2023, when a change in DFFE funding priorities brought an end to the Tsitsa Project.

The thesis focusses on water erosion processes. It does not consider wind erosion processes, or other processes that physically remove soil from fields, such as those associated with vegetation/crop removal or by farm machinery, although the influence of land use and management practices on sediment availability and water erosion rates is considered. The impact of mass wastage on variability and uncertainty in SSL and SSY estimation (for example from riverbank undercutting) is briefly examined (**Section 9.2.3**) but is not quantified separately from other water erosion processes. Downstream relationships between discharge and SSC are considered as part of the SSY estimator selection process (**Chapter 7.3**) whilst seasonality and data scarcity are considered in terms of their impact on SSY uncertainty, and of optimising scarce human and financial resources for future SSC sampling programme design (**Section 9.3.3**).

The motivation for estimating measured SSLs and SSYs for the Tsitsa River catchment was to provide calibration and validation data for use in estimating modelled SSYs, and to provide measured SSLs and SSYs for use by DFFE and other government departments. Both purposes required statements regarding the error and uncertainty associated with the measured SSLs/SSYs. If the CT-based, flood focused, direct SSC sampling campaigns were to be expanded into other catchments, both natural resource project managers and researchers would need to know the error and uncertainty associated with sampling protocols, spatiotemporal sampling programme design, discharge monitoring and calculations, laboratory analysis protocols, and SSL estimation methods, and their implications for the resulting SSLs and SSYs. As importantly, assessing the uncertainty associated with the SSC data would support further research into sediment transport and dynamics in the Tsitsa River catchment, for example into the effects on hysteresis of antecedent rainfall conditions, rainfall erosivity, catchment morphology, and land use and management approaches.

Quantifying the potentially substantial contribution of bedload to the total sediment load (Millares & Moñino, 2018) was outside the scope of this study.

1.4.2 Research structure

Tables 1-1 to 1-4 link each objective with the actions and methods used to achieve the outputs.

Table 1-1: Objective 1

Objective 1	Identify and assess where feasible, sources of uncertainty associated with the input SSC database in terms of its spatiotemporal coverage and data quality
Action	Using data from the SSC monitoring programme a) Develop sub-catchment SSC time-series b) Assess the spatiotemporal extent, the representativeness, and where feasible the precision and uncertainty of the input SSC databases c) critically evaluate the uncertainty intrinsic to the discharge data
Method	a) Laboratory SSC and turbidity analysis b) Spatiotemporal and precision analysis
Output	Statements of spatiotemporal coverage, representativeness and uncertainty for the input SSC dataset.

Table 1-2: Objective 2

Objective 2	Estimate the project-period measured SSYs for each sub-catchment for the project period with, where feasible, statements of the uncertainty
Action	a) Derive SSC from turbidity measurements. b) Derive daily SSC. c) Estimate sub-catchment SSL and SSY using the daily SSC and daily discharge time-series.
Method	a) Establish a site-specific SSC/turbidity relationship and calculate SSC from turbidity for samples <200 ntu ⁶ . b) Derive daily time-weighted mean SSC (mg L ⁻¹) from measured and calculated SSC. c) Select an appropriate SSL estimator d) Estimate SSL and SSY for all sub-catchments
Output	a) Site-specific SSC/turbidity relationships b) Daily SSC (mg L ⁻¹) c) Measured sub-catchment SSLs (t) and SSYs (t km ⁻²) d) Where feasible, statements of uncertainty for these outputs

⁶ Nephelometric turbidity unit

Table 1-3: Objective 3

Objective 3	Investigate the effect of using stratified and decimated data on the precision of SSL estimation
Action	a) Estimate sub-catchment SSL and SSY using limited datasets b) Compare with SSL estimated from complete daily SSL datasets.
Method	a) Stratify the complete daily SSL dataset using discharge, and seasonal limiting b) Decimate the complete daily SSL dataset using permutations of weekdays. c) Estimate limited SSLs and SSYs d) Compare limited SSLs and SSYs with those estimated from complete daily SSL datasets
Output	Statements of the effects of limited sampling on SSL/SSY precision

Table 1-4: Objective 4

Objective 4	Consider approaches to SS monitoring and yield estimation in support of catchment management decision making in large, inaccessible, and ungauged catchments where resources are limited.
Action	Synthesise the findings from the above objectives and literature review
Method	Review and discuss the research findings in the context of the research aim
Output	Reasoned arguments regarding spatiotemporal SS monitoring programme design and SSY estimation methods that will constrain and describe the uncertainty associated with SSL and SSY estimation, in support of decision-making in inaccessible, ungauged catchments with limited management resources

1.4.3 Thesis structure

Abstract

Chapter 1 provides the research background, motivation, aims, objectives, and thesis structure.

Chapter 2 Describes the location of the study area, and the biophysical and socio-economic characteristics that influence soil erosion and sediment transport in the Tsitsa River catchment.

Chapter 3 reviews the relevant literature pertaining to uncertainty in SSL and SSY estimation.

Chapter 4 reviews the relevant literature pertaining to SSLs and SSYs in southern and South Africa

Chapter 5 describes the actions, methods, and outputs associated with identifying, and assessing where feasible, uncertainty associated with the input SSC dataset. A critical evaluation of the uncertainty associated with the received discharge datasets is also included (**Objective 1**).

Chapter 6 describes the actions, methods, and outputs associated with calculating instantaneous SSC from measured turbidity (**Objective 2**).

Chapter 7 describes the actions, methods, and outputs associated with calculating daily SSC and estimating annual SSLs and SSYs (**Objective 2**).

Chapter 8 describes the actions, methods, and outputs associated with investigating the effect of using stratified and limited data on the precision of SSL estimation (**Objective 3**).

Chapter 9 discusses the research findings, and considers their implications for SSL and SSY estimation in support of catchment management decision making in large, inaccessible, and ungauged catchments where resources are limited (**Objective 4**).

2 The Tsitsa River catchment

2.1 Introduction

This Chapter describes the location of the Tsitsa River catchment and identifies the biophysical characteristics and human factors influencing soil erosion in the study area. The influence of these characteristics and factors on the approaches to fieldwork and to SSC sampling programme design are mentioned, but are discussed in greater detail later in the thesis (**Chapter 5**).

2.2 Location and overview

The study area is the 4900 km² Tsitsa River catchment (a tributary of the Mzimvubu River), located in the Eastern Cape Province of South Africa (**Figure 2-1**).

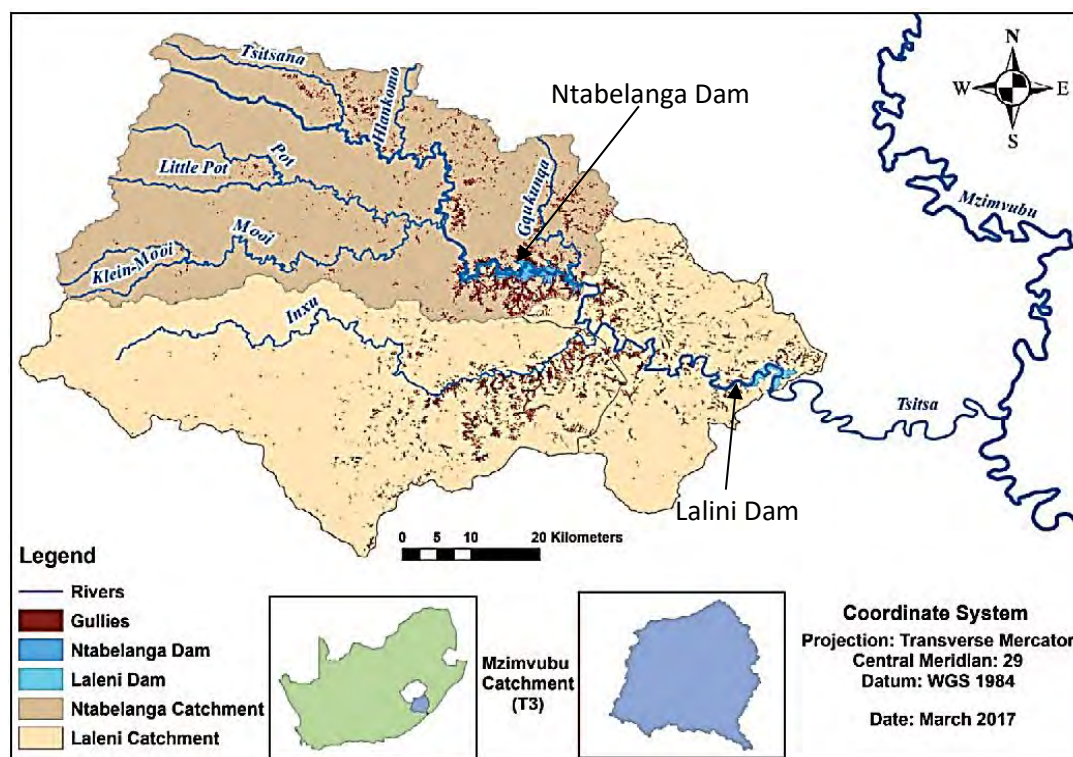


Figure 2-1: Study area with major rivers, gullied areas, and catchments of the proposed Ntabelanga and Lalini dams (Bannatyne et al., 2017). Gully data provided by Le Roux & Sumner (2012).

The Tsitsa River catchment typifies much of the biophysical and social/economic/governance complexity associated with sustainable land and water resources management decision-making in South Africa. It lies 500 km (~6 hrs by vehicle) from the research base at Rhodes University, Makhanda (Grahamstown), and is a predominantly rural, poorly developed area (**Figure 2-2**).



Figure 2-2: A landscape in the communal area of the middle Tsitsa River catchment showing (from foreground) typical dwellings, a deeply incised river channel, sparse grassland with sheet and rill erosion, and gully erosion near settlements in the middle distance (Image: B van der Waal)

The Tsitsa River catchment is socio-economically depressed with poor infrastructure. The headwater catchments that lie mainly to the west are typified by commercial and private forestry and farmland. The communal areas that lie mainly to the east are typified by unemployment, reliance on land-based livelihoods, and land degradation. In the communal areas, gullying and soil piping are large scale and widespread, due to water-related erosion processes. The soil erosion and sediment transport characteristics relate to the variable geology and soils and to associated patterns of land tenure and land management. Rainfall and hydrology are seasonally and annually highly variable.

Most of the roads are unsurfaced, mobile phone networks are patchy and sometimes unreliable, and electricity supply is largely restricted to major centres and private farms. Parts of the catchment become inaccessible for periods during the Austral summer wet season (October – March) when severe storms result in flooding rivers and side channels. Rivers become dangerous to approach and enter, runoff and flooding cause damage to steep unmade roads, as well as overtopping, damage to, and sometimes destruction of bridges. These factors limit fieldwork largely to the dry, Austral winter months (April – September).

2.3 Biophysical characteristics that influence soil erosion and sediment transport

The biophysical characteristics of the study area that influence soil erosion and sediment transport are summarised in **Table 2-1**.

Table 2-1: Summary description of the Tsitsa River catchment: biophysical characteristics

Characteristic	Description	Reference
Area	~2000 km ² above proposed Ntabelanga Dam; ~4900 km ² above proposed Lalini Dam.	Le Roux et al. (2015)
Climate	Sub-humid: Koppen-Geiger zone Cwa (Warm temperate climate with dry winter and hot summer).	Le Roux et al. (2015) Adesina et al. (2016)
Rainfall (Figure 2-3)	~1300 mm in the headwaters to ~620 mm nearer the confluence with the Mzimvubu. 75% of mean annual precipitation (824 mm) falls between November and March. Highly variable mean annual rainfall. Rainfall and rainfall erosivity varies throughout the catchment.	ARC (2012) Moore (2016)
Discharge (Figures 2-4 to 2-16)	Highly variable mean annual and peak annual discharges	ARC (2012) DWS (2022)
Temperature	Monthly means of daily minima and maxima, respectively -4.5 and 10.7 °C (winter), 17.1 and 29.8 °C (summer).	Le Roux et al. (2015)
Geology and soils (Figure 2-21)	Drakensberg Formation basalt dominates the headwaters. All geological units in the interior parts of the catchment belong to the Karoo Supergroup: Clarens and Elliot Formation sandstones give way to Molteno and Tarkastad Formation mudstones (with some sandstones). Dispersive, duplex soils occur on the Tarkastad mudstones of the lower catchments in the former homeland areas. Intrusive dolerite sills and dykes with associated metamorphic zones occur throughout the catchment.	Le Roux et al. (2015)
Geomorphology	“Great Escarpment” geomorphic province; Active erosion; Neogene (25 – 0 Mya) uplift; Steep, often incised, stepped, river profile. Channels poorly connected to floodplains.	Partridge et al. (2010) Baby et al. (2020)
Topography	2 730 m in north-east, ~600 m in south-west. Hilly to rolling; steep escarpments in headwaters and middle catchment.	1: 50 000 Topographic maps
Erosion risk	High, especially in south-west.	Msadala et al. (2010)
Sediment yield	500 t km ⁻² yr ⁻¹ average, ranging between 100 t km ⁻² yr ⁻¹ – 2300 t km ⁻² yr ⁻¹ .	Le Roux et al. (2015)

2.3.1 Catchment-scale rainfall and discharge

During a short-term (August 2015 – May 2016) study at five sites Moore (2016) found that rainfall and rainfall erosivity varied throughout the Tsitsa River catchment, with the highest rainfall and rainfall erosivity occurring in the area closest to the proposed Ntabelanga Dam. Moore (2016) also analysed longer-term rainfall data (1978 – 2012) obtained from The Agricultural Research Council – Institute for Soil, Climate and Weather (ARC-ISCW), finding that annual rainfall ranged from 503 mm to 1144 mm during this period (**Figure 2-3**).

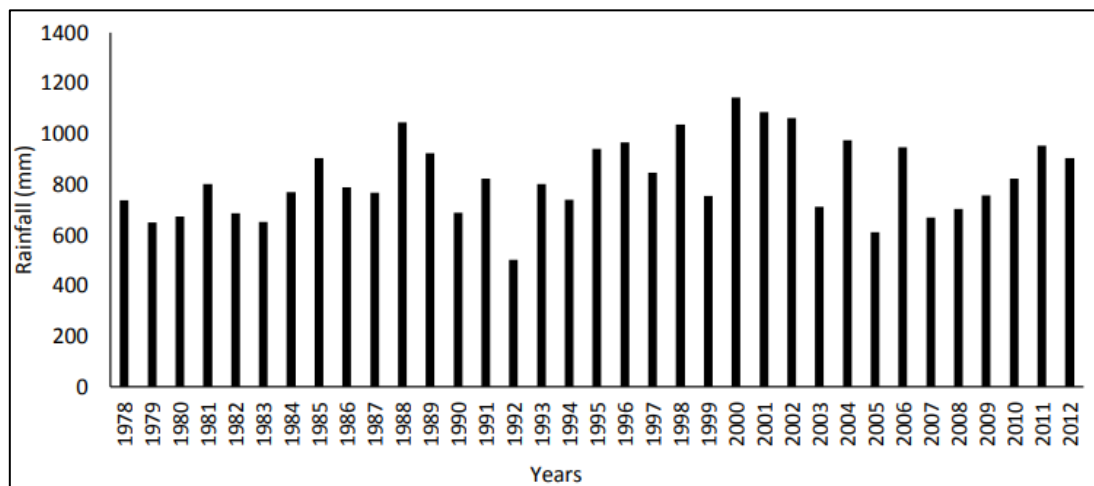


Figure 2-3: Annual rainfall (from ARC-ISCW) for Maclear 1978 – 2012

The temporal variability of rainfall and mean annual runoff (ARC, 2012; Moore, 2016) are evidenced by the highly variable mean annual discharge shown in **Figure 2-4**, which suggests that natural uncertainty may be a significant contributing factor to uncertainty in SSL and SSY estimations. Natural and epistemic uncertainty are discussed in **Chapter 3**. The dark bars in **Figure 2-4** indicate the study period, which represented a relatively dry period.

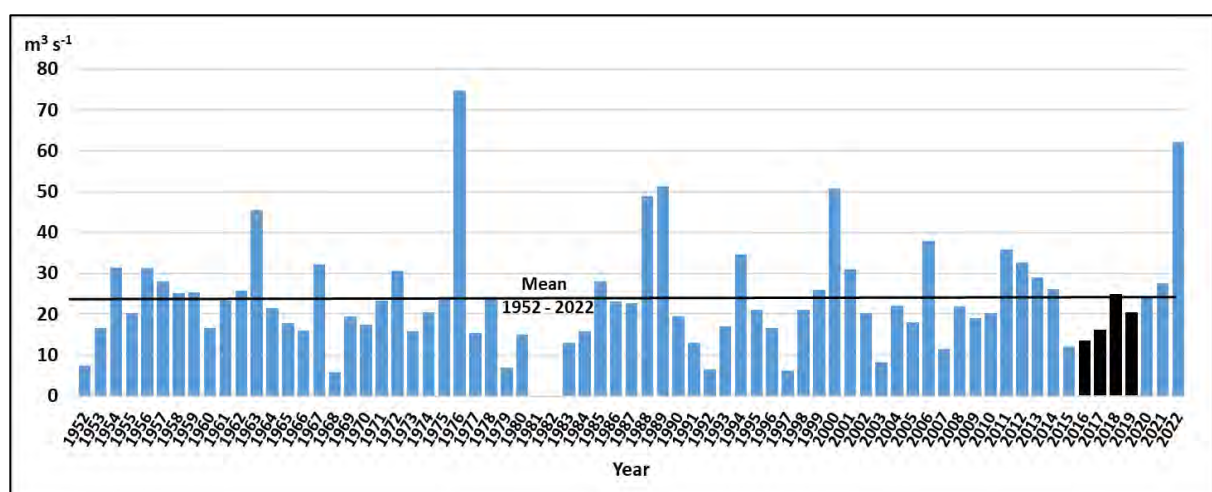


Figure 2-4: Mean annual discharges for the Tsitsa River at DWS gauging station T3H006 1952 – 2020 (DWS, 2022). The four darker bars represent the study period, whilst the black line indicates the mean discharge 1952 - 2022

Cycles of wetter and dryer periods are evident in **Figure 2-4**. The mean annual discharge for the 2018-19 wet season barely exceeded the mean for 1951 - 2022 whilst the other three years were below the mean, with 2015 – 2016 amongst the lowest mean annual discharges recorded since 1951. However, further insight into the hydrological variability (i.e., natural uncertainty) in the Tsitsa River catchment is provided by the annual peak daily flows (**Figure 2-5**).

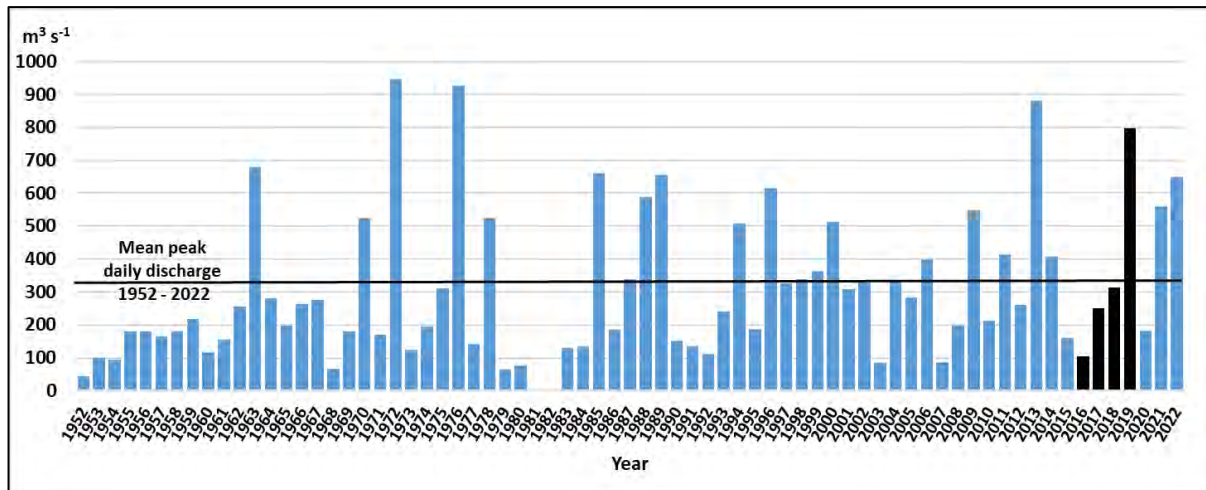


Figure 2-5: Annual peak daily discharges for the Tsitsa River at DWS gauging station T3H006 1952 – 2020 (DWS, 2022). The four darker bars represent the study period, whilst the black line indicates the mean peak daily discharge 1951 - 2022

Comparing **Figure 2-4** and **Figure 2-5** reveals that relatively high annual peak daily discharges frequently occurred not only in relatively wet years, but also in relatively dry years, for example 1970, 1972, 1976, 1985, 2013, 2019, and 2021. This suggests that, although almost certainly restricted to the summer months when 75% of precipitation occurs (Moore, 2016) single events that could transport significant SSLs may occur independently of the prevailing wetter or dryer conditions.

2.3.2 Sub-catchment scale discharge variability

Discharge data were required for SSL and SSY estimation. Hourly discharge data were available from DWS records for two sub-catchments: the Mooi at Maclear (gauging station T3H009) and the Tsitsa at Mbelembushe (gauging station T3H006). Discharge data for the nine previously ungauged sub-catchments were supplied at 20-minute timestep by other researchers as part of the wider Tsitsa Project biophysical monitoring. The discharge monitoring and calculation methods for the nine previously ungauged catchments are described in **Appendix 2**, whilst the uncertainty associated with the discharge data are described in **Chapter 5**.

Time series for daily average discharge for all sub-catchments 01/12/2015 – 31/05/2019 are shown in **Figures 2-6 to 2-16**. Note that the y-axes values are site-specific, ranging from 14 m³ s⁻¹ to 900 m³ s⁻¹.

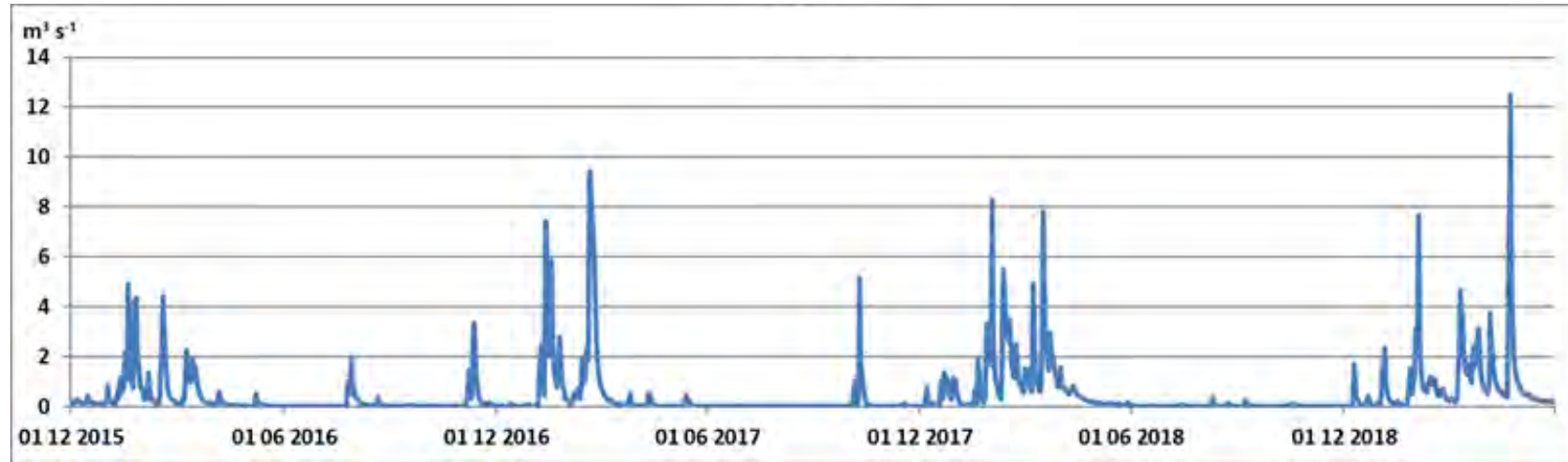


Figure 2-6: Daily discharge 01 12 2015 – 31 05 2019 at Little Pot (75 km²)

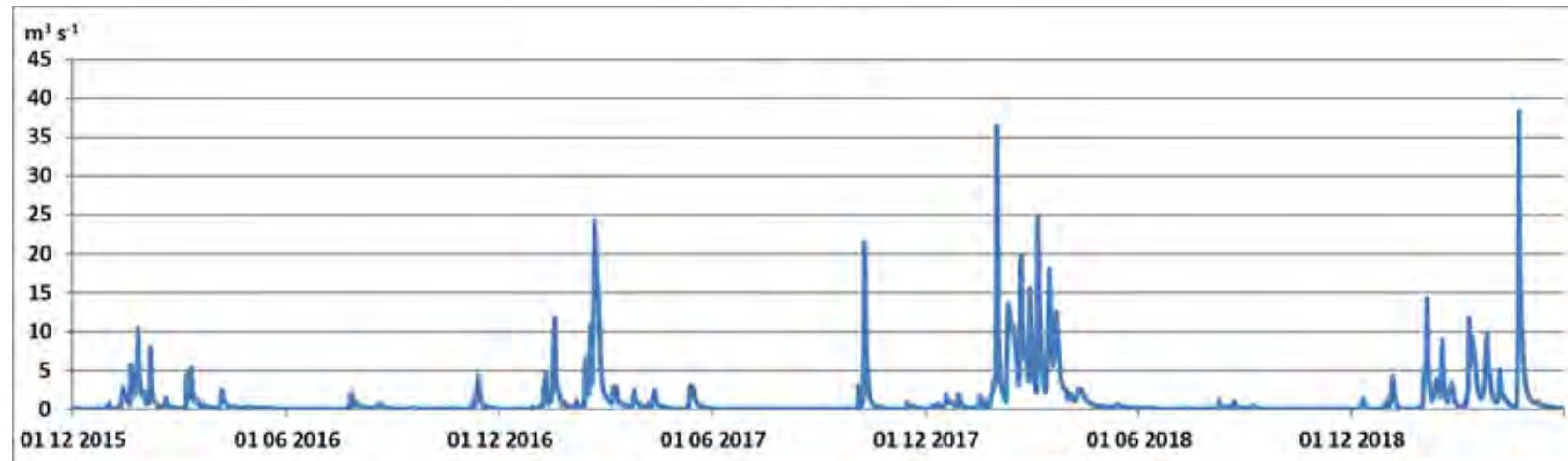


Figure 2-7: Daily discharge 01 12 2015 – 31 05 2019 at Tsitsana (135 km²)

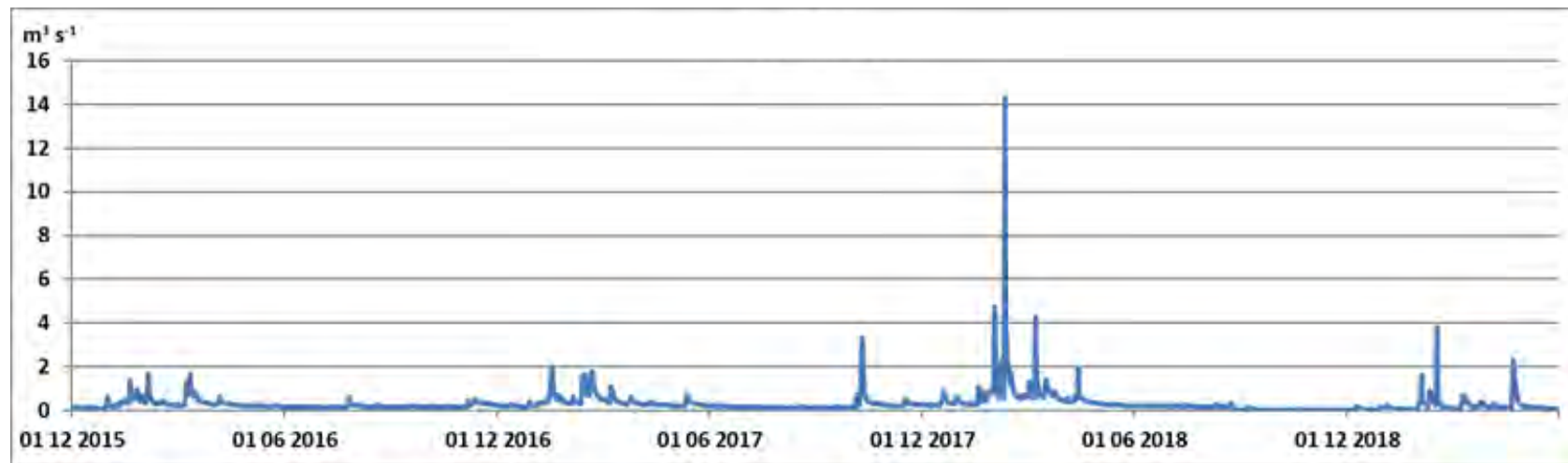


Figure 2-8: Daily discharge 01 12 2015 – 31 05 2019 at Hlankomo (64 km²)

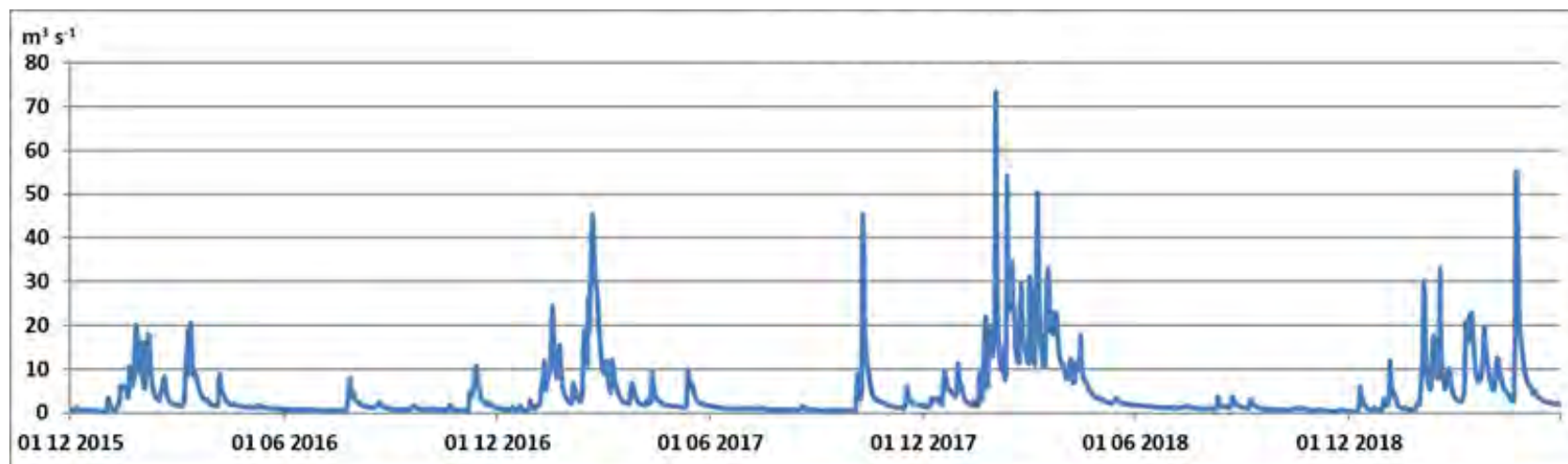


Figure 2-9: Daily discharge 01 12 2015 – 31 05 2019 at T4 (Tsitsa at the Falls, 607km²)

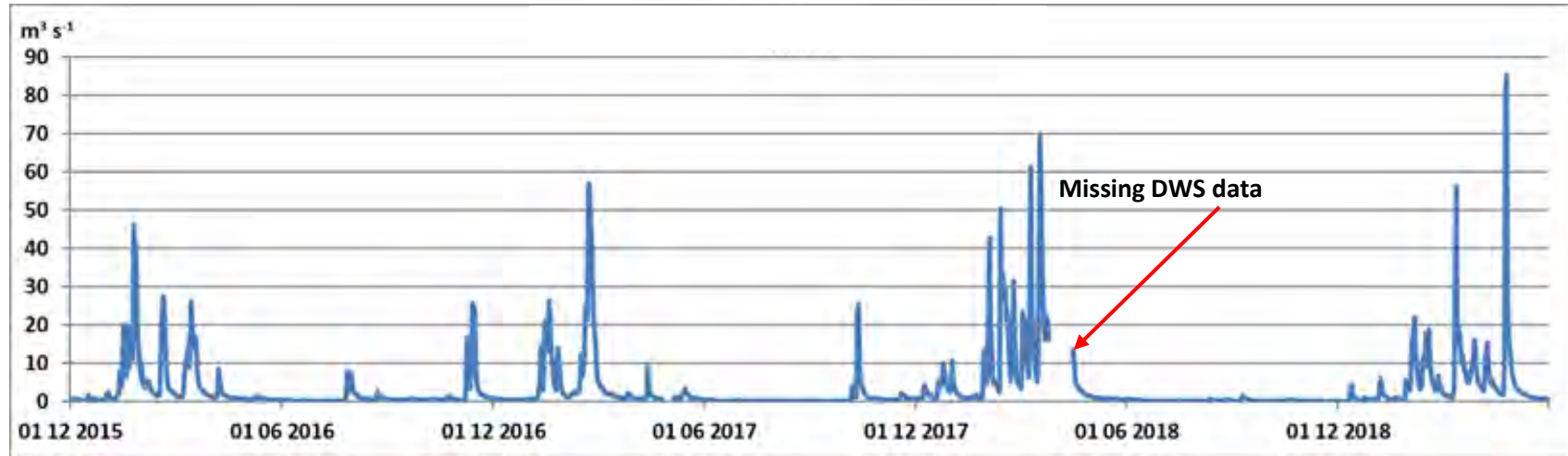


Figure 2-10: Daily discharge 01 12 2015 – 31 05 2019 at Mooi (306 km^2)

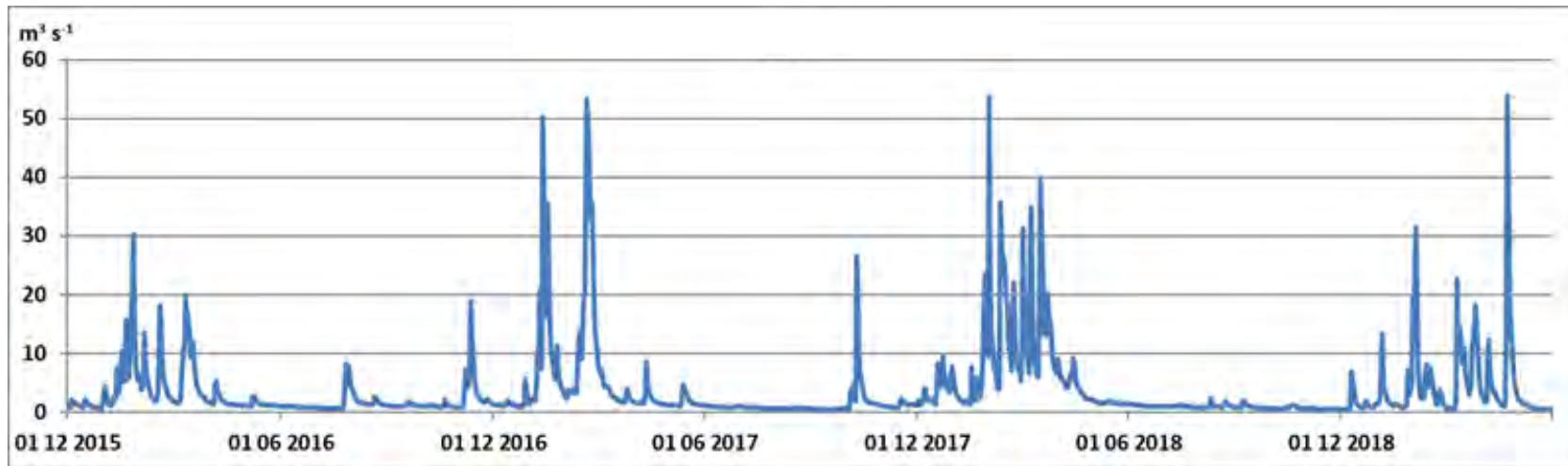


Figure 2-11: Daily discharge 01 12 2015 – 31 05 2019 at Pot (432 km^2)

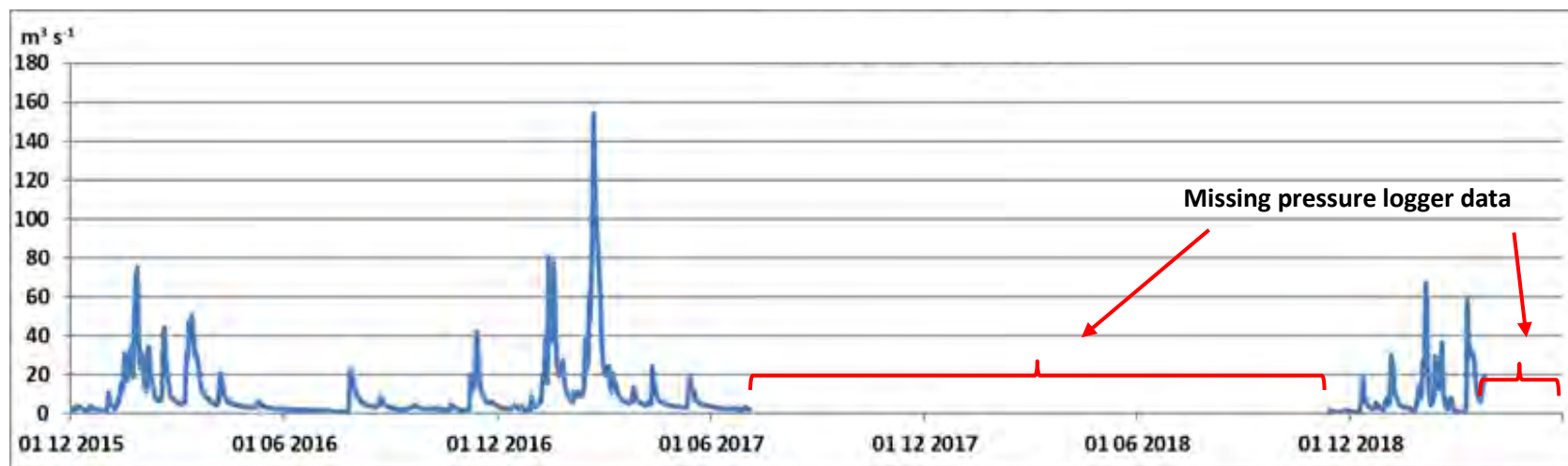


Figure 2-12: Daily discharge 01 12 2015 – 31 05 2019 at T3 (Tsitsa at the Gorge, 1550 km²)

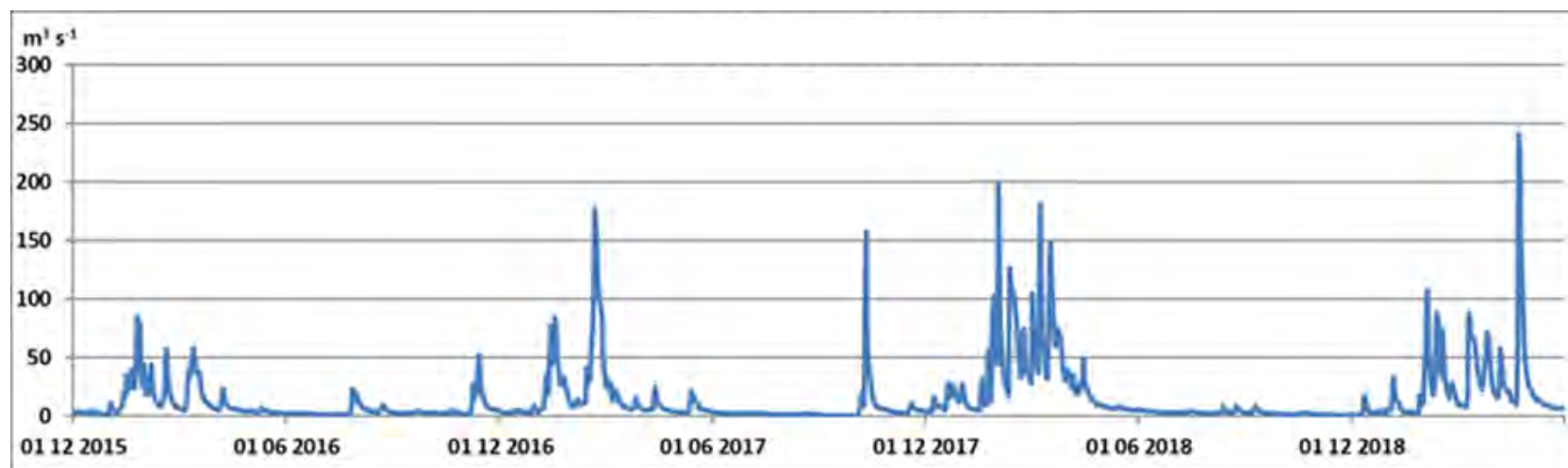


Figure 2-13: Daily discharge 01 12 2015 – 31 05 2019 at T2 (Tsitsa at Qulungashe Bridge, 1881 km²)

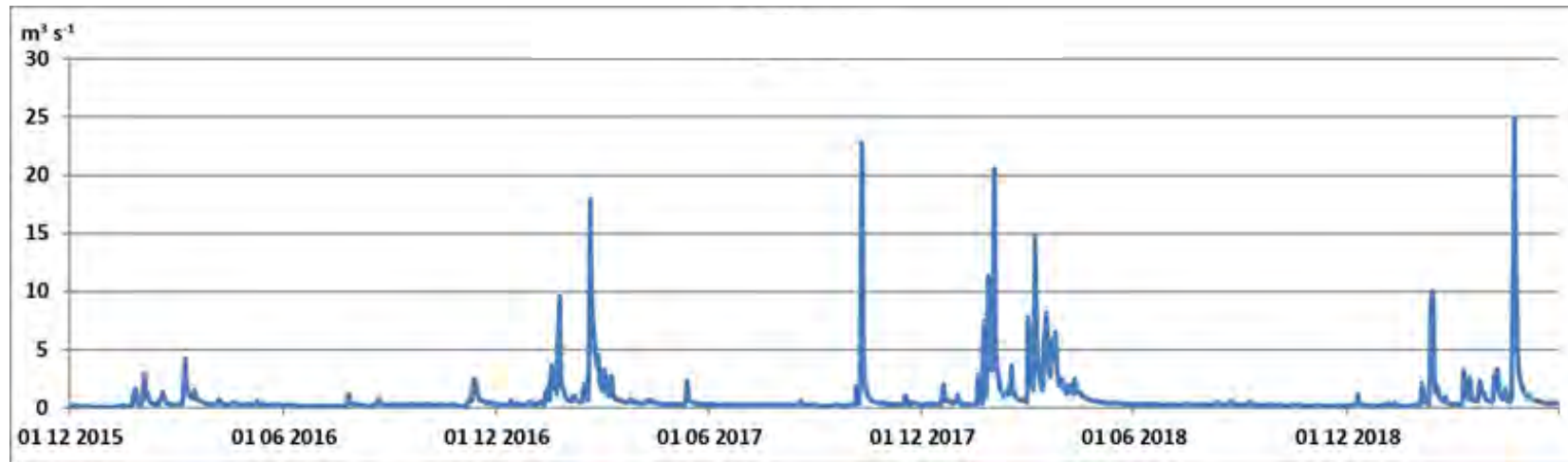


Figure 2-14: Daily discharge 01 12 2015 – 31 05 2019 at Gqunqa (204 km²)

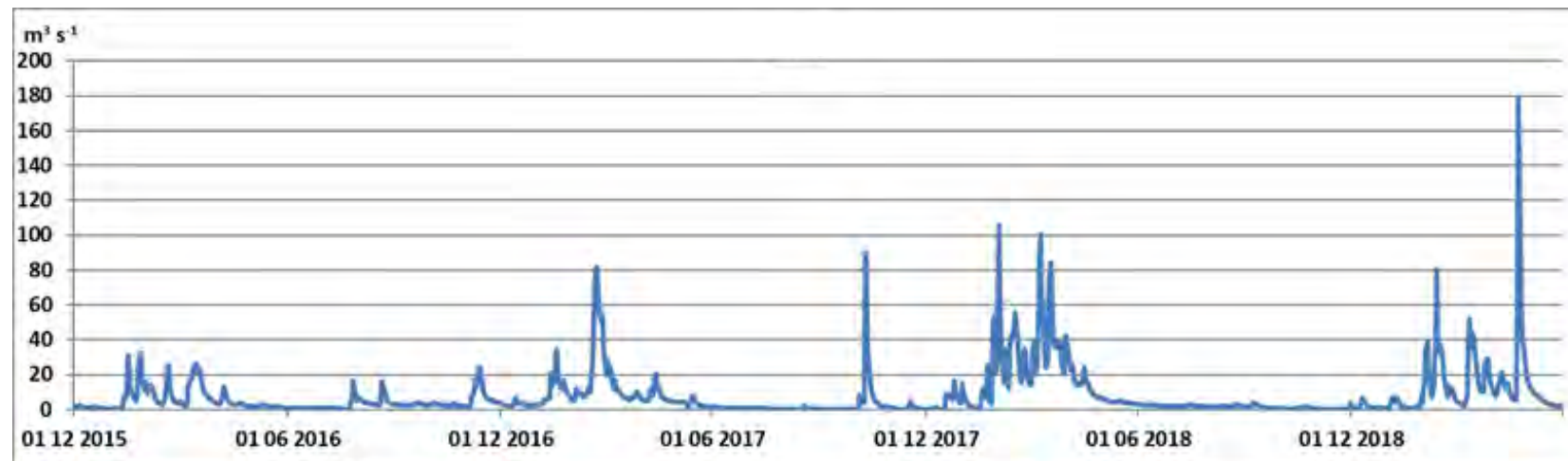


Figure 2-15: Daily discharge 01 12 2015 – 31 05 2019 at Inxu (1452 km²)

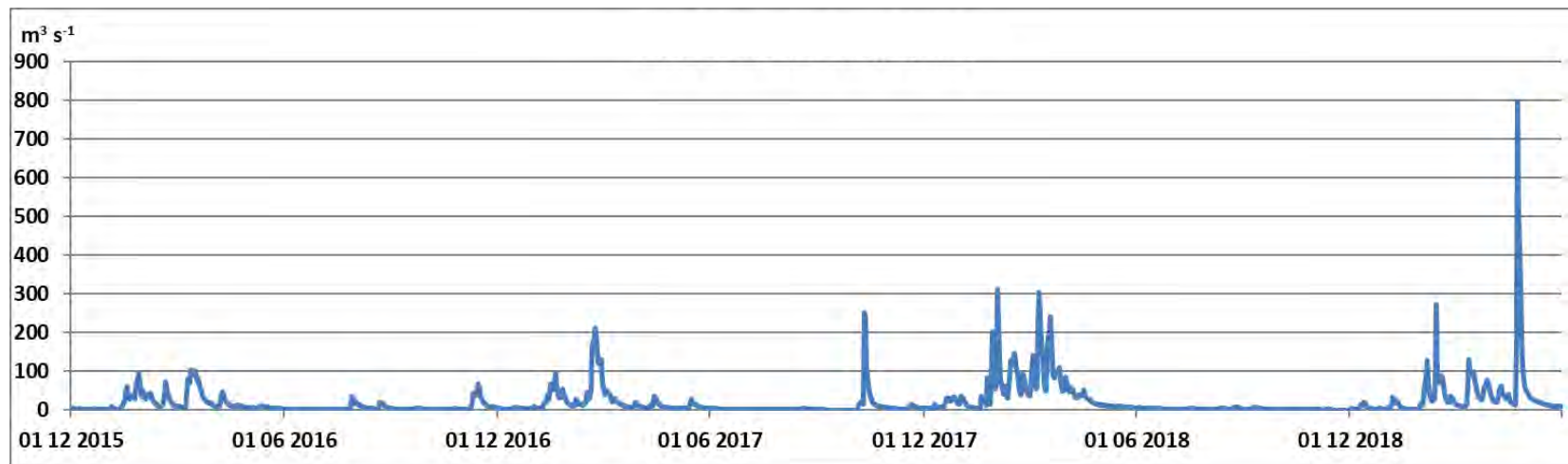


Figure 2-16: Daily discharge 01 12 2015 – 31 05 2019 at TN2 (Tsitsa at Mbelembushe, 4285 km²)

The hydrographs in **Figures 2-6 to 2-16** show a recognisable catchment-wide pattern of wet season high flows, although this pattern was less distinct at Hlankomo. At all sites except Hlankomo, the highest flood flow of the project period occurred towards the end of the 2018 – 19 wet season. Throughout the project period the onset of the wet season varied from October to December, but always ended by June. There was no distinct inter-annual pattern to the wet season high flows: at all sites, variable flood magnitudes and frequencies occurred both within and between seasons. Low dry season/baseflow discharges were evident throughout the system. **Figure 2-17** depicts the percentage of time for which flows occurred (as a percentage of sub-catchment maximum flow (QMAX)) from 01 12 2015 to 31 05 2019 for all sub-catchments from headwaters to confluence.

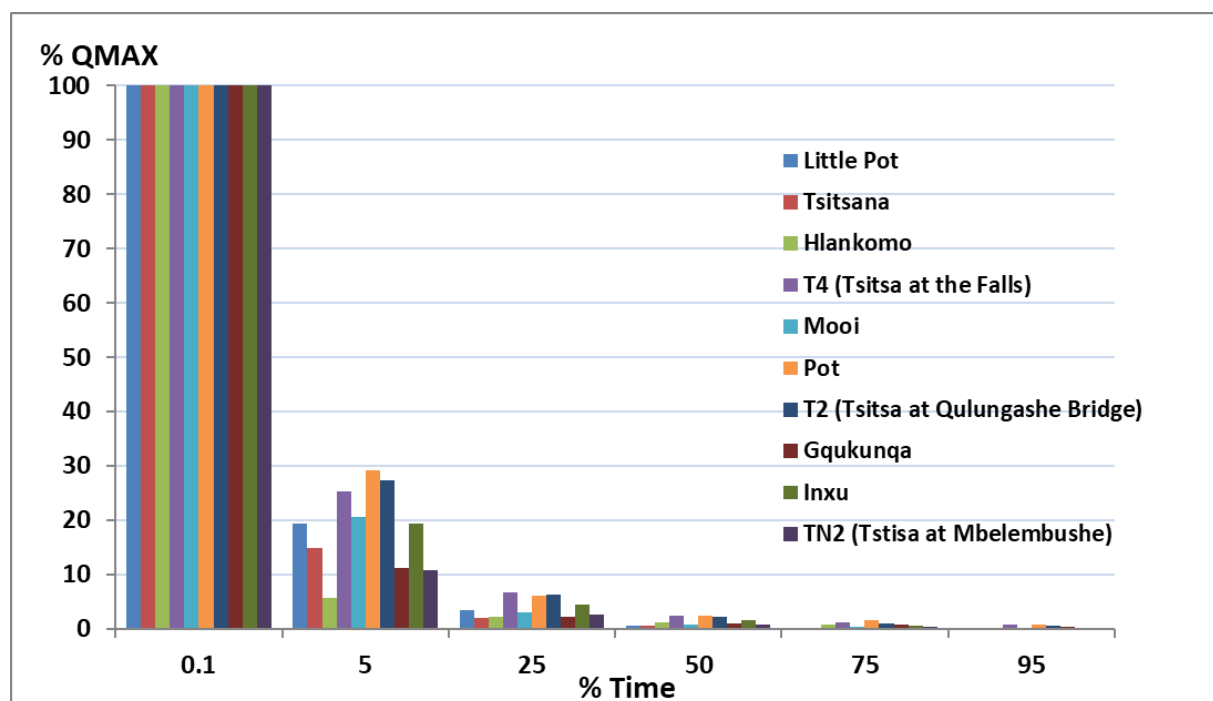


Figure 2-17: Flow duration at all sites 01 12 2015 – 31 05 2019 expressed as a percentage of maximum flow (QMAX)

Figure 2-17 confirms the visual perception that low flows dominated throughout the project period. Flows exceeded 20% of QMAX less than 5% of the time except for Tsitsa at the Falls (T4), Pot, and Tsitsa at Qulungashe Bridge (T2), where flows were still below 30% of QMAX 95% of the time.

Table 2-2 summarises the maximum daily discharges, and the upper 5% of daily discharges⁷ for the 11 sub-catchments.

Table 2-2: Maximum daily discharge, 5% exceedance discharge, and catchment area

Site	Maximum daily discharge (m ³ s ⁻¹)	5% exceedance discharge (m ³ s ⁻¹)	Catchment area (km ²)
Little Pot	12.48	2.43	75
Tsitsana	38.31	5.70	135
Hlankomo	14.32	0.83	64
T4 (Tsitsa at the Falls)	73.40	18.54	607
Mooi*	85.50	17.64	306
Pot	53.79	15.73	432
T3 (Tsitsa at the Gorge)	154.42	37.07	1550
T2 (Tsitsa at Qulungashe Bridge)	241.10	66.03	1881
Gqukunqa	24.90	2.82	204
Inxu	179.24	34.77	1452
TN2 (Tsitsa at Mbelembushe)*	797.19	86.68	4285

*From DWS gauging station data

Table 2-2 shows that maximum recorded discharges were an order of magnitude greater than the discharge exceeded 5% of the time except at T4 (Tsitsa at the Falls), Mooi, and Pot, suggesting flashy catchments (Richards, 1990) that were characterised by intense events likely to supply large volumes of sediment to channels (Buendia et al., 2016). The short record length for the ungauged sub-catchments precluded the analysis of flood frequency, flow duration, and flood magnitude indices (Olden & Poff, 2003) that are routinely undertaken to determine discharge variability and short term change (i.e., flashiness) as an indicator of this likelihood. Therefore, the dimensionless Richards-Baker Flashiness Index (R-B Index, (Baker et al., 2004; Gannon et al., 2022) was applied to annual discharge records with a daily timestep. **Table 2-3** summarises sub-catchment flashiness according to the R-B Index.

⁷ The method for determining the exceedance percentages is described in Chapter 5

Table 2-3: R-B Index classification of Tsitsa River catchments (after Baker et al. (2004))

R-B Index quartile	Catchment area grouping (km ²)				
	0-78	79 - 260	261 - 780	781-2660	2661 - 7800
Very Flashy			Mooi 0.43		TN2 0.34
Flashy		Tsitsana 0.50 Gqukunqa 0.45	Pot (0.34)	T2 0.29 Inxu 0.29	
Stable to flashy	Little Pot 0.47		T4 0.29	T3 0.27	
Stable	Hlankomo 0.34				

The R-B Index defines a continuum from “stable” (i.e., 0, slow rates of little change) to “extremely flashy” (i.e., 1.5, rapid rates of great change). However, the thresholds (for example between “Flashy” and “Very Flashy”) on the continuum are modified by catchment area, as indicated in **Table 2-3** (Baker et al., 2004; Gannon et al., 2022). The R-B Index indicates that the Hlankomo was “stable” whilst the Mooi, and TN2 (Tsitsa at Mbelembushe) were very flashy. Six of the remaining sub-catchments fell within the flashy to very flashy grouping, except for Little Pot, T4 (Tsitsa at the Falls) and T3 (Tsitsa at the Gorge), which were less flashy.

2.3.3 Geology, soils, gully erosion and soil piping

The extremely large and deep gullies that are the consequence of water erosion on the highly dispersive soils of the catchment (Kakembo & Rowntree, 2003; Le Roux et al., 2015; Itzkin et al., 2021) are a prominent landscape feature in the middle and lower parts of the catchment(**Figures 2-18 to 2-20**).



Figure 2-18: Gully, sheet, and rill erosion near dwellings in the middle Tsitsa River catchment (image: B van der Waal)



Figure 2-19: The largest gully (Le Roux et al., 2022) in the Tsitsa River catchment (image: B van der Waal)



Figure 2-20: A soil pipe in the lower Tsitsa River catchment (image: L Bannatyne)

Gullies and soil pipes are associated with the dispersive soils that occur on the Tarkastad Formation in the middle and lower Tsitsa River catchment (Le Roux & Sumner, 2012; Le Roux et al., 2015). The sandstones of the Clarens Formation predominate in the upper catchment. These progress to Elliot Formation mud- and sandstones in the middle catchment. Molteno Formation sand- and mudstones,

and Tarkastad Formation mudstones form the lower catchment. Karoo dolerite intrusives with associated metamorphic rocks are found throughout the area (CGS, 2018). The Elliot and Tarkastad Formations are the most erodible of the lithologies present (Rowntree et al., 2017). The study area geology is shown in **Figure 2-21**.

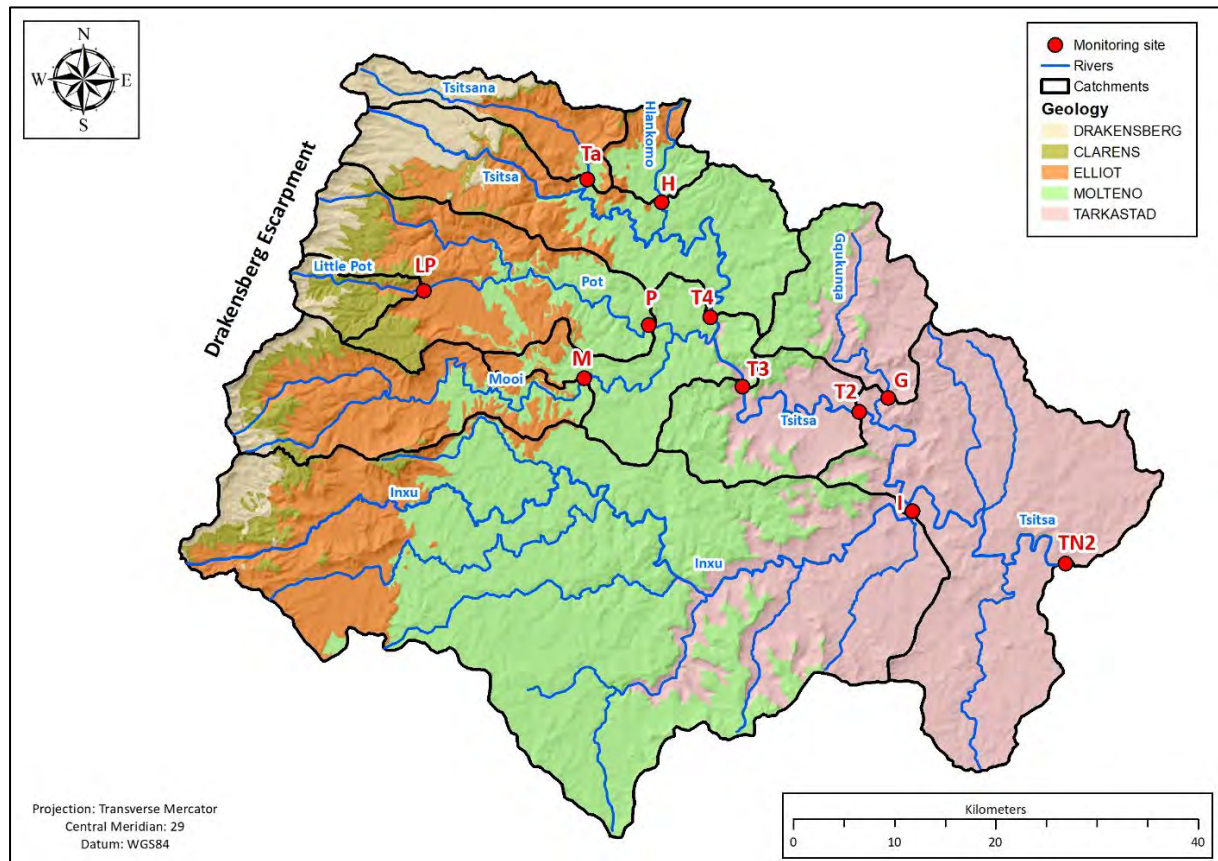


Figure 2-21: The geology of the Tsitsa River catchment, with monitoring sites and catchment boundaries. (Data provided by CGS, (2018), Cartography: N. Huchzermeyer)

Gullies comprise approximately 62 km² of the 4900km² study area (Le Roux, 2018). Gullies and soil pipes typically occur in the duplex soils on the Tarkastad Formation mudstones in the middle and lower Tsitsa River catchment (Beckedahl & De Villiers, 2000). The increased clay content of the impermeable subsoil leads to piping, whilst continuous grazing and cropland abandonment, combined with the dispersive nature of topsoils, leads to gully initiation and growth (Le Roux, 2018). However, quantifying their contribution to SSLs/SSYs has proved to be challenging (Le Roux et al., 2022). Studies that have aimed to include the contributions of gullies in SSLs/SSYs for the Tsitsa River catchment are reviewed in **Chapter 4** of this thesis (**Section 4.5.3**).

2.4 Human impacts that may influence soil erosion and sediment transport

The human activities in the Tsitsa River catchment that may influence soil erosion and sediment transport are summarised in **Table 2-4**. The distribution of land cover and land tenure types is illustrated in **Figure 2-22**.

Table 2-4: Summary description of the Tsitsa River catchment: human impacts

Characteristic	Description	Reference
Land tenure	Commercial/private to northwest, communal to south-east (Figure 2-22).	Le Roux et al. (2015)
Land cover	Grassland, commercial, indigenous & alien invader forests. Agriculture on both private and communal land.	2013-14 GTI SA National Land-Cover (SANBI, 2016)
Land use	Predominantly grassland with some plantations and woodlots. Mainly grazing and cultivated commercial crops on private/commercial land in the upper catchments. Grasslands, cultivated subsistence and field crops on communal land in the middle and lower catchments, much of it degraded.	Le Roux et al. (2015)
Level of income	The communal area of the Tsitsa River catchment is one of the poorest and least developed regions in the country.	Calmeyer & Muruven (2015)
Level of education and employment	Secondary schooling completion is low, whilst experience of higher education is scarce. < 25% of people aged 18 - 65 reported in 2011 that they were employed.	Hodgson (2017)

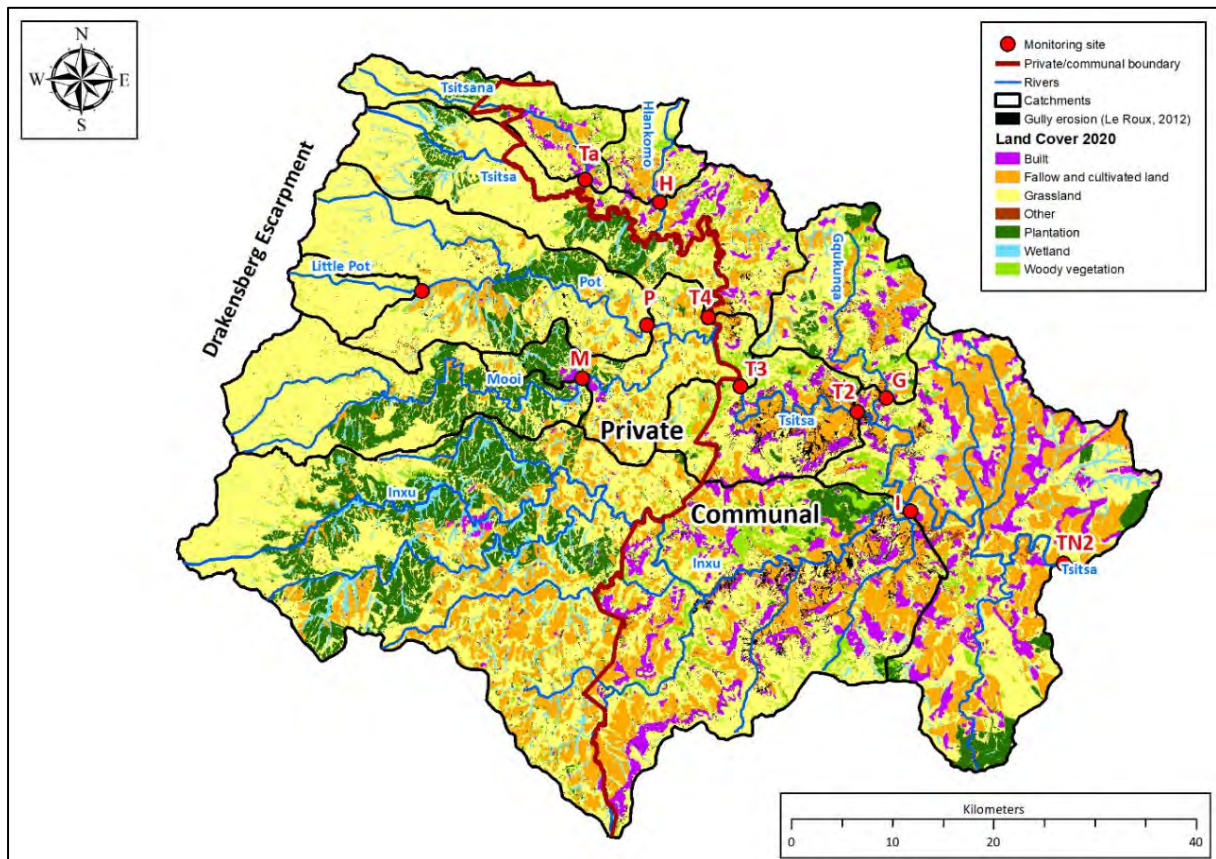


Figure 2-22: Land tenure (red line) and land cover of the Tsitsa River catchment, with study sites and major towns (data provided by DFFE (2020), Cartography: N Huchzermeyer)

The upper, or headwater catchments to the west of the study area are dominated by commercial and privately-owned farms. This includes the Little Pot, Pot and Mooi and upper Inxu River catchments. The eastern edge and lower catchments (i.e., the Tsitsana, Hlankomo, Middle Tsitsa, Gqukunqa, and lower Inxu River catchments lie in a communal, former homeland area (Rowntree et al., 2018). Grasslands are the most prevalent land cover throughout the catchment. Plantation forestry is found in the upper Tsitsa, Pot, Mooi and Inxu River catchments, whilst wetlands are found in the valley bottoms of these and of the Little Pot catchment. Although small in area, these wetlands can function as significant sediment traps and can also attenuate floods (Wiener & Grenfell, 2024; Wiener et al., 2022). Land management is related to land tenure and can affect, for example, the vegetation cover and erosion risk. Fire is frequently used throughout the Tsitsa River catchment as a management tool to encourage early spring growth of palatable grass, to create fire breaks around plantations, and to control ticks (Snyman, 2019). Other negative impacts that can affect sediment supply include cultivation, plantations, alien invasive tree species, and urban and rural settlements. The predominant grasslands are further degraded in the communal areas by continuous grazing practices. These

practices exacerbate the water-related erosion and gully formation in the former homeland areas that were typically established in agriculturally marginal areas that are coincident with the Tarkastad Formation and dispersive, erosion-prone duplex soils (Kakembo & Rowntree, 2003; Le Roux et al., 2015; Itzkin et al., 2021).

Lack of formal education and joblessness contribute to poverty, increasing peoples' reliance on the land and associated ecosystem services for food security and livelihoods. Poverty therefore directly influences land use and degradation, particularly where livelihoods/ food security are closely tied to land as in the communal areas (Calmeyer & Muruven, 2015).

2.5 Summary

Rainfall is seasonally and annually highly variable in the Tsitsa River catchment. Whilst rainfall and rainfall erosivity generally decrease downstream, they are variable and are relatively high in the communal areas that are proximal the site of the proposed Ntabelanga Dam. Discharge is also seasonally and annually highly variable, and generally flashy, particularly in the smaller sub-catchments. The influence of hydrological variability on uncertainty is reviewed in **Chapter 3**.

Soil erosion characteristics vary across the Tsitsa River catchment due to the variable geology and soils, and to associated patterns of land tenure and land management. The headwater catchments that lie mainly to the west are typified by commercial and private forestry and farmland. Elevation, private land-ownership, and socio-economic conditions tend to decrease from north-west to south-east (i.e., downstream), with the communal areas that lie mainly to the east typified by unemployment, reliance on land-based livelihoods, higher population density, and land degradation. The boundary of the former homeland area is broadly coincident with the changes in underlying geology that give rise to dispersive, erodible soil types where gullying and soil piping are large scale and widespread due to water-related erosion processes.

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3 Sources of uncertainty associated with suspended sediment load and yield estimation

3.1 Introduction

The original research described in this thesis focused on limiting, as far as possible, the uncertainty associated with estimating SSLs using a manual, citizen technician based sampling approach, as a solution to other constraints on SSC sampling in South Africa. The literature reviewed here provides the foundation for the approaches and methodologies used in this research, as well as background to the later discussion of results. Since SS load is the product of SSC and discharge, the uncertainty associated with measuring and calculating discharge was also considered, although measuring and calculating discharge was a component of the wider Tsitsa Project and not the direct responsibility of the candidate. **Appendix 2** provides a description of the methods used to measure and calculate discharge.

This chapter first introduces and defines the concepts of natural and epistemic uncertainty, and explains the distinction between precision and accuracy. Key sources of natural uncertainty are identified, and the drivers, controls, and spatiotemporal variability of sediment delivery to channels are reviewed. After identifying the key sources of epistemic uncertainty, internationally-recognised SSC sampling methods are reviewed, and the challenges of accommodating spatiotemporal variability into the design of SSC sampling programmes are examined with reference to remote, data-scarce regions. An examination of the uncertainty associated with the field measurement of discharge and with calculating discharge time-series as input to SSL estimation follows, with reference to resource availability and safety/logistics considerations. Lastly, since they are used in this thesis to provide comparative data, the uncertainty associated with indirect approaches to SSY estimation are also discussed.

Modelled approaches are not discussed in this chapter but are covered in **Chapter 4** as part of the review of existing SSY estimations for the Tsitsa River catchment, which prior to this study were mainly derived from modelling.

3.2 Uncertainty, risk, and resource management decision-making

Uncertainty encompasses the elements of probability, risk, error or variation, unpredictability, and unreliability (Taylor, 1997; Beven, 2000; Montanari, 2007). The degree of acceptable uncertainty is directly related to the scale and purpose of measurement (Taylor, 1997).

Catchment management decisions based on SSL (and SSY) information can have significant long-term cost and risk implications for ecological and built infrastructure (Walling, 1977a). As a key component of risk analysis, the degree of acceptable uncertainty is inversely proportional to the risk and cost of a poorly-founded, ultimately “wrong” decision (Chapman et al., 2002). Uncertainty should therefore be acknowledged and clearly described, in order to enhance reliability and support decision-making (Chapman et al., 2002; Beven, 2006; Meissner et al., 2017). This is particularly important when there is a great degree of uncertainty that may impact water resource managers’ ability to assess risks and make sustainable decisions (Hughes & Lawrence, 2024).

Merz & Thielen's (2005) separation of uncertainty into natural and epistemic sources is used in this study to distinguish between the uncertainty inherent to natural systems, and that associated with monitoring them. Natural uncertainty stems from, and is directly related to, the unknown variability intrinsic to the hydrological/SS transport system (Beven et al., 2018). Epistemic uncertainty is associated with monitoring, analysis, estimation, and prediction (Merz & Thielen, 2005) and is inevitable in any branch of scientific measurement (Taylor, 1997). Beven et al.(2018) similarly acknowledge the distinction between aleatory (random) and epistemic uncertainty.

3.3 Natural uncertainty

3.3.1 Overview

Natural uncertainty can be better understood, but not constrained or reduced, by collecting additional data: natural systems are open, and stochastic in their functioning (Merz & Thielen, 2005). Natural uncertainty varies between sites, over time, and at all scales, due to site-specific and climate-related factors including hydrological variability, sediment characteristics, availability, transport, and hysteresis (Novic et al., 2018). Extreme events and non-stationarity increase the spatiotemporal variability of sediment delivery systems, significantly increasing the potential magnitude of natural uncertainty (Walling et al., 2007; Fryirs & Brierley, 2012). **Table 3-1** provides examples of natural

uncertainty associated with the estimation of SSL/SSY. The relationship between natural uncertainty and SSC variability is then investigated.

Table 3-1: Examples of natural uncertainty in SSL/SSY estimation

Component	Source of uncertainty	References
Open natural systems	Impossibility of complete data input Data that are incompletely or only approximately known	Oreskes et al. (1994)
Hydrological variability	Drought and flood cycles ¹ Rainfall pattern, volume, and erosivity “Flashiness” of channel response	Walling (1977b) Schumm (2005) Fryirs & Brierley (2012) Baker et al. (2004)
Sediment characteristics	Organic flocs, variability in SS particle mineralogy, colour, and size distributions, e.g., through floods (leading to non-unique turbidity:SSC relationships).	Minella et al. (2008) Walling et al. (2000) Regüés (2013) Ramoithello (2021)
Sediment availability and hysteresis	Seasonal erosion/transport/deposition cycles (weather and land use/vegetation cover) ^{1, 2} Event-based sediment exhaustion/pulses Mass wastage into channels	Walling (1974) Gao (2008) Walling (1977a: 1977b)
Sediment delivery to channel	Connectivity, buffers, barriers and blankets ¹	Walling (1983) Fryirs et al. (2007) Fryirs (2013)
In-channel SSC variation	Channel cross-sectional (width and depth) transport capacity	Walling (1977b) Walling & Webb (1981) Gao (2008) (Horowitz, 2008) Novic et al. (2018)
Non-stationarity	Anthropogenic: Water abstractions and impoundments Cumulative impacts of e.g., sand-mining, catchment hardening (reduced permeability due to urban development). Land-use change Climate change	Fryirs & Brierley (2012) White (2005) Bester et al. (2019) Theron et al. (2021)
	Natural: Pulse, pressure and ramp events and relaxation periods Climate change: A key issue in South Africa and globally.	Fryirs & Brierley (2012) Milly et al. (2008) Theron et al. (2021)

¹ Factors determining catchment SSY were reviewed in Bannatyne (2018).

^{2,2} The relationship between SSC and Q was reviewed in Bannatyne (2018).

3.3.2 Drivers and controls of sediment supply to channels

The macro-scale natural spatiotemporal variability of SS transport is largely driven by climate (Horowitz et al., 1990; Williams, 2011; Vercruysse et al., 2017). The resulting supply of sediment relates to regional- and catchment-scale drivers such as rainfall, snowmelt, and climate, and to controls such as topography, catchment connectivity, and land use (Gordon et al., 2004; Schumm, 2005; Fryirs & Brierley, 2012). The Tsitsa River catchment experiences occasional snowfalls in winter which can mobilise some sediment during the typically dry season (Huchzermeyer, 2017). However, in some parts of the world and in high mountain catchments, snow accumulation and melt processes strongly influence the timing and characteristics of seasonal sediment transport, for example in the central Spanish Pyrenees (Lana-Renault et al., 2011) and in North America (Langlois et al., 2005). Nevertheless, natural uncertainty is greatest in hydrologically more variable arid and semi-arid areas where in addition to the influence on sediment availability and transport of wet and dry seasons, long drought periods may be interspersed with wet periods characterised by occasionally extreme storm events (Fryirs & Brierley, 2012). Hydrological variability in the southern hemisphere generally exceeds that of the northern hemisphere, with the greatest variability occurring in southern Africa⁸ and Australia (Peel et al., 2004).

The frequency and rapidity of sediment delivery during storm events is influenced by sediment availability due to natural and anthropogenic processes, soil erodibility, antecedent rainfall and soil moisture, and is typically linked to catchment slope and area (Baker et al., 2004). Changing combinations of these variables are evidenced by changing patterns and directions of sediment-discharge hysteresis loops (Aich et al., 2014). Conceptual frameworks can characterise the non-linear, sporadic, connected and/or cascaded transfer of sediment from the catchment surface to the channel at a range of spatiotemporal scales, but the prediction of SSC as a result of the interaction of drivers and controls over space and time still remains challenging (Vercruysse et al., 2017).

Rainfall heterogeneity strongly influences the relationships between rainfall, runoff and SSLs/SSYs (Buendia et al., 2016). Where rainfall patterns are dominated by storms, for example in the wet season in arid, semi-arid, and sub-humid regions, SSC measured at a specific site can vary greatly throughout

⁸ Here taken to mean the continental member states of the Southern African Development Community (SADC), i.e., Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe, plus Kenya.

and between events. In such regions, SSC is influenced by rapidly-changing sediment availability, rainfall pattern, rainfall erosivity, catchment connectivity, stream power, seasonal vegetation changes, sediment flow-dependency, and particle size, often producing a weak relationship between SSC and discharge, a source of uncertainty for the prediction of SSC from discharge using for example sediment/discharge rating curves (Gao, 2008; Regüés, 2013; Gulati et al., 2014; Novic et al., 2018).

Vanmaercke et al. (2012) reviewed northern hemisphere catchments ranging in area from between 0.07 km^2 to $1.84 \times 10^6 \text{ km}^2$, finding that the variation of SS transport over seasons to decades can be extremely high (e.g., 6 %– 313% with an average of 75%). Variability was greatest for erosion-prone catchments (Vanmaercke et al., 2012). This limits the potential to assess or compare annual results for the same catchment, or to benchmark the accuracy of SSL/SSY estimates against those of similar catchments. The uncertainty in spatial variability and scaling is acknowledged by Question 5 of the “Twenty-three Unsolved Problems in Hydrology”: *What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients?* (Blöschl et al., 2019 p 1148).

The complex spatiotemporal relationships between the drivers and controls of sediment supply, transport, and deposition contribute to the uncertainty associated with sediment delivery ratios (Walling, 1983) and preclude the simplistic scaling of SSL and SSY according to catchment area, even in “similar” catchments. Studies of nested catchments variously report that SSY increases, decreases, or is variable in relation to catchment area (Mills & Bathurst, 2015; Richards, 2002; Golosov & Tsyplenkov, 2021).

By contrast to the spatial and temporal variability described in the preceding paragraphs, stationarity implies insignificant long-term (decades to centuries) change in the biophysical drivers and controls of catchment processes and, therefore, in the temporal SSC/discharge relationship (Horowitz et al., 2015). Anthropogenic activities (e.g. land use change, impoundments and transfer schemes) negate this assumption in most catchments, and climate change drives widespread non-stationarity (Milly et al., 2008; Bester et al., 2019) . For example, SSC and discharge data collected for the Orange River in South Africa in the 1980s are now redundant, due to the degree of urban and, particularly, intensive agricultural development that has taken place in the catchment over the intervening 40 years (Ash, 2022).

3.3.3 Hydrological variability

Hydrological variability is a major component of natural uncertainty in SSL/SSY estimation, encompassing the variable hydrological responses of a catchment to long term flood and drought cycles, seasonal rainfall trends, and individual rainfall events (Walling et al., 1992).

The indicators available to characterise the hydrological responses of catchments include flood frequency, flow duration, and flood magnitude indices (Olden & Poff, 2003). These indices typically require at least 20 years of continuous streamflow data to accurately represent and predict hydrological responses (Olden & Poff, 2003). Similarly, characterising study period hydrology within the context of the overall hydrological variability of a study catchment requires several decades of historical data. This can present challenges in data-scarce areas such as southern Africa (Hughes et al., 2010).

Acknowledging sediment availability and transport from hillslope to channel as a control, seasonal precipitation, runoff, and discharge are the main drivers of SSC. Discharge records are typically more readily available for longer record-lengths and shorter measurement timestep than SSC data, so characterising the frequency and rapidity of short-term change in catchment hydrology (or “flashiness”) may provide similar insight into catchment-scale SSC variability (Onwuka et al., 2021). Understanding the hydrological variability of a catchment thus informs temporal SSC sampling programme design, constraining epistemic uncertainty by ensuring that changes in SSC are monitored (Walling et al., 1992). Where only relatively short (<5 year) hydrological records are available, the Richards-Baker Flashiness Index (R-B index) is widely used to compare site-specific inter-annual hydrological variability (Baker et al., 2004; Gannon et al., 2022).

3.4 Epistemic uncertainty

3.4.1 Overview

The epistemic uncertainty associated with SSL estimation can be described in terms of precision and accuracy (Walling & Webb, 1981; Taylor, 1997). Precision describes the degree of variability in repeated measurements, whilst accuracy describes the divergence of an analysed value from a known true value (Walling & Webb, 1981; Taylor, 1997). Precision and accuracy in SSL/SSY estimates are influenced by sampling, analytical, and load estimation methods (Wren et al., 2000; Gao, 2008; Horowitz, 2008; 2013). Precision can be quantified for example by repeating a series of

measurements, and analysing the resulting variability. Accuracy is however impossible to determine if, as in the case of estimated SSL and SSY, there is no absolute reference value against which to compare (Taylor, 1997).

Precision is inversely related to uncertainty. The International Standardisation Organisation (ISO) defines precision as the closeness of agreement between replicate measurements (Vim, 2004). Standard deviation (SD), variance, and/or percentage coefficient of variation (%CV) are suggested for reporting precision (Vim, 2004). SD and variance should not be calculated for as few as three data points, whereas three is the minimum number of data points required for calculating %CV (e.g., for replicate SSC and/or turbidity samples). Further, %CV allows comparison between variables with different measurement units, i.e., between turbidity (nephelometric turbidity units: ntu) and SSC (mg L^{-1}).

Precision and accuracy are influenced by systematic and random errors (Taylor, 1997), for example when sampling or during laboratory analysis. Systematic error is uni-directional (either under- or over-estimates), and is often consistent but may increase over time, and is typically associated with equipment, for example bias derived from a balance that consistently under-weighs (Taylor, 1997). Systematic error is revealed and corrected by regular calibration, for example with a known mass. Systematic error may change gradually, for example when abrasive wear on a sieve increases mesh size and allows larger grains to pass through, incrementally impacting coarse particle size analysis. In the absence of calibration, systematic errors go undetected, and the unknown, uncorrected extent and direction of the introduced uncertainty propagates throughout the SSL estimation process, resulting in unquantified uncertainty (Horowitz, 2013).

Epistemic uncertainty in data interpolation, extrapolation, and prediction is influenced by data availability; spatiotemporal representativeness; record length; and by the specific approach used (Walling et al., 2007; Beven et al., 2018). Novic et al. (2018) classified these as input, contextual, and model structure uncertainties. Epistemic uncertainty varies spatiotemporally, between methods, and between researchers (operator technique and error): SS data collected by different operators, and/or using different sampling or laboratory analysis programmes may not be consistent or comparable (Horowitz, 1997; 2008; Gray & Simoes, 2008; Vanmaercke et al., 2014). For example, government monitoring programmes may adopt standardised protocols, but these often change over time, and often differ between countries. Similarly, the uncertainty associated with SSYs derived using different

estimators (for example, ratio estimators and sediment/discharge rating curves) will also differ (Walling et al., 2007).

The estimation of catchment topography including catchment area and average slope length and steepness, is a further source of uncertainty associated with estimating SSLs and SSYs (Keys & Baade, 2019). It affects modelled SSY estimates (in deriving the input factors for soil loss equations as well as deriving SSY from SSL) and directly measured SSYs. Whether topographical data is for example manually derived from paper maps, or from a digital elevation model (DEM), or remotely using Light Detection and Ranging (LiDAR), the uncertainty associated with catchment area is influenced by the acquisition method and directly related to the accuracy with which the true catchment topography is represented by the resulting data (Keys & Baade, 2019). This, in turn, is influenced by the resolution of the available data, and the methods used by specific DEMs to for example delineate catchments and sub-catchments, calculate area, derive slopes, and route hydrological pathways (Keys & Baade, 2019). Baade et al. (2014) compared the performance of six DEMs in a ground-truthed study of 21 small (<100 km²) catchments in the northeastern part of South Africa. The resolution offered by the DEMs ranged from 0.4 to 3 arc-seconds, with three different acquisition methods offered. Baade et al. (2014) reported that relative uncertainty for catchment area was between 1% and 5% on a 95% confidence level. A similar study of 49 mountain catchments in Tibet comparing nine DEMs found that mean catchment area differed by <1% from that of the highest resolution DEM, with a standard error of 0.13% .(Keys & Baade, 2019). However, Keys & Baade (2019) also noted the potential for random errors that could produce drastically different results, particularly in areas with low slopes. The importance of selecting a DEM suited to the research question and terrain was highlighted, as well as the increased potential for uncertainty associated with older, lower-resolution DEMs.

This underlines the importance of transparent, standardised statements that allow results to be assessed, compared and collated (Beven, 2006; Vanmaercke et al., 2014; Li et al., 2020). It also emphasises the importance of consistent, standardised approaches to sampling, analysis, and SSY estimation within and throughout a specific study or programme (Horowitz, 1997).

Epistemic uncertainty is quantified using validation techniques and evaluation statistics (Moriassi et al., 2007). Epistemic uncertainty can be constrained (but not eliminated) by collecting more representative data, for example at shorter time-steps over longer durations (Oreskes et al., 1994; Gao, 2008; Horowitz, 2013), and through flood-focused rather than calendar-based SSC sampling

regimes (Walling et al., 2007). **Table 3-2** provides examples of epistemic uncertainty associated with SSL/SSY estimation, which are examined further in the sections that follow.

Table 3-2: Examples of epistemic uncertainty in SSL/SSY estimation

Component	Source of uncertainty	Reference
SS monitoring	Spatiotemporal inconsistency (e.g., people/equipment at sites/over time)	Bannatyne et al. (2017) Duerdoth et al. (2014)
	Frequency	Ferguson (1987) Walling et al. (1992) Horowitz et al. (2015)
	Representativeness (e.g., channel, of flow regime, of high flows)	Horowitz et al. (2015) Novic et al. (2018)
	Surrogate measures e.g., turbidity measurement	Wass & Leeks (1999) Minella et al. (2008) Horowitz (2013)
	Method (e.g., probes, auto-samplers, manual, turbidity as surrogate for SSC)	Wren et al. (2000) Gao (2008)
Data record	Length and representativeness	Walling (2005) Vanmaercke et al. (2012) Foster & Boardman (2018)
	Data scarcity	Xie et al. (2019) Kapangaziwiri et al. (2012)
	“historical” data not reflecting development	Msadala et al. (2010)
SS Laboratory analysis	Precision/accuracy/consistency of e.g., filtering, measuring, recording Representativeness e.g., size/split of aliquots	Horowitz (2013) Novic et al. (2018)
Data interpolation and extrapolation	missing records, representativeness of adjacent or substitute records	Wang et al. (2011) Novic et al. (2018)
Q estimation	Flow measurement, Q calculation (e.g. Channel roughness, overbank flows)	Hughes et al. (2010) Oosthuizen et al. (2018)
Scaling	Mismatch of sampling and predictive scales, e.g. from plot to catchment	Oreskes et al. (1994) (Gwapedza et al., 2018)
SSL estimation approaches	Averaging and ratio estimators	Walling & Webb (1981) (Phillips et al., 1999) Quilbé et al. (2006)
	Regression estimators	Asselman, (2000) Horowitz (2003; 2008)
Topographical data	Catchment area, slope length and steepness	Keys & Baade (2019)
Indirect approaches	Modelling	Oreskes et al. (1994) Le Roux et al. (2015) Gwapedza et al. (2021)
	Dam sedimentation studies	Boardman et al. (2010) Rowntree & Foster (2012) Reinwarth et al. (2019)

	Sediment fingerprinting and tracing	Kitch et al. (2019) Liu et al. (2023)
	Systems dynamics	(Bester et al., 2019)

3.4.2 Sampling SSC variability in channels

Sample representativeness accounts for the majority of the epistemic uncertainty associated with SSL/SSY estimation, particularly during erosive rainfall/high flow events (Ferguson, 1987; Walling et al., 1992; Horowitz, 2008; Hapsari et al., 2019). Walling (1977a) highlighted sampling techniques and procedures as significant sources of error, stating “It is to be expected that the greatest errors will result from the inadequacy of the sampling program in defining the detailed temporal record of suspended sediment concentration” (Walling, 1977a p 532). Thus, epistemic SSL uncertainty is related to the degree to which spatiotemporal variability (i.e. natural uncertainty) is understood and accommodated within the SSC sampling programme, and represented by the resulting SSC data.

Spatiotemporal variability of SS transport at reach scale, i.e., within the river channel, is associated with the complex interactions on the velocity and direction of helicoidal and shear flow of the wetted perimeter and surface of the channel, which is affected by and dependent on stage (Alexander, 1979). One of the challenges of SS monitoring programme design is the need to accommodate this four-dimensional variability (three space dimensions plus time) into sampling protocols, in order to optimise the representativeness of the resulting measurements.

Spatially, SSC is usually variable throughout the cross-section of a channel, typically increasing towards the centre due to increased velocity/stream power to transport SS particles (Horowitz, 1997). Similarly, SSC typically increases towards the bottom of the water column due to the presence of larger/heavier (>63 μm) SS particles above the channel bed (Gippel, 1995). Width-and-depth integrated SSC measurements should therefore routinely be taken through as wide a range of flow conditions as possible to provide site-specific insight into point representativeness (Horowitz, 1997; Gao, 2008; Horowitz, 2013; Gray & O’Halloran, 2015), but this is physically unsafe during target high flows (Gurnell et al., 1992). At some sites, bridges may offer width-and-depth-integrated sampling opportunities, but the combination of traffic, bridge height, and in some cases the absence of railings may make sampling from bridges too hazardous. Additionally, large woody debris that may be transported during floods could snag sampling equipment lowered from a bridge.

Sampling the available water column from the channel bank (as in this study) could lead to under-estimation of SSC, and by extension of SSLs/SSYs. However, Gurnell et al. (1992) found high but

random spatial variability within and between cross-sections, as well as at single points in pro-glacial streams during two (flood-flow) ablation seasons. Gurnell et al. (1992) concluded that due to the randomness of the variability, little improvement in measurement reliability would accrue from attempting to sample from other than bank-side. Further, Msadala et al. (2010) stated that 75% of the sediment transported in South African rivers is clay and silt sized ($<63\ \mu\text{m}$). This statement is given some support by a particle size analysis of four flood events (January – March 2016) that were sampled at two sites in the Tsitsa River catchment. Ramothello (2021) found that for three floods that occurred during the course of the wet season (after late January), between 80% and 100% of particles sampled throughout the flood hydrographs were $<63\ \mu\text{m}$ ($n = 30$). However, for a flood that occurred in early January at the beginning of the wet season, the $<63\ \mu\text{m}$ fraction varied between 30% and 68% (average 48%, $n = 5$). The typically high transport capacity of South African rivers together with the presumed uniform distribution of fine ($<63\ \mu\text{m}$) sediment through the channel may nevertheless mean that a depth integrated bank-side sample could be representative of the channel cross-section (Msadala et al., (2010), although further research is needed to confirm Msadala et al.'s (2010) assumption and Ramothello's (2021) limited findings.

The variability of an open hydrological system is characterised in terms of the magnitude, frequency, timing, duration and rate of change of flows (Poff et al., 1997). Temporally, flood events carry most of the SSL during any given period (Sun et al., 2001; Regüés, 2013). For example, in rivers in the United Kingdom, 80% of SSL is estimated to be transported in 2% of the time (Walling et al., 2007): SSL/SSY will be underestimated if flood events are not adequately monitored (Horowitz, 2008; Harrington & Harrington, 2013). Hydrologically-based (i.e., flood-focussed) direct SSC sampling is therefore preferable to calendar- or time-based sampling (Horowitz, 2008; Horowitz et al., 2015), which may result in flood and extreme events being missed altogether (Gao, 2008; Bannatyne, 2018; Novic et al., 2018). Further, SSL estimates are subject to greater uncertainty unless both limbs of the storm hydrograph are sampled to determine both the rising and falling SSC/discharge relationships and the possibility of either leading or lagging hysteresis effects (Williams, 1989).

Sampling intervals that exceed the period over which SSC changes increase the uncertainty in estimated SSLs/SSYs (Walling et al., 1992). Research findings suggest that the smaller the catchment, the more rapid the changes in SSC, therefore requiring shorter sampling intervals to ensure representativeness. In all cases a longer record is representative of a wider range of catchment conditions and decreases uncertainty (Horowitz et al., 2015). This implies a trade-off between study

costs and data reliability, particularly in small catchments. **Table 3-3** summarises the uncertainty associated with a range of catchment areas and record lengths in selected Northern hemisphere catchments. No data were specifically available for southern hemisphere catchments, although in their global review Li et al. (2020) suggest a record-length of at least 30 years, (continuous or not), to detect trends spanning > 4 decades in catchments >1000 km².

Table 3-3: SSL/SSY uncertainty range linked to catchment area and record length in Northern hemisphere catchments

Uncertainty (%)	Catchment area (km ²)	Record length (yr)	Locality	Reference
-65 - +359/month -49 - +159/year	160	8	Owenabue (Ireland)	Harrington & Harrington (2013)
-90 to +900/month +280 /year	258	2	River Creedy (UK)	Walling (1977a)
-76 - +63/month -49 - +159/year	608	8	Bandon (Ireland)	Harrington & Harrington (2013)
±20/year	1 000 – 1 000 000	5	Rhine at Maxau (Germany)	Horowitz (2003)
<1/year	>1 000 000	20	Mississippi at Thebes (USA)	Horowitz (2003)

Table 3-3 indicates that uncertainty is constrained to <20% yr⁻¹ in 1 000 km² – 1 000 000 km² catchments with at least 5 years of data, and that, generally, annual estimation periods have a narrower range of uncertainty than monthly. Conversely, uncertainty in the SSLs derived from short studies (<2 years) in small catchments (e.g., 258 km²) can range from -90% to +900% for monthly estimates and 280% for annual estimates. Uncertainty, and therefore the implications for planning and management, is much more significant in smaller catchments: a greater investment of resources would be required to constrain uncertainty to <20% in catchments smaller than 1000 km², for example through more frequent sampling over longer periods. Data records that span decades are more likely to reveal the overall SSL/SSY trends due for example to climate change and anthropogenic change in the catchment (Horowitz et al., 2015). Reciprocally, non-stationarity of long term data requires periodic recalibration, for example where SSC/discharge rating curves are used for SSL/SSY prediction (Horowitz et al., 2015). **Table 3-4** summarises monitored data assessment criteria compiled by Vanmaercke et al. (2014), whilst **Table 3-5** summarises the quality framework compiled by Walling et al. (2007).

Table 3-4: Quality assessment criteria for monitored SS data (after Vanmaercke et al., 2014)

Metadata	Poor	Acceptable	Good
Q	> Daily intervals< 5 yrs	At least daily > 5 yrs	< daily > 5 yrs
SS	> Weekly intervals < 5 yrs	At least weekly > 5 yrs	At least daily > 5 yrs
Rating curve values	< 50 data points	> 50 data points	Not stated

Table 3-5: Quality assessment criteria for monitored SS data (after Walling et al., 2007)

Metadata	Poor	Acceptable	Good
Continuous turbidity monitoring	< 1 yr	< 2 yrs	> 2 yrs
SS sampling*	> weekly < 2 yrs	daily + storm events < 2 yrs	daily + storm events > 2 yrs

* Walling et al. (2007) distinguished between manual and automatic sampling but in this context only the frequency is considered.

Whilst both sets of criteria are subjective, there is reasonable agreement regarding the input data timestep, although Vanmaercke et al.'s (2014) criteria for record length are more stringent, and Walling et al. (2007) highlight the need for storm event sampling as well as daily sampling. The frameworks nevertheless provide useful benchmarks against which to gauge input data quality.

3.5 Sampling approaches

3.5.1 Overview

A brief review of SS monitoring methods is given here, taken largely from Bannatyne (2018).⁹ SS monitoring methods can be grouped into those employing direct manual sampling or monitoring, and those which use fixed equipment or instruments to sample or monitor (Wren et al., 2000; Kuhnle, 2013; Hicks & Gomez, 2016), including those which monitor surrogates such as turbidity or visual clarity. Wren et al (2000) categorised the available field techniques for SS measurement as follows:

⁹ Bannatyne (2018) provided a more extensive review, as context for the design of the citizen technician-based direct SS sampling approach which was the focus of the candidate's MSc research.

- Sampling:
 - o Manual (Bottle)
 - o Automated (Pump)
- Installed sensors and probes:
 - o Acoustic
 - o Focused beam reflectance
 - o Laser diffraction
 - o Nuclear
 - o Optical
 - o Remote spectral reflectance

Manual turbidity and visual clarity measurements can be added to this categorisation.

3.5.2 *Manual sampling*

Historically, most SS sampling campaigns relied on manual sampling (Ballantine et al., 2015). Water samples can be collected by hand for later analysis, and/or turbidity meters, Secchi disks or clarity tubes can be used to measure in-channel turbidity or visual clarity and later used to calculate SSC from SSC/turbidity rating curves.

Manual samples do not require a power source or fixed housing and can be taken on a fixed or flexible (e.g. flood-responsive) schedule. The relatively low cost and unsophisticated equipment, comprising either open vessels for grab sampling or simple isokinetic samplers for depth-integrated sampling through the water column can be deployed by a relatively unskilled operator. Accuracy and precision relies heavily on operator training and compliance, which may be a significant, ongoing commitment throughout a sampling campaign (Duerdoth et al., 2014). Representativeness relies on sustained presence at the sampling point to notice and monitor flood flows, failing which SS loads and yields may be under-estimated (Horowitz, 2013). This is a limitation on sample site selection, which may be mitigated if, for example, local people can be trained to take samples according to the required protocols. Safety considerations at night and during dangerous weather and/or flow conditions may also negatively impact representativeness by potentially precluding flood flow sampling (Furuichi et al., 2016). Due to this, manual sampling has been described as labour intensive, expensive, inconvenient, difficult and hazardous (Kuhnle, 2013), not only compared with instrumented approaches, but also due to the cost of laboratory sample analysis (Ballantine et al. 2015). However, this “first world” view may apply less to developing countries such as South Africa where employment is scarce and labour costs are low, and where involvement in a sampling programme provides direct

financial and social benefits in terms of job creation and poverty alleviation to individuals and their communities (Bannatyne et al., 2017).

Grab samples that are only representative of near-surface SSC provide good data in homogenous conditions, e.g. where flows are uniform and where silt-sized particles predominate (Gordon et al. 2004). However, isokinetic depth-integrated sampling allows a more representative sample to be taken throughout channel depth, with accuracy depending on the operator using the correct transit rate to prevent over-filling the vessel during sampling (Gordon et al. 2004).

3.5.3 Fixed passive sampling equipment

Passive (and pump) point and rising-stage samplers (i.e. automatic samplers) are a medium-cost option for installed equipment. Like manual sampling, they extract a water sample either from a single point, or at stages from the rising water column, including close to the river bed. They are commonly used in large-scale, long-term monitoring applications by agencies such as the United States Geological Survey (USGS) (Kuhnle, 2013), but are not in widespread use in South Africa. They can be set to sample at specific times or to be triggered by rising flows, and offer 24 hour sampling potential. The greater sample volumes required to accurately determine load and yield at low SSC can more easily be accommodated with automatic than with manual sampling (where large vessel sizes become unwieldy). However, low flow/low SSC is a less important component of load and yield estimations than the high flow/high SSC which can be accurately sampled with smaller vessels (Gordon et al 2004).

Automatic samplers reduce the dependency on operator presence to an extent, but they still require regular emptying, servicing and maintenance (Kuhnle 2013) and may have insufficient capacity to sample through large storm events (Furuichi et al., 2016). Sample times are not always known for rising stage samplers, pump samplers require a power supply, and both rising-stage and pump samplers require a secure housing or installation point, being vulnerable to theft, vandalism, and damage by floods and large debris. This limits their use and placement due to high associated costs. Further, the samples taken at “rising stages” throughout a flood event are always extracted from the water surface area and are thus not representative of SS throughout the full depth of such flows (Gordon et al 2004), particularly the sand-sized fraction. Similarly, pumped samples are always taken from a fixed point above the bed and may not be representative of the upper water column during high flows. Gurnell et al. (1992) compared the results from bank-side hand and pump sampling in pro-glacial streams. They found a clear positive trend in the results from the two methods

($R^2 = 0.822$, $n = 52$), implying that installing pump samplers, where logistically and financially possible, does not necessarily constrain epistemic uncertainty in comparison with hand sampling.

In common with manual sampling, representativeness should be achieved, where possible, by correlating point or depth-integrated automatically-collected samples with periodic width- and depth-integrated sampling of the channel cross-section (Gordon et al 2004), as relationships at different discharges between such samples and cross-sectional SSC are not constant (Kuhnle 2013). This will not always be possible at high flows where conditions for working in the channel become dangerous

Turbidity and visual clarity as a surrogate for SSC can be monitored in-channel or using samples, with the same advantages and disadvantages as manual SSC sampling, although laboratory analysis is not required (Ballantine et al., 2015). However, robust relationships between turbidity, visual clarity and SSC can be difficult to accurately establish (Ballantine, 2015). Further, turbidity meters typically have a limited measurement range which may not cope with the very high sediment concentrations typically found in South Africa during high flows, meaning that sampling and SSC analysis would still be needed at those times (Bannatyne et al 2017).

3.5.4 *Installed sensors and probes*

Wren et al. (2000) and Kuhnle (2013) concur on many points regarding the benefits and limitations of installed sensors and probes for the acquisition of near continuous SS data. Fixed instruments offer consistent and accurate results from 24-hour monitoring, and avoid reliance on and training/administration of operators. However, they require skilled installation, set-up, calibration, and maintenance, such as periodic servicing and maintenance due to biofouling of sensors, as well as download of stored data if not continuously sent electronically or via the cellular network to off-site storage (Furuichi et al., 2016).

A wide range of sensors and probes are manufactured, typically in northern hemisphere countries, using either optical turbidity as a surrogate for SS, or measuring SS by acoustic or optical backscatter, or laser diffraction. These sophisticated instruments require secure placement and often a mains or solar power supply. They are vulnerable to theft, vandalism and flood damage. Most are relatively expensive capital items, some extremely so, which in combination with the foregoing factors limits their use and placement, typically reducing the spatial coverage of a programme (Wren et al, 2000; Kuhnle 2013). Such instruments are typically not manufactured and/or repaired in South Africa, which experiences a weak currency value against those of the (generally European or American)

manufacturers. All this leads at best to lengthy delays in supply/repair, and at worst to unaffordability, or non-replacement if the instrument is damaged or lost. Further, their purchase conveys no benefit to the local community or economy (Bannatyne et al 2017).

Being fixed at a point in the channel, most fixed instruments require calibration at least against local conditions and particle sizes, typically requiring manual width and depth integrated channel sampling. This implies that limited manual sampling must still be included in monitoring programme design and implementation (Wren et al. 2000; Gordon et al. 2004; Kuhnle 2013), and that the difficulties of high flow sampling still pertain.

3.6 Discharge

3.6.1 Overview

Uncertainties in discharge data will propagate to the SSLs and SSYs estimated from them. This section considers the uncertainty associated with discharge measurements as input to flow rating curves; with rating curve derivation; and with extrapolating rating curves to calculate high flows.

The discharge data required for SSL estimation is typically monitored at a gauging weir or calculated from flow data, ideally measured at or within the same reach as the SSC sampling site (De Girolamo et al., 2018). Gauging weirs are large, expensive, invasive structures, and tend to be preferentially installed on larger channels that are considered important to water resource management programmes (De Girolamo et al., 2022). Additionally, such structures, their related instruments, and their power supplies and telemetry require constant maintenance, precluding their widespread installation in many developing countries (De Girolamo et al., 2022). Where no established gauging weir is available, researchers must measure flow velocities and the channel cross-section where SSL is to be estimated in order to calculate discharge at each site (Gordon et al., (2004)).

If discharge at a site is measured regularly over a wide range of flows, a site-specific relationship can be established between observed discharge and water level or “stage” (Le Coz, 2012). This stage-discharge relationship, or “rating curve” is then used to develop a discharge time series for each site by calculating discharge from measured, usually near-continuous water level data (Paoletti et al., 2023). For short-term research projects there are typically insufficient measured data to construct a stable, robust rating curve (Gordon et al., 2004). In this instance, a rating curve is modelled using an indirect method such as the slope-area method (Gordon et al., 2004).

With regard to the accuracy of the resulting discharge time series calculated from near-continuous stage measurements, Le Coz (2012) noted the important distinction between the uncertainty associated with the measured instantaneous discharge, and the uncertainty associated with the rating curve. Each of these is considered in the following sections.

3.6.2 Discharge measurement

Instantaneous discharge measurement is typically done in natural water-courses by researchers using hand-held flow-metering equipment, over as wide a range of flow conditions as possible, at a surveyed cross-section of known area. Discharge is calculated using the velocity- area method (**Equation 3-1**, Gordon et al. (2004)).

Equation 3-1: $Q = VA$

Where:

Q = Discharge ($\text{m}^3 \text{s}^{-1}$)

V = Velocity (m s^{-1})

A = Area of channel cross-section (m^2)

Braca (2008) recommends that twelve to fifteen discharge measurements should be made through a range of stages (water depths) and over time to establish a stage-discharge relationship, since multiple discharge measurements improve representativeness and reduce epistemic uncertainty by monitoring the effects of variable controls on discharge. A considerable investment of human and financial resources would be required to satisfy this requirement at multiple sites in remote study areas, presenting a challenge to discrete research studies and even to national-level programmes. For example, Renouf et al. (2005) noted in a survey of 325 Ministry of Environment gauging stations in France that discharges had been measured for flows with a >2 year return period at fewer than 40% of the stations. Fewer than 10% of stations had discharge measurements for flows >10 year return period. A quote by the Australian Water Resources Council, given in Gordon et al. (2004, p28), succinctly captures this difficulty: *Gauging streams under high flow conditions is expensive, dangerous, uncomfortable and requires skilled and dedicated staff. Cuts in funding usually result in less resources being available for high flow gaugings, loss of morale of staff trying to do a professional job, and an eventual unsatisfactory set of records, which rely heavily on subjective and tenuous extrapolations of rating curves.*

Measured discharge is only an estimate of the “true” discharge. The difference between the two is the measurement or epistemic error, but it is impractical to empirically determine this (WMO, 2010). Discharge measurements are subject to natural uncertainty at a range of scales, for example, from wind or from transient flow effects and variable hydraulic controls such as backwatering at the time of measuring, to seasonal changes in vegetation growth or to channel cross-section due to scouring or deposition during floods (Le Coz, 2012). To reduce the influence of reach-scale flow variability (i.e., natural uncertainty) on discharge measurements, sites for flow measurements and water depth monitoring should ideally be a straight, stable reach with a length of at least five times the mean channel width, and with uniform water slope, depth, and velocity, channel geometry and roughness (Gordon et al., 2004). Unfortunately, these ideal conditions rarely exist in natural channels, increasing the natural complexity and uncertainty associated with discharge measurements (Braca, 2008).

Discharge measurements are subject to epistemic uncertainty, for example associated with the accuracy and precision of measured water velocity and depth, and with surveyed channel dimensions (Braca, 2008; Cohn et al., 2013). Operator, equipment, and calibration errors contribute to epistemic uncertainty (Di Baldassarre & Montanari, 2009). Errors in the range of 8 – 20% were estimated from a review of 140 papers dealing with the velocity-area Q calculation method (Pelletier, 1988). An error of at least 10% is widely assumed (Braca, 2008). Although often considered relatively minor compared with other potential sources of uncertainty in SSL/SSY estimation, such errors may propagate through the stage/discharge relationship. This may lead to significant uncertainty (e.g., >40% for the Po River, Italy, Di Baldassarre & Montanari, 2009) and to either under- or over-estimation of SSL/SSY. (Braca, 2008).

3.6.3 *Stage/discharge rating curves*

The uncertainty associated with a rating curve can be ascribed to error in the individual ratings, as well as to the modelled representation of the physical processes that link stage and discharge. The first factor has been considered in the preceding section, given that uncertainty in stage measurements is widely held to be negligible compared with the uncertainty associated with discharge measurement (Le Coz, 2012).

There are two components to the second factor: the variability of flow velocity controls in response to changes in stage, and the method used to calculate the rating curve from measured discharge (Le Coz, 2012; Söregård & Di Baldassarre, 2017). This significant source of uncertainty in modelled rating

curves is considered here using as an example the slope area method (**Equation 3-2**, Gordon et al., 2004). This approach is commonly used in South Africa to develop rating curves, for example in a model such as HEC-RAS (Brunner, 1995).

Equation 3-2:
$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$

Where:

Q = Discharge ($\text{m}^3 \text{s}^{-1}$)

n = Manning's 'n'

A = Area of channel cross-section (m^2)

R = hydraulic radius (m)

S = Slope (%)

A, R, and S are derived from the channel geometry surveys. In HEC-RAS, channel width irregularities are accommodated in a contraction/expansion coefficient, and Manning's 'n' is used as an adjustable variable to fit the calculated discharge more closely to the observed discharge, i.e., it is a calibration variable rather than a measured variable (Reistad et al., 2007). This is an accepted practice, but an unknown and potentially significant source of error in discharge calculations for natural channels (Gordon et al., 2004; Reistad et al., 2007; Di Baldassarre & Montanari, 2009).

Equation 3-2 ideally requires uniform flow conditions and does not account for the variability of flow velocity controls in response to changes in stage. Low flows are typically section-controlled by natural or man-made features such as woody debris, riffles or weirs that partially or completely block or narrow the channel, decreasing the upstream flow velocity in that reach or section (Braca, 2008). As these section controls become submerged with rising flows, downstream channel geometry and roughness begin to exert more influence on flow velocity until these channel controls dominate. The use of the co-efficient and Manning's "n" to accommodate these recognized but unquantified changes is a significant source of uncertainty in discharges calculated using **Equation 3-2** (Braca, 2008; Di Baldassarre & Montanari, 2009). As with sediment rating curves, stage discharge rating curves are often derived using a single power law function (Söregård & Di Baldassarre, 2017). To constrain the uncertainty associated with the variability of flow velocity controls, this approach may be refined by segmenting the rating curve i.e. using different parameters to account for the changes in channel roughness and geometry that are associated with different stages (Söregård & Di Baldassarre, 2017). However, when measured data are few, segmenting the rating curve may lead to overfitting due to

the difficulty in distinguishing between the “noise” and the trend in the measured discharge data (Söregård & Di Baldassarre, 2017).

Extrapolating rating curves to high flows is common practice, since high flows are the most important not only for sediment transport but also due to flooding and risks to infrastructure. However, extrapolation to estimate high flow discharges that were not measured can introduce errors of up to 40% into rating curves (Di Baldassarre & Montanari, 2009). Errors from extrapolation necessarily propagate into the resulting discharge time series calculated from stage data (Söregård & Di Baldassarre, 2017), and thence into SSL estimation.

3.7 Suspended sediment load estimation

3.7.1 Background

Although sampling method, frequency, and representativeness are responsible for much of the error associated with SSL/SSY estimation, it is known that the approach taken to estimating daily SSC and to estimating annual SSL impacts the bias, precision and accuracy of the resulting SSL (Walling & Webb, 1985; Lee et al., 2016; De Girolamo et al., 2018). There is no universally superior method to constraining epistemic uncertainty in SSL estimation, as estimator performance in this regard depends on the available data, conditions in the catchment, and the objectives of the study (Lee et al., 2016). In practice, the “best” approach to SSL estimation is the one that adds the least additional uncertainty or error (Walling, 1977a; Walling & Webb, 1985).

SSL is the mass of SS transported through a river gauging site for a specific time period such as a year or a decade. SSL is typically estimated by first organising the available SSC and discharge data into daily timeseries using interpolation and/or reduction (i.e., averaging), and then multiplying daily SSC by daily discharge (Lee et al., 2016). The basic formula for SSL estimation is shown in **Equation 3-3**.

Equation 3-3: $Q_s = SSC \cdot Q$

Where:

Q_s = Sediment load (e.g., $g\ s^{-1}$)

SSC = SSC (e.g., $g\ m^{-3}$)

Q = Discharge (e.g., $m^3\ s^{-1}$)

Often however, **Equation 3-3** cannot be applied due to limited data availability (De Girolamo et al., 2018). Even in countries with well-developed water resources monitoring programmes, SSC data are often more difficult and costly to acquire than discharge data (Lee et al., 2016). Discharge data are typically available as a near-continuous daily timeseries, whereas SSC sampling (especially when flood-focussed) may be infrequent or irregular, resulting in days without data, as well as days with several data points at irregular intervals (De Girolamo et al., 2018). This mismatch between SSC and discharge data, and the uncertainty associated with subsequent SSL estimation, has been described as “the load estimation problem” (Lee et al., 2016). This problem has been widely investigated, and various approaches have been investigated to constrain uncertainty when generating daily time series from irregular SSC data, and using these timeseries to estimate SSL.

3.7.2 Averaging

It is well understood that flood-focused sampling is less likely to lead to underestimation of SSL than calendar-based sampling (Walling et al., 2007), and it is widely accepted practice to use a daily timestep as input to annual SSL estimation (Lee et al., 2016). However, flood-focused direct SSC sampling is likely to result in a variable number of SSC samples in any 24-hour period, as well as days when no SSC data are collected.

In preparation for annual SSL estimation, the SSC and the discharge data collected in a 24-hour period are averaged, and the resulting daily SSC and discharge are used to estimate annual SSLs (Walling & Webb, 1985). Averaging the data from flood-focused SSC samples collected at intervals throughout the day provides a more representative daily SSC value than that of a single daily sample, which might for example represent only the highest or lowest SSC (Fisher & Yates, 1990; De Girolamo et al., 2018). Simple averaging can be used to derive daily discharge time-series from near continuous discharge data, and to derive annual SSL from daily SSL when 365 days are represented. However, SSC may be sampled at irregular intervals within a 24 hour period, and the number of SSC samples may vary from day to day. Similarly, available daily SSL data may vary in frequency throughout and between years.

Failure to compensate for the differing time periods that each sample represents would lead to underestimation (Walling & Webb, 1985). Using Time Weighted Mean Concentration (TWMC), for example to derive daily SSC for input into daily SSL calculations, results in less bias (**Equation 3-4** Richards & Baker, 1993).

Equation 3-4:
$$TWMC = \frac{\sum_i^n (c_i * t_i)}{\sum_i^n (t_i)}$$

Where:

c_i = SSC (mg L⁻¹) for the i^{th} sample

t_i = time for the i^{th} sample

n = number of samples

Deriving daily SSC using TWMC rather than the arithmetic mean may still lead to underestimation, because TWMC is independent of the rate of flow, whilst SS transport is positively flow-dependent (Walling & Webb, 1985; Richards & Baker, 1993). Error will also occur due to the necessary (but wrong) assumption that each SSC sample (i.e., c_i in **Equation 3-4**) fully represents SSC throughout the preceding time period, particularly if the sampling interval exceeds the period over which significant change in SSC is likely to occur. This assumption is also made when linear interpolation methods are used to derive daily SSC for days when no SSC samples were collected, again introducing error (Lee et al., 2016).

3.7.3 Ratio estimators

Ratio estimators may produce less biased results than averaging and interpolation estimators (Richards, 1998). To derive annual SSL, daily load is calculated from daily SSC and discharge for the days that SSC data are available, and averaged. The resulting averaged annual SSL is multiplied by a Q ratio that is derived by dividing the average annual flow by the average of the sampled flow (**Equation 3-5**, Quilbé et al., 2006)).

Equation 3-5:
$$\left(Total\ SSL = \overline{CQ} \frac{\mu_q}{\bar{Q}} n \right)$$

Where:

$\overline{CQ}$ = Mean daily load (g m⁻³)

$\bar{Q}$ = Mean discharge of sampled days (m³ s⁻¹)

μ_q = Mean of all daily discharge measurements for the year (m³ s⁻¹)

n = number of samples

The Q ratio ($\frac{\mu_q}{\bar{Q}}$) helps to correct annual loads for non-representativeness of the annual discharge, while giving an indication of the uncertainty associated with the resulting SSL (Quilbé et al., 2006). A correction factor is applied when SSC data are sparse (Richards, 1998). While not a statement of uncertainty *per se*, a “Q ratio” of 1 would indicate that the full range of flows had been sampled, whilst a ratio exceeding 1.2 would indicate that high flows were under-represented by more than 20% in the

sampled discharge and that the resulting SSL/SSY would be under-estimated. Conversely, a ratio of less than 0.8 would indicate that available high flows were fully sampled, whilst the low flows that contributed to the mean annual discharge at the site were under-represented.

3.7.4 Sediment rating curves

Sediment rating curves have been found to be the most accurate and precise method of SSL estimation where relatively good quality, decades-long, preferably near-continuous SSC data are available (Walling, 1977a, b; Walling & Webb, 1981; Asselman, 2000; Horowitz, 2003, 2008; Gao, 2008; Kuhnert et al., 2012). Rating curves express the empirical relationship between discharge and SSC (Walling & Webb, 1981). Typically, though not exclusively, a power function is used, either as an untransformed power regression (Asselman (2000), **Equation 3-6**), or as a log/log linear rating curve (Quilbé et al. (2006), **Equation 3-7**).

Equation 3-6: $C = aQ^b$

Equation 3-7: $\log_{10} (C) = a + b \log_{10} (Q)$

Where:

C = SSC (mg L⁻¹)

Q = discharge (m³ s⁻¹)

a = slope

b = intercept

Importantly, although sediment rating curves can accommodate relatively sparse SSC data, they require a strong (e.g., $r^2 \geq 0.5$) correlation between discharge and SSC to constrain uncertainty (Quilbé et al., 2006; Grenfell & Ellery, 2009). An $r^2 < 0.5$ signifies that less than half the variability in the SSC is attributable to discharge (Quilbé et al., 2006). Using regression in that case, including when SSC data are few, and/or are weakly correlated with discharge data, leads to greater uncertainty in estimated annual loads than using an averaging or a ratio estimator (Quilbé et al., 2006).

Correlations may be improved by subdividing or “stratifying” the available data, for example by stage and/or season, which limits the range of catchment conditions and processes represented in the subset (Skarbøvik et al., 2012; Harrington & Harrington, 2013; Novic et al., 2018).

3.8 Indirect approaches to suspended sediment yield estimation

Objective 2 of the research described in this thesis estimates the project period SSLs and SSY for the study sites with, where feasible, a critical assessment of the uncertainty in the estimates. Given the dearth of SSLs and SSYs estimated from direct measurement, this required the comparison of the results from this study with those derived from indirect methods including modelling, reservoir studies, sediment fingerprinting and tracing, and systems dynamics (**Section 9.2.3**). The sources of uncertainty associated with these approaches are considered in **Chapter 4**, as each of these methods has been applied in the Tsitsa River catchment.

3.9 Summary

Natural variability associated with SSC and with discharge are important contributors to SSL uncertainty, but this thesis focuses on limiting, as far as possible, the epistemic uncertainty associated with estimating SSLs using data from a manual, citizen technician based sampling approach, as a solution to other constraints on SSC sampling in southern Africa and other developing regions. This chapter therefore introduced and defined natural and epistemic uncertainty, related variability to uncertainty and to risk in decision-making, and explained the distinction between precision and accuracy. It went on to identify key sources of natural and epistemic uncertainty related to SSC sampling and analysis, and to SSL and SSY estimation. The spatiotemporal variability of sediment supply at a range of scales was examined as an important source of natural uncertainty, often seasonally related to antecedent conditions, rainfall erosivity and sediment availability. These factors were considered as a means to limit epistemic uncertainty through the selection of appropriate sampling and analysis methods, and SSL estimators. Lastly, the natural and epistemic uncertainty associated with discharge measurement and with SSL estimators were reviewed.

The implications of not knowing or not stating the uncertainty associated with SSL and SSY estimates could be profound for the planning and prioritisation of catchment management activities and water resources infrastructure, but the acceptable degree of error is dependent on the scale and purpose of the study, and constraining uncertainty is resource-intensive. Efforts in this regard can only be focused on the epistemic uncertainties associated with measurement and representativeness, since natural uncertainty cannot be quantified and/or constrained, only better understood through measurement. This is ideally achieved by precise and accurate measurements of SSC and discharge through the full range of possible conditions, at intervals that align to the expected rate of change. This aim is typically

too resource-intensive even for established government monitoring programmes to fully achieve. It is particularly challenging for discrete research projects with limited financial and human resources in remote, less-developed regions where existing data are scarce and instrumented approaches are precluded by socio-economic and physical conditions. This is especially the case for SSC and discharge measurements during high flows.

Uncertainty should be expressed, where feasible, for all results in relative (percentage) and absolute (units) terms that allow comparison with other benchmarks. Although cross-comparing SSLs and SSYs derived by different methods and/or for other areas may provide insight to the accuracy of survey results, it is risky in the absence of statements of uncertainty for all methods, as is the assumption of stationarity when comparing data and results that represent different time periods.

The range of expected/accepted uncertainty associated with estimating SSLs/SSYs is unlikely to be less than 20% but may exceed several hundred percent (**Table 3-4** and **Table 3-5**). The limit is difficult to define, particularly in small, highly variable systems, for reconnaissance surveys, and in the absence of other relevant data.

4 Suspended sediment yields in southern Africa

4.1 Introduction

This chapter reviews the existing knowledge of SSYs in southern Africa, and specifically in the Tsitsa River catchment, providing the background and context for the research described in this thesis. The chapter synthesises relevant historical and current information and data, and describes the methods used to obtain them, the purpose and challenges associated with their collection, the degree of associated uncertainty, and the resulting implications for contemporary catchment management decision-making in South Africa.

SS yield (SSY) is the total mass of sediment in suspension that is transported out of a drainage basin, and is expressed per unit of catchment area per unit time (e.g., $\text{t km}^{-2} \text{yr}^{-1}$). Surface denudation is also referred to as erosion, and is often expressed as a rate of ground surface lowering (e.g., mm yr^{-1}) or of soil loss, expressed either in volumetric (e.g., $\text{m}^3 \text{ha}^{-1}$) or mass units (e.g., t ha^{-1}). Original published figures reproduced in this chapter, (for example **Figure 4-5**) give erosion rates, soil loss and/or SSY in $\text{t ha}^{-1} \text{yr}^{-1}$. Insets have been added to the figures that convert the original values to $\text{t km}^{-2} \text{yr}^{-1}$, as used in the text. Soil erosion studies tend to report in t ha^{-1} , whereas fluvial geomorphologists tend use t km^{-2} . Standardising on the latter avoids confusion.

4.2 African representation in global suspended sediment yield studies

Global-scale SSY reviews typically collate and sometimes re-analyse existing discharge, SSC and/or SSY data, for example to determine continental SS trends (Walling & Webb, 1996; Walling & Probst, 1997; Meybeck et al., 2003; Walling & Fang, 2003; Syvitski et al., 2005; Milliman & Farnsworth, 2011). They provide comparative and temporal trend information and, in some cases, examine and/or correlate the factors determining continental-scale SSYs, but are not intended to provide information on which catchment-scale management decisions could be made.

African rivers are under-represented in global SS studies (Vanmaercke et al., 2014). Vanmaercke et al. (2014) reviewed eleven global studies and found that, in all but two, SSY data from African rivers typically contributed less than 10% of the total data used. SS data are globally scarce and are particularly under-represented in Africa, where SS data are available for significantly fewer stations and for much shorter and discontinuous monitoring periods than are discharge data (Merritt et al., 2003; Msadala, 2010; Li et al., 2020). The difficulties associated with collecting representative SS data

due to extreme system variability are compounded by the lack of monitoring infrastructure and financial resources (Walling, 1984; Chakela, 1992; Foster & Boardman, 2018; Grauso et al., 2020).

In their global review, Li et al. (2020) examined the longest records available for 4307 catchments >1000 km² to determine trends in discharge and SS delivery to coastal waters. While their discharge data comprised many stations in Africa, they show few data-points (<15) for SSC records and SSYs (Figure 4-1).

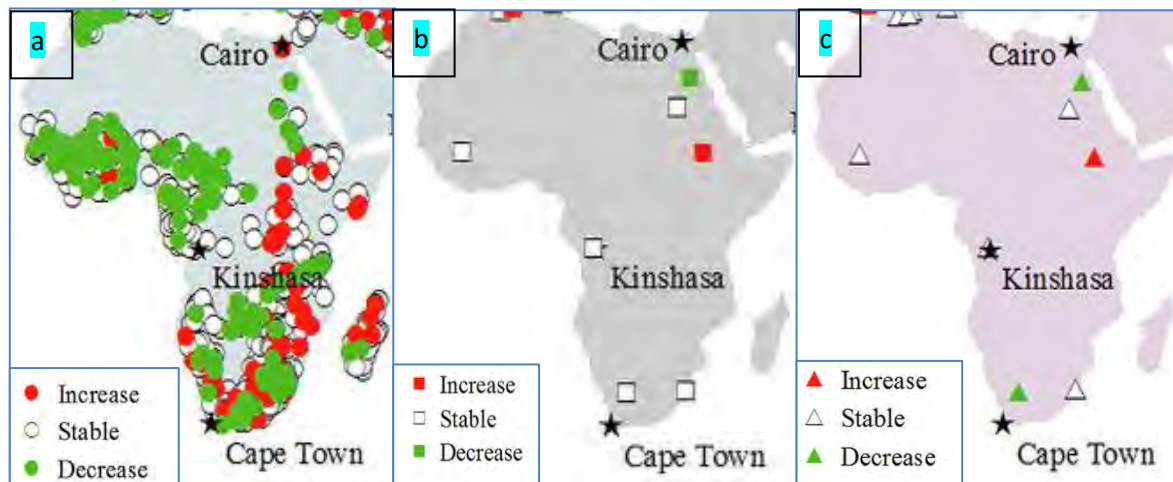


Figure 4-1: African datapoints and trends for a) discharge, b) SSC, and c) annual SSY as reported in Li et al. (2020, reproduced with permission)

Li et al's. (2020) analyses underline the scarcity of recent SS data in Africa, which is not useful as an input to catchment management decision-making: discharge, SSC and SSY trends are reported at a continental rather than catchment scale, where uncertainty is likely to be extremely high (Walling, 1984).

4.3 Southern African suspended sediment yields

Certain major rivers in eastern and southern Africa, such as the Tana in Kenya and the Orange (Senqu) in South Africa and Lesotho, have historically long (e.g. 1948 – 1982 for the Tana, pre 1966 – 1977 for the Orange) and relatively continuous historical sampled SS records. This is due to their nationally important infrastructural development in terms of power generation, irrigation supply, and/or domestic water supply (Walling, 1984). These SS data were typically collected as part of multi-year, national-level government programmes to support the planning and operation of water-supply transfer schemes and impoundments. Nevertheless, the resulting SSYs may be subject to significant uncertainty, as illustrated by Walling (1984) for the upper Tana River at Kamburu. Mean annual SSL estimates from 1959 to 1982 ranged from $\sim 0.4 \times 10^6 \text{ t yr}^{-1}$ to $\sim 7.5 \times 10^6 \text{ t yr}^{-1}$ (Walling, 1984). Both

natural and epistemic uncertainty (**Chapter 3**) due to variable climatic conditions and the use of different estimation methods played a role in the wide range of results (Walling, 1984). This order-of-magnitude uncertainty has significant forecasting and planning implications over a 50-year timeframe. Informed by these and other available SS data, and selecting maxima but avoiding what he considered to be human-influenced extreme SS values, Walling (1984) refined Fournier's (1960) and Strakhov's (1967) widely contrasting and somewhat speculative African yield estimates to develop the “tentative and generalised” continental-scale SSY map reproduced in **Figure 4-2** (Walling, 1984).

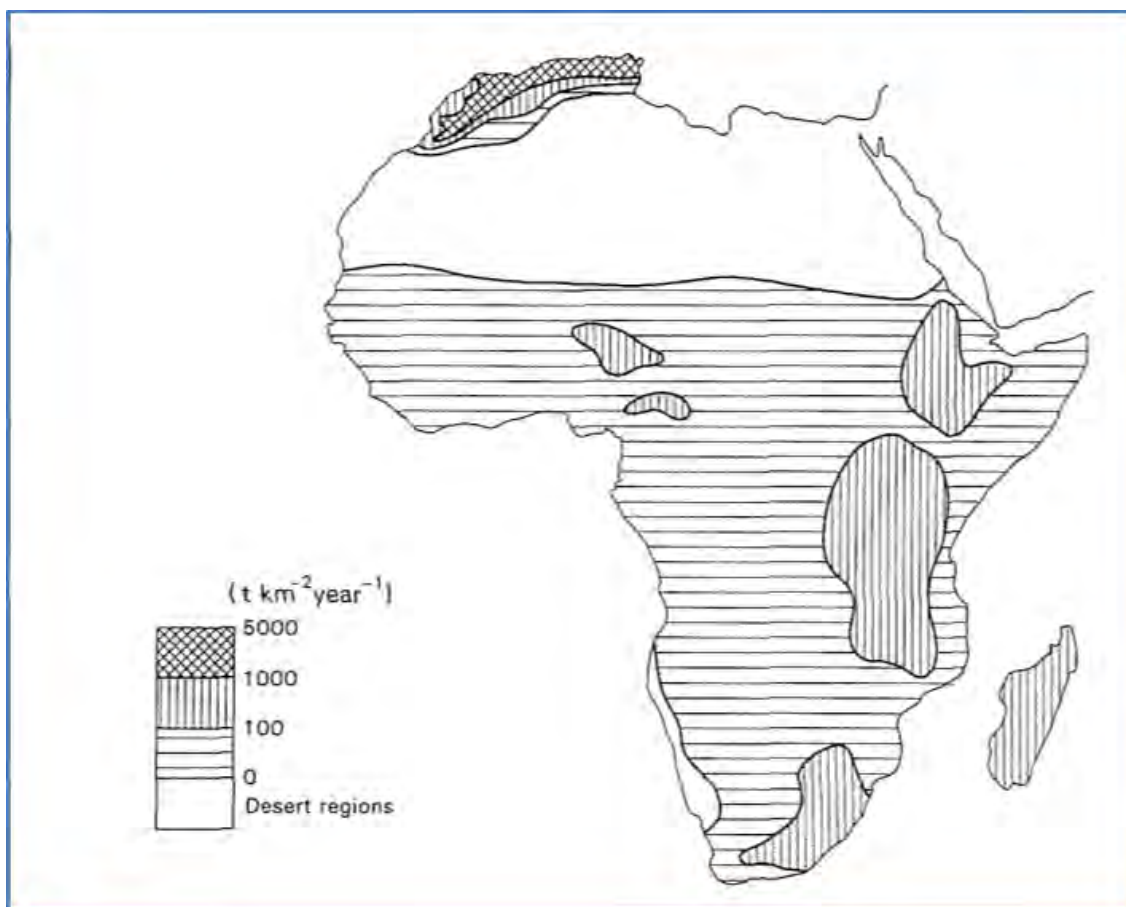


Figure 4-2: “Tentative and generalised” SSY map for the African continent (after Walling, 1984)

Mean SSYs of between $100 \text{ t km}^{-2} \text{ yr}^{-1}$ and $1\,000 \text{ t km}^{-2} \text{ yr}^{-1}$ in the eastern part of South Africa and the Kenya/Tanzania region are distinguished from the lowest reported range of $< 100 \text{ t km}^{-2} \text{ yr}^{-1}$, but these ranges are too broad to support catchment-scale decision-making.

Vanmaercke et al. (2014) specifically addressed the contemporary gap in African SSY information. In addition to scientific publications, they also reviewed theses, conference proceedings, and institutional reports for SSC monitoring as well as reservoir (locally: dam) sedimentation studies that reported SSY from at least one year of measured data. This provided an important historical

benchmark which remains a keystone resource for pre-2013 measured African SSY data. Vanmaercke et al. (2014) described the measurement method, the estimated SSY, and their perception of each study's associated uncertainty.

Vanmaercke et al. (2014) found that, pre-2013, SS studies meeting their criteria of > 1 yr of data had been collected for 682 African catchments, of which 377 were based on gauging station data. Vanmaercke et al.'s (2014) data-points are depicted in **Figure 4-3**.

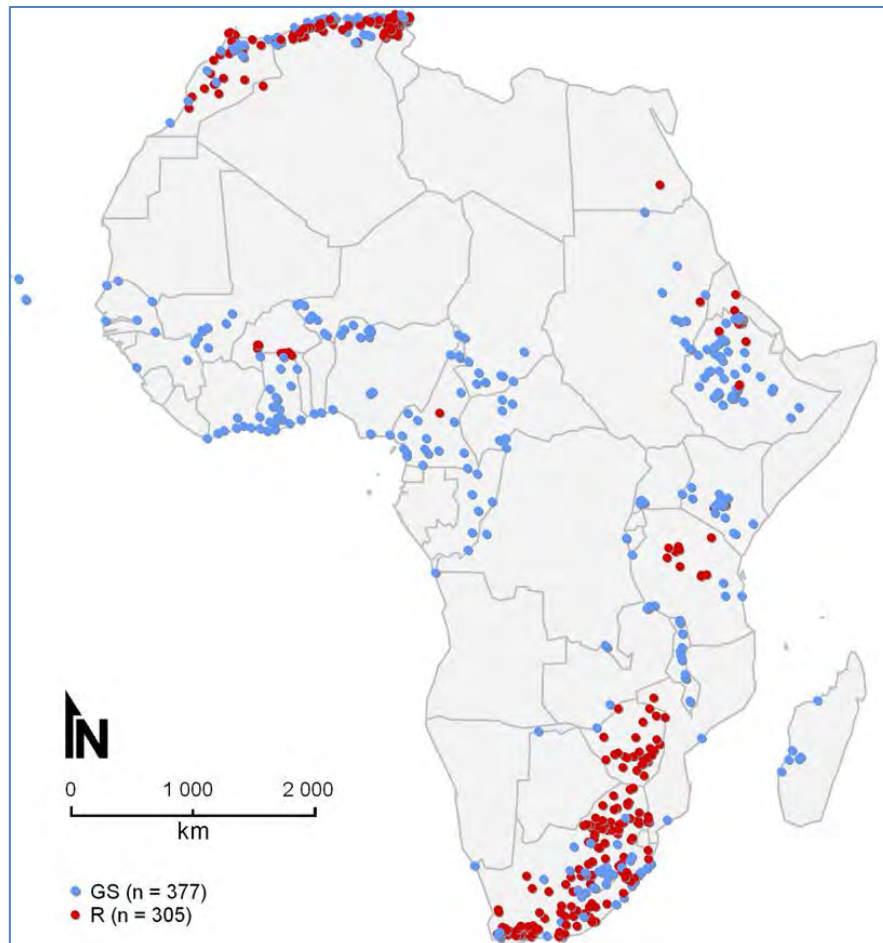


Figure 4-3: Data points used in Vanmaercke et al.'s (2014) review of measured SS data. (Reproduced with permission). GS denotes gauging station data whilst R denotes data from a reservoir sedimentation study

Compared with record lengths for European rivers (average ~13 years), African sediment yields were on average based on only 6 years of data. Available SS data are thus seen to be spatiotemporally sparse. The review studies collated by Vanmaercke et al. (2014) provide an important historical benchmark, but the SSYs they report are not useful as input to present-day catchment management decision-making, both due to their regional scale and uncertainty, and because the data used in most of the studies were collected pre-2010.

Vanmaercke et al. (2014) re-analysed the collated observed data to estimate catchment and regional-scale SSYs for the African continent. The estimated (left) and observed (right) SSYs are depicted in **Figure 4-4**.

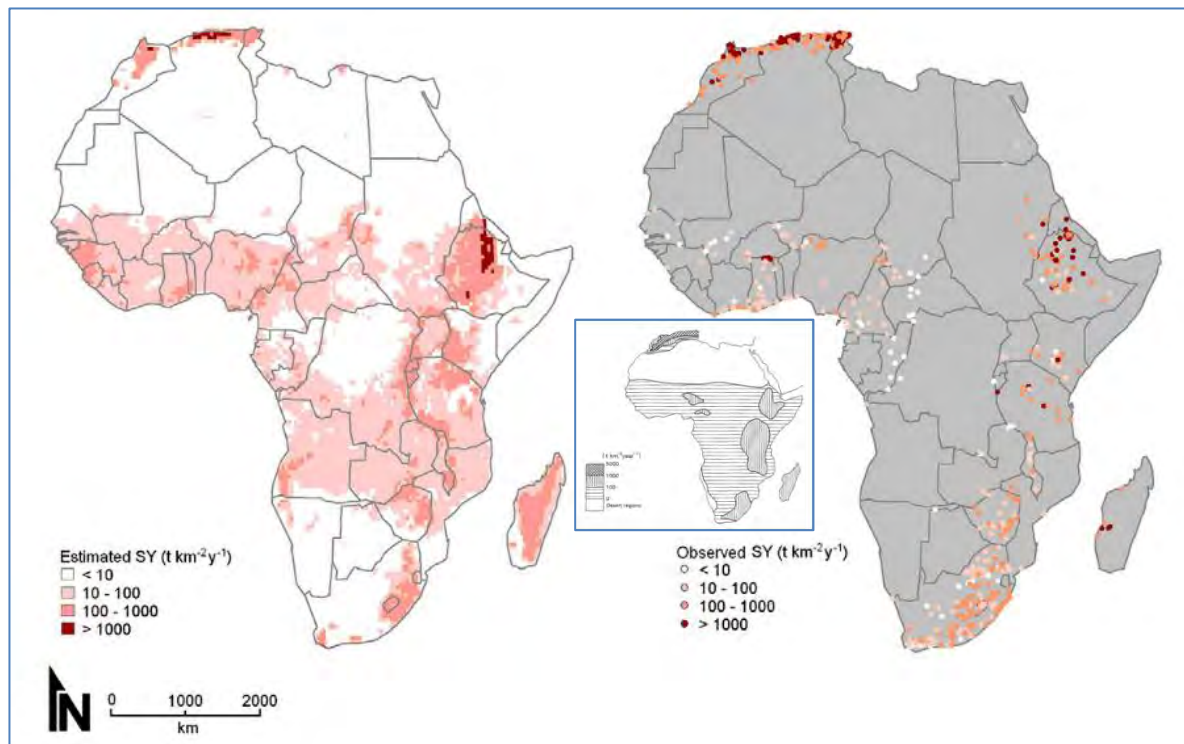


Figure 4-4: Catchment SSYs determined by Vanmaercke et al. (2014) (Reproduced with permission). Inset: Walling's 1984 SSY values

The pattern of higher and lower SSYs is somewhat more detailed than, but broadly similar to Walling's (1984) values: Vanmaercke et al. (2014) used some of the same data as Walling (1984) for Tunisia, Cote d'Ivoire, Cameroon, Kenya, and South Africa. Vanmaercke et al. (2014) also recognised that their assessments of historical data uncertainty were themselves subject to uncertainty, and acknowledged their reliance in that regard on the statements made by the original study authors, for example in terms of the survey location, data monitoring duration and frequency, trap efficiency of dams, and SSY estimation method.

4.4 Suspended sediment yields in South Africa and Lesotho

4.4.1 History

South Africa's contribution to the southern African regional data reviewed by Vanmaercke et al. (2014) is significant. 41% of southern African SSC-based data (67% of catchment years) and 77% of southern

African dam¹⁰ sediment-based data (88% of catchment years) were derived from South African rivers. These were mainly discrete case studies and government-funded decision-support studies. Vanmaercke et al.'s (2014) data for South Africa and Lesotho are summarised in **Table 4-1**.

Table 4-1: Southern African data sources used in Vanmaercke et al.'s (2014) review of measured SS data

Country	SSC data # Catchments (catchment yrs)	Dam sed. Data # Catchments (catchment yrs)	Total # (catchment yrs)	Catchment area Min –max (km ²)	Min-max SSY (t km ⁻² y ⁻¹)	Sources
Lesotho	16 (98)	N.A.	16 (98)	212–19,875	3–2050	FAO (2008)
South Africa	38 (333)	136 (4318)	174 (4651)	0.18–1,000,000	1–890	(Rooseboom, 1978) Dedkov & Mozzherin (1984) Rooseboom & Lotriet (1992) Scott et al. (1998) FAO (2008) Milliman & Farnsworth (2011) Baade et al. (2012) Foster & Rowntree (2012)
All southern Africa data	92 (495)	177 (4919)			0.4 - 3132	

The SSY prediction for South Africa by Msadala et al. (2010) is notably absent here, perhaps overlooked because it was published as a research report by the WRC rather than as an academic paper. The discrete case-studies located in the mountains of the Western Cape province (Scott et al., 1998), within the Kruger Park in Limpopo and Mpumalanga Provinces (Baade et al., 2012), and in the Karoo uplands in the Eastern Cape Province (Foster & Rowntree, 2012) provide insight to specific biophysical and anthropogenic conditions. They demonstrate site-specific sediment erosion, transport and deposition processes, particularly with regard to the accelerated rates from the mid 20th century onwards that were estimated from reservoir studies (Foster & Boardman, 2018). These descriptions and the scale of the SS data provide useful information against which to compare SSYs from the same

¹⁰ In South Africa, “dam” denotes a reservoir. The structure impounding the dam is the dam wall.

or geomorphologically similar areas, but more recent data would be required for catchment management planning today and in the future.

Data for the spatiotemporally intensive, government-funded yield estimates for South African catchments (Rooseboom, 1978; Rooseboom & Lotriet, 1992) were collected even earlier (pre ~1990) in response to sedimentation concerns related to the large-scale dam and transfer scheme construction that took place in South Africa during the period ~1970 to ~1980 (Roberts, 2008; Van Vuuren, 2012). As the products of well-regulated government-programmes, the quality of these data is likely to be relatively high and consistent. Makhoalibe (1984), however emphasised that the SSYs estimated from data collected by the Lesotho Ministry of Water, Energy and Mining at 17 gauging stations in Lesotho from 1976 – 1982¹¹ were only an *approximate* estimate, due to a combination of natural and epistemic uncertainties. Despite this, they remain the only data against which modelled SSY estimates for Lesotho can be calibrated and validated (Grauso et al., 2020).

Vanmaercke et al. (2014) state that a global loss of appetite for hydrological monitoring occurred from the 1990s, as evidenced by a drop-off in the number of direct SS observations and reservoir sediment surveys, and echoed by a significant reduction in hydrological data collection. Whilst the former is true in South Africa, the latter is not: SS monitoring has largely ceased, but discharge monitoring has generally been maintained (Global Runoff Data Centre, 2020; Rivers-Moore et al., 2020). (Meissner et al., 2017, p2), referring specifically to South Africa, conversely state that “soil erosion and sediments received more attention by scientists since the mid-1990s than before”. This is borne out by the 2013 WRC initiative to develop an integrated framework for the assessment and management of sediment related impacts on water resources in South Africa (Jeleni et al., 2013) and their more recent launch, with DWS, of a national siltation management strategy for dams in South Africa (WRC, 2020). However, the loss of appetite for SS sampling is reflected in the fact that the WRC initiatives were predicated on modelled SS data, with no call for direct sampling other than for model validation.

Despite the dangers of basing potentially expensive management decisions on untested and uncalibrated models, SSY estimation in South Africa has, since ~2005, relied almost exclusively on dam sedimentation studies and modelling.

¹¹ This study forms part of the dataset included by the FAO (2008) in Vanmaercke et al. (2014)

4.4.2 *Suspended sediment yield estimation from dam sedimentation studies*

In developing countries, and other areas such as South Africa where no measured SSC data are available, SSY from reservoir or dam sedimentation surveys can be an important source of catchment SSY data (Verstraeten & Poesen, 2000; Foster & Rowntree, 2012; Reinwarth et al., 2019). Dam sedimentation rates are extensively used as a source of national- and regional-scale SSY information in South Africa, against which the findings of this study are later compared (**Chapter 9**).

Spatially, the estimation of SSY from dam sedimentation is self-evidently limited to catchments where suitable impoundments occur. Temporally, the sediment trapped in a reservoir or dam is a time-integrated sample that represents the minimum SSY of the upstream catchment from the date of construction (Verstraeten & Poesen, 2000; Verstraeten & Poesen, 2002; Hicks & Gomez, 2016). SSY change over time can be estimated either by physical resurvey or by coring and dating the sediment column (Foster & Walling, 1994).

Sources of natural uncertainty relate to the variability of impoundment hydraulics, the transport and deposition of material, and the retention of both bedload and SSL in the impoundment (Foster & Boardman, 2018). Sources of epistemic uncertainty include determining the geometry of the impoundment, the determination of impoundment trap efficiency (TE), and calculating the density and volume of trapped material (Reinwarth et al., 2019). The inclusion of unknown percentages of bedload adds further uncertainty. The uncertainty associated with SSY estimation (~20 – 40%) from sediment deposition is within the range of uncertainties associated with other methods such as rating curves (Verstraeten & Poesen, 2002; Foster & Boardman, 2018; Reinwarth et al., 2019). However, the degree to which dam sediment surveys in other catchments can be used to benchmark SSY in unimpounded catchments is limited: data scarcity and system variability may greatly impact runoff regimes and sediment characteristics and therefore, by extension, TE (Reinwarth et al., 2019).

Driven by the challenges associated with effective and representative direct SS sampling, models are increasingly used to estimate SSY in areas where SS data are scarce or absent. In these instances, ad hoc and spatiotemporally limited SS monitoring may be undertaken in an effort to train and confirm the output of SS models. SSY models are reviewed in **Section 4.5.2** in connection with existing studies in the Mzimvubu catchment.

4.4.3 National scale soil erosion risk modelling

SSY modelling at a national scale in South Africa was based on, and preceded by, improved soil erosion risk predictions. It is crucial at this point to re-emphasise the distinction between soil erosion rates and SSYs. Given the uncertainty associated with sediment delivery ratios (SDRs, Walling, 1983) and with the conversion from volume (m^3) to mass (t) when soil erosion is derived from reservoir studies (M'Cormick et al., 1992), it is to be expected that soil erosion risk estimates greatly exceed SSY estimates.

Le Roux et al. (2008) improved the spatial modelling of soil erosion risk at national scale for South Africa by revising model components and techniques. National datasets for indicators such as rainfall, soils, topography and vegetation cover were developed/updated, and used as input to a simplified version of the Revised Universal Soil Loss Equation (RUSLE) to develop a water erosion prediction map (Figure 4-5) representing the RUSLE outputs in digital geographic information system (GIS) form (Le Roux et al., 2008).

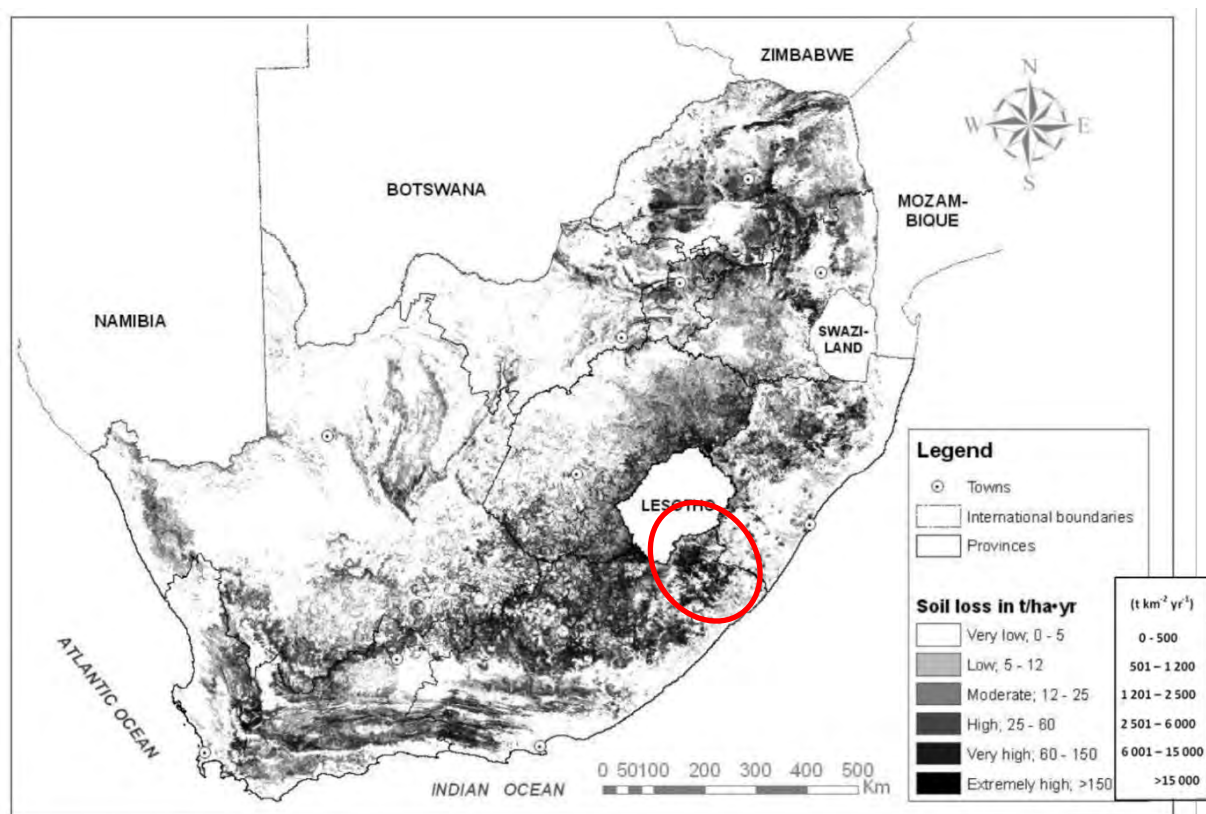


Figure 4-5: National water erosion prediction map for South Africa (Le Roux et al., 2008) with the Mzimvubu River system indicated by a red oval and the ha to km^2 conversion inset

In many parts of the world, the “low” $500 \text{ t km}^{-2} \text{yr}^{-1}$ - $1\,200 \text{ t km}^{-2} \text{yr}^{-1}$ water erosion risk (not to be confused with SSY) predicted for parts of South Africa would be considered extremely high, but Le

Roux et al. (2008) reserve that classification for the $> 15\,000\text{ t km}^{-2}\text{ yr}^{-1}$ potential soil loss in the eastern and north-eastern parts of South Africa. Given the absence of gully erosion input, they may in fact be *under-estimates*.

The Mzimvubu River catchment, of which the Tsitsa River is a tributary, is indicated by the red oval in **Figure 4-5**. Predicted soil loss in this area appears to range from “Moderate” ($>1\,200\text{ t km}^{-2}\text{ yr}^{-1}$) to “Extremely high” ($> 15\,000\text{ t km}^{-2}\text{ yr}^{-1}$). In terms of the uncertainty of the results, Le Roux et al. (2008) report 77% accuracy between their predicted and observed erosion rates, noting that the use of RUSLE factors means that their findings are attributable to sheet and rill erosion with no allowance for the widespread and often severe gully erosion present in parts of South Africa (See **Section 4.5.3**).

4.4.4 National erosion index and sediment yield mapping

The information depicted in **Figure 4-5** was used by Msadala et al. (2010) as input to their national (water) erosion index map (**Figure 4-6**), derived from four major factors: rainfall erosivity, topography, soil erodibility and land cover (Msadala et al., 2010).

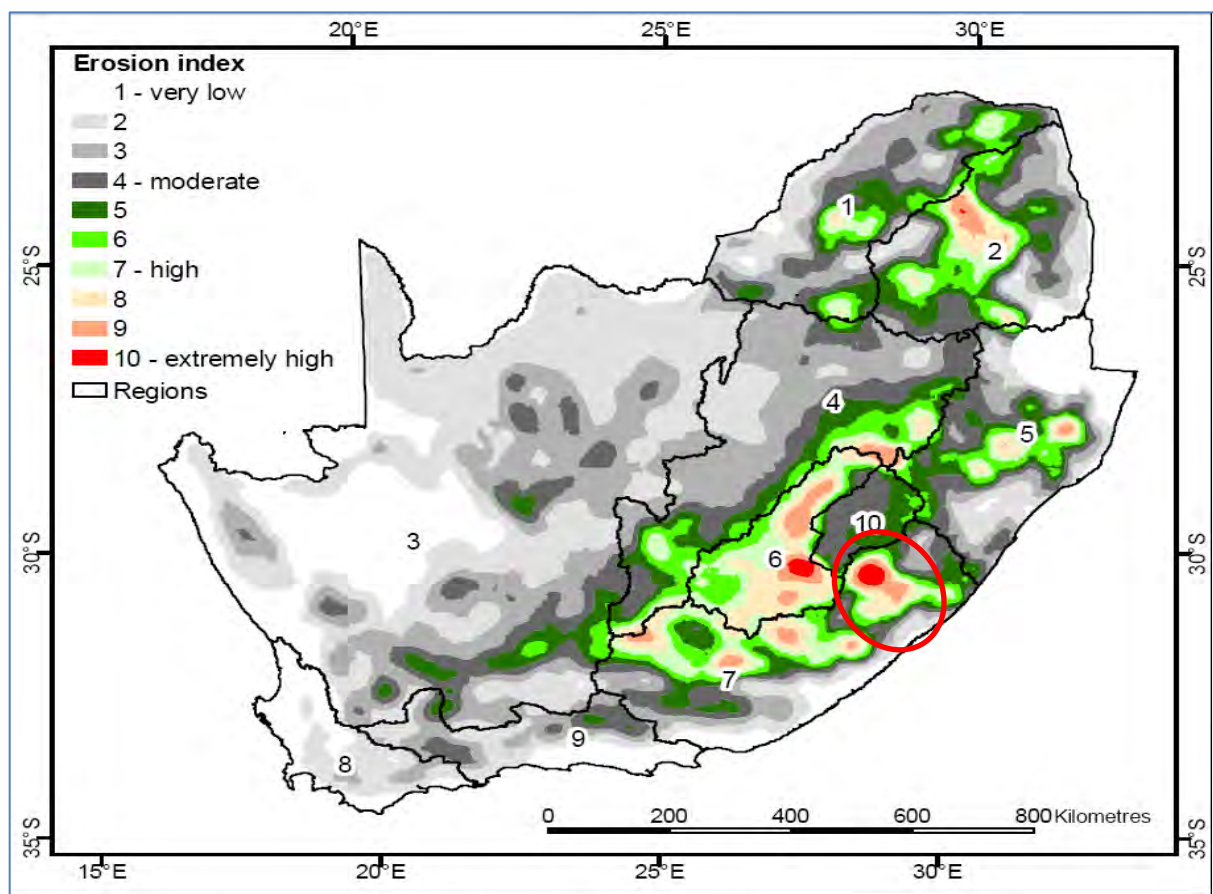


Figure 4-6: Erosion index map (Msadala et al., 2010) with the Mzimvubu River system indicated by a red oval

The patterns shown in **Figure 4-5** and **Figure 4-6** are broadly similar, with the Tsitsa River area of the Mzimvubu catchment (indicated by the red oval in **Figure 4-6**) depicted as “Extremely high”, whilst a “High” erosion index is depicted for most of the rest of the system.

Msadala et al. (2010) used the information shown in **Figure 4-6**, together with updated and improved analytical approaches and mathematical modelling to revise Rooseboom & Lotriet's (1992) SSY map for South Africa (**Figure 4-7**). The Mzimvubu catchment is indicated by the red circle, and lies within the area designated “Region 7” by Msadala et al. (2010).

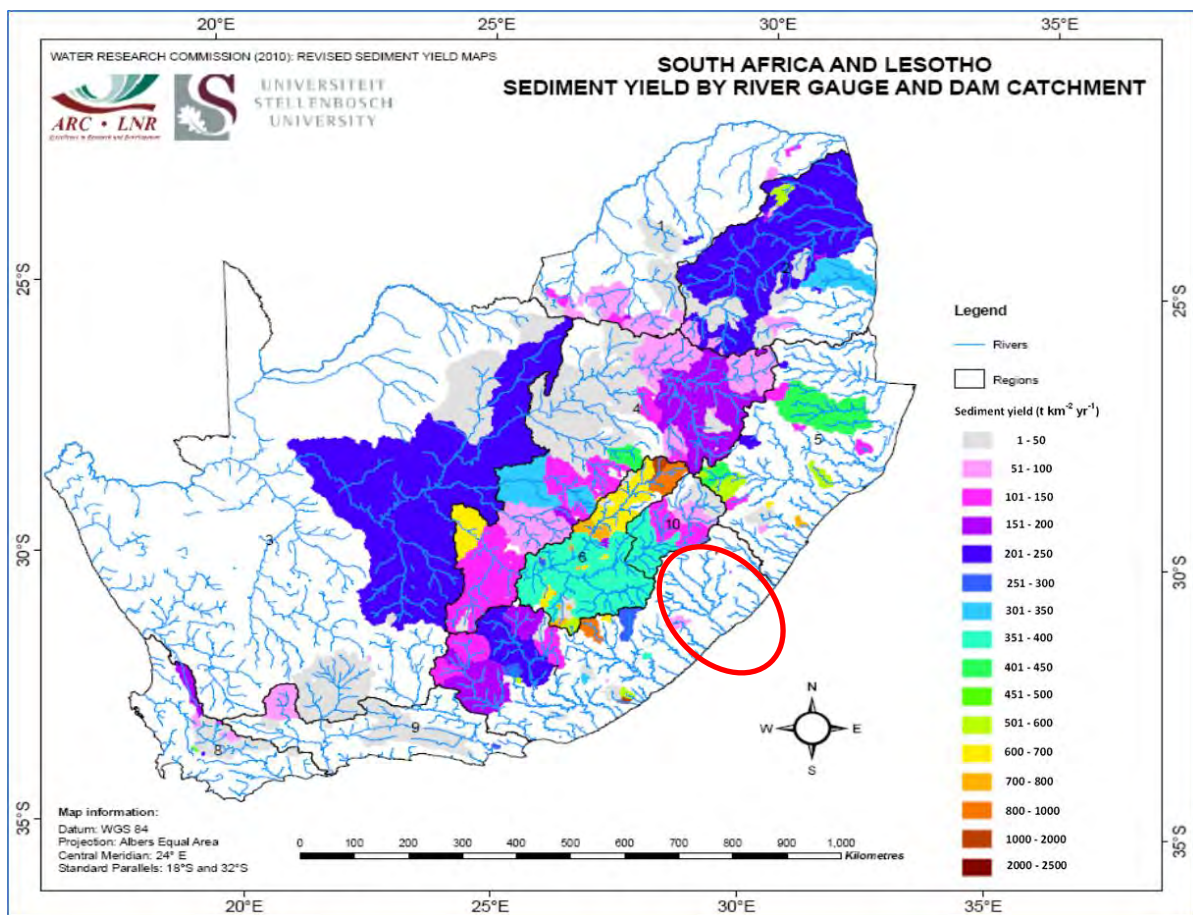


Figure 4-7: Msadala et al.'s (2010) sediment yield map for South Africa with the Mzimvubu River system (no SSYs estimated) indicated by a red oval.

Msadala et al.'s (2010) results (**Figure 4-7**) broadly emulate those of Walling (1984) and Vanmaercke (2014) at a national scale, although the greater level of detail reveals that, with the exception of a few relatively small areas, most values are in fact below $500\ t\ km^{-2}\ yr^{-1}$. No monitoring or reservoir surveys were available for the Mzimvubu catchment per se, but Msadala et al. (2010) reported that data from 18 reservoirs was available for Region 7, giving measured SSY ranging between $94\ t\ km^{-2}\ yr^{-1}$ and $1\ 509\ t\ km^{-2}\ yr^{-1}$ SSYs for the dams in Region 7 that are closest to the Mzimvubu catchment are summarised in **Table 4-2**.

Table 4-2: Summary of SSY and effective catchment area for dams in Region 7 and close to the Mzimvubu catchment

Dam name	SSY (t km ⁻² yr ⁻¹)	Effective catchment area (km ²)
Doringrivier	617	310
Mthatha	262	882
Ncora	219	1775
Xilinx	378	209
Xonxa	888	1476

With the exception of the Xonxa, SSY tends to decrease with catchment area. It is widely stated that SSY is typically inversely proportional to catchment area (De Vente et al., 2009). Water erosion, transport, and deposition processes are indeed scale dependent, with opportunities for erosion and transport increasing from the scale of m² to km² (for example from erosion plot to small catchment scale). However, when scaling from tens, to hundreds, and to thousands of square kilometres, not only do processes become more complex across multiple spatiotemporal scales (Vercruysse et al., 2017), but opportunities for deposition and storage increase, and are subject to numerous dynamic variables including soil type, slope, land management practices, connectivity, land-use, and vegetation (Fryirs, 2013). The combinations of sheet, rill, and gully erosion processes found within and between catchments, together with the mentioned variables, may give rise to positive or non-linear SSY/area relationships that belie the "rule of thumb" of an inverse SSY/area relationship (De Vente & Poesen, 2005; De Vente et al., 2009; Vanmaercke et al., 2011).

Msadala et al.'s (2010) revised SSY predictions were made available in GIS and .pdf format specifically to support catchment-scale land-use management and planning with a particular focus on preventing soil loss and exercising reservoir sediment control in ungauged catchments (Msadala et al., 2010). The finer detail, updated input data sources, and digital output mean that this SSY map represents considerable progress over that produced by Rooseboom & Lotriet (1992). The authors caution, however, that since the methods are based on long-term average sediment yields i.e. chiefly from reservoir sedimentation studies, expert knowledge and scaling would be required in their application to specific areas, and that wherever possible more recent, direct observations should supplement or replace these estimated results. Such observational data would reflect climate and land use change, and thus likely provide more accurate SSY predictions as part of catchment planning and management for water resources infrastructure sustainability. At the time of writing, Msadala et al.'s (2010) information is already more than a decade old.

4.5 Suspended sediment data in the Mzimvubu and Tsitsa River catchments

4.5.1 Overview

In this section, the geographical focus is narrowed to the study area. Existing studies and available data, and the relevance of these to hillslope rehabilitation and water resource management in the Tsitsa River catchment are reviewed as context to the research described in this thesis.

Given the dearth of SSLs and SSYs estimated from direct measurement, these studies employed indirect methods including modelling, gully growth mapping, sediment fingerprinting and tracing, and systems dynamics to estimate SSY. The sources of uncertainty associated with these approaches are reviewed in this chapter, as each of these methods has been applied in the Tsitsa River catchment.

4.5.2 Catchment scale modelled suspended sediment yield estimates

Modelled SSY estimates have been undertaken in the Tsitsa river catchment by Le Roux et al. (2015), using the Soil and Water Assessment Tool (SWAT) a Modified Universal Soil Loss Equation (MUSLE)-based empirical model, by Gwapedza (2020) using the Water Quality and Sediment Model (WQSED), and by Gwapedza et al. (2021) using a version of the MUSLE. **Table 4-3** summarises some of the key attributes of these models.

Table 4-3: Summary of some key attributes of SS yield models used in the Tsitsa River catchment

Model	Type	Erosional process	Distribution	Data requirements	Scale	Components	Reference
USLE	Empirical	Sheet-rill	Not distributed	Decadal biophysical data to calculate erosion factors	Developed for 100 m ² plots. Applied at catchment scale	Rainfall erosivity Soil erodibility Slope length and gradient Plant cover Erosion control factor	Wischmeier & Smith (1960)
MUSLE	As for USLE, but estimating storm sediment runoff					Runoff volume instead of rainfall erosivity Sediment lag represents delivery to channel	Williams & Berndt (1977) Fu et al. (2019)
SWAT	Empirical + physically-based	Sheet-rill Gully erosion estimates calculated separately (Le Roux, 2018)	Semi-distributed hydrological response units (HRUs)	GIS: Catchment outline/area Digital elevation model Land cover data Soil data Weather statistics	HRU input area in km ² Sub-catchment to catchment scale output (10 – 10 000 km ²)	Erosion (MUSLE) Hydrology Nutrients Crop growth Stream routing	Williams & Berndt (1977) De Vente et al. (2013)
WQSED	Empirical + physically-based	Sheet-rill	Semi-distributed: (Sub-catchment scale sediment storage and transport components)	GIS: Catchment outline/area Digital elevation model Land cover data Soil data Weather statistics	Sub-catchment to catchment scale input and output (10 – 10 000 km ²)	Flow (Pitman model) Erosion (MUSLE) Sediment storage & Transport	Pitman (1973) Williams & Berndt (1977) Gwapedza (2020)

The USLE, or its revised (RUSLE) or modified (MUSLE) forms, provide the soil loss component of many SSY models, including SWAT and WQSED in the case of MUSLE. The USLE was developed in the 1960s to estimate soil loss from $<100\text{m}^2$ plots and has been described as “*the most widely used and misused soil loss estimation equation in the world*” (Sadeghi et al., 2014). However, parallel to advances in processing power and software capabilities, water quality model development has focused on better representation of the biophysical processes influencing water erosion, sediment transport, and deposition. The USLE was modified (i.e., MUSLE) to estimate SSY in rangeland areas, using runoff characteristics during storm events (Williams & Berndt, 1977) rather than rainfall erosivity to estimate soil loss. It was developed on slightly larger areas (up 15 km^2) than the USLE, but is routinely applied to catchments of several thousand square kilometres, including the Mzimvubu and Tsitsa River catchments. With appropriate calibration, the MUSLE can produce good results (Sadeghi et al., 2014). However, Fu et al. (2019) noted that while water resources management requires monitoring *and* modelling, models are increasingly used to predict water quality where monitoring is difficult and data are scarce.

SWAT uses a range of land cover/land use, meteorological and hydrological data, as well as digital elevation models (to define catchment slope and area) and stream morphology, in its input parameters (Fu et al., 2019). Soil loss estimates are derived using MUSCLE. SWAT has the capacity to generate scenarios resulting for example from climate change, flow variability, and catchment management interventions including differing land use practices and erosion control (Fu et al., 2019). However, it has been found that model effectiveness can be negatively impacted by the number of sub-catchments included in the model, and that even when calibrated and validated, obtaining a good fit between observed and modelled SSY at the catchment outlet may be at the cost of mis-representing upstream conditions and processes (Fu et al., 2019). Further, SWAT is highly sensitive to estimated sub-catchment area (Arabi et al., 2006). As discussed in **Section 3.4.1**, although studies comparing DEMs found that most calculated consistent catchment areas, uncertainty in modelled SSYs can result from errors associated with terrain representation, slope estimation, and hydrological routing (Keys & Baade, 2019). WQSED is discussed in **Section 4.5.4**.

As noted, both Le Roux et al.’s (2008) water erosion predictions and Msadala et al.’s (2010) erosion index suggested extremely high soil loss rates for the Mzimvubu River catchment, where gullies were known to be widespread and their contribution to SSYs was unknown, but expected to be significant. The challenge of identifying and mapping gullies and their development is evident in the following

studies that aimed to estimate SSY using modelling in this catchment, leading to a specific focus on gully development and expansion processes in the Tsitsa River catchment.

Mararakanye & Le Roux (2012) used SPOT-5¹² satellite imagery to detect > 18 000 gullies in the Mzimvubu River catchment, which they estimated affected approximately 22.6 km² (0.46%) of the 4900 km² catchment. The modelling of SSYs in the Mzimvubu River catchment by Le Roux et al. (2015) was the first attempt in South Africa to incorporate gully erosion into a modelled approach, and gave special attention to the Tsitsa River catchment in order to estimate the operational lifespans of the proposed dams. Le Roux et al. (2015) combined SWAT with remote sensing and integrated GIS techniques, to compensate for the inability of SWAT to accommodate gully erosion.

However, where observed data are scarce, as in the Tsitsa River catchment, erosional processes may not be fully understood: If the erosion factors selected to solve MUSLE in SWAT are not in fact the dominant processes taking place, the predicted SSYs may be unreliable (De Vente et al., 2013). Further, SWAT is spatial-scale dependent in terms of erosivity and topographical factors: when coupled with hydrological components, scale factors exacerbate modelled SSY uncertainties (Gwapedza et al., 2018). Hence, if plot-scale spatial and temporal errors are present, they are highly likely to propagate through to the catchment-scale (Breetzke et al., 2013).

Figure 4-8 depicts Le Roux et al.'s (2015) uncalibrated, estimated annual average SSY for the Mzimvubu River catchment for the period 2007 – 2012 (the Tsitsa River catchment is indicated by the red oval).

¹² Satellite Pour l'Observation de la Terre (Satellite for the Observation of Earth)

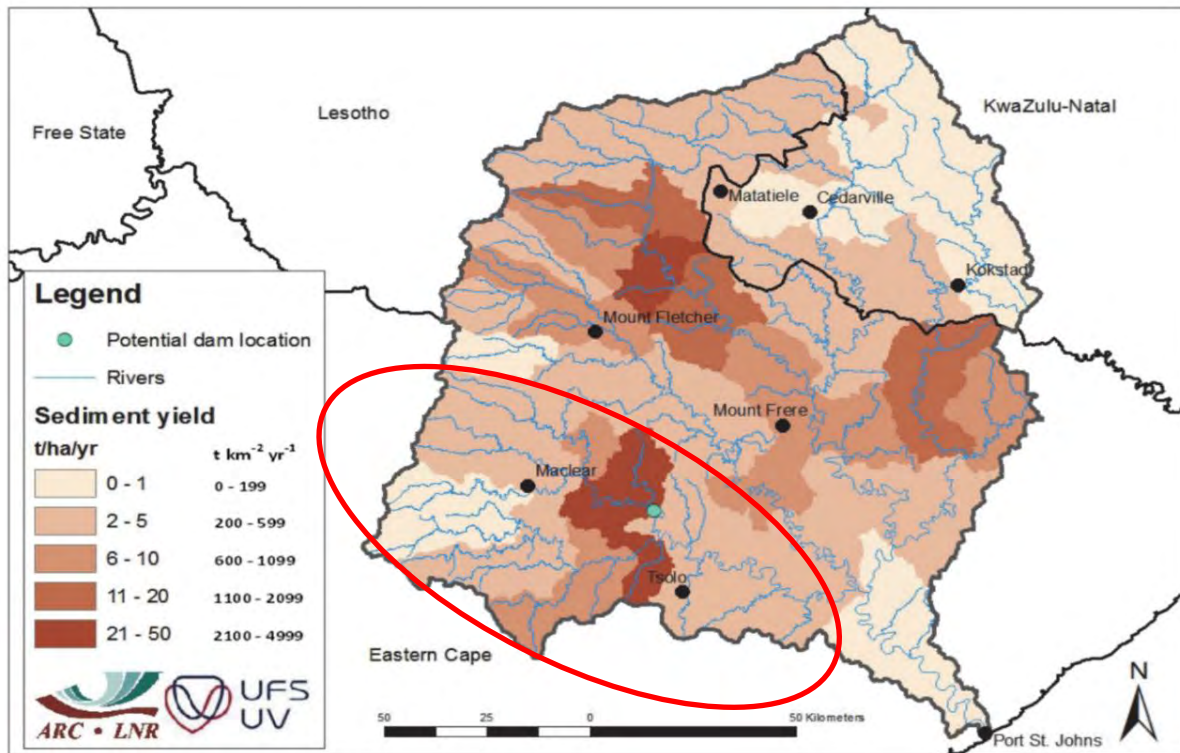


Figure 4-8: Average annual SSY map for the Mzimvubu catchment with the Tsitsa River catchment indicated by a red oval (Le Roux et al., 2015) and ha to km² conversion inset

Average annual SSY (NB, these are not *erosion* or *soil loss* figures) for the Tsitsa River catchment as a whole was estimated by Le Roux et al. (2015) at 500 t km⁻² yr⁻¹. At a sub-catchment scale, SSYs ranged from ~100 t km⁻² yr⁻¹ in the headwater areas through 200 t km⁻² yr⁻¹ – 500 t km⁻² yr⁻¹ for the majority of the catchment, to 2250 t km⁻² yr⁻¹ in the highly-gullied sub-catchment at the proposed Ntabelanga Dam inlet. Le Roux et al. (2015) estimated that gully erosion contributed 20 times more to SSY than sheet/rill erosion. The 500 t km⁻² yr⁻¹ average for the Tsitsa River catchment aligns well with Walling's (1984), Msadala et al.'s (2010) and Vanmaercke et al.'s (2014) estimates for the area. However, 2250 t km⁻² yr⁻¹ in the gullied areas seems disproportionately high given the relatively small area (i.e., 68 km²) directly affected by gullies (Le Roux, 2018), and the 560 t km⁻² yr⁻¹ to 1420 t km⁻² yr⁻¹ estimated for active soil pipes in a nearby part of the Eastern Cape (Beckedahl & De Villiers, 2000).

Le Roux et al.'s (2015) modelled SSYs were, however, subject to considerable uncertainty. The absence of measured SSC for model calibration was recognised as a limitation. Fewer than 10 SSC grab-samples were taken for calibration purposes throughout the Mzimvubu catchment as a whole (Le Roux et al., 2015), with the three that were collected at the site of the proposed Ntabelanga Dam inlet on the

Tsitsa River taken during the winter dry season (June 2014). Aside from being outside the study period, SSC would be negligible, and thus highly unrepresentative, during winter base flow conditions.

Appendix 1 of Le Roux et al.'s (2015) report indicates that comprehensive gully mapping was carried out during fieldwork to verify the digitised gully growth/soil loss data. However, the estimated sediment delivery percentages that were applied to the active gullies were based on classification factors such as gully depth, shape, connectivity, slope, and soil type. These factors were themselves estimated or inferred from other criteria and assumptions, for example that gullies would first erode to bedrock before expanding, which was later shown to be the case only in some parts of gully systems (Le Roux et al., 2022; Anderson et al., 2023). Assumptions regarding SDR are problematic due to the dynamic “black box” nature of catchment-scale SS transport and deposition processes (Walling, 1983). This estimation of SDR represents a major source of uncertainty, which was compounded by the non-determination of soil loss values from the prevalent but unquantified soil pipe erosion which occurs in the lower Tsitsa River catchment (Le Roux et al., 2015). The lifespan of Ntabelanga Dam was estimated to range from 34 to 49 years without siltation prevention, but the authors cautioned that the natural variability of soil erosion and transport processes meant that this was not a firm prediction.

Pretorius et al. (2016) undertook a similar study in the Tsitsa River catchment, also using SWAT for sheet/rill SSY and remote sensing/object-based image analysis (OBIA) to estimate gully growth (which they estimate to be 97.2% accurate) and SSY predictions from 2007 - 2012. Their aim was to improve understanding of the factors controlling erosion, particularly associated with gullies, in order to inform water and agricultural resource development and management. Pretorius et al. (2016) applied a universal 50% delivery rate for eroded gully material, rather than calculating a factor-based per-gully SDR. An average SSY of $\sim 1\,050\text{ t km}^{-2}\text{ yr}^{-1}$ was estimated for the Tsitsa River catchment as a whole, with gully erosion contributing 55 times more than sheet/rill erosion to SSYs, illustrating the effect that different estimation methods have on the resulting SSY.

Gwapedza (2020) developed the WQSED in an attempt to improve the applicability of MUSLE to African catchments. WQSED has three main components: the locally developed Pitman hydrological model to drive erosional processes (Pitman, 1973); MUSLE to estimate sheet-rill erosion (Williams & Berndt, 1977); and a conceptual estimate of sediment storage and delivery, allowing sediment transport processes to be simplified within the model (Gwapedza, 2020). The model is best suited for use where observed data are available for calibration and validation, and was shown to perform

consistently when such data were available. However, at event scale, peak SSC was under-estimated due to gully contributions not being accommodated in the model (Gwapedza, 2020). In catchments where only reservoir siltation data were available for comparison, WQSED predictions were highly variable (-30% - >4000%), again likely due to WQSED modelling only sheet/rill erosion rather than reflecting the total catchment as a source (Gwapedza, 2020). The estimated mean SSY for the Tsitsa River catchment using WQSED was $153 \text{ t km}^{-2} \text{ yr}^{-1}$.

Le Roux & van der Waal (2020) used GIS to map gully-free areas of the Tsitsa River catchment that had the same characteristics as currently gullied areas, and classified them in terms of their susceptibility to gully development (**Table 4-4, Figure 4-9**). Their aim was to highlight the need to avoid further land degradation by calculating the potential loss of storage in the proposed Ntabelanga and Lalini dams if these areas became fully degraded.

Table 4-4: Erosion susceptibility of currently undegraded areas of the Tsitsa River catchment (Le Roux & van der Waal, 2020)

Classification	Area (km ²)	Percentage of Tsitsa River catchment	SSY potential
Low	3562	72%	445 million tons (from 4900 km ²) over 50 years. Average SSY = $1816 \text{ t km}^{-2} \text{ yr}^{-1}$
Low to moderate	1038	21%	
Highly susceptible	325	7%	

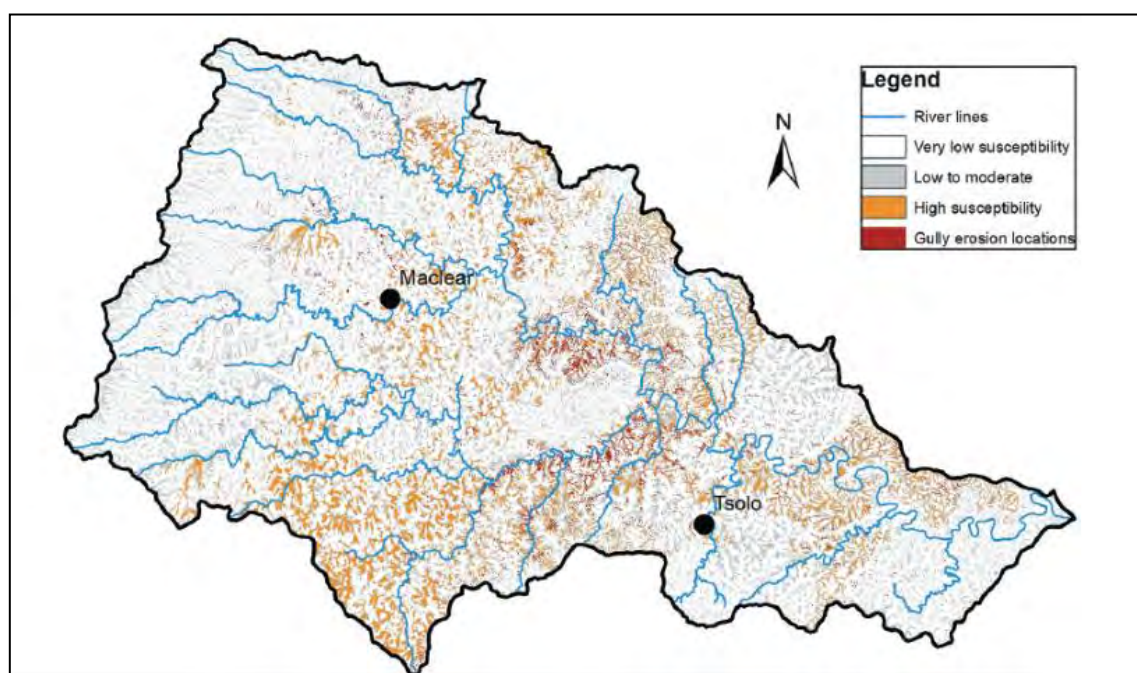


Figure 4-9: Erosion susceptibility of currently undegraded areas of the Tsitsa River catchment (Le Roux & van der Waal, 2020)

Le Roux & van der Waal (2020) undertook a “worst case” scenario analysis of the “potential SSY” by calculating the potential volume of soil loss (gully surface area, soil depth and average bulk density). This worst case made a number of extreme assumptions that comprise an unlikely land management scenario: that vegetation cover decreased, that no mitigation was undertaken, and that maximum erosion would occur in each of the three classes of susceptible areas. Le Roux & van der Waal (2020) used an average bulk density of $1\,500\text{ kg m}^{-3}$ which they determined by sampling the duplex soils in which most gullies occur. Their reported “worst-case” soil-loss figure of 445 million tons thus equated to a maximum of 297 million m^3 of soil lost from the susceptible areas, which if deposited entirely into the proposed Ntabelanga and Lalini Dams respectively, would result in a ~50% to ~60% loss of storage over the 50 year lifespan of the dams.

There is considerable uncertainty intrinsic to this study, which actually reports soil loss from the catchment surface, *not* SSY as measured at the catchment outlet. Le Roux & van der Waal (2020) acknowledged the difficulty of determining the initiation and eventual extent of gully erosion in areas that have not yet eroded, yet they assumed maximum erosion for their three classes of susceptibility. Le Roux & van der Waal (2020) also acknowledged that not all eroded material would be conveyed to the catchment outlet, that the SDR would need to be ~100% to realise their predictions, and that transport potential and sediment residence times were unaccounted for in their estimates. Total potential soil loss from gullies was equated to sediment delivery to the river network and in turn equated with dam storage loss percentages (i.e. implying that all material lost from the gullies would be deposited in the dams).

Due to the level of uncertainty involved, it is challenging to directly compare the results of Le Roux & van der Waal's (2020) study with other work done in the Tsitsa River catchment in terms of SSYs and the estimated impact on the storage capacity of the proposed dams, or to view it as a firm foundation for catchment management decision making. It does, however, add new and valuable data and guidance in terms of identifying areas for management interventions aimed at avoiding degradation, and in forecasting the potential impact on sustainable rural livelihoods as a result of the estimated soil loss.

Theron et al. (2021) used SWAT to investigate the potential effects of climate change on sheet-rill erosion for the Tsitsa River catchment upstream of Qulungashe Bridge (See **Figure 5-1**). They used observed temperature and rainfall data for a 15-year control period (2002–2017), and temperature

and rainfall data determined from several climate change projections for 2015–2100. Hydrological data from DWS gauging station T3H006, (near monitoring site TN2 (Tsitsa at Mbelembushe), (**Figure 5-1**) was used to calibrate the model in the absence of SSC data. Dividing the 75-year projection period into three equal periods (short, medium, and long term), Theron et al. (2021) predicted relatively low short-term SSY (2015 – 2035) between $1 \text{ t km}^{-2} \text{ yr}^{-1}$ and $30 \text{ t km}^{-2} \text{ yr}^{-1}$, depending on the climate projection model used to predict the input rainfall data. Epistemic uncertainty acknowledged by Theron et al. (2021) include the likely under-estimation of rainfall (particularly extreme events) by the climate projection models, and the under-estimation of erosion rates as SWAT does not account for gully erosion.

As a by-product of an assessment of the applicability of MUSLE to provide SSYs in support of catchment management decision-making, Gwapedza et al. (2021) estimated $5000 \text{ t km}^{-2} \text{ yr}^{-1}$ SSY for 2016 – 17 for the Inxu catchment. This was deemed by Gwapedza et al. (2021) to be excessively high, but in fact is identical to Le Roux et al.'s (2008) water erosion predictions for the Tsitsa River catchment (i.e., an SDR of 100%). While it was noted that calibration using measured data and the addition of a storage module improved the performance of the model, comparative annual SSYs were not reported.

4.5.3 Gully growth and soil loss estimates using drones

Attention has recently been focused on a large (4.2 km^2) gully in the Inxu River catchment (See **Figure 2-19**). The aim of two complementary studies was to support and improve gully management through a better understanding of the erosional/depositional processes and features associated with gully evolution (Le Roux et al., 2022), and to quantify the resulting gully growth and associated sediment loss (Anderson et al., 2023). These studies were undertaken between September 2017 and November 2020 and used unmanned aerial vehicles (i.e., drones) and Structure from Motion photogrammetry to create high resolution digital surface models. The gully was mapped and classified into extension, expansion, deposition and transfer zones (Le Roux et al., 2022; Anderson et al., 2023). Changes (detected by a series of flown surveys) in gully structure and volume due to erosion and deposition in each of these zones were linked to runoff generated by high intensity rainfall events ($>20 \text{ mm day}^{-1}$).

Predictably, gullies generally expanded more rapidly (i.e., displaced more sediment) during wetter periods (2017 – 19), with much of the recorded erosion and deposition attributed to a single high-intensity 64.2 mm storm event in April 2019. Gully erosion rates of $134\,500 \text{ t km}^{-2} \text{ yr}^{-1}$ were estimated for the relatively wet period between 2017 and 2019, and $129\,100 \text{ t km}^{-2} \text{ yr}^{-1}$ for the relatively dry

period between 2019 - 2020 (Anderson et al., 2023). These extremely high rates, even if extrapolated to *all* gullies in the Tsitsa River catchment, would, as previously mentioned, be restricted to 68 km² of the 4900 km² catchment (Le Roux, 2018), and focused on the lower catchment where an overall rate of 2100 – 4999 t km⁻² yr⁻¹ was modelled (Le Roux et al., 2015).

Importantly, the complex and episodic nature of gully expansion, and sediment erosion, transport, and deposition within the gully system discussed earlier in this chapter was confirmed by these studies. The side branches, erosion, expansion, and transport/deposition zones were all observed to respond differently (in terms of sediment erosion, transport, and deposition) to differing antecedent conditions and rainfall intensities, whilst some of the eroded sediment was deposited within the gully system. These responses were linked to the influence on runoff of the immediate catchment topography. In the expansion and deposition/transport zones, the presence of bedrock influenced gully width (Anderson et al., 2023). This suggests that while the processes of gully initiation and growth described by these studies could be similar in other, similar areas, their *rates* could be specific to each part of each gully system, complicating the allocation and/or prediction of gully contributions to SSLs/SSYs in the Tsitsa River catchment. Recognising that different gully zones require different management strategies, these authors concluded that the rehabilitation of large established gullies should be focussed on depositional zones within gullies, to reduce sediment export (Le Roux et al., 2022), and the heads of side branches to protect dwellings and associated land-based livelihoods (Anderson et al., 2023).

The research into gully processes and sediment contributions focussed on a crucial, but very small area of the Tsitsa River catchment. They provided new, detailed information to support catchment management decisions, and a baseline from which to monitor gully initiation and growth in relation to drivers such as rainfall, and controls such as rehabilitation interventions. They were prompted by catchment-scale SSY modelling that recognised and highlighted the need for additional and specific approaches to quantifying the sediment contributions of gullies which models were unable to accommodate. Gully surveys can supplement catchment scale SSY models, but cannot produce data to calibrate or verify them. For this, models require catchment-scale measured SSC data.

4.5.4 Catchment scale suspended sediment yield estimates using direct sampling

Nyamela (2018) provided the only analysis of measured SSC in the Tsitsa River catchment prior to the research described in this thesis, using data from May 2016 to May 2017 for the lower Inxu catchment. These spatiotemporally limited data were gathered as part of the monitoring programme upon which the research described in this thesis is based, and which is fully described for December 2015 – June 2019 and eleven sub-catchments in later chapters. Nyamela's (2018) measured SSY of $550 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Inxu compares well with the $700 \text{ t km}^{-2} \text{ yr}^{-1}$ modelled for this highly eroded and gullied area by Le Roux et al. (2015), whilst their investigations of catchment characteristics using SWAT provided a first insight to possible SS source areas in the Inxu catchment. A summary of modelled SSY for the Tsitsa River catchment above T3H006 is given in **Table 4-5**.

Table 4-5: Comparison of modelled SSY for the Tsitsa River catchment above T3H006

Approach	SSY $\text{t km}^{-2} \text{ yr}^{-1}$	Study period	Reference
RUSLE and GIS	1200 – 15 000	Rainfall data from 1984 - 2000 Imagery and remote sensing from 2000 - 2006 Fieldwork 2007	Le Roux et al. (2008)
SWAT with GIS	100 - 2250 500 average	2007 - 2012	Le Roux et al. (2015) Le Roux (2018)
SWAT and remote sensing/object- based image analysis (OBIA)	1050	2007 - 2012	Pretorius et al. (2016)
WQSED	153	2015 - 2017	Gwapedza (2020)
SWAT	1 to 30	predicted average 2015 – 35	Theron et al. (2021)

4.5.5 Confluence-based sediment fingerprinting and source apportionment

Sediment fingerprinting and tracing is a relatively low-cost method that is well-suited to providing insight to spatial patterns of sediment transport in data scarce regions (Walling et al., 2003; Furuichi et al., 2016). The technique discriminates between sediment sources using the measurable physicochemical properties (i.e. the “fingerprint”) of fine ($<63 \mu\text{m}$) sediments (Foster & Lees, 2000; Collins et al., 2020). Sediment tracing relies on spatiotemporal constancy and conservative behaviour, i.e. that the physicochemical fingerprint do not change over time and distance, and that the

proportions found in the contributing source samples are accommodated by the sink sample (Collins et al., 2020).

Sediment fingerprinting and tracing can identify and apportion sediment sources from samples collected in sediment sinks, and the findings can be compared with those from other SS monitoring and SSL/SSY approaches that can directly quantify SSY in the same catchment (Furuichi et al., 2016). In other words, if a downstream SSY estimate is available from a quantitative study in $t\ km^{-2}\ yr^{-1}$, fingerprinting and tracing can apportion this as percentages to upstream sources such as contributing tributaries or lithologies (D E Walling et al., 2003; Miller et al., 2022).

Potential tracers include mineral magnetic properties, colour, radionuclide activities, geochemistry, particle size, and pollen (Walling & Foster, 2016; Stander et al., 2020). The “fingerprint” is developed using statistical methods based on the measured physicochemical properties. Unmixing models, ranging from simple to complex, according to the complexity and aims of the study itself are used to apportion the fingerprints in the sink sample to the contributing sources (Collins et al., 2020).

Sampling programme design, sampling, and analysis can introduce uncertainty to sediment fingerprinting and tracing in ways already described in **Chapter 3.4** but specific sources of uncertainty relate to a number of assumptions about the representativeness of the sampled source and sink sediments. Using confluence-based source apportionment as an example, this can be related to the natural uncertainty associated with sediment transport and deposition processes (Caitcheon, 1993; Bannatyne et al., 2024). Further, the assumption is made that the same time-period is represented by the source and sink samples, but this is unknown unless the residence time of the sequestered sediment in the source and sink samples is determined (Walling & Foster, 2016; Kitch et al., 2019; Liu et al., 2023). Likewise, the sequestered sediment is assumed, but not known, to be fully representative of upstream catchment characteristics. Regardless of variations in particle size, sediment is also assumed to have been similarly transported from each source to the sink, due to the “averaging” effect of repeated flows of different magnitudes (Caitcheon, 1993; Walling et al., 2007; Walling, 2013; Walling & Foster, 2016; Vale et al., 2016; Collins et al., 2017; Patault et al., 2019). These factors could impact the apportionment between sources, although this uncertainty could be constrained through repeat sampling and/or the use of time-integrated samplers (c.f. Patault et al., 2019).

In South Africa, sediment fingerprinting has been used to determine source lithologies, to identify sediment sources during storm events, and to apportion reservoir sediments to discrete sources (Foster et al., 2005; Foster et al., 2007; Rowntree & Foster, 2012; Manjoro et al., 2017; Stander et al., 2020; Miller et al., 2022). Recently, composite fingerprinting has been used (in a discrete study) in the Tsitsa River catchment to apportion the relative SS contributions of tributaries to the catchments downstream (Bannatyne et al., 2024).

An exploratory confluence-based sediment fingerprinting and tracing study was undertaken as a separate project in November 2018 at seven confluences that represented the outlets of the sub-catchments where SSC and discharge monitoring was taking place in the Tsitsa River catchment (Bannatyne et al. (2024) **Figure 4-10**).

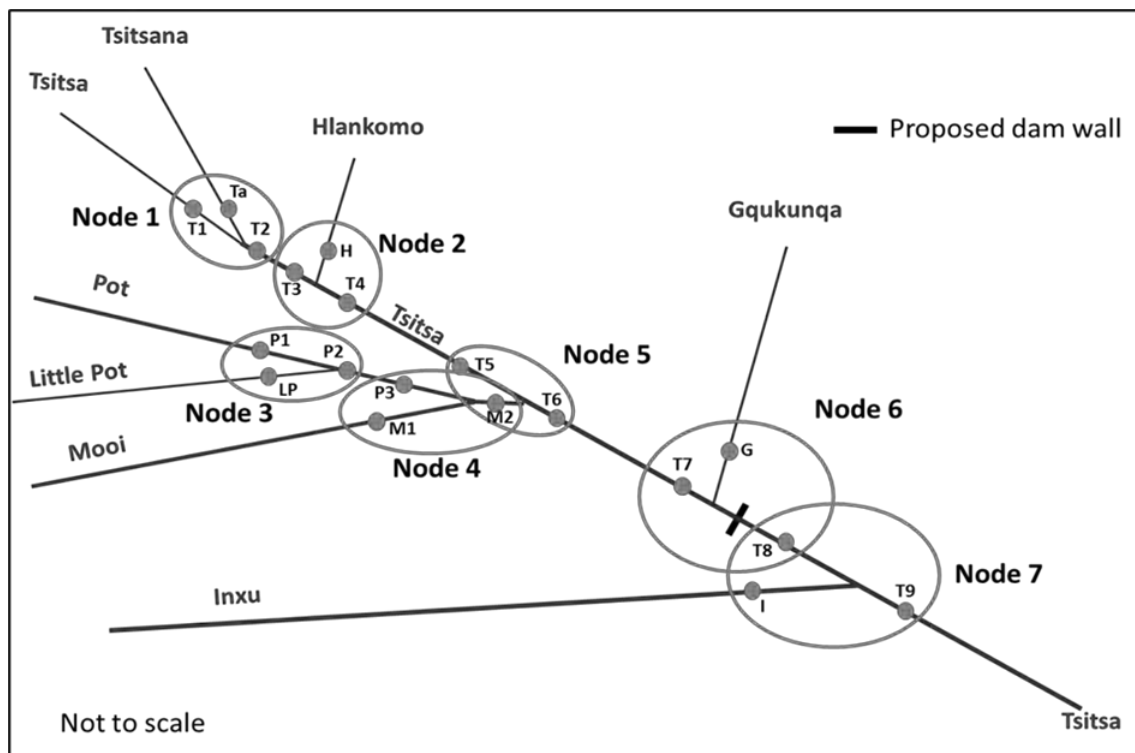


Figure 4-10: Schematic diagram of sediment fingerprinting nodes and sites in the Tsitsa River catchment (Bannatyne et al., 2024).

The aim was to make a preliminary estimate of sub-catchment contributions to downstream sediment. Pioneered by Caitcheon (1993) in Australian catchments, this relatively rapid and low-cost approach had the potential to provide reconnaissance and supplementary catchment scale data.

Fine sediment that had been sequestered in bed substrates was sampled above and below confluences, using a resuspension technique (Lambert & Walling, 1988; Walling et al., 2003). The

<63 µm sample fraction was analysed to identify suitable tracers, including mineral magnetic properties, gamma emitting radionuclide activities and geochemistry. Different combinations of composite fingerprints were selected at the seven confluences, using conservatism and range tests. Bivariate source apportionment was undertaken using an unmixing model. The findings are summarised in **Table 4-6** and shown in **Figure 4-11**.

Table 4-6: Sub-catchment area, relative area, sediment contributions and contribution ratio to downstream sediment at each node in the Tsitsa River catchment

Node	Sub-catchment	Contributing catchment area (km ²)	Relative area (%)	Sub-catchment sediment contribution (%)	Ratio of sediment contributions
1	Tsitsa above Tsitsana	179	0.56	14	1
	Tsitsana	138	0.44	86	6.14
2	Tsitsa above Hlankomo	368	0.86	49	1
	Hlankomo	65	0.14	51	1.04
3	Pot above Little Pot	148	0.50	67	2.03
	Little Pot	146	0.50	33	1
4	Pot above Mooi	434	0.51	61	1.56
	Mooi	420	0.49	39	1
5	Tsitsa above Mooi	615	0.41	79	3.76
	Mooi below Pot	875	0.59	21	1
6	Tsitsa above Gqukunqa	1740	0.90	77	3.35
	Gqukunqa	203	0.10	23	1
7	Tsitsa above Inxu	1986	0.55	60	1.50
	Inxu	1639	0.45	40	1

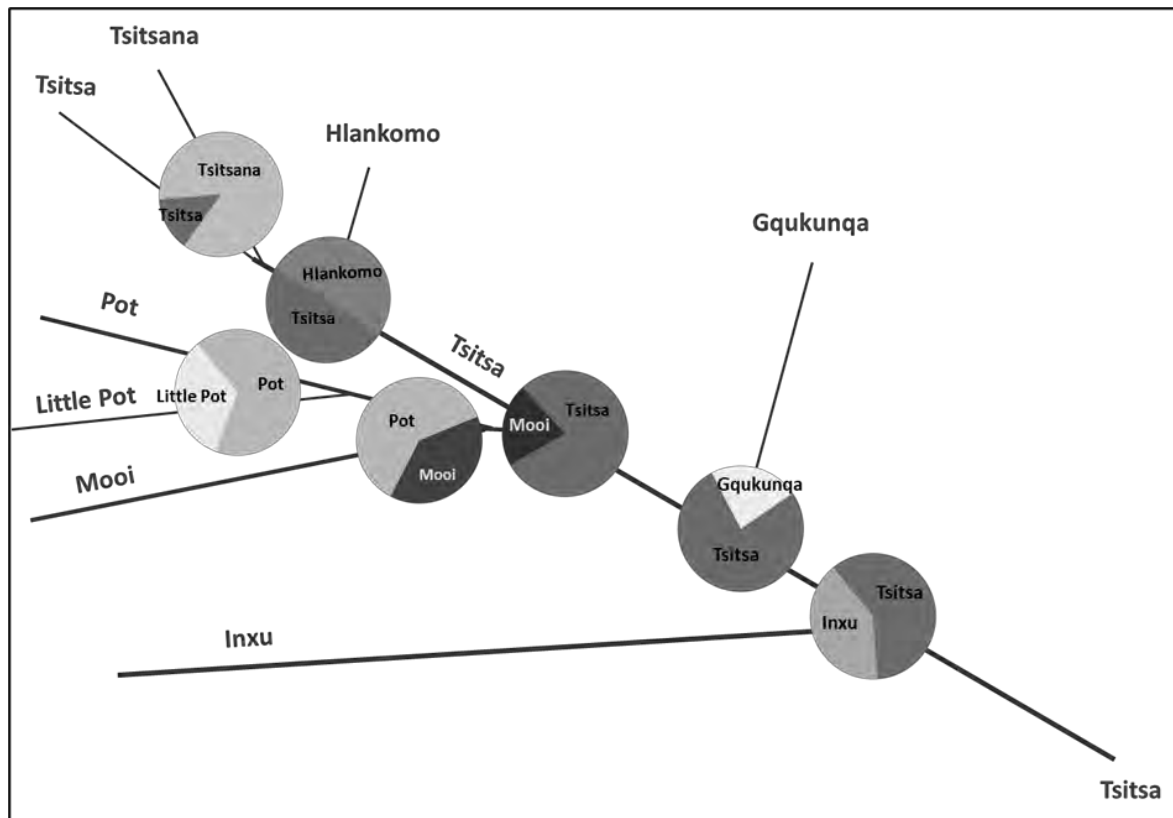


Figure 4-11: The proportional contribution of sub-catchments to downstream SSL at each confluence of the Tsitsa River catchment (Bannatyne et al., 2024)

The findings indicated that proportionally more sediment was contributed by sub-catchments in the former homeland areas of the middle and lower Tsitsa River catchment (i.e., associated with the dispersive soils of the Tarkastad Formation), than by those sub-catchments located on the Clarens and Elliot Formation sandstones where private and commercial tenure predominated. Uncertainty associated with these results included the reliance on a single sampling campaign, the unknown period represented by the sampled sediment, and the assumption that sediment transport and deposition occurred in a similar way in the two paired sub-catchments and in the downstream sink (Walling & Foster, 2016; Kitch et al., 2019; Liu et al., 2023).

4.5.6 Systems dynamics

Bester et al. (2019) did not estimate SSY per se but took an innovative systems dynamics approach to predicting the lifespan of the Ntabelanga Dam. Bester et al. (2019) argued that the construction of the dam would result in an inflow of financial capital to the communities in the catchment. This would result in population growth, economic development, and changes in social behaviours. The systems dynamics approach acknowledged the erodible nature of the soils in the catchment, took existing

modelled SSYs into account, and recognised the interconnectedness of the natural, social and economic systems that span the catchment.

However, in contrast to the methods and studies already described, human behaviour (rather than hydrology and sediment availability) was seen as driving the rates of soil erosion and dam sedimentation. Using Monte Carlo simulation analysis to model a range of scenarios, Bester et al. (2019) suggested a bench-mark operational lifespan for Ntabelanga Dam of between 55 and 68 years, based on Le Roux et al's (2015) modelled results. A worst-case was modelled using the systems approach, where the lifespan of the dam could be reduced to between 31 and 44 years if population growth and economic development progressed on the expected trajectory with no catchment restoration or behaviour changes. Implementing catchment restoration as well as community development and capacity-building were suggested as mitigating measures that could reduce the impact of development and allow Ntabelanga Dam to remain operational for between 50 and 65 years.

Bester et al (2019) used systems dynamics to model sedimentation rates because *“a variety of models and modelling techniques have been developed by subject experts to estimate the level and rate of sedimentation for differing levels of data availability. These complicated models are inaccessible to most decision-makers and economic analysts, thus requiring the coordinated efforts of a heterogeneous group of experts covering various disciplines such as restoration ecologists, hydrologists, geologists, economists and, in some instances, animal scientists, sociologists, and policy makers. The costs of hiring the services of such a group of experts and facilitating their interactions is likely to be very high”* (Bester et al., 2019).

The consideration of human behaviour change is a valuable approach to estimating the lifespan of the Ntabelanga Dam, particularly in an under-resourced, rural area where the inflow of capital due to development is highly likely to affect social and economic behaviour. However, the systems model parameters and relationships seems no less complex than those of an SSYM (for example, **Figure 4-12**), and the professional expertise required to research the systems, develop the model, and analyse the results is unlikely to be less costly, and may in fact require scarcer skills than those for example required to use and interpret the results from the SWAT model. As noted, the systems dynamics approach relied on modelled results (which were themselves uncalibrated with measured data) to verify its predictions

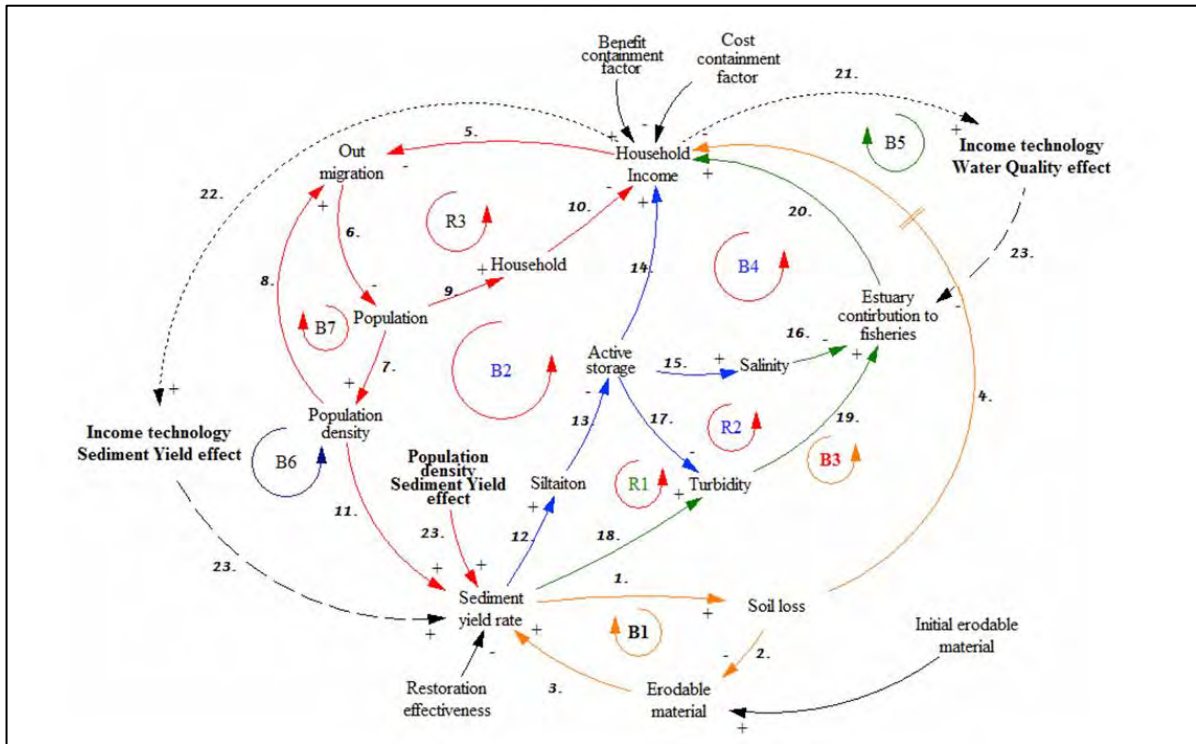


Figure 4-12: Example of a systems dynamics diagram indicating the relationships between natural, social, and economic systems in the Tsitsa River catchment ((Bester et al. (2019), reproduced with permission)

4.6 Summary

SSY estimates have been undertaken at regional scale for Africa since the 1960s (Fournier, 1960), but African rivers tend historically to be under-represented in global sediment yield studies. Soil loss and SSY have been estimated for South Africa since 1978, with intensive SS sampling associated with impoundments and irrigation schemes in the 1980s giving way to modelled soil erosion, and later modelled SSYs at national, regional, and (selectively) catchment scale. In the absence of recent SS measurements in South Africa, model calibration has relied heavily on dam (reservoir) studies. Indirect methods of SSY estimation such as confluence-based SS tracing can provide preliminary insight into the relative contributions of confluent sub-catchments to downstream sediment, whilst modelling systems dynamics allows the influence of human social and economic behaviour change on dam sedimentation rates to be better understood.

Estimated SSYs for the eastern parts of South Africa are high to very high compared with global and regional rates, and those in the rest of the country. SSYs of up to $2250 \text{ t km}^{-2} \text{ yr}^{-1}$ were modelled for parts of the Tsitsa River catchment, whilst both measured and modelled yields for the Inxu, a major

tributary catchment of the Tsitsa, indicate SSYs of $550 \text{ t km}^{-2} \text{ yr}^{-1}$ – $700 \text{ t km}^{-2} \text{ yr}^{-1}$. Modelled SSYs for the Tsitsa River catchment vary widely depending on the approach and data used. The range of results, the inherent uncertainty, and the lack of measured SSC data for the Mzimvubu River catchment against which to compare, calibrate, or validate modelled yields, confirms the veracity of the statement *“There is a need for datasets comprising spatially distributed data of recorded flow and sedimentation, especially for calibration and validation”* (Le Roux et al. 2015 p 64) which prompted the research described in this thesis.

The 2015 – 2019 citizen-technician-based, flood focussed SS monitoring programme that provided the data for the research described in this thesis is, to the writer’s knowledge, the most spatiotemporally extensive and intensive direct SS sampling programme that has been undertaken in southern Africa since the 1980s, and the only such study, perhaps globally, to rely on a citizen science-based approach to obtain direct SSC measurements. However, no assumptions can be made that measured SSLs/SSYs would be intrinsically more reliable than estimates derived from modelling and from dam sedimentations studies. This study therefore focuses on the uncertainty associated with SSL/SSY estimation using limited resources, and the implications of that for catchment management decision-making in resource-scarce catchments.

5 Uncertainty associated with the input data (Objective 1)

5.1 Introduction

This chapter describes the potential sources of natural and epistemic uncertainty (as reviewed in **Chapter 3**) associated with the input SSC and discharge data, and the methods used to identify and (where feasible) to assess the uncertainty.

Firstly, the spatiotemporal design of the citizen technician-based SSC monitoring programme and the SSC sampling and laboratory analysis methods are briefly reviewed to identify the potential sources of uncertainty associated with novel design and implementation of the SS sampling program. These methods were developed and the CT-based direct, flood-focussed SSC sampling programme was established as part of the author's Master's research (Bannatyne, 2018). The author's presence in the field at that time is evidenced in **Appendix 1**. Novel approaches were adopted in response to the challenging physical and socio-economic conditions in the study area (**See Chapter 2**), and due to financial and technical resource constraints.

These challenges and constraints are similar to those found in many developing countries and regions, yet there is little to no available literature describing SS sampling methods specifically designed to accommodate the sources and mitigation of epistemic uncertainty typical of these circumstances (**Chapters 3 and 4**). The methodologies used to assess the spatiotemporal representativeness and the precision of the SSC data are described, and the results are then presented.

Discharge data were required for the estimation of SSL from SSC data. Hence, potential sources of epistemic uncertainty in the received DWS and monitored discharge data are also identified and described. Methods are also described for deriving discharge exceedance percentages and assessing high flow discharge accuracy and hydrological variability, and the results are presented.

The discharge monitoring, channel surveying, and discharge data calculation methods are described in **Appendix 2** as they were not the direct responsibility of the author, although the author assisted in taking many of the flow and cross sectional measurements. The actions and methods used to achieve **Objective 1** are summarised **Table 5-1**.

Table 5-1: Objective 1 action, methods, and output

Objective 1	Identify and assess (where feasible) sources of uncertainty associated with the input SSC and discharge databases in terms of their spatiotemporal coverage and data quality.
Action	<i>Using SSC and turbidity data from the SSC monitoring programme:</i> a) Evaluate (where feasible) the uncertainty associated with the input SSC database. <i>Using supplied daily discharge time-series:</i> b) Evaluate (where feasible) the uncertainty associated with the input discharge database.
Method	a) Review and evaluate the SSC sample collection and analysis methods b). Undertake spatiotemporal, flow representativeness, and precision analysis of input SSC data c) Critically evaluate the discharge data collection and calculation methods
Output	An assessment (where feasible) of the uncertainty associated with the SSC sample collection and analysis methods, evidenced by the spatiotemporal coverage, flow representativeness, and precision of the input SSC dataset. A critical evaluation (where feasible) of the uncertainty associated with the input discharge data sets.

5.2 Establishing the suspended sediment concentration sampling programme

The inception phase of the sampling programme was undertaken from June 2015 to December 2016 by the author as part of her Master's research (Bannatyne, 2018). The author selected SSC sampling sites (May - August 2015), developed SSC sampling protocols including the phone-based data collection forms and receiving database, developed safety training material, purchased smartphones, PPE, etc., designed and oversaw the manufacture of customised sampling equipment, undertook citizen technician recruitment, selection and training (September – December 2015), and developed sample handling protocols, and SSC laboratory analysis protocols. The author also oversaw the contractual and financial administration of the CTs, and later, trained and managed the field and laboratory technicians, and laboratory assistants. These foundational steps towards SSC data collection are described in full in Bannatyne (2018) and briefly summarised later in this chapter. **Appendix 1** contains a timeline, photographs, and examples of field notebooks and progress reports from this period, evidencing the author's involvement in these activities.

A suite of supporting guideline and administrative documents was also developed by the author as part of her Master's research project, and were included as appendices to her MSc thesis (Bannatyne 2018). These included citizen technician aptitude tests, sampling and safety training manuals, template contracts and associated documents, sample collection protocols (including sample inventory, equipment management, and initial quality control protocols), laboratory results sheets, laboratory and field staff job descriptions, and citizen technician payment protocols and spreadsheets. A comprehensive guideline document for the establishment and implementation of SSC sampling

programmes in resource-scarce areas was also developed at that time by the author, outlining the steps and considerations for SSC sampling programme design, and incorporating the above-mentioned documents as templates and examples.

Unless otherwise attributed, SSC samples were collected by CTs. Laboratory analysis was initially carried out by the author as part of her MSc research, but due to the high volume of samples (ultimately ~26 000), the author trained a succession of field and laboratory technicians to carry out these routine tasks from March 2016 onwards. These individuals administered and managed the citizen technicians and laboratory assistants, undertook field collection of samples from CTs, and managed laboratory operations, guided by the above-mentioned protocol documents and supervised by and reporting to the author. All SSC data quality control, manipulations, and statistical analyses were carried out by the author using MS Excel (Microsoft Office 365).

5.3 Suspended sediment concentration sampling programme design

SSC monitoring site selection was primarily influenced by the availability of a citizen technician who was resident within 500 m of a river sampling site that was safe to access under all but extreme flow conditions. An exception to this was the siting of a LISST-ABS acoustic backscatter SSC probe that was installed in the main stem of the Tsitsa River at the DWS gauging weir T3H006, near sampling site TN2, (**Figure 5-1**) as part of initial sampling design. However, the instrument was destroyed by lightning before it began monitoring and financial constraints precluded its replacement. **Figure 5-1** shows the eleven SSC monitoring sites and their effective catchments that were established in December 2015.

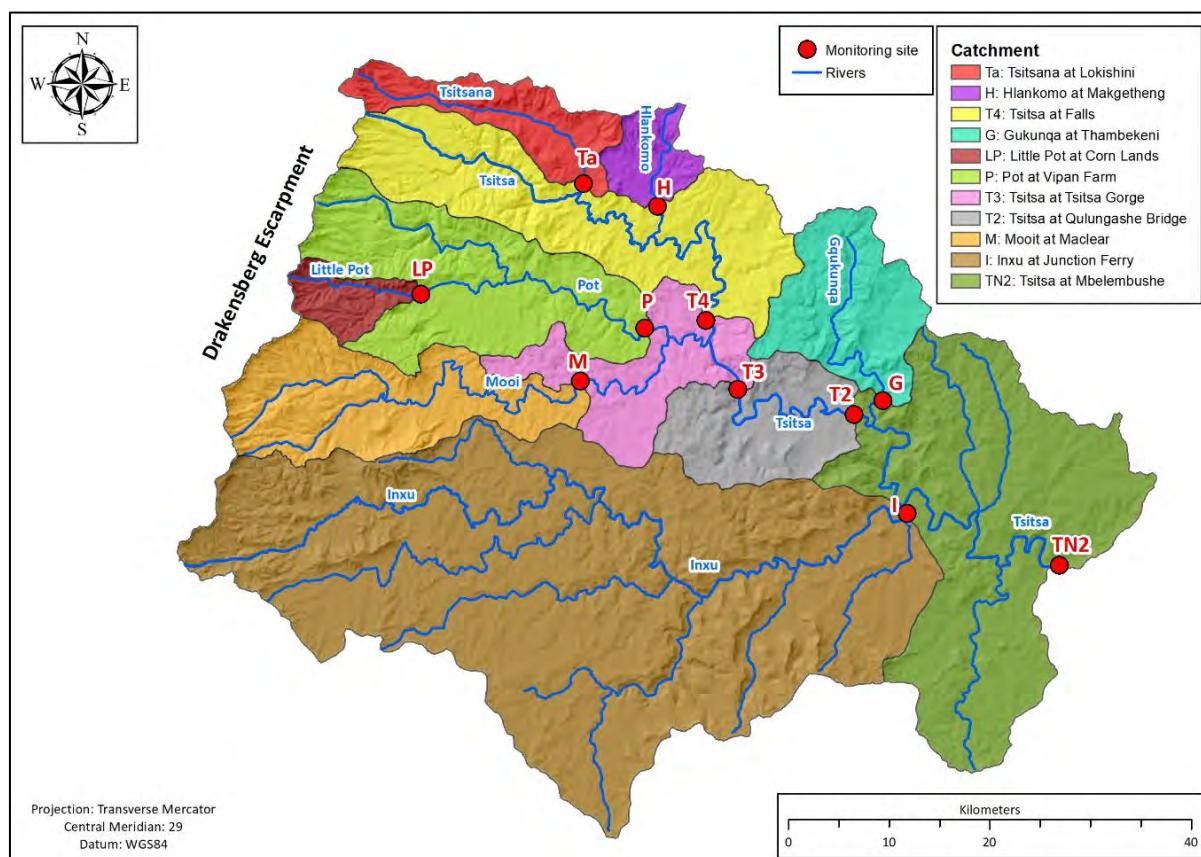


Figure 5-1: Monitoring sites and their effective catchments on the Tsitsa River and its tributaries (Cartography N Huchzermeyer)

Table 5-2 summarises the relevant details of the sampling sites. Note that only seven sites were active for the full project period. Further sites were later established by another researcher in the Inxu River catchment as part of a separate but related Masters project that aimed to provide more detailed insight into sediment sources associated with the proposed Lalini Dam (Nyamela, 2018).

Table 5-2: Details of SS monitoring sites in the Tsitsa River catchment

Site Name	Code	Latitude	Longitude	Start	End	Area (km ²)	Flood sample timing*
Little Pot at Cornlands	LP	-30.98294	28.22462	30/12/15	11/10/16	75	10 minutes
Tsitsana at Lokishini	Ta	-30.89443	28.35694	04/12/15	30/04/17	135	15 minutes
Hlankomo at Makgetheng	H	-30.91863	28.43537	04/12/15	03/05/17	64	10 minutes
Tsitsa at The Falls	T4	-31.01372	28.48845	09/12/15	12/09/17	607	1 st ten samples: 30 minutes 2 nd ten samples: 1 hour
Pot at Vipan Farm	P	-31.0262	28.43181	05/12/15	31/05/19	432	1st ten samples: 30 minutes 2nd ten samples: 1 hour
Mooi at Maclear	M	-31.0826	28.37584	12/12/15	31/05/19	306	1st ten samples: 30 minutes 2nd ten samples: 1 hour
Tsitsa at the Gorge	T3	-31.09301	28.52112	02/12/15	31/05/19	1550	1st ten samples: 45 minutes 2nd ten samples: 1.5 hour
Tsitsa at Qulungashe Bridge	T2	-31.10318	28.63863	03/12/15	31/05/19	1881	1st ten samples: 45 minutes 2nd ten samples: 1.5 hour
Gqukunqa at Thambekeni	G	-31.09027	28.66896	08/12/15	31/05/19	204	15 minutes
Inxu at Junction Ferry	I	-31.18838	28.69073	11/12/15	31/05/19	1452	1st ten samples: 30 minutes 2nd ten samples: 1 hour
Tsitsa at Mbelembushe	TN2	-31.23852	28.83447	10/12/15	31/05/19	4285	1st ten samples: 1 hour 2nd ten samples: 2 hours

* Estimated from flood duration analysis of DWS historic records (Mooi at Maclear and Tsitsa at Mbelembushe)

5.4 Suspended sediment concentration sampling protocols

CTs took samples during daylight hours only: at least once daily in the dry season (June - October) and at least twice daily in the wet season, specifically before 11h00 and after 14h00, since more frequent changes in river level could be expected in the wet season (Bannatyne et al., 2017).

A series of 20 flood samples was triggered when the citizen technician noted that the water level had risen since their previous observation. Initially, locally manufactured clarity tubes were used to provide a visual indication of turbidity (Graham et al., 2023). Clarity tube readings can, however, be subjective and require extensive calibration to provide empirical data that can be used to determine SSC (Graham et al., 2023). Compliance with this part of the sampling protocol was difficult to ensure, and it was later abandoned.

Flood sampling intervals were site-specific (**Table 5-2**). They were estimated from flood duration analyses of DWS historic records for the Mooi at Maclear and TN2 (Tsitsa at Mbelembushe). Sampling intervals were shorter in smaller catchments with shorter expected flood durations, to optimise the likelihood of sampling rapid changes in SSC, especially during the rising limb and through the peak of a flood event. From a preliminary investigation at four sites between December 2015 and June 2016 (Bannatyne 2018) it was noted that compliance with their sampling schedule varied between citizen technicians but that, generally, between 50% to 100% of daylight floods were sampled at least once.

Sampling was never undertaken at night or when bank conditions were unsafe (for example during extreme flooding, or lightning storms). This meant that the rising limbs of floods were sometimes missed, and that overnight floods that occurred due to late afternoon summer thunderstorms were not sampled. These sampling restrictions could be expected to impact the representativeness of the resulting SS data: findings from Bannatyne (2018) suggested that the restriction on over-night sampling had a greater impact on flood monitoring than the variations in individual CTs' sampling schedule compliance. Flood flow representativeness for all sites throughout the project period is described later in this chapter.

The citizen technicians used a 2 m pole-and-jar isokinetic sampler to collect depth-integrated samples in a labelled, 450 ml clear plastic jar at the riverbank. Plastic jars were used rather than glassware as they were far cheaper, much lighter, and unlikely to break during transport over the unmade roads and tracks of the Tsitsa River catchment, or accidentally at the riverbank. As importantly, the plastic jars retained their sample number when written with permanent marker, despite frequent handling and washing (See **Section 5.5**: Laboratory analysis). Sample numbers were removed using a solvent once analysis was complete so that the jar could be re-used. This was a crucial consideration, since

permanent marker washes and rubs off glass jars. Paper labels would have degraded (lost mass or fallen off completely) during handling and washing, interfering with the determination of SSC by mass. 5000 sample jars and 100 plastic crates were purchased at the beginning of the project, re-used throughout the project, and recycled at its close in March 2023.

Isokinetic sampling was achieved by having a 5 mm diameter plastic inlet pipe protruding from the locally-fabricated head assembly of the sampling pole, and a breather pipe extending up the handle of the pole (**Figure 5-2 A, B, and C**). This allowed water to enter the sample jar at the rate of river flow (Bannatyne et al., 2017).



Figure 5-2: citizen technician sampling (A and B) at the riverbank with an isokinetic pole-and-jar sampler. C shows the 450 ml plastic jar being screwed into the head assembly of the wooden pole (Bannatyne et al., 2017).

This was a relatively crude sampler design compared with the commercially-available, specialised isokinetic samplers used, for example, by the United States Geological Survey (USGS) and the New Zealand Ministry for the Environment, for standardised SS sampling (NEMS, 2020). Financial resource constraints precluded the use of commercial samplers. Groten et al. (2023) conducted side-by-side sampling and found that there was no significant difference in the results from an even simpler depth integrated sampler and USGS-approved US DH-48, US-D74 and US D96 samplers (**Figure 5-3**).

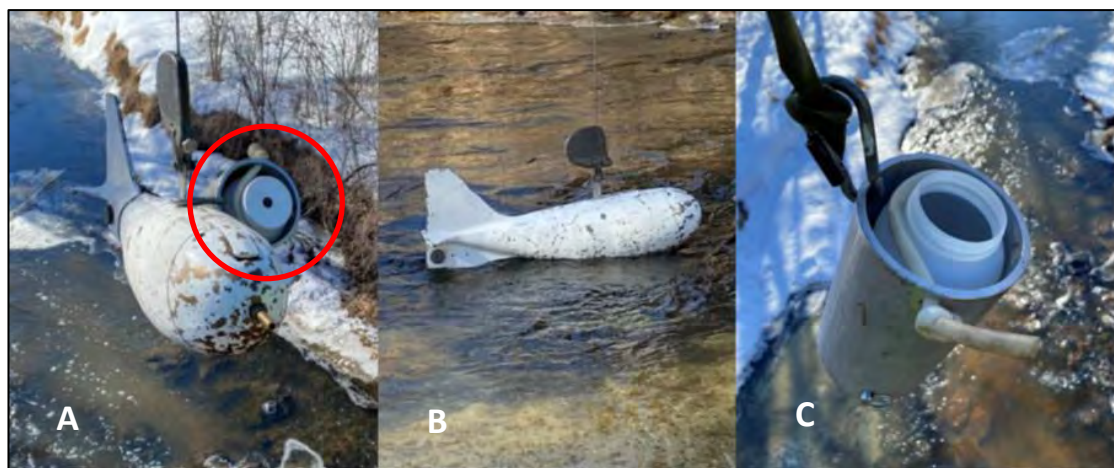


Figure 5-3: (A) simple, non-isokinetic depth-integrated SS sampler (red circle) attached to a D-74 SS sampler; (B) D-74 SS sampler; (C) US WBH-96 grab SS sampler with an open-mouth (Groten et al., 2023)

By contrast, the results from open jar grab-sampling showed a significant difference compared with the D-74 results (Groten et al., 2023), indicating that the samplers used in the Tsitsa River were an improvement on open-jar sampling, and were no greater source of epistemic uncertainty than their commercially available and more widely used counterparts. Channel representativeness of the bank-side samples was unquantified in this study due to the risks involved with undertaking width-and-depth integrated sampling during any but unrepresentative low flows. This was considered to be a potential source of SSL/SSY uncertainty, which would also have been present even if financial, infrastructural, physical, and socio-economic conditions had allowed the use of installed pump samplers. However, Gurnell et al. (1992) found that results from both hand and pump bank-side sampling in pro-glacial streams demonstrated a clear positive trend ($R^2 = 0.822$, $n = 52$), implying that the CT-based direct sampling method was an appropriate solution to the logistical and financial challenges to installing sampling equipment in the Tsitsa River catchment.

Samples were preserved using a commercially available water purification tablet as an algacide (17 mg sodium dichloroisocyanurate) before being capped. Three replicate samples, intended as an indication of data precision were taken at each site once each week, with citizen technicians collecting three consecutive samples as rapidly as possible (Bannatyne et al., 2017). Sample jars were stored in a cool dark place inside the citizen technicians' homes, and were picked up from them at ~8-weekly intervals by a laboratory and field technician and taken to Rhodes University for analysis (Bannatyne et al., 2017).

Smartphones loaded with electronic forms linked to the Open Data Kit (ODK) platform guided the citizen technicians through their sampling protocol. Manual entries, GPS, and photographs were used to record sample numbers, positional data, river and weather conditions, and the date and time of

sampling. The forms were sent to an ODK Aggregate database (**Figure 5-4**) using the local cellular network.

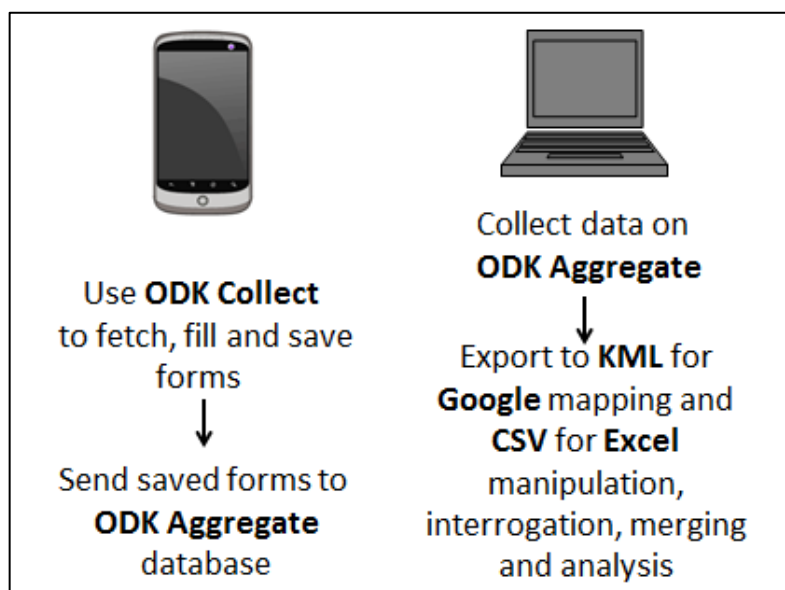


Figure 5-4: Collection of SSC data via the ODK platform (Bannatyne 2018)

Sampling information was therefore usually available to researchers at Rhodes University in near real-time, ensuring compliance with sampling protocols as the first step in data quality control.

5.5 Laboratory analysis

5.5.1 Suspended sediment concentration

There was lack of sufficient filtration equipment and no qualified laboratory staff to deal with either the expected high number of samples, or with technically demanding laboratory procedures that would avoid cross-contamination or loss of sample material and guarantee sample-number integrity/tracking throughout the process. This precluded the use of a filtration approach. A method of measuring SSC was therefore developed (Bannatyne et al., 2017) that could be carried out by any previously inexperienced worker who was trained to use basic equipment and to manually record data in a standardised, consistent manner.

During the early development of the laboratory analysis protocols in 2016, it was found that the 0.01 to 999 ntu measuring range of the available Eutech TN-100 turbidity meter was insufficient for most high SSC samples (Bannatyne et al., 2017). A simple evaporation method using temperature controlled drying ovens was found to be appropriate to determine SSC (mg L^{-1}) for high concentration samples. However, inaccuracies occurred when using this method for low-concentration samples with a turbidity of < 200 ntu (Bannatyne, 2018). A combined measured turbidity/evaporation approach was therefore chosen, whereby turbidity was measured for samples < 200 ntu and later converted to SSC

using site specific SSC/turbidity relationships (See **Chapter 6**) and the evaporation method was used for samples >200 ntu. For both methods, samples remained in their labelled collection jars throughout the analysis process, avoiding loss of sample material, sample cross-contamination, and sample-numbering errors that could have occurred using a filtration approach, for example during decanting, filtration, drying, and weighing. The relative contributions of low- and high-sediment samples to annual SSL and SSY is discussed in **Chapter 8**.

Bench turbidity measurements were taken to sort samples with turbidity of <200 ntu from those with turbidity of >200 ntu. Samples to be measured were thoroughly shaken until all settled sediment was re-suspended. A 10 ml sub-sample was taken from the bottom to the top of the jar using a 20 ml surgical syringe and placed in a double-rinsed measuring vial. Two turbidity measurements were made to confirm accuracy and provide an average turbidity value using the Eutech TN-100 turbidity meter (Bannatyne, 2018). Samples >200 ntu were analysed using the evaporative method to determine SSC, using **Equation 5-1** to **Equation 5-3**:

Equation 5-1: Mass of water (Mass A) = Mass a - Mass b

Equation 5-2: Mass of sediment (Mass B) = Mass b - Mass c

Equation 5-3: $\text{SSC (mg L}^{-1}\text{)} = \frac{\text{Mass B}}{\text{Mass A}} \times 10^6$

Where:

The volume of water is directly proportional to its mass: 1 gm = 1 ml

Mass A = Water (g)

Mass B = Sediment (g)

Mass a = The whole sample + jar (g)

Mass b = The dried sediment + jar (g)

Mass c = The sample jar (g)

Both SSC and turbidity were determined in order to develop site-specific SSC/turbidity relationships using a sub-set of ~ 500 samples from each site that ranged from low to high concentration (see **Chapter 6**). This sub-set included the replicate samples (i.e. “triplicates”) that were collected once per week to determine precision (**Section 5.6.3**). However, variations in particle size distributions, and the presence of flocs (agglomerations of sediment < 6µm) and/or organic matter) are known to affect the expected linear relationship between turbidity and SCC (Bright et al., 2020). From previous research in the Tsitsa catchment (Ramothello, 2021) and in for example New Zealand (Bright et al., 2020) it is known that particle size distribution is dynamic through flood events and can vary between flood

events at the same site. The impact of this potential source of uncertainty on the turbidity/SSC relationship was not quantified, but was restricted to samples <200 ntu.

For the evaporative method, sample jars were allowed to settle for at least one month (**Figure 5-5A**). After weighing the whole sample (**Figure 5-5B**), the supernatant was siphoned off using a J-tube (**Figure 5-5C**). The remaining 50 ml of water was evaporated by oven drying at 60° C (**Figure 5-5D**) to the point where a petri dish of silicon dioxide crystals kept in the oven changed from pink (wet) to blue (dry) indicating that no moisture was present in the drying oven (typically after three to five days). In oven tests, temperatures higher than 60° C caused the sample jars to distort which influenced their mass and would have caused errors in the SSC determination (Bannatyne 2018). After oven drying, the jar with dried sediment was weighed, then washed (but preserving the sample number) and oven-dried, and weighed again empty (**Figure 5-5E**). Mass was recorded in grams (± 0.0001 g accuracy) to give SSC in mg L^{-1} (Bannatyne, 2018).



Figure 5-5 A: Settling samples, B: weighing whole sample, C: removing supernatant, D: oven drying and E: weighing empty jars during the laboratory SSC analysis

An early analysis of the precision of laboratory results using data from “triplicate” samples collected in the first six months of the project identified poor performance by laboratory workers, coupled with inconsistencies in sample drying due to the use of several different ovens, as major sources of error (Bannatyne, 2018). These sources of error were successfully mitigated by purchasing and using only one oven, and by improving laboratory staff attention to protocols and detail.

5.5.2 Total dissolved solids

Total dissolved solids, or salts (TDS) are part of the suspended load carried by rivers (Gordon et al., 2004). TDS comprises ions, (for example sodium, magnesium, and calcium cations, chloride, sulphate, carbonate, and bicarbonate anions) that enter watercourses via runoff and groundwater from sedimentary rocks such as chalk and limestone (Gordon et al., 2004). TDS concentrations may therefore fall during flood conditions and rise during baseflow conditions.

Self-evidently, TDS need not be accounted for when determining SSC using standard filtration approaches (Butler & Ford, 2018). Due to the evaporative laboratory process used here to derive the mass of sediment present in water samples, it was necessary to measure TDS to either compensate for or dismiss its contribution to sediment mass after evaporation (i.e. Mass B, Equation 5-1 to Equation 5-3). During the first six months of the sampling programme, electrical conductivity (EC, $\mu\text{S cm}^{-1}$) was measured and converted to TDS using the ratio method (TDS, mg L^{-1} Equation 5-4 Rusydi, 2018).

Equation 5-4:
$$\text{TDS} = \left(\frac{\text{EC}}{1000} \right) 640$$

Where:

TDS = Total dissolved solids (mg L^{-1})

EC = Electrical conductivity ($\mu\text{S cm}^{-1}$)

Approximately 100 whole-water samples from each site that were representative of the range of flows were tested (Bannatyne, 2018). TDS at each site (including the 17 mg sodium dichloroisocyanurate algicide) was low: Maximum TDS ranged between 131.20 mg L^{-1} at Pot and 239.68 mg L^{-1} at Gqukunqa. These highest TDS values were representative of low, baseflow-dominated flows during the dry season. Since most of the sample was siphoned off prior to SSC analysis, the TDS in the remaining 50 ml of the sample was low (average 6 mg) in comparison to the remaining SS, particularly for high concentration samples. Whilst TDS would introduce a minor bias, and was more significant at sites such as the Pot River, TDS measurements were discontinued following this analysis. The MS Excel workbook containing these calculations is included as **Appendix 4**.

5.6 Suspended sediment sample representativeness

5.6.1 Temporal representativeness

As noted in **Chapter 5.3**, sampling was undertaken through flood flows to avoid the under-estimation that would be expected to occur due to calendar-based sampling (Walling et al., 2007). As noted in **Chapter 3.7**, daily input timestep is widely used as input to annual SSL estimation (Lee et al., 2016). Temporal SS data representativeness for each site was therefore expressed as the number of days when at least one turbidity or SSC value was available. The resulting SS sampling days were expressed both as a percentage of the total project period (1278 days: 01/12/2015 – 31/05/2019), and as a percentage of the period that each site was active. The use of TWMC to accommodate variable numbers of samples in the calculation of average daily SSC is described in **Section 3.7.2**.

5.6.2 Representativeness of high flow sampling

High, sediment-transporting flows were the target of the SS sampling programme. Determining the degree to which high flows were sampled allowed a statement of sampling representativeness to be made. At each site, daily flows were ranked (**Section 5.8.3**). Days with at least one SS value were matched (by date) to the ranked daily discharges that were in the highest 1%, 5%, and 20% of flows during the site monitoring period.

5.6.3 Suspended sediment concentration and turbidity data precision

5.6.3.1 Precision analysis

Precision was determined using repeat (triplicate) samples that were taken once a week as per the sampling protocol. As noted in **Section 3.4.1**, standard deviation and variance were unsuitable descriptors as they should not be calculated for as few as three data points. %CV was chosen to express precision as it allows comparison between variables with different measurement units, i.e., between turbidity (ntu) and SSC (mg L^{-1}), and can be determined with only three datapoints.

The %CV was calculated for the three turbidity and the three SSC values in each triplicate set. Turbidity was directly measured in the sample, so the %CV of the turbidity values was assumed to reflect both the variability of SS at the time the triplicate sample was taken (natural uncertainty), and the consistency of bank-side sampling (epistemic uncertainty). SSC was determined through laboratory analysis, so the %CV SSC was assumed to indicate the precision/epistemic uncertainty associated with the laboratory analysis.

Criteria for *acceptable*, or *low* or *high* %CV are dependent on the research question. Here, 25% was selected as an arbitrary class break between low and high %CV, and was used to classify the triplicate samples into three groups (A, B, & C) for the precision analysis (**Table 5-3**).

Table 5-3: SSC/turbidity %CV criteria for SS precision analysis

Group	Turbidity %CV	SSC %CV	Natural uncertainty	Sampling precision	Analytical precision
A	< 25%	< 25%	Low	High	High
B	< 25%	> 25%	Low	High	Low
C	> 25%	N/A	High?	Low?	N/A

Group A: Sampling and laboratory analysis both had low %CV, implying low uncertainty for results satisfying these criteria.

Group B: Sampling had a low %CV, but laboratory analysis had a high %CV, implying that laboratory analysis was the source of uncertainty in these results.

Group C: Sampling had a high %CV: This could mean either that sediment transport at the time of sampling was highly variable, and/or that sampling was inconsistent. This implied that uncertainty was high and that the source of the uncertainty could not reliably be determined for results in Group C.

5.6.3.2 Representativeness of the precision analysis

The temporal representativeness of the triplicate samples of the site period was determined from the percentage of actual to potential triplicate sets taken by the CTs.

Earlier work indicated a positive relationship between SSC and precision (Bannatyne, 2018), so precision and representativeness were separately assessed for low, medium and high sediment samples. Turbidity (rather than SSC) was used for this classification because turbidity was directly measured, whereas SSC resulted from laboratory analysis which could introduce further error. Turbidity values of <200 ntu were classed as low sediment concentration; >200 ntu to <500 ntu were classed as medium sediment concentration; and >500 ntu were classed as high sediment concentration.

5.7 Suspended sediment results

5.7.1 Suspended sediment data representativeness

5.7.1.1 Spatial representativeness

Approximately 26,000 SS data points were collected during the project period of 1276 days. The number of samples taken each day at each site depended on a combination of catchment area, season, river conditions, day length, and the individual performance of the citizen technician (Bannatyne, 2018). The following factors influenced the number of samples collected from specific sites during the project period 01/12/2015 – 31/05/2019:

- Sampling at Little Pot stopped in October 2016 after 287 days when it was decided that enough data had been collected at this site in terms of its function as a near-pristine reference catchment.
- Sampling at Tsitsana and Hlankomo stopped at the end of May 2017 after 514 and 518 days respectively due to financial limitations.
- Sampling at the T4 (Tsitsa at the Falls) stopped in early September 2018 after 645 days when the left and no replacement was available.
- CTs left and were replaced at Mooi, T3 (Tsitsa at the Gorge), Gqukunqa, and TN2 (Tsitsa at Mbelembushe), leaving gaps of 612 days, 262 days, 386 days, and 584 days respectively in the sampling record. At Mooi the sampling site was moved ~2km downstream from 2017 onwards.
- One citizen technician sampled continuously throughout the full project period at Pot, T2 (Tsitsa at the Qulungashe Bridge) and Inxu.

Table 5-4 summarises the SS coverage at each site for the period when sites were active and for the project period.

Table 5-4: Distribution of SS sampling data

SITE	# Samples	Days sampled	Site period (days)	Site period coverage (%)	Project period coverage (%)
Little Pot	790	283	316	98.6	22.1
Tsitsana	1724	484	517	94.2	37.9
Hlankomo	1201	403	520	77.8	31.5
T4 (Tsitsa at the Fall)	2261	623	653	96.6	48.7
Mooi	2155	666	1278	52.2	52.1
Pot	2566	1040	1278	81.4	81.4
T3 (Tsitsa at the Gorge)	3234	1016	1278	79.5	79.5
T2 (Tsitsa at Qulungashe Bridge)	2676	1050	1278	82.2	82.2
Gqukunqa	3320	892	1278	69.8	69.9
Inxu	3613	1147	1278	89.7	89.7
TN2 (Tsitsa at Mbelembushe)	2179	694	1278	54.4	54.3
SS Total (Average)	25719	8298	10910	(79.7)	(59.0)

At most sites, citizen technicians sampled on more than ~78% of the days available to them. Even at the three sites where the first citizen technician left and was later replaced, more than half the available days were sampled. Due to the curtailment of certain sites, project period coverage varied between sites from ~22 % to ~90 %, although on average ~59 % of days were still represented by at least one SS data point.

5.7.1.2 Temporal representativeness

Figure 5-6 depicts in calendar format the days on which at least one SS sample was collected at each site (brown shading), revealing individual sampling patterns that are not apparent from the percentages in **Table 5-4**. At Mooi, T3 (Tsitsa at the Gorge), Gqukunqa, and TN2 (Tsitsa at Mbelembushe), sequences of different shading represent different CTs.

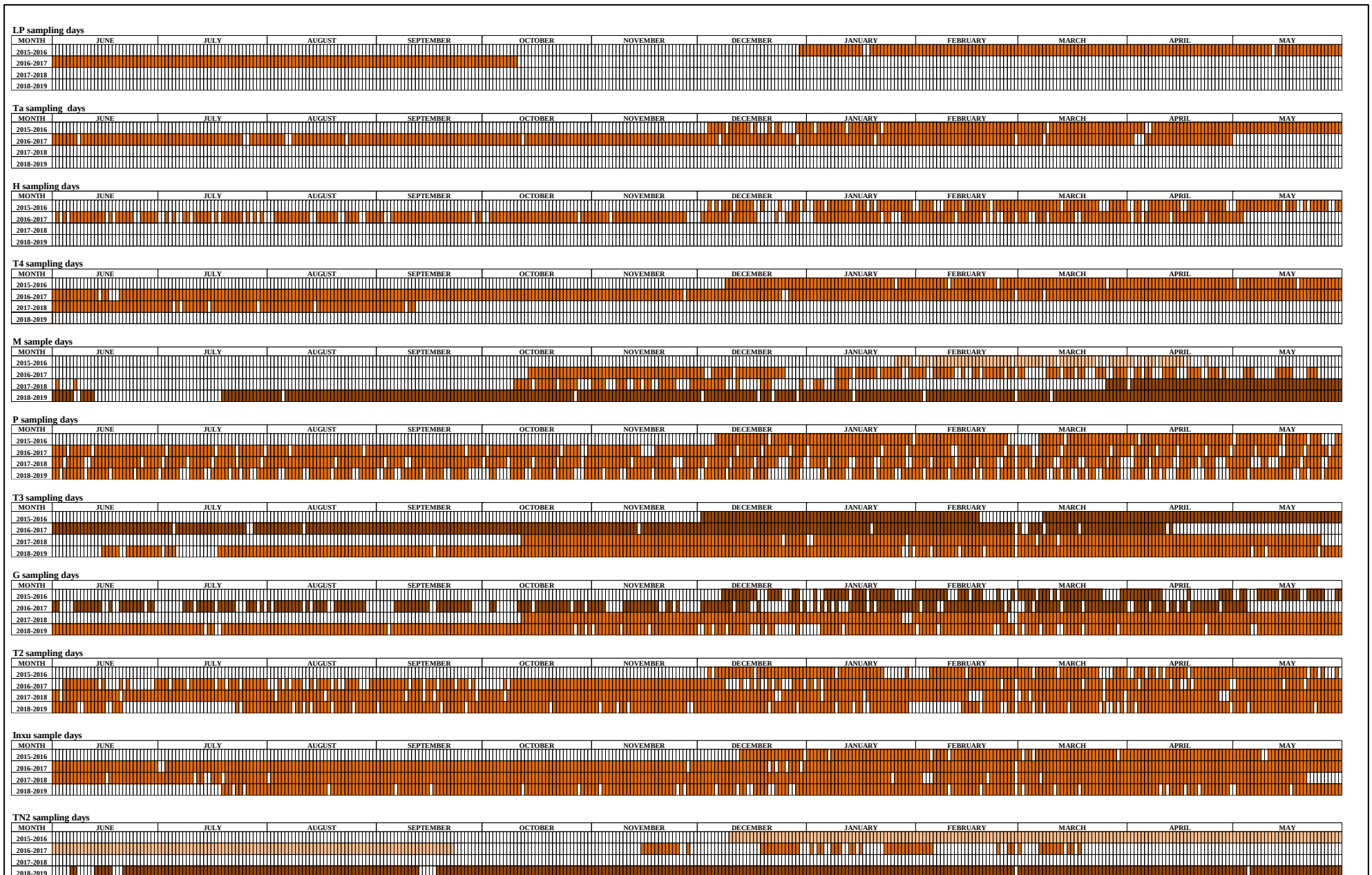


Figure 5-6: Days on which at least one SS sample was collected at each site

The sampling patterns in **Figure 5-6** were inconsistent within and between sites, due to the performance of individual citizen technicians:

Some sampled consistently on most days.

Some tended to frequently skip one or more days.

Some sampled erratically, with many days left unsampled.

5.7.1.3 Sampling of high flows

Secondary discharge data are described in **Chapter 5.8**. Most of the sites had a complete or near-complete discharge record from which to calculate the percentage of high flows that were sampled (**Table 5-10**). The site at T3 (Tsitsa at the Gorge) was however impacted by two discrete losses of discharge data, due to the failure of two different pressure loggers installed at the site. When the T3 pressure logger was downloaded in June 2019 and June 2020 it was found not to have recorded any data for the periods 5/07/2017 – 12/11/2018, and 25/03/2019 – 31/05/2019. As a result, discharge data were available for only 716 days of the 1278 day project period even though regular SS sampling had been undertaken (**Table 5-4; Figure 5-6**). The MS Excel workbook containing the calculations for the sampling coverage of high flows is included as **Appendix 6. Table 5-5** summarises days with at least one SS value as a percentage of the days when discharges in the highest 1%, 5%, and 20% of flows for the site period occurred.

Table 5-5: Percentage of daily high flows sampled at each site

	Site period SS coverage (%)	Flows < =1%			Flows >1%<5%			Flows>5% <20%		
		Q days	SS days	% Q days sampled	Q days	SS days	% Q days sampled	Q days	SS days	% Q days sampled
Little Pot	89.6	3	3	100.0	12	11	91.7	63	60	95.5
Tsitsana	93.6	5	5	100.0	20	20	100.0	103	93	90.3
Hlankomo	77.5	5	4	80.0	20	15	75.0	103	80	77.7
T4 (Tsitsa at the Falls)	95.4	6	6	100.0	26	24	92.3	130	126	96.9
Mooi	52.1	12	7	58.3	51	26	51.0	255	159	62.4
Pot	81.4	12	10	83.3	51	42	82.4	255	201	78.8
T3 (Tsitsa at the Gorge)	79.5	7	7	100.0	28	26	92.9	140	127	90.7
T2 (Tsitsa at Qulungashe Bridge)	82.2	12	12	100.0	51	37	72.5	255	209	82.0
Gqukunqa	69.8	12	9	75.0	51	46	90.2	255	221	86.7
Inxu	89.7	12	11	91.7	51	48	94.1	255	235	92.2
TN2 (Tsitsa at Mbelembushe)	54.3	12	4	33.3	51	19	37.3	255	121	47.5

Predictably, the sites with the least coverage of the available high flows were those with low site period temporal coverage (i.e., Mooi, and TN2 (Tsitsa at Mbelembushe)) due to there being no citizen technician available for long periods. Excluding these two sites, the manual flood-focused sampling approach was successful in capturing at between 78% and 97% of the highest 20% of flows that occurred while each site was active.

5.7.2 Suspended sediment concentration and turbidity data precision

5.7.2.1 Temporal representativeness of the precision analysis

The number of weeks that each site was active (from 1 December 2015) was used to calculate the potential number of weekly triplicate samples that citizen technicians could have taken. **Table 5-6** summarises the potential and actual number of triplicate samples taken per site monitoring period and expresses the latter as a percentage of the former.

Table 5-6: Potential and actual number of triplicate samples taken per site expressed as a percentage of triplicate samples taken

SITE	Potential triplicate samples (#)	Triplicate samples taken (#)	Triplicate samples taken (%)
Little Pot	44	20	45.5
Tsitsana	74	42	56.8
Hlankomo	74	33	44.6
T4 (Tsitsa at the Falls)	93	30	32.3
Mooi	183	69	37.7
Pot	183	141	77.0
T3 (Tsitsa at the Gorge)	183	91	49.7
T2 (Tsitsa at Qulungashe Bridge)	183	113	61.7
Gqukunqa	183	93	50.8
Inxu	183	89	48.6
TN2 (Tsitsa at Mbelembushe)	183	64	35.0
Total (Average)	1183	785	(49.1)

785 of a possible 1183 triplicate sets were available for the precision analysis. Triplicate sample representativeness was mainly influenced by citizen technician availability and diligence. At all but three sites, fewer than half the potential triplicate samples were taken, reducing the representativeness of the precision analyses.

5.7.2.2 Suspended sediment representativeness of the precision analysis

Most samples in the precision analysis had low turbidity i.e., ~86% (n=676). Fewer than 10% (n=74) and 5% (n=35) were medium and high turbidity samples respectively. This was to be expected since low flows dominated the hydrographs and flow duration curve shown in **Chapter 2.3**.

5.7.2.3 Precision analysis

The MS Excel workbook containing summary data for the precision analysis is included in **Appendix 5**. **Table 5-7** summarises the data in terms of natural uncertainty, sampling precision, and analytical precision for all triplicate samples.

Table 5-7: Percentage of all triplicate samples in Groups A, B, and C, and associated natural and epistemic uncertainty

Group*	%	n	Natural uncertainty	Sampling Precision	Analytical precision
A	48	377	Low	High	High
B	40	314	Low	High	Low
C	12	94	High?	Low?	N/A

*See **Table 5-3** for definitions of Groups.

88% (n=691) of triplicate samples were classified as Groups A and B. This means that natural variability was low and sampling precision was high for most samples. Analytical precision was high for the 48% (n=377) of triplicate samples classified as Group A, low for the 40% (n= 314) in Group B, and indeterminate for the samples in group C (12%, n=94). This highlights laboratory analysis as the main source of uncertainty in SSC values, affecting between 40% and 52% of the samples analysed.

The numbers of low, medium and high sediment triplicate samples present within Groups A, B, and C are summarised in **Table 5-8** and illustrated in **Figure 5-7**.

Table 5-8: Summary of low, medium and high sediment triplicate sets within each Group

Group*	Low sediment (<200 ntu)	Medium sediment (201 – 500 ntu)	High sediment (>500 ntu)	Total
A	294	52	31	377
B	295	17	2	314
C	87	5	2	94
Total	676	74	35	785

*See **Table 5-3** for definitions of Groups.

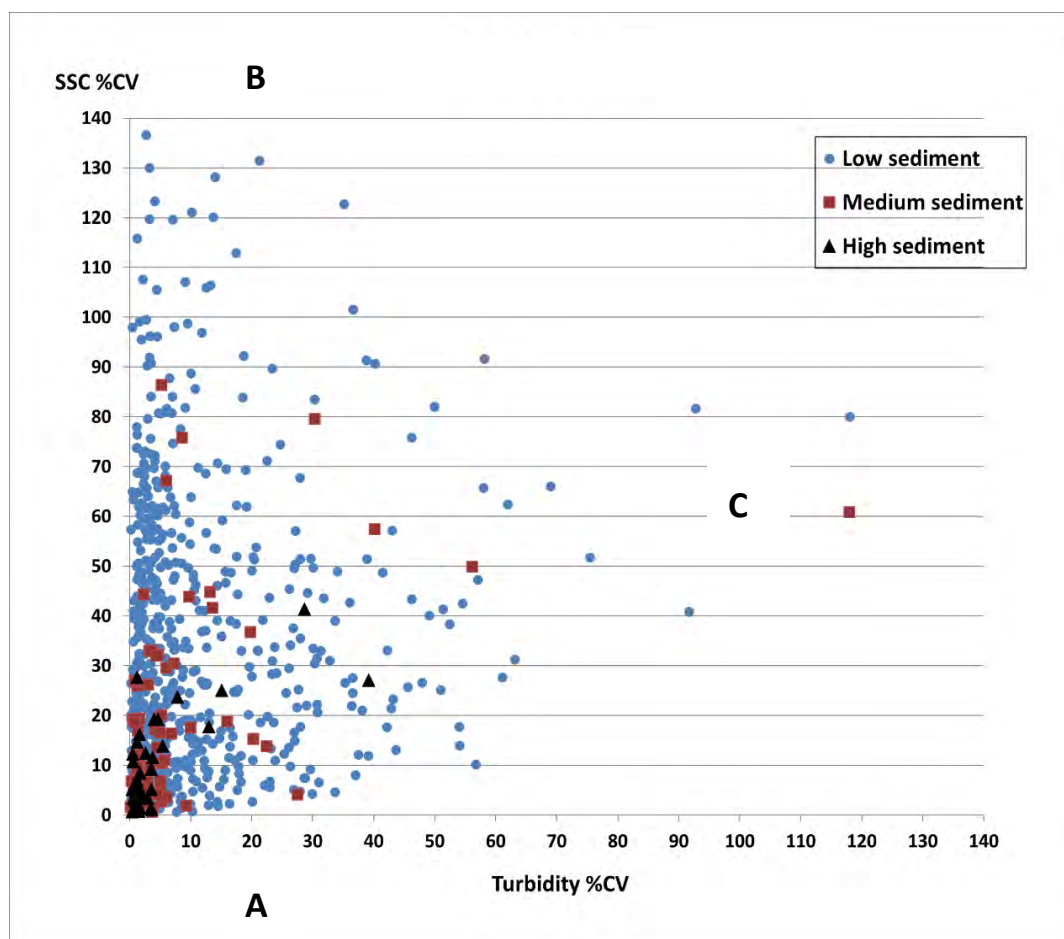


Figure 5-7: Turbidity %CV plotted against SSC %CV for all triplicate samples at all sites. A, B, and C defined by the SSC/turbidity %CV criteria in Table 5-3

All but four of the 35 high sediment triplicate sets in **Table 5-8** were classified as Group A. Most had <10 %CV turbidity, and <20 %CV SSC (**Figure 5-7**). This indicates very low natural uncertainty and low epistemic uncertainty for the high sediment samples.

Medium sediment samples were unevenly dispersed through all Groups. The majority classified as Group A and B, and most were bounded by ~10 %CV turbidity, indicating low natural uncertainty and high sampling precision for medium sediment samples (**Table 5-8, Figure 5-7**). Analytical precision for medium sediment samples was however much more variable than sampling precision: Whilst 52 of the 74 medium sediment samples were classified as Group A, the remainder were dispersed widely, mainly throughout Group B but also into Group C, indicating variable analytical precision.

Low sediment triplicate samples dominated all groups, with most samples classified as Group B and C (**Table 5-8, Figure 5-7**). Whilst sampling precision was relatively high for many samples, analytical precision was very low.

The precision analysis identified that the main source of uncertainty for low, medium and high sediment samples was epistemic, relating to the evaporative laboratory analysis, particularly for low sediment samples. This confirmed the findings of the preliminary analysis undertaken using the first 6 months of data from four sites as part of the candidate's Master's research (Bannatyne 2018). Factors such as particle size and geology (i.e., natural uncertainty) would have affected the precision of the turbidity measurements. However, the analysis showed that natural uncertainty was generally low, and sampling precision (as indicated by the turbidity %CV) was generally high. Conversely, laboratory precision from the evaporative process was relatively low. Further analysis by catchment was therefore not indicated as the laboratory analysed all samples from all catchments, thus physical factors such as particle size and geology did not contribute to the epistemic uncertainty.

5.8 Secondary discharge data

The sub-catchment scale discharge variability and flashiness (i.e., sources of *natural* uncertainty) were described in **Chapter 2**. This section therefore identifies, where feasible, sources of *epistemic* uncertainty associated with the secondary discharge data, with reference to the literature reviewed in **Section 3.6**. Discharge data were received from DWS and from other researchers involved with the Tsitsa Project. Hourly discharge data were available from DWS records for two sub-catchments: the Mooi at Maclear (gauging station T3H009) and the Tsitsa at Mbelembushe (gauging station T3H006). Discharge data for the remaining nine previously ungauged sub-catchments were provided at 20-minute timestep. The discharge monitoring and calculation methods for these nine sub-catchments are described in **Appendix 2**.

5.8.1 Uncertainty associated with Department of Water and Sanitation data

DWS applies quality codes as statements of uncertainty to the discharge data that is released to the public. **Table 5-9** summarises the quality of the daily discharge data for the project period for the DWS gauging weirs at Mooi (T3H009) and TN2 (Tsitsa at Mbelembushe, T3H006).

Table 5-9: Summary of data quality at DWS gauging stations

Quality code	Description	Mooi T3H009 (%)	TN2 T3H006 (%)
2	Good, edited data	12.0	99.9
47	Edited and checked, still unaudited	85.4	0
64	Audited Estimate		0.1
173	Data Unreliable	2.6	0

The discharge data at TN2 (Tsitsa at Mbelembushe, T3H006) was almost 100% “good, edited data” whilst uncertainty was far greater at Mooi (T3H009) where only 12% of the data were considered good and the remainder was either checked but unaudited, or unreliable. The maximum measurable discharge was not exceeded at either gauging station during the project period.

5.8.2 Uncertainty associated with monitored discharge data

5.8.2.1 Background

The discharge monitoring programme was constrained by financial and technical resources, and by the physical characteristics of the Tsitsa River catchment which was 500km distant from the research base, often inaccessible during the wet season due to unmade roads, and subject to extreme floods. Related to the choice of SSC monitoring sites i.e. chiefly influenced by the ability of nearby residents to safely undertake sampling), the choice of discharge monitoring sites was chiefly influenced by the location of the SSC monitoring sites.

5.8.2.2 Monitoring site characteristics

Discharge monitoring reaches should have stable bed forms (i.e. bed-rock or armoured), be free from obstructions, backwaters and eddies, and be fairly straight with relatively uniform width, depth, slope and velocity (Gordon et al., 2004). However, steep channel gradients and typically sinuous planforms in the Tsitsa River catchment meant that the selected reaches generally did not exhibit ideal characteristics for discharge measurements, in terms of their section and channel controls. Most of the discharge monitoring reaches were not homogenous, and at the Hlankomo and Inxu sites the monitoring reach was of necessity located at a bend (dictated by the presence of hard rock for pressure logger placement). These characteristics imply that flow monitoring was likely to have been subject to inaccuracies due to turbulent flows.

5.8.2.3 Channel cross-section surveys

Channels were typically incised with one or more flood benches on one or both banks, and infrequently connected with their floodplains (See **Appendix 2** for channel cross-sections). The channel cross-

sections were changeable during the wet season due to the transport of large volumes of sand, particularly at the Inxu River monitoring site. The monitoring reaches at Pot, Hlankomo, and the Tsitsa River were dominated by bedrock, but were subject to episodic deposition and removal of significant volumes of sand throughout each wet season (Pers. Comm. A Badenhorst). At T2 (Tsitsa at Qulungashe Bridge) the bed was a mixture of dolomite outcroppings and sand. Little Pot, Tsitsana, and Gqukunqa were gravel/cobble bed rivers and perhaps less prone to changes in cross section.

Ideally, river cross sections would have been frequently surveyed to measure these changes. However, due to financial constraints and the need to combine the field work aims of different projects/students to optimise resources, channels were surveyed annually at best, and only during the winter dry season to coincide with accessing and downloading the pressure loggers. Thus, changes in cross-section between floods, or even from the beginning to the end of the wet season were not quantified. This introduced an unknown degree of inaccuracy and uncertainty into the discharge calculations that were based on depth measurements and the assumption of a stable cross-section. Further, due to the limited measured flow data (next section) only one discharge rating curve was generated from all flow measurements. In other words, channel cross-sectional change between June 2015 and June 2019 was not accommodated in the discharge calculations.

5.8.2.4 Discharge monitoring

Discharge should be monitored twelve to fifteen times per site whilst recording the full stage range, in order to allow the accurate construction of stage discharge curves for calculating discharge from depth measurements (Gordon et al., 2004; Braca, 2008). The low number of measured discharges at each site throughout the project period (See **Appendix 2**) was a manifestation of the resource scarcity that is commonplace in developing regions, where ungauged channels are the norm (Kapangaziwiri et al., 2012). In the Tsitsa River catchment flow measurements were only possible during the four winter dry seasons June 2015 – June 2019, due largely to the mentioned financial constraints and access challenges, but equally to safety concerns during discharges $\Rightarrow$ 1m in depth. Other constraints included the absence of any equipment other than a Marsh-McBirney Flo-Mate 2000, as well as the obvious issue of unsteady high flows which would impact the accuracy of velocity measurements (Mansanarez et al., 2019).

Discharge modelling was therefore based on very few measured flows at each site (i.e., between 1 and 6, see **Appendix 2: Table A-2**), almost all of which were undertaken during baseflow conditions. Had the available finances allowed additional summer discharge monitoring field work, the unpredictable rainfall/flood flows, and the associated safety concerns would still have precluded high flow monitoring.

Lack of measured flows is a recognised challenge not only in South Africa and in other resource scarce regions (Kapangaziwiri et al., 2012), but in many parts of the world (Mansanarez et al., 2019), introducing an unknown but possibly significant degree of epistemic uncertainty to the discharge calculations.

5.8.2.5 Discharge calculations

Calculations were undertaken by other researchers to derive stage data from the 20-minute pressure measurements, and discharge values from the stage data. Deriving stage data entailed compensating pressure logger data with that from a synchronised barologger measuring only air pressure (See **Appendix 2**). The maximum distance between a pressure logger and a barologger was on the Little Pot, ~30 km distant from the barologger at T4 (Tsitsa at the Falls). This distance may have introduced errors in the derived stages, due to possible temperature differences and to rapid changes leading to different air pressure at the pressure loggers and at the barologger, for example during the build-up and movement of storms (McLaughlin & Cohen, 2011).

Discharge was calculated using HEC-RAS, a widely accepted approach (See **Appendix 2**) but the calculations were dependent for their accuracy on the described measured cross-sectional and flow data. Therefore, whilst (where possible) avoiding the introduction of further error, the calculated discharges were subject to an unknown degree of epistemic uncertainty due to changes in channel cross-section, and probably to a greater degree by the absence of measured high flow data. This uncertainty would more greatly impact the accuracy of calculated high flows, but no independent discharge data were available for benchmarking. There were too few measured flows available to evaluate site-specific rating curve performance, for example using k-fold (or even two-fold) cross-validation, regression, and Mean Absolute Error (MAE). Hydraulic models have been developed that can rely on fewer, low to medium flow measurements require detailed, accurate, channel cross-sectional data for the measurement reach (using for example lidar surveying techniques) as well as reach-scale vegetation surveys to accurately determine channel roughness (Mansanarez et al., 2019). These approaches were not available to the project team.

5.8.3 Daily discharge data

5.8.3.1 Averaging

Daily discharges were averaged from the calculated ~72 x 20-minute timestep data points. The period 00:00:00 to 23:40:00 on each day was chosen rather than the customary 08:00:00 – 07:40:00 period typically used in South Africa, to more easily align daily discharge with daily SSC: the citizen technicians' sampling day extended from dawn until dusk. The project-period daily discharge graphs for each sub-

catchment are included in the study area description (**Chapter 2, Figures 2-6 to 2-16**). The daily discharge data were used for:

- The calculation of discharge data temporal coverage to determine the temporal representativeness of the discharge data,
- The calculation of discharge exceedance percentages to describe, to an extent, the sub-catchment flow regime,
- Regression of high flows against catchment area as a measure of discharge calculation accuracy, and
- Estimation of SSL (**Chapter 7**).

They were also used in the calculation of the Richards-Baker Flashiness Index to indicate the natural uncertainty due to the variability and unpredictability of flows (**Section 2.3.2**).

5.8.3.2 Temporal coverage

The percentage of days on which daily flow data were available is expressed as a percentage of the total number of project days in **Table 5-10**.

Table 5-10: Distribution of daily discharge data

SITE	Project period coverage (%)
Little Pot	99.8
Tsitsana	99.8
Hlankomo	99.9
T4 (Tsitsa at the Falls)	99.9
Mooi	97.4
Pot	99.9
T3 (Tsitsa at the Gorge)	55.9
Gqukunqa	99.9
T2 (Tsitsa at Qulungashe Bridge)	100.0
Inxu	100.0
TN2 (Tsitsa at Mbelembushe)	100.0
Total (Average)	(95.7)

Project period coverage for daily discharge data was better than 99% at all sites except for T3 (Tsitsa at the Gorge, 55.9%), where significant losses of measured water level data occurred as a result of pressure logger malfunctions, and at Mooi (97.4%) where some DWS data were missing.

5.8.3.3 Maximum discharges and discharge exceedance percentages

The maximum discharges, and percentage discharge exceedances were required for an analysis of high-flow SS sampling representativeness (**Table 5-5**) and to characterise the flow regime (dominance of low flows, (**Figure 2-17**). Additionally, maximum discharges and the 5% exceedance discharges were regressed against catchment area as a coarse assessment of the accuracy of the discharge calculations (**Figure 5-8**), based on the assumption that discharge and catchment area are positively related (Galster et al., 2006).

To determine percentage exceedance (P), the daily discharge recorded at each site was sorted and ranked from maximum discharge (1) to minimum discharge, typically over 1278 days for sites with a complete discharge record. The rank represented the number of days with a discharge equal to or exceeding that discharge. Dividing the rank by the total number of days for which daily discharge records were available at that site gave the percentage of time (P) for which that discharge was exceeded (**Equation 5-5**).

Equation 5-5:
$$P_q = \frac{R}{n}$$

Where:

P_q = the probability of discharge P being exceeded

R = the rank of that discharge

n = the total number of measurement days

5.8.3.4 High flow discharge accuracy

High flows are positively related to catchment area (Galster et al., 2006). As a coarse assessment of their accuracy, the daily high flow discharges were regressed against catchment area (**Figure 5-8**). Significance (p) was determined using the Regression function in the Data analysis Toolpak in MS Excel. P-value was reported for Alpha value of 0.05.

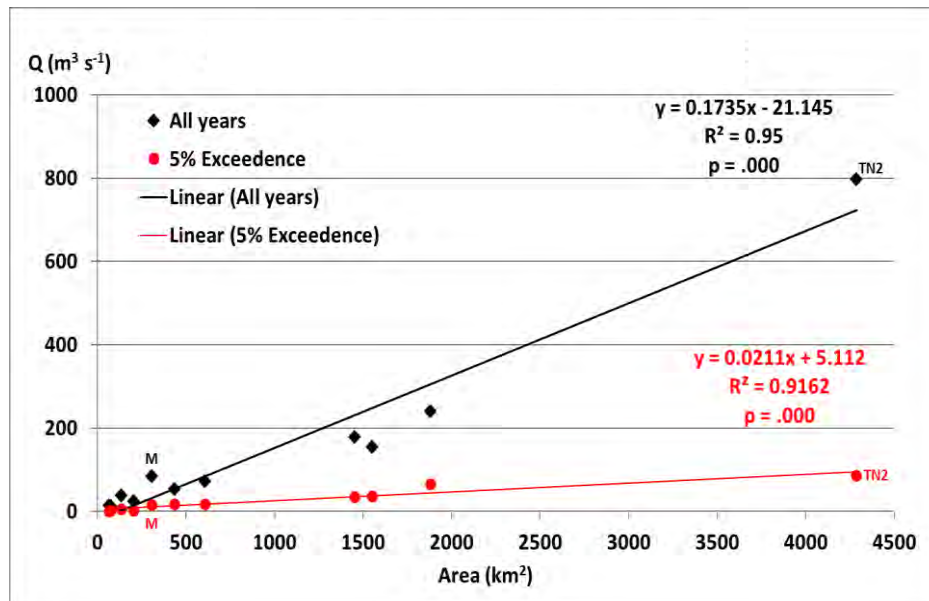


Figure 5-8: The relationship between catchment area and calculated daily discharge (maximum and 5% exceedance)

The modelled maximum and upper 5% of discharges conform to the expected positive and statistically significant ($p < 0.05$) relationship between peak calculated discharge and catchment area. This does not however indicate or mitigate the unknown degree of uncertainty associated with the daily discharge measurement.

5.9 Summary: The uncertainty associated with input data (Objective 1)

The selection of SSC sampling sites and the design and implementation of the SSC sampling programme and laboratory analysis protocols were undertaken by the author as part of her Master's research from 2015 - 2018. The design accommodated the physical and socio-economic circumstances in the Tsitsa river catchment and were limited by financial and technical resources. SSC samples were manually collected during daylight hours by local residents at eleven sites from 1 December 2015. Depth integrated isokinetic SSC samples were collected at the riverbank. Width and depth integrated SSC sampling to determine bankside representativeness was not possible during target high flows, but the uncertainty associated with the design of the sampling equipment, and with bank-side sampling was likely to be low.

Due to financial constraints, sites were active for differing periods of time, with record lengths ranging from 316 to 1278 days. The site-specific SSC sample coverage varied according to the availability and the diligence of individual CTs. Samples were taken on more than 80% of the days that sites were active,

and flow variability was well represented with 78% of high flows (i.e. the focus of this study) sampled at nine of the eleven sites.

Turbidity was measured for samples <200 ntu, whilst a basic evaporative method was used to determine SSC for the samples > 200 ntu. A sampling and laboratory precision analysis using weekly “triplicate” samples showed that the high sediment samples (>500 ntu) that were the focus of this study generally had <10 %CV turbidity, and <20 %CV SSC, implying low natural and epistemic uncertainty. Laboratory analysis was found to be an important source of uncertainty for low SSC samples.

Daily discharge data coverage at most sites was >97% (**Table 5-10**), except at T3 (Tsitsa at the Gorge, ~50%). The pattern of high flows was well-recorded at all sites except T3 (Tsitsa at the Gorge).

Discharge data for nine previously ungauged sub-catchments were collected (at 20 minute time-step) as part of the wider Tsitsa Project biophysical monitoring programme. Discharges for these sites were calculated by N Huchzermeyer and Dr B van der Waal. Discharge data for the other two sites were provided by DWS.

The reaches where flows were measured were heterogenous and dynamic, and the discharges calculated using HEC-RAS relied on only one surveyed cross section and few, low-flow discharge observations to constrain rating curve uncertainty. The uncertainty associated with calculated discharges was therefore unknown, but possibly high, especially at high discharges. However, the positive relationship between maximum daily discharge and catchment area gave general support to the accuracy of modelled discharges, but no indication of the associated uncertainty (**Figure 5-8**).

6 Calculating suspended sediment concentration from measured turbidity (Objective 2)

6.1 Overview

This chapter describes the actions, methods, and outputs associated with using instantaneous turbidity and SSC data to derive site-specific relationships from which to calculate SSC from turbidity for samples where turbidity <200 ntu (**Objective 2, Output a and d, Table 6-1**).

Table 6-1: Objective 2 actions, methods, and outputs

Objective 2	Estimate the project period measured SSLs and SSYs for each sub-catchment with, where feasible, an assessment of the sources and extent of the uncertainty in the estimate
Action	a) Derive SSC from turbidity measurements. b) Derive daily SSC. c) Estimate sub-catchment SSL and SSY using the daily SSC and daily discharge time-series.
Method	a) Establish a site-specific SSC/turbidity relationship and calculate SSC from turbidity for samples <200 ntu. b) Derive daily time-weighted mean SSC (mg L^{-1}) from measured and calculated SSC. c) Select an appropriate SSL estimator: d) Estimate SSL and SSY for all sub-catchments
Output	a) Site-specific SSC/turbidity relationships b) Daily SSC (mg L^{-1}) c) Measured sub-catchment SSLs (t) and SSYs (t km^2) d) Where feasible, statements of uncertainty for these outputs

There were three steps for the calculation of SSC from measured turbidity <200 ntu. Firstly, outliers were removed from the input datasets (**Section 6.3**), secondly, regression analysis was undertaken (**Section 6.4**), and thirdly, the error associated with the regression was estimated (**Section 6.5**).

6.2 Input data

Three subsets of records were available from the laboratory analysis of the samples collected at each site by the CTs:

- Subset 1: Records with only measured turbidity data (ntu), for samples ≤ 200 ntu
- Subset 2: Records with only measured SSC data (mg L^{-1}), for samples >200 ntu
- Subset 3: Records with both measured turbidity data (ntu) and measured SSC (mg L^{-1}).

As noted in **Section 5.7.1.2**, the number of samples taken at each site depended on a combination of catchment area, season, river conditions, day length, and the individual performance of the citizen

technician. **Table 6-2** summarises the number of samples in each subset, before the removal of outliers from Subset 3 (paired turbidity and SSC values).

Table 6-2: Number of samples at each site with turbidity only (Subset 1), SSC only (Subset 2), and both turbidity and SSC (paired values, Subset 3)

Site Name	Code	Total samples at site (#)	Turbidity only Subset 1 (#)	SSC only Subset 2 (#)	SSC and turbidity Subset 3 (#)
Little Pot at Cornlands	LP	673	498	63	112
Tsitsana at Lokishini	Ta	1580	858	416	306
Hlankomo at Makgetheng	H	1108	698	211	199
Tsitsa at The Falls	T4	2205	1219	753	233
Pot at Vipan Farm	P	2403	1386	461	556
Mooi at Maclear	M	1918	1319	277	322
Tsitsa at the Gorge	T3	2971	1602	922	447
Tsitsa at Qulungashe Bridge	T2	2492	1073	855	592
Gqukunqa at Thambekeni	G	3251	877	1850	524
Inxu at Junction Ferry	I	3277	986	1787	504
Tsitsa at Mbelembushe	TN2	1874	763	871	240
Total (%)		23752	11279 (47%)	8466 (36%)	4007 (17%)

The data are heavily skewed towards those for which turbidity ≤ 200 ntu. At all sites except at Gqukunqa, Inxu, and the TN2 (Tsitsa at Mbelembushe), Subset 1 (turbidity only) comprised the most records. Subset 2 (SSC only) comprised the records that were the target of the sampling programme and that would most strongly influence SSL/SSY calculations, i.e., those with turbidity >200 ntu. Subset 3 (paired values) comprised the fewest records at each site, other than at Little Pot, and Pot.

6.3 Outlier removal from Subset 3

The paired SSC and turbidity values of Subset 3 were from triple samples, and from paired samples that were selected to represent the turbidity meter measurement range of 0.1 ntu to 999 ntu specifically for the purpose of establishing a site-specific SSC/turbidity relationship to apply to the turbidity values in Subset 1. The precision analysis (**Section 5.6.3.1**) found that the triple samples were heavily skewed towards low values due to site-specific operator, seasonal, and stage influences. Epistemic uncertainty due to sampling and laboratory imprecision, as well as natural uncertainty, was evident, particularly at low sediment concentrations (**Figure 5-7**). Natural uncertainty may be attributable to changes for example in particle size and shape, or sediment mineralogy or colour through flood events, which would

lead to non-unique SSC/turbidity relationships (Minella et al., 2008; Ramothello, 2021). SSC/turbidity regression was undertaken using the entire range of available turbidity values, (i.e., from 1 – 999 ntu, rather than only those from 0 – 200 ntu), to mitigate the natural and epistemic uncertainty associated with the low SSC/turbidity samples.

Natural and epistemic uncertainty both evidence in datasets as outliers, which can increase error variance in statistical analyses (Osborne & Overbay, 2019). Rejecting outliers caused by epistemic errors is a standard procedure ahead of correlation (Hadi et al., 2009), but there is a risk of rejecting valid datapoints resulting from natural variability.

Outliers are vaguely defined, for example as values far outside the norm, or even as values that appear dubious to the researcher (Osborne & Overbay, 2019). Rule formulation to define a data point as erroneous, and to remove it as an outlier, is case-specific (Hadi et al., 2009). Standardised methods such as removing values >2 SD from the mean, or above a particular threshold value, are inappropriate for heavily skewed datasets (Osborne & Overbay, 2019) and could result in the removal of valid high-SSC values present in Subset 3. This would lead to underestimation of SSL/SSY.

In this study, data points in Subset 3 were identified and removed as outliers using a three-step statistical and visual process, on the assumption that a linear relationship existed between turbidity and SSC (Gippel, 1995; Lewis, 1996; Minella et al., 2008; Regüés, 2013; Tananaev & Debolsky, 2014; Nadal-Romero et al., 2018):

- Firstly, the anomalous value of a “triple” set was removed when the %CV SSC was $> 25\%$,
- Secondly, *global* outliers were removed that were anomalous to the entire dataset (i.e., apparent from a graphed time-series and a regression analysis of SSC and turbidity),
- Thirdly, *contextual* outliers that were identified from a regression analysis were removed using case-based rules when anomalous within the range of adjacent data.

6.4 Regression analysis and error determination

Two-fold cross-validation, regression, and Mean Absolute Error (MAE) were used to develop, evaluate, and select the site-specific SSC/turbidity relationship that resulted in the least error when applied to turbidity values to calculate SSC.

Two-fold cross-validation evaluates estimator performance (in this case linear regression) in the absence of a “true” or reference value. The SSC/turbidity data pairs were divided into two subsets, and the linear regression developed from one subset was applied to the turbidity values in the other (Ronchetti et al.,

1997; Singh & Panda, 2011). The resulting calculated SSC was statistically evaluated against the measured SSC using MAE. The following actions were performed using MS Excel (Microsoft Office 365):

- For each site, the records in Subset 3 were divided equally into *odd* and *even* subsets by using **Data>Sort>largest to smallest** on SSC values, then selecting every other record.
- An SSC/turbidity regression was derived for Subset 3*odd* using **Insert> Chart> Scatter** and **Chart Tools>Trendline** functions.
- The regression equation from Subset 3*odd* was applied to the turbidity values ≤ 200 ntu of Subset 3*even* to calculate SSC in mg L^{-1} , giving the dataset CalcSSC*even*.
- Reciprocally, linear regression was performed using Subset 3*even*, and the result applied to turbidity ≤ 200 ntu in Subset 3*odd* (CalcSSC*odd*)
- MAE (**Equation 6-1**) was calculated for the samples in CalcSSC*odd* and in CalcSSC*even*, and the regression equation that gave the lowest MAE in mg L^{-1} was applied to all the turbidity values in Subset 1.

In this way, the full range of values (i.e., 0 to 999 ntu) was used to derive the SSC/turbidity relationship, whilst the error analysis was applied to the samples with turbidity < 200 ntu for which SSC was calculated.

Equation 6-1: $MAE = \frac{1}{n} \sum_{i=1}^n |x_i - x|$

Where:

n= number of samples

x = measured SSC (mg L^{-1}) where turbidity ≤ 200 ntu

x_i = CalcSSC*t* where turbidity ≤ 200 ntu

MAE statistically compares estimated to measured values in terms of fit, offset, noise, error, and bias, providing a more robust and practical comparison of estimator accuracy than the coefficient of determination, (Cohn et al., 1992; Ronchetti et al., 1997; Horowitz, 2003). Helpfully, in terms of conveying error statements to non-scientists including policy and decision makers, MAE gives results in the units of interest (i.e., mg L^{-1}) and is easier to interpret than for example Root Mean Square Error (Moriasi et al., 2007). It is important to note that the performance of the regression equation was assessed, *not* the absolute accuracy of the resulting SSC values.

6.5 Results

The results from the site at T2 (Tsitsa at Qulungashe Bridge) are fully reported here to illustrate the process by which outliers were removed and SSC/turbidity regression undertaken. The MS Excel workbook containing regression equations and error analysis for T2 (Tsitsa at Qulungashe Bridge) is included as **Appendix 7**.

6.5.1 T2 (Tsitsa at Qulungashe Bridge)

Firstly, outliers were removed from the triple sets with %CV SSC ≥ 25 ($n = 28$). Next, SSC/turbidity regression of T2 (Tsitsa at Qulungashe Bridge) Subset 3 ($n = 563$) was undertaken to reveal global outliers by visual inspection. **Figure 6-1** shows the SSC/turbidity relationship for T2 Subset 3 ($r^2 = 0.39$) before the removal of global outliers.

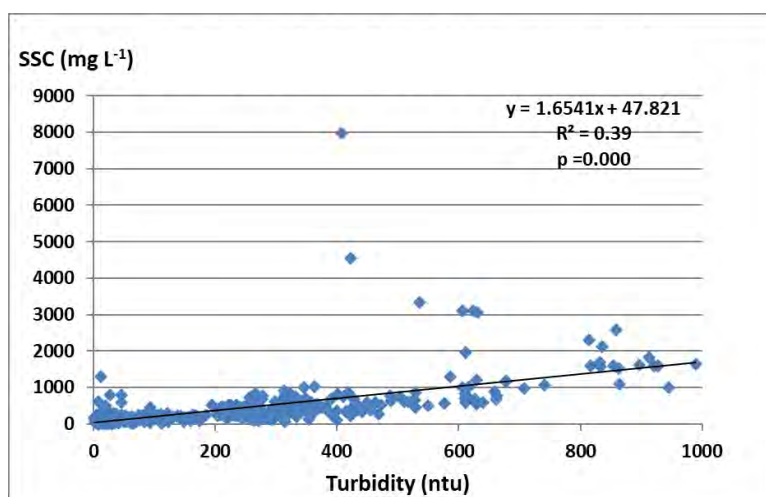


Figure 6-1: Regression of T2 Subset 3 before global outlier removal

Due to relatively high data density, **Figure 6-1** revealed global outliers where $SSC \geq 3000$ mg L⁻¹. These global outliers ($n = 6$) were removed from Subset 3 (**Figure 6-2**, $r^2 = 0.70$).

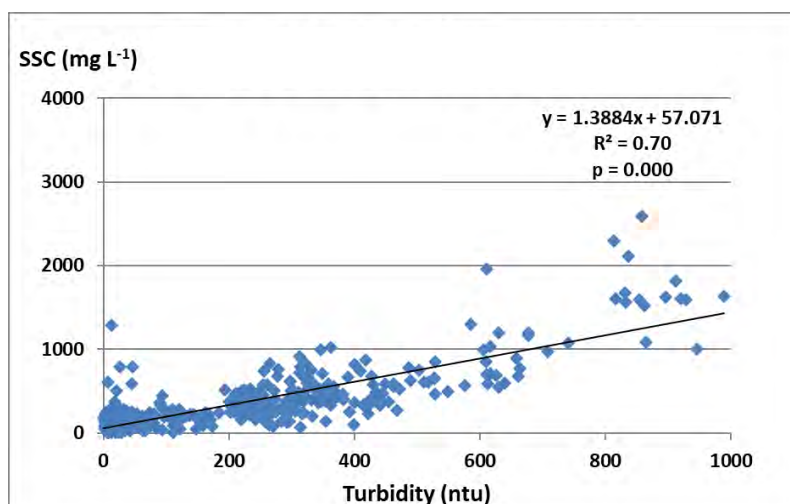


Figure 6-2: T2 Subset 3 after global outlier removal

Following global outlier removal, case-based rules were developed to identify contextual outliers. The paired SSC/turbidity values were first grouped using the turbidity values, for example 0 – 10 ntu, 10 – 20 ntu and so on (**Figure 6-3**, n=557). These groups provided the “context” within which the specific “cases” for outlier identification and removal were made, since due to the “noisy” nature of the data (**Figure 5-7**) no single, universal rule could be formulated and applied, even at a single site.

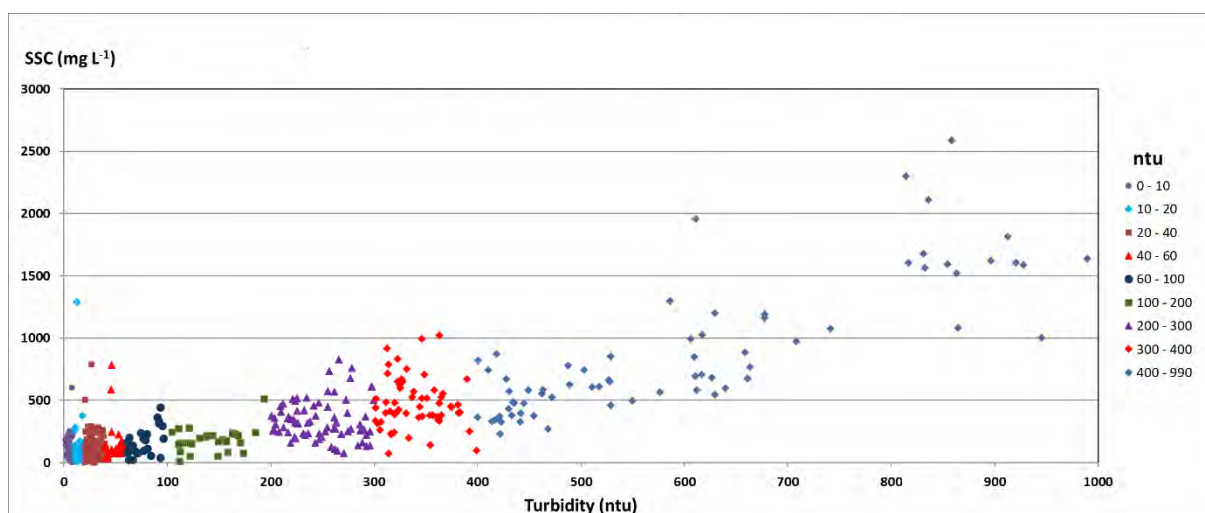


Figure 6-3: T2 Subset 3 grouped by turbidity (groups shown in different colours) before contextual outlier removal (n = 557)

Next, each group was visually inspected to identify SSC values that were out of context within that group, and “case-based” rules for outlier removal from each group were determined. The case-based rules that were applied to remove outliers from the data shown in **Figure 6-3** are summarised in **Table 6-3**, whilst **Figure 6-4** shows T2 Subset 3 grouped by sorted turbidity values after contextual outlier removal (n=517). No rule was formulated for groups where no outliers were revealed by visual inspection.

Table 6-3: Case-based rules for the identification and removal of contextual outliers from groups defined by turbidity values (ntu, shown in the same colours as Figure 6-3)

ntu	0 - 10	10 - 20	20 - 40	40 - 60	60 - 100	100-200	200 - 300	300 - 400	400-990
SSC>	300	200	300	300	250	300	220	850	1900
SSC<	no rule	no rule	no rule	no rule	no rule	100	no rule	150	no rule

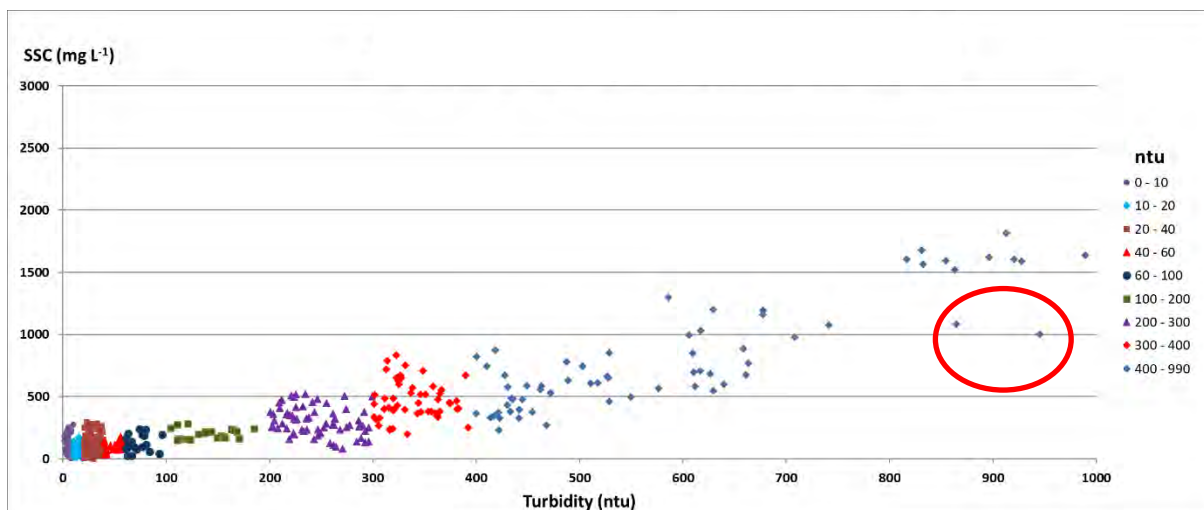


Figure 6-4: T2 Subset 3 grouped by turbidity after application of case-based rules for contextual outlier removal (shown in the same colours as Figure 6-3 and Table 6-3, n = 517)

The two points within the red oval in **Figure 6-4** were checked against adjacent SSC values in the chronologically ordered laboratory results dataset, and were found to be valid. **Figure 6-5** shows the SSC/turbidity relationship for Subset 3 (n= 517, $r^2 = 0.81$) after the removal of contextual outliers.

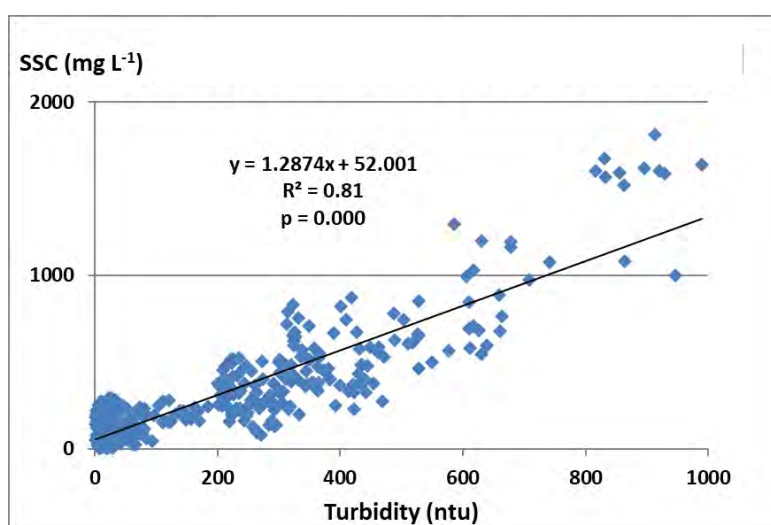


Figure 6-5: T2 Subset 3 after contextual outlier removal (n = 517)

Two-fold cross-validation and calculation of MAE was undertaken to derive the optimal SSC/turbidity relationship for Subset 3, and at the same time indicate the uncertainty in the relationship, in mg L⁻¹ (**Figures 6-6 and 6-7**). **Table 6-4** summarises the outcomes of two-fold cross-validation for T2 (Tsitsa at Qulungashe Bridge).

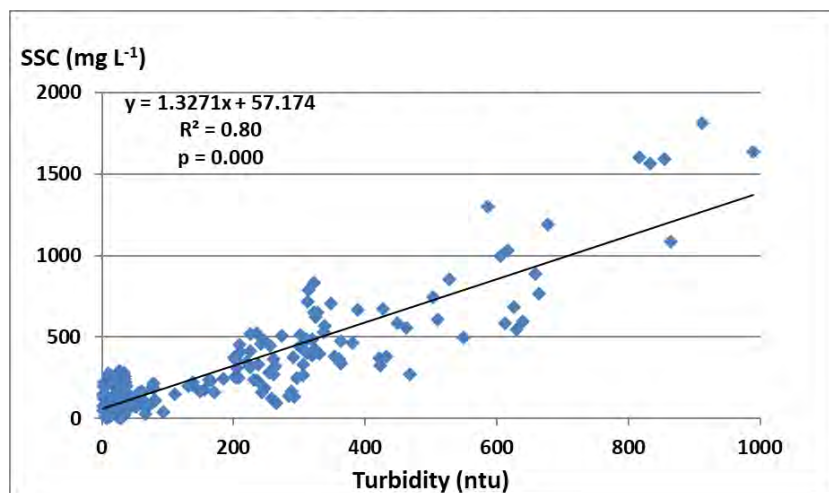


Figure 6-6: SSC/turbidity relationship for T2 (All pairs in Subset 3_{odd})

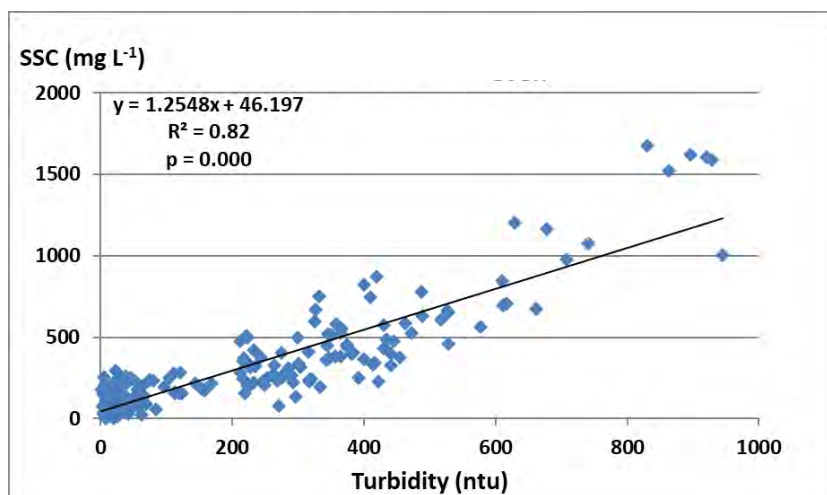


Figure 6-7: SSC/turbidity relationship for T2 (All pairs in Subset 3_{even})

Table 6-4: Summary of two-fold cross-validation of the SSC/turbidity relationship for T2

Data subset	All samples in subset					Samples where turbidity =<200 ntu				
	n	Turbidity range (average) ntu	SSC range (average) mg L ⁻¹	Regression	r ²	n	Average turbidity (ntu)	MAE mg L ⁻¹	calcSSCt range mg L ⁻¹	calcSSCt average mg L ⁻¹
<i>d_{odd}</i>	259	1.48 – 989.50 (153.86)	1.89 – 1813.53 (261.36)	$y = 1.3271x + 57.174$	0.80	170	33.14	54.55	48.05 – 278.34	87.78
<i>d_{even}</i>	258	1.26 – 945.5 (169.83)	2.80 – 1677.45 (259.29)	$y = 1.2548x + 46.197$	0.82	163	34.32	44.92	58.85 – 280.79	102.72

The equation from the Subset 3_{even} dataset resulted in the lowest MAE (44.92 mg L⁻¹) and was therefore applied to the measured turbidity of the records in Subset 1.

6.5.2 Outlier removal from Subset 3 (All sites)

Table 6-5 summarises the outliers removed from Subset 3 at each site.

Table 6-5: Summary of outliers removed from Subset 3 at each site

Site Name	Code	Samples in Subset 3	# Outliers removed	% Outliers removed
Little Pot at Cornlands	LP	112	25	22
Tsitsana at Lokishini	Ta	306	74	24
Hlankomo at Makgetheng	H	217	40	18
Tsitsa at The Falls	T4	240	16	7
Pot at Vipan Farm	P	556	54	10
Mooi at Maclear*	M	347	77	22
Tsitsa at the Gorge	T3	497	67	13
Tsitsa at Qulungashe Bridge	T2	591	74	13
Gqukunqa at Thambekeni	G	521	80	15
Inxu at Junction Ferry	I	550	140	25
Tsitsa at Mbelembushe**	TN2	421	99	24

At all sites except at T4 (Tsitsa at the Falls) where few triple samples were taken (Table 5-6), more than 10% of samples were removed as outliers. At five sites, 20% - 25% of the samples in Subset 3 were removed. This high percentage of outliers implies a high degree of uncertainty, which, notably, exclusively affects samples with low turbidity (<200 ntu) and axiomatically, low calculated SSC.

6.5.3 Regression analysis and error determination (All sites)

Table 6-6 summarises the number of samples, the SSC/turbidity relationships, the r^2 , the p value, and the MAE in mg L^{-1} for the eleven sites in the Tsitsa River catchment. Average and maximum SSC (mg L^{-1}) after outlier removal in Subset 3 are included in Table 6-6 for comparison with MAE at each site.

Table 6-6: Summary of site-specific SSC/turbidity relationships in the Tsitsa River catchment

Site	n	Equation	r ²	p	MAE (mg L ⁻¹)	Average SSC of Subset 3* (mg L ⁻¹)	Maximum SSC of Subset 3* (mg L ⁻¹)
Little Pot	44	y = 0.6243x + 106.43	0.56	0.000	36.67	123.58	909.95
Tsitsana	115	y = 0.8396x + 78.267	0.85	0.000	51.09	226.73	1378.03
Hlankomo	89	y = 0.3894x + 76.764	0.38	0.001	41.19	104.85	397.63
T4 (Tsitsa at the Falls)	112	y = 0.7494x + 105.07	0.76	0.000	56.37	213.08	1089.98
Mooi	135	y = 1.1813x + 32.875	0.66	0.000	37.81	166.60	1041.00
Pot	251	y = 0.8607x + 85.063	0.68	0.000	50.28	150.67	1273.48
T3 (Tsitsa at the Gorge)	215	y = 1.0345x + 59.645	0.82	0.000	45.91	175.50	1343.45
T2 (Tsitsa at Qulungashe Bridge)	258	y = 1.2548x + 46.197	0.82	0.000	44.92	260.33	1813.53
Gqukunqa	221	y = 1.2137x + 36.547	0.76	0.000	49.55	290.75	1810.23
Inxu	205	y = 1.2919x + 50.169	0.77	0.000	52.91	409.39	3364.49
TN2 (Tsitsa at Mbelembushe)	161	y = 0.9633x + 57.854	0.89	0.000	45.98	244.01	1038.19

*After outlier removal

SSC and turbidity were strongly correlated at all sites except at Hlankomo ($r^2 = 0.38$), and all were highly significant. MAE had a relatively narrow range, between 36.67 mg L⁻¹ (Little Pot) and 56.37 mg L⁻¹ (T4, Tsitsa at the Falls). As noted, MAE provides insight into uncertainty using the units of interest (mg L⁻¹). MAE was less significant where the average SSC was relatively high, i.e., at the four sites representing the most downstream catchments that were dominated by Tarkastad Formation geology: T2 (Tsitsa at the Qulungashe Bridge), Gqukunqa, Inxu, and TN2 (Tsitsa at Mbelembushe). MAE was more significant for the remainder of the sites, where the difference between average SSC and MAE was less, and where MAE => 20% of average SSC. These sites represent the middle and upper catchments. The contrast in these relationships was most notable between Hlankomo and Inxu.

6.5.4 Instantaneous suspended sediment concentration time series (All sites)

Figures 6-8 to 6-18 show the instantaneous SSC at each site as time-series, comprising SSC calculated from turbidity (Subset 1) and measured SSC from Subsets 2 and 3. Note that the time-period and the scale (mg L⁻¹) of each graph are site-specific.

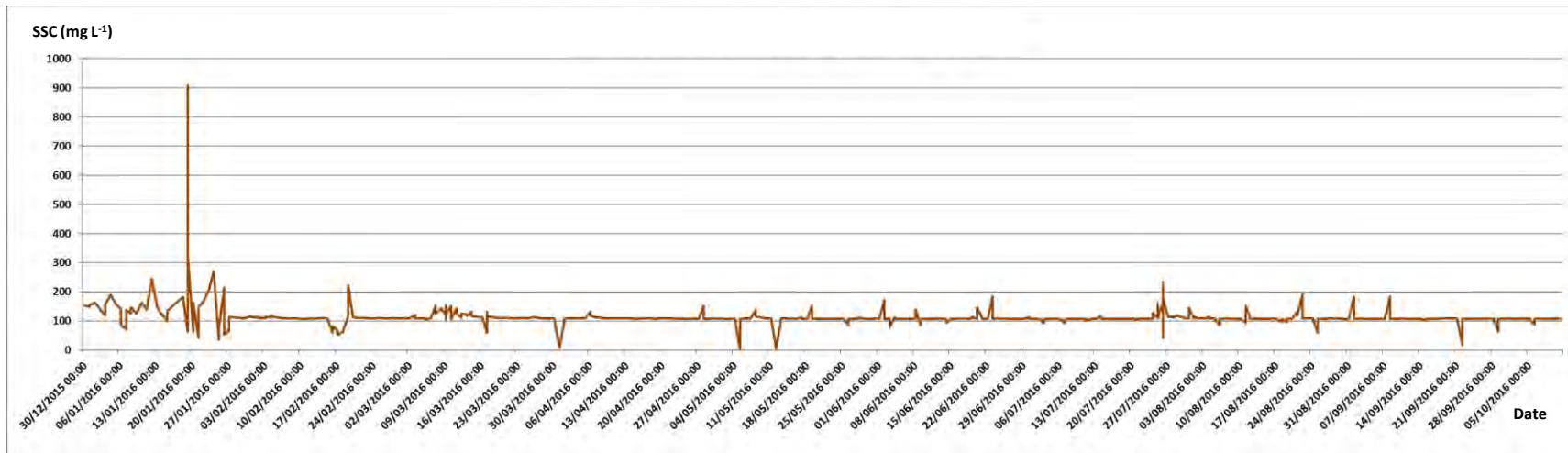


Figure 6-8: Instantaneous SSC (measured and calculated) 30 12 2015 - 11 10 2016 at Little Pot

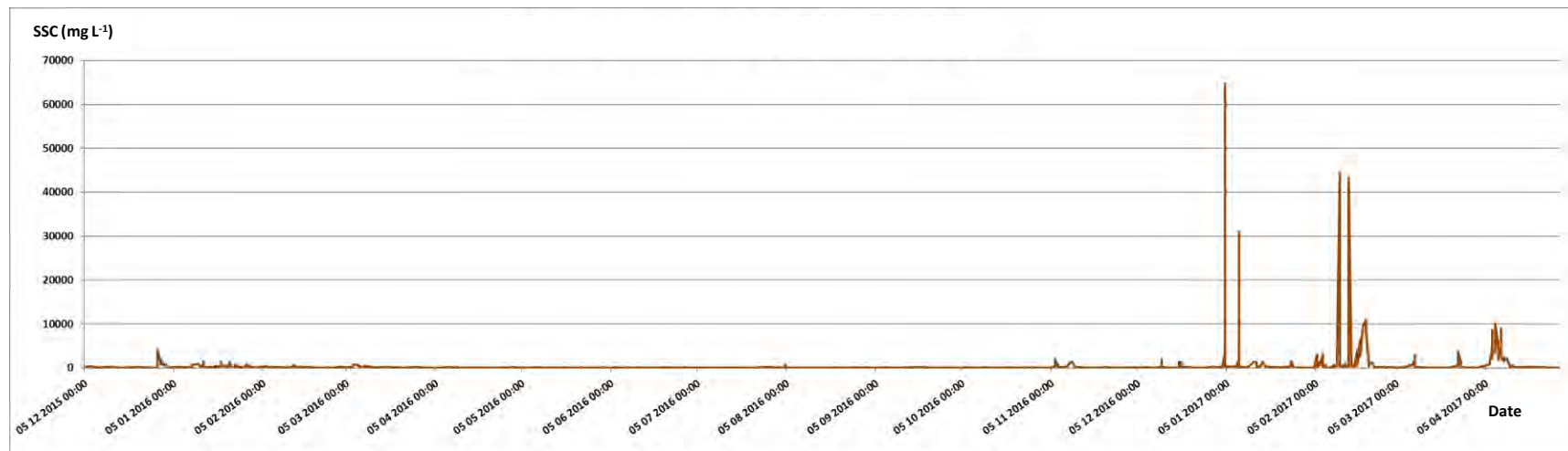


Figure 6-9: Instantaneous SSC (measured and calculated) 05 12 2015 – 30 04 2017 at Tsitsana

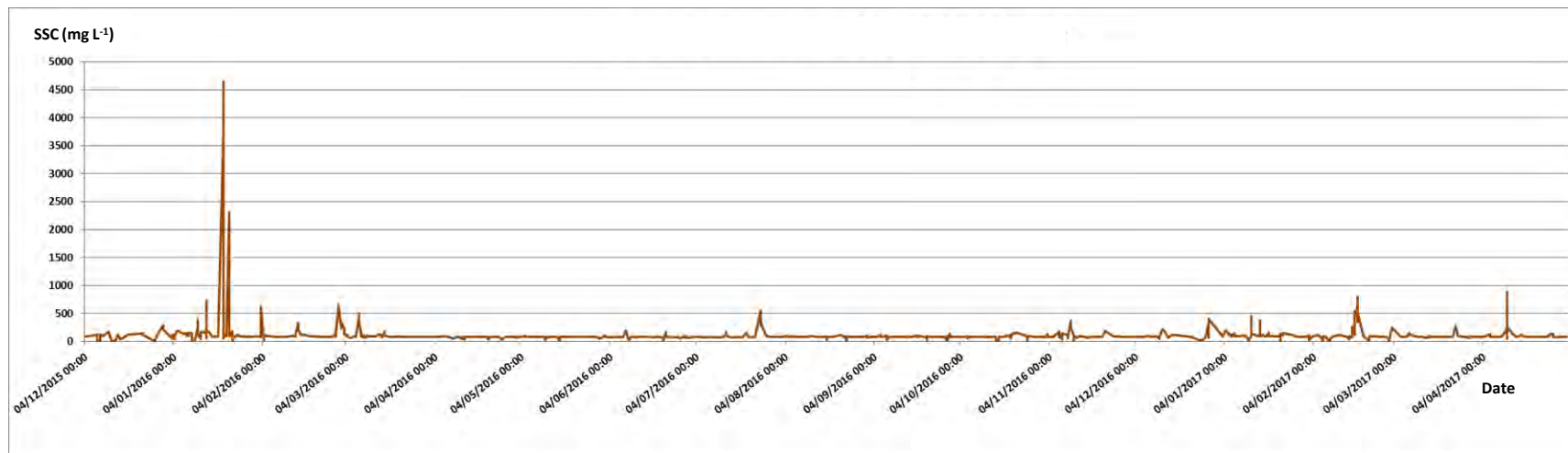


Figure 6-10: Instantaneous SSC (measured and calculated) 04 12 2015 – 03 05 2017 at Hlankomo

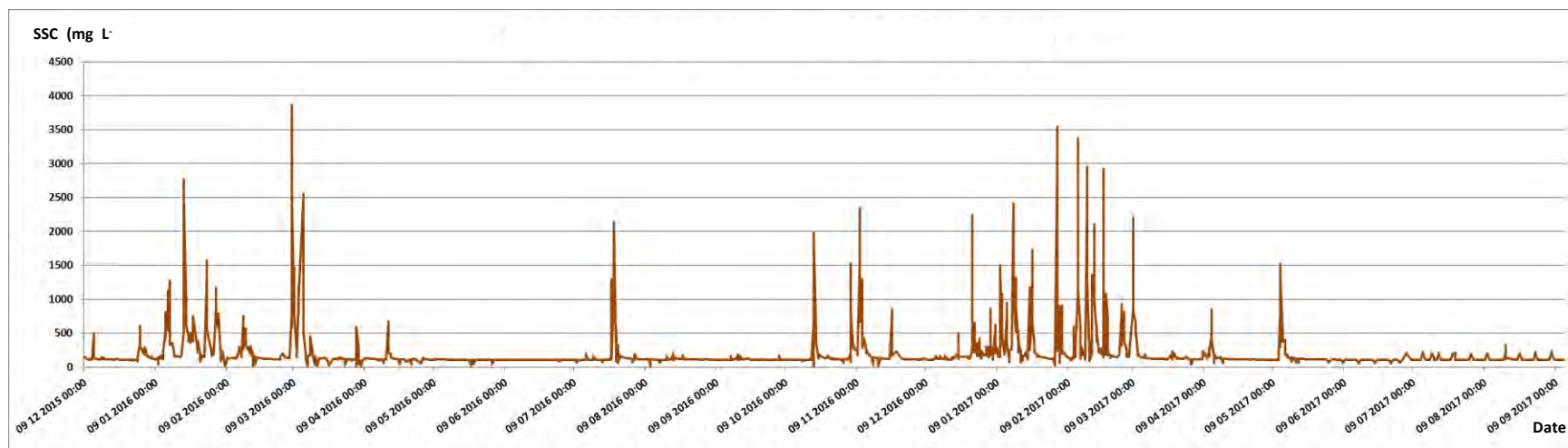


Figure 6-11: Instantaneous SSC (measured and calculated) 09 12 2015 – 12 09 2017 at T4 (Tsitsa at the Falls)

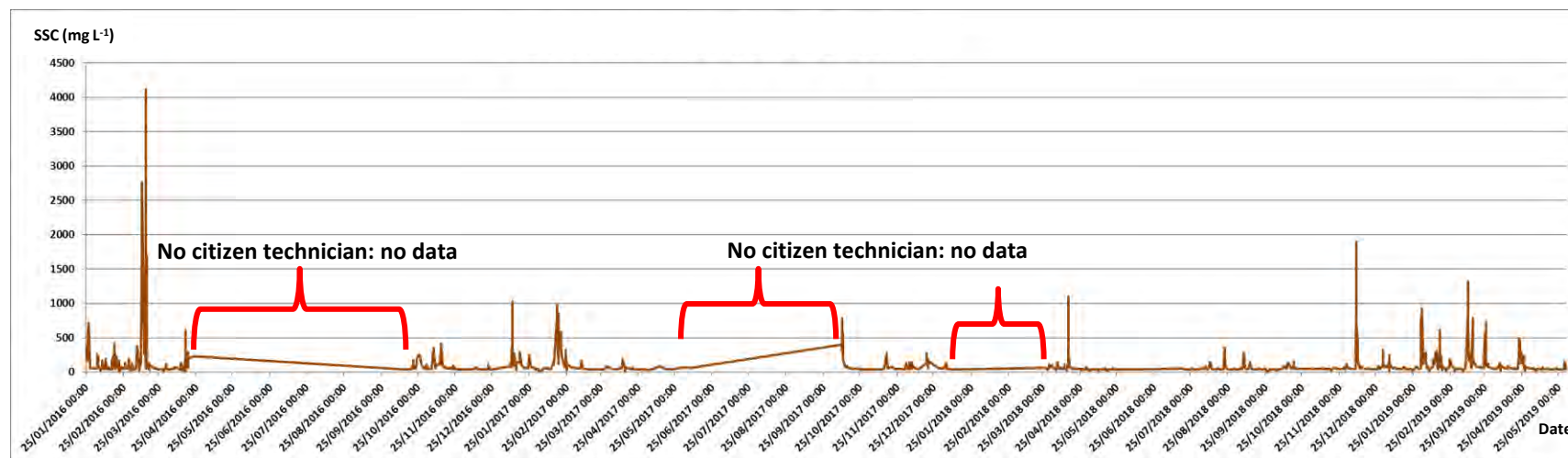


Figure 6-12: Instantaneous SSC (measured and calculated) 25 01 2016 - 31 05 2019 at Mooi

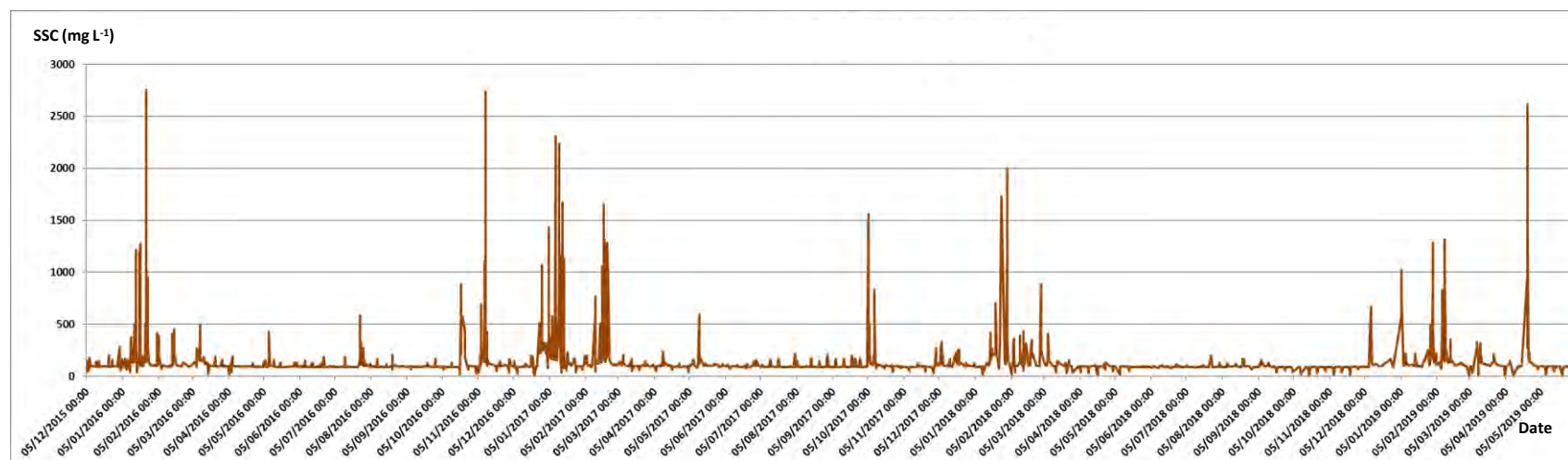


Figure 6-13: Instantaneous SSC (measured and calculated) 05 12 2015 - 31 05 2019 at Pot

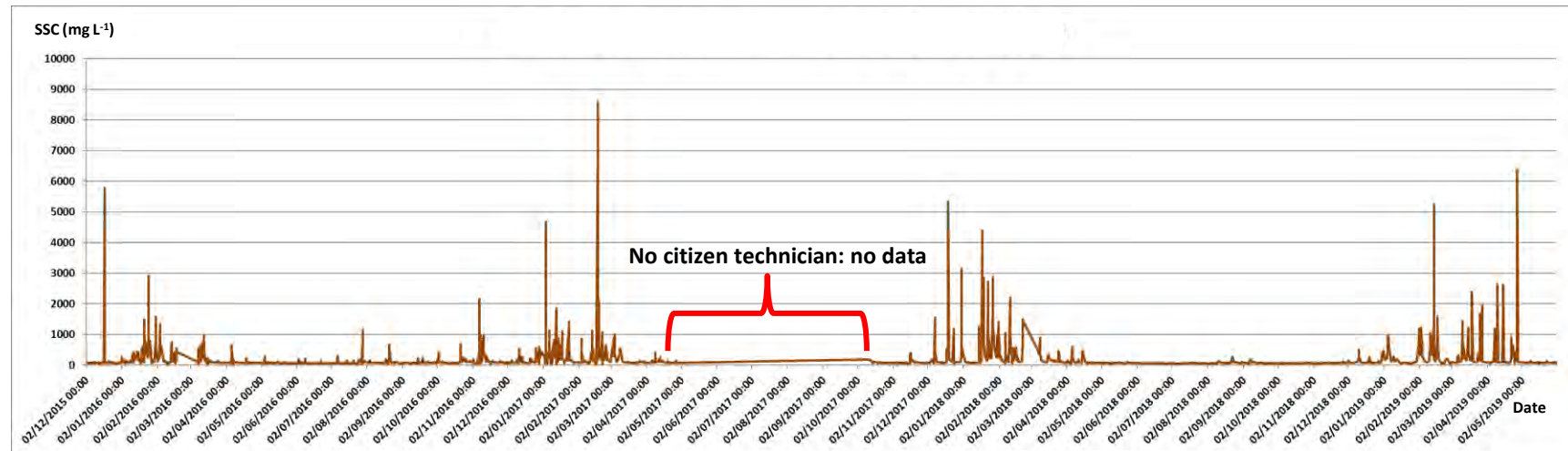


Figure 6-14: Instantaneous SSC (measured and calculated) 02 12 2015 - 31 05 2019 at T3 (Tsitsa at the Gorge)

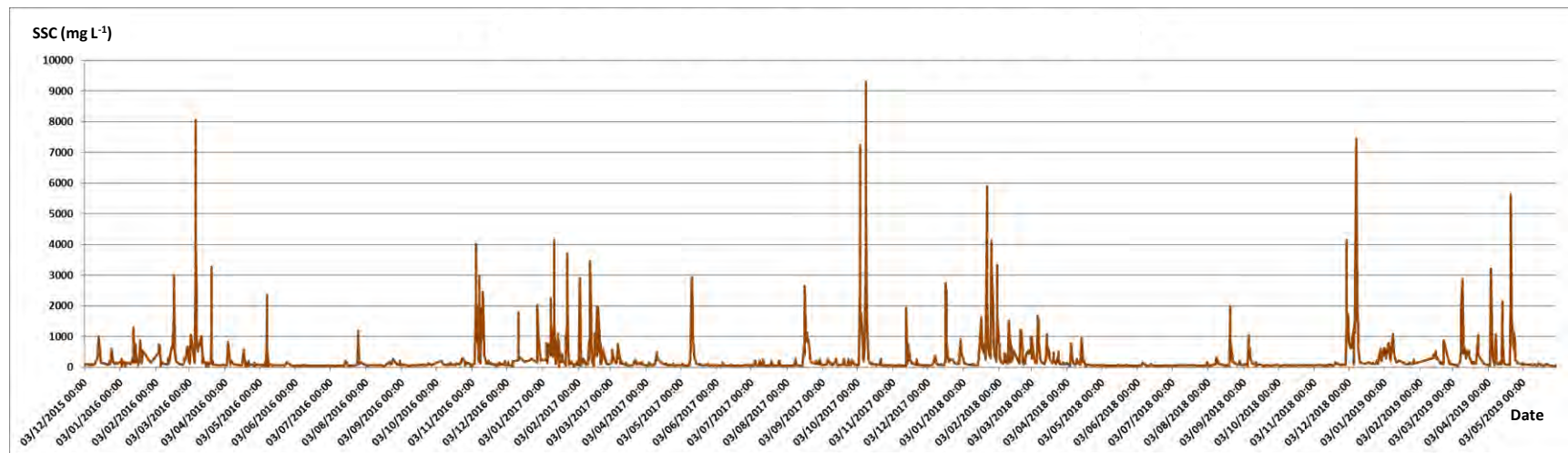


Figure 6-15: Instantaneous SSC (measured and calculated) 03 12 2015 - 31 05 2019 at T2 (Tsitsa at Qulungashe Bridge (T2))

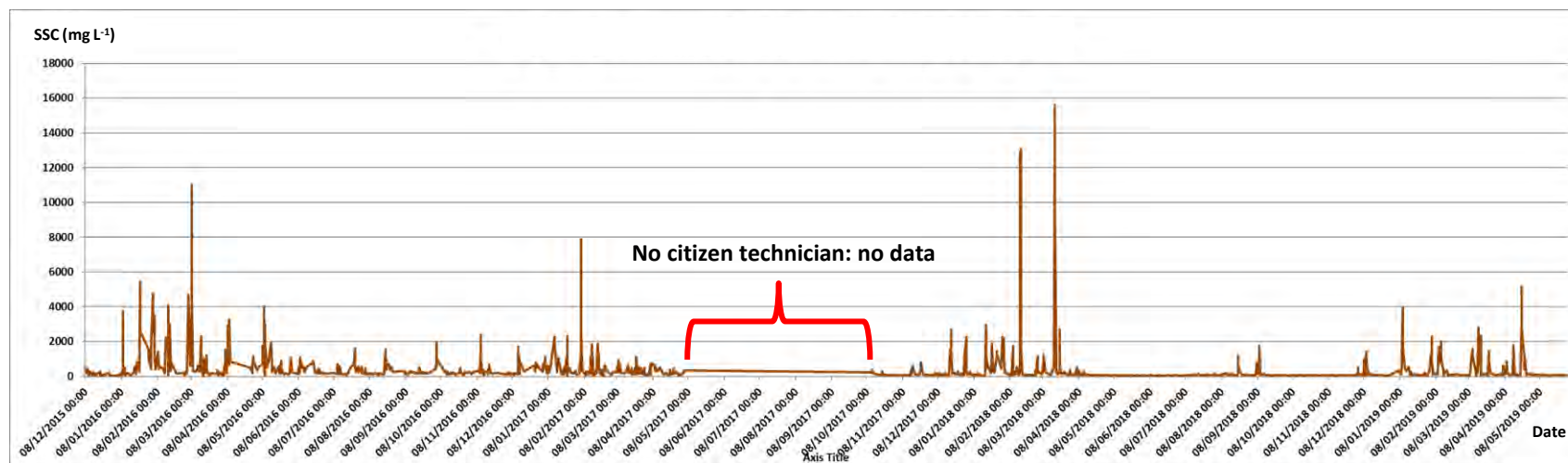


Figure 6-16: Instantaneous SSC (measured and calculated) 08 12 2015 - 31 05 2019 at Gqukunqa

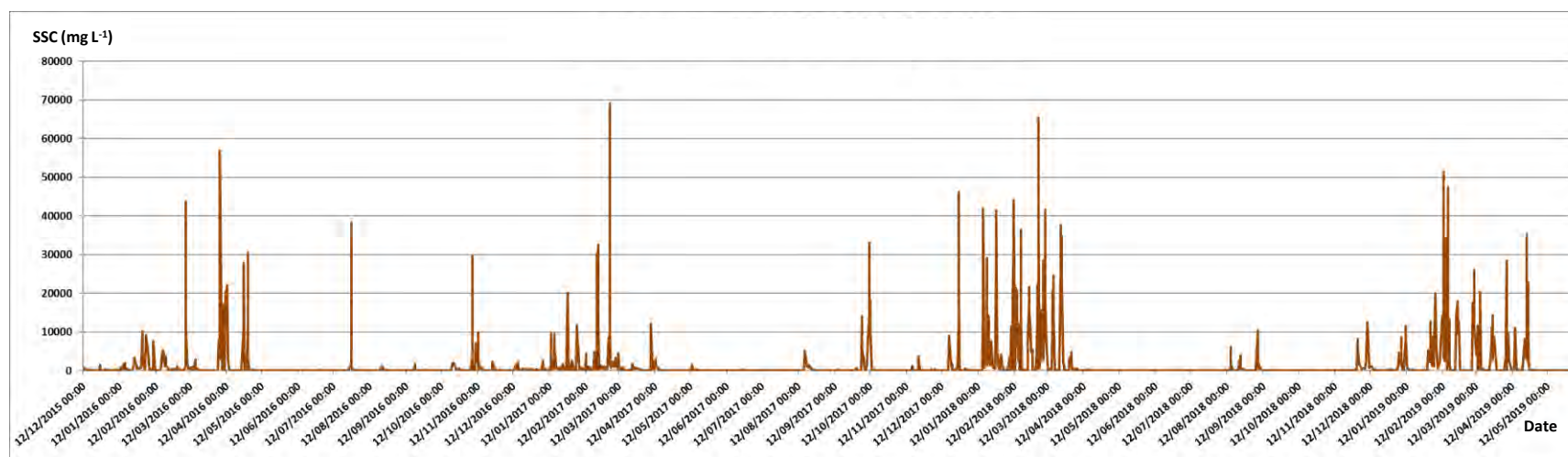


Figure 6-17: Instantaneous SSC (measured and calculated) 12 12 2015 - 31 05 2019 at Inxu

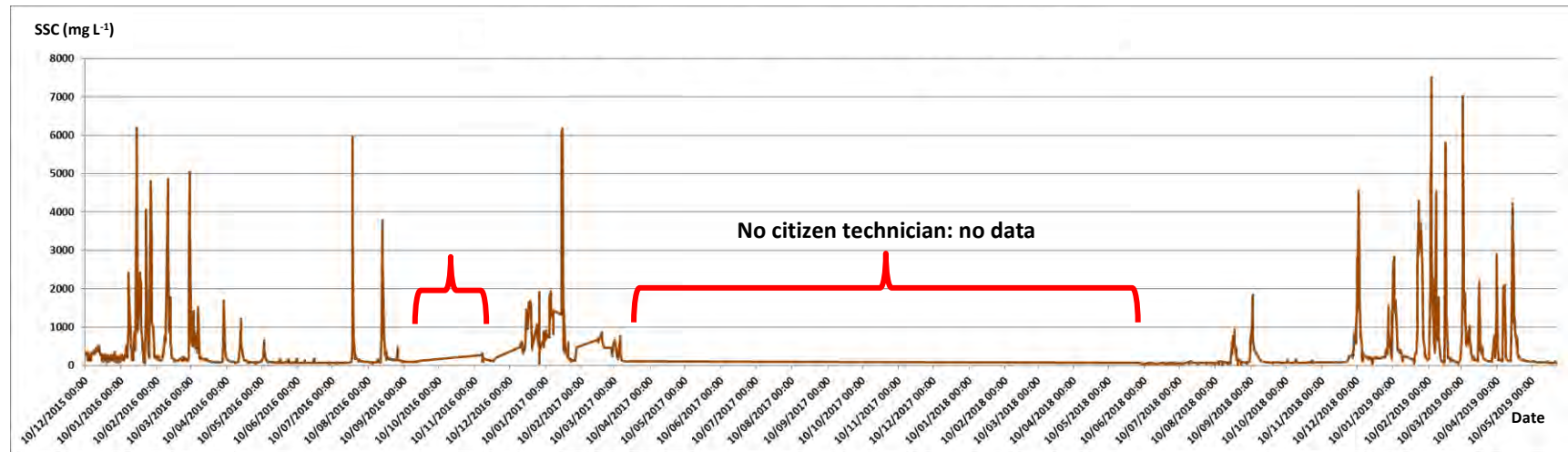


Figure 6-18: Instantaneous SSC (measured and calculated) 10 12 2015 - 31 05 2019 at TN2 (Tsitsa at Mbelembushe)

The error associated with calculating SSC from turbidity was most evident at Little Pot, where peak and average SSC was the lowest of all monitoring sites and most SSC values were calculated from turbidity < 200 ntu. The least apparent error in the SSC/turbidity calculation was at Inxu where peak and average SSC were the highest recorded for all monitoring sites.

There are notably high (and at some sites, apparently isolated) SSC values. Recalling that outliers have been removed (Section

6.6 Summary: The uncertainty associated with calculating suspended sediment concentration from measured turbidity (Objective 2)

Site-specific SSC/turbidity relationships were derived using linear regression to calculate instantaneous SSC data from turbidity data, following outlier removal. MAE was used to select the optimal SSC/turbidity relationship and to calculate error estimates in mg L^{-1} for each site. The error associated with calculating SSC from turbidity was greatest at Little Pot where peak and average SSC was the lowest of all monitoring sites and most SSC values were calculated from turbidity < 200 ntu. The least error in the SSC/turbidity calculation was at Inxu, where peak and average SSC were the highest recorded for all monitoring sites. The relative significance of the uncertainty associated with low and high SSC samples is discussed in **Section 9.2.2**. In the following chapter, calculated SSC and observed SSC are used to derive daily SSC.

7 Calculating suspended sediment loads and yields (Objective 2)

7.1 Overview

Chapter 5 reported that, for this study, SSC and turbidity data were measured at variable timesteps and were discontinuous at all sites. **Chapter 6** described the actions and methods used to calculate SSC from turbidity data ≤ 200 ntu. This chapter describes the actions, methods, and outputs associated with deriving daily SSC data from instantaneous measured and calculated SSC, and estimating sub-catchment annual SSL and SSY using the daily SSC and discharge data as input (**Objective 2 (outputs b, c, and d)**, **Table 7-1**).

Table 7-1: Objective 2 actions, methods, and outputs

Objective 2	Estimate the project period measured SSLs and SSYs for each sub-catchment with, where feasible, an assessment of the sources and extent of the uncertainty in the estimate
Action	a) Derive SSC from turbidity measurements. b) Derive daily SSC. c) Estimate sub-catchment SSL and SSY using the daily SSC and daily discharge time-series.
Method	a) Establish a site-specific SSC/turbidity relationship and calculate SSC from turbidity for samples < 200 ntu. b) Derive daily time-weighted mean SSC (mg L^{-1}) from instantaneous measured and calculated SSC. c) Select an appropriate SSL estimator. d) Estimate SSL and SSY for all sub-catchments.
Output	a) Site-specific SSC/turbidity relationships b) Daily SSC (mg L^{-1}) c) Measured sub-catchment SSLs (t) and SSYs (t km^2) d) Where feasible, statements of uncertainty for these outputs

The following steps were undertaken to estimate annual SSLs:

- Daily average SSC was derived using time-weighted mean concentration (TWMC)
- Outliers were removed from the daily SSC data base.
- SSC/discharge correlations were undertaken to determine r^2 .
- An appropriate SSL estimator was selected using r^2 as a criterion.
- Annual SSLs/SSYs were estimated for each monitoring site.
- SSL/SSY variability was determined using %CV as a measure of uncertainty where possible.

7.2 Calculating daily suspended sediment concentration

As noted in **Chapter 5**, at all sites for any given day during the project period, one of three cases applied regarding instantaneous observed SSC values:

- 1) No SSC data were available
- 2) One SSC value was available (e.g., during the dry, winter months 1 June – 30 September)
- 3) Several SSC values were available (e.g., due to flood sampling during the wet, summer months October - May)

Time-weighted mean concentration (TWMC, **Section 3.7.2**) was therefore used as an averaging estimator to accommodate variable sampling frequency (**Equation 7-1**, Richards & Baker, 1993).

Equation 7-1:

$$TWMC = \frac{\sum_i^n (c_i * t_i)}{\sum_i^n (t_i)}$$

Where:

c_i = SSC (mg L⁻¹) for the i^{th} sample

t_i = time for the i^{th} sample

n = number of samples

Deriving daily SSC using TWMC rather than the arithmetic mean will still (to a lesser extent) lead to underestimated SSL/SSY, because SS transport is positively flow-dependent (Walling & Webb, 1985; Richards & Baker, 1993). Error will also occur due to the necessary (but wrong) assumption that each SSC sample (i.e., c_i in **Equation 7-1**) fully represents SSC throughout the preceding time period, particularly if the sampling interval exceeds the period over which significant change in SSC is likely to occur.

The MS Excel workbook containing the calculations for T2 (Tsitsa at Qulungashe Bridge) as an example of applying TWMC to instantaneous SSC is included as **Appendix 8**. **Figures 7-1 to 7-11** illustrate the results as daily SSC timeseries, plotted together with daily discharge to provide a first insight into the relationship between SSC and discharge at each site. Note that the primary and secondary y-axes are site specific.

As summarised in **Table 5-4**, sampling periods varied from site to site. These “site periods” are reflected on the x-axes of **Figures 7-1 to 7-11**. Also indicated are the periods at each site for which either SSC or discharge data were not available, i.e., periods for which daily SSL could therefore not be estimated. These were also shown for SSC in **Figure 5-6**.

Table 7-2 summarises the number of datapoints and the mean, median and maximum value of both instantaneous and daily SSC at each site for the project period, to show the degree of data “smoothing” that occurred as a result of deriving daily SSC. **Table 7-3** shows the same information for discharge.

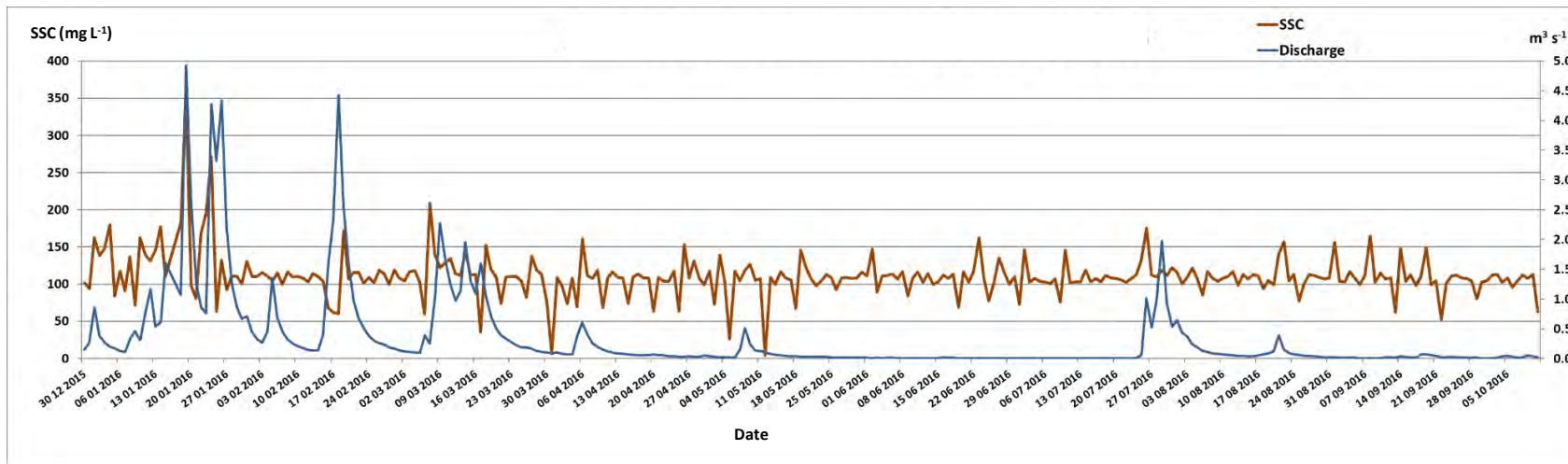


Figure 7-1: Daily SSC and discharge 30 12 2015 - 11 10 2016 at Little Pot

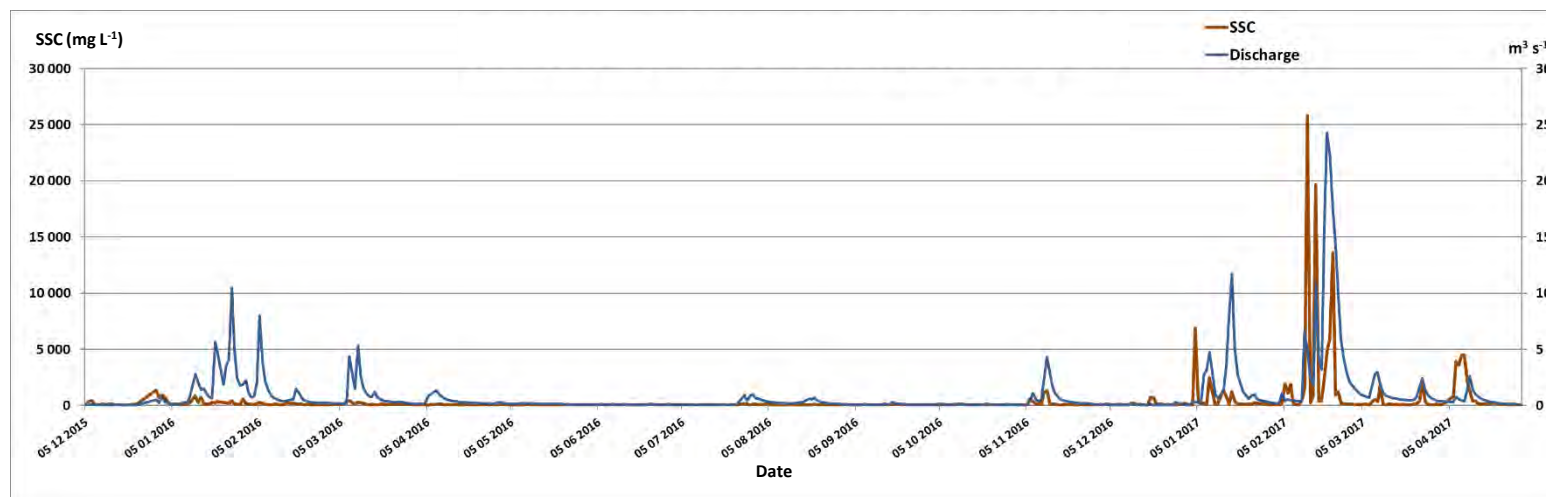


Figure 7-2: Daily SSC and discharge 05 12 2015 – 30 04 2017 at Tsitsana

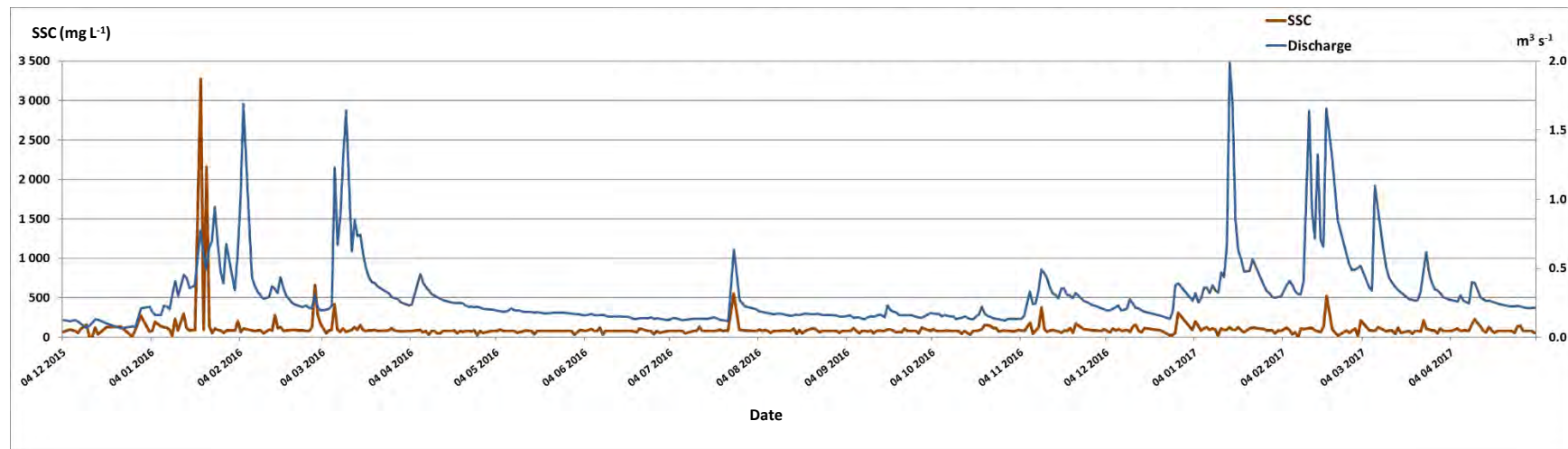


Figure 7-3: Daily SSC and discharge 04 12 2015 – 03 05 2017 at Hlankomo

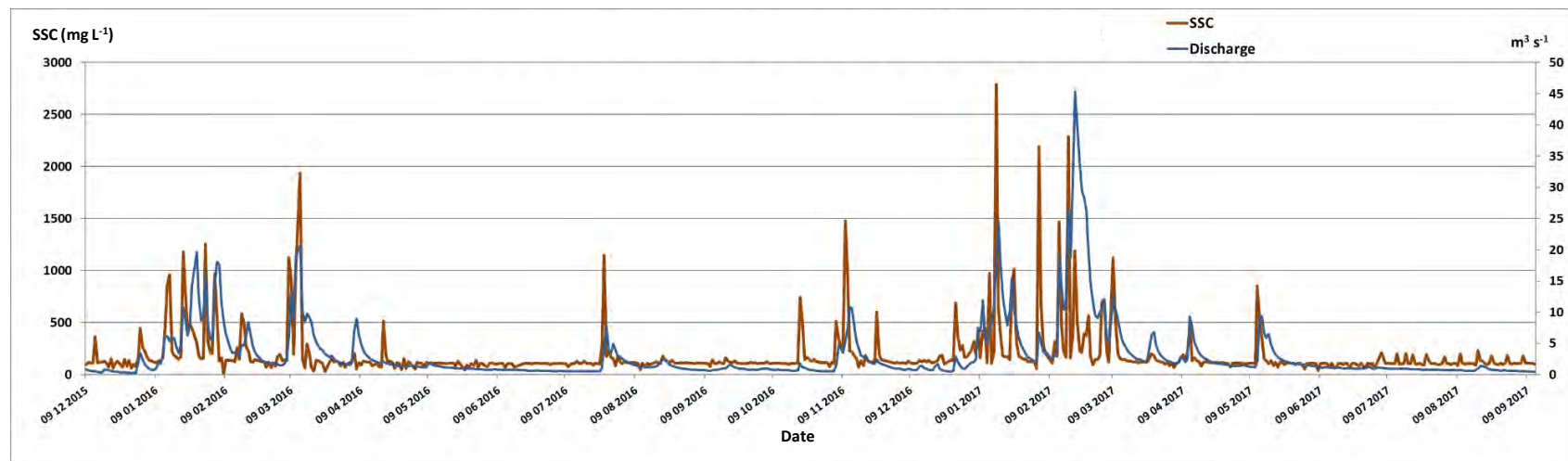


Figure 7-4: Daily SSC and discharge 09 12 2015 – 12 09 2017 at T4 (Tsitsa at the Falls)

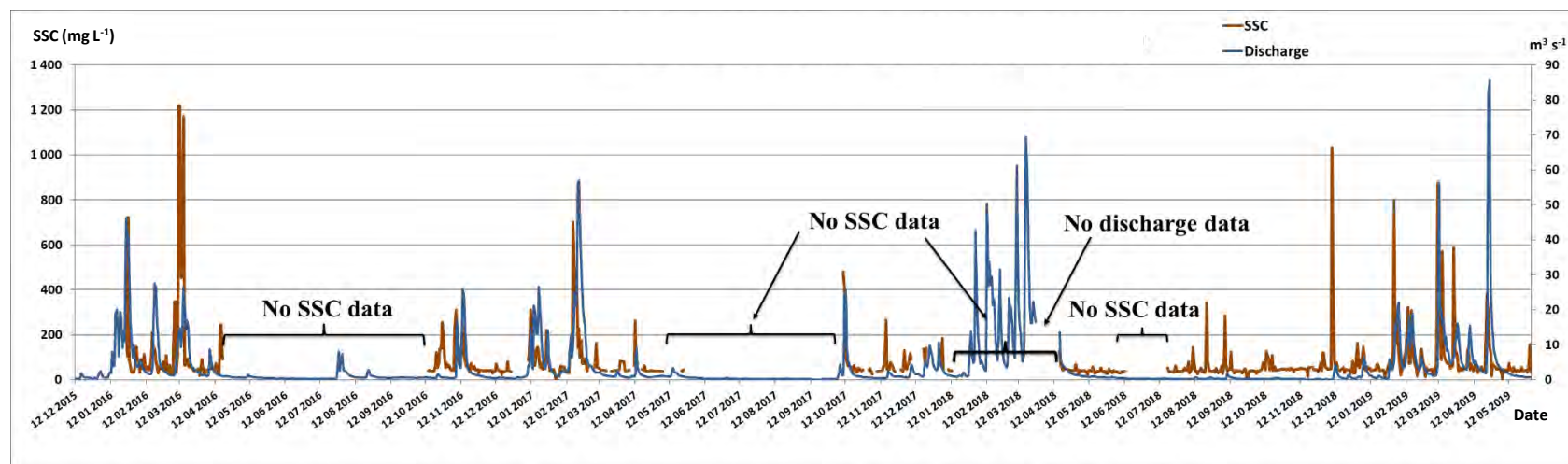


Figure 7-5: Daily SSC and discharge 25 01 2015 - 31 05 2019 at Mooi

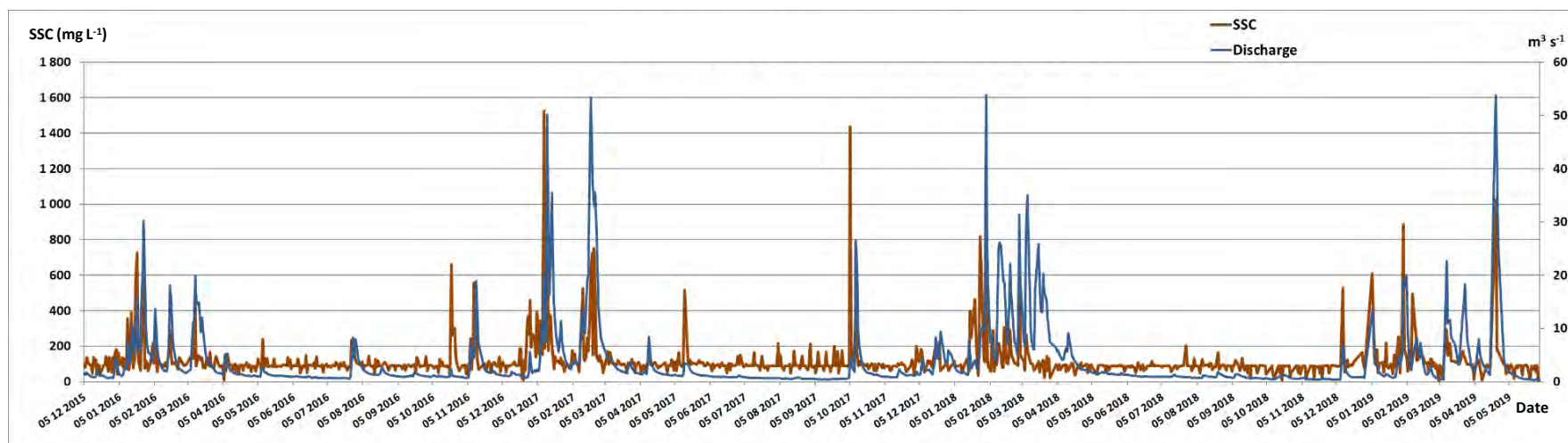


Figure 7-6: Daily SSC and discharge 05 12 2015 - 31 05 2019 at Pot

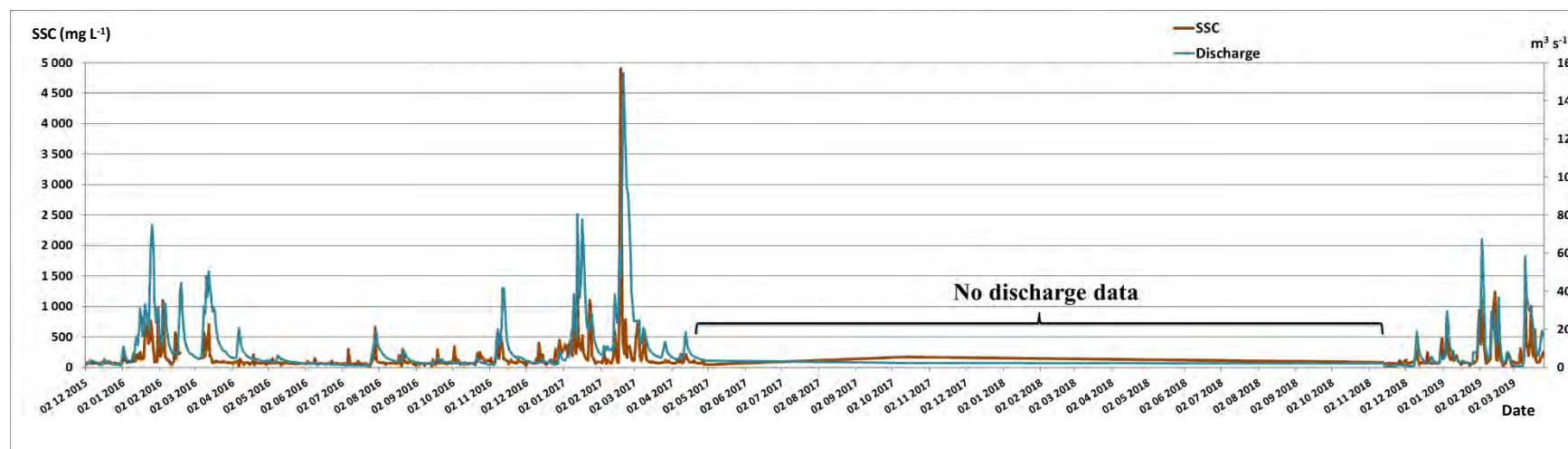


Figure 7-7: Daily SSC and discharge 02 12 2015 – 26 03 2019 at T3 (Tsitsa at the Gorge)

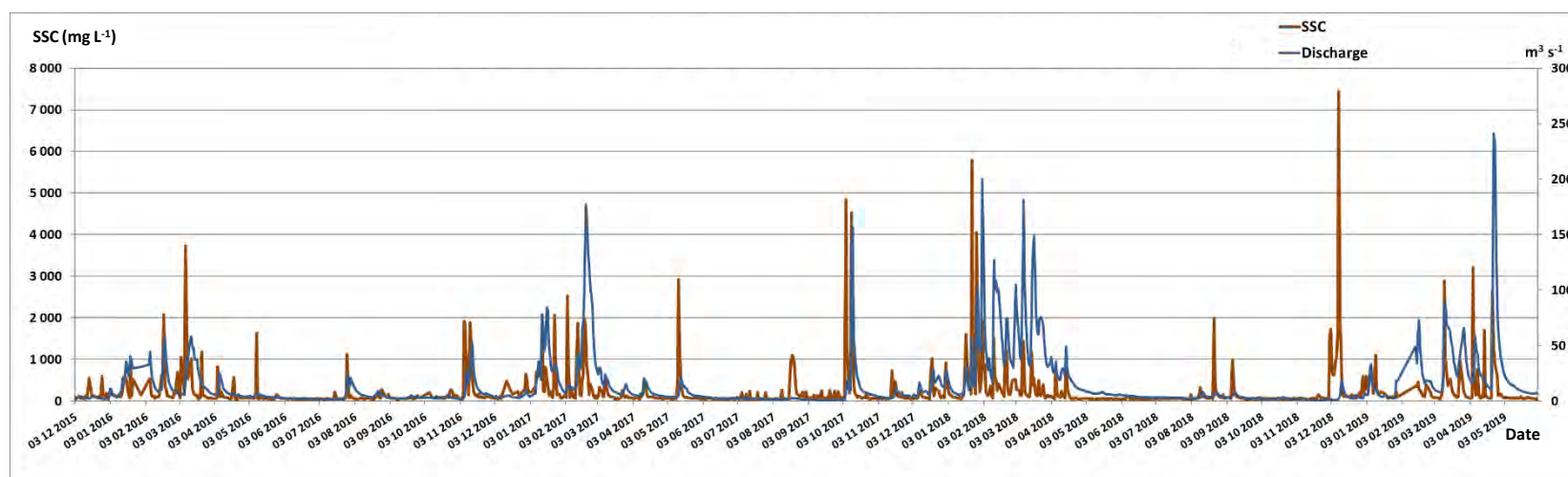


Figure 7-8: Daily SSC and discharge 03 12 2015 - 31 05 2019 at T2 (Tsitsa at Qulungashe Bridge)

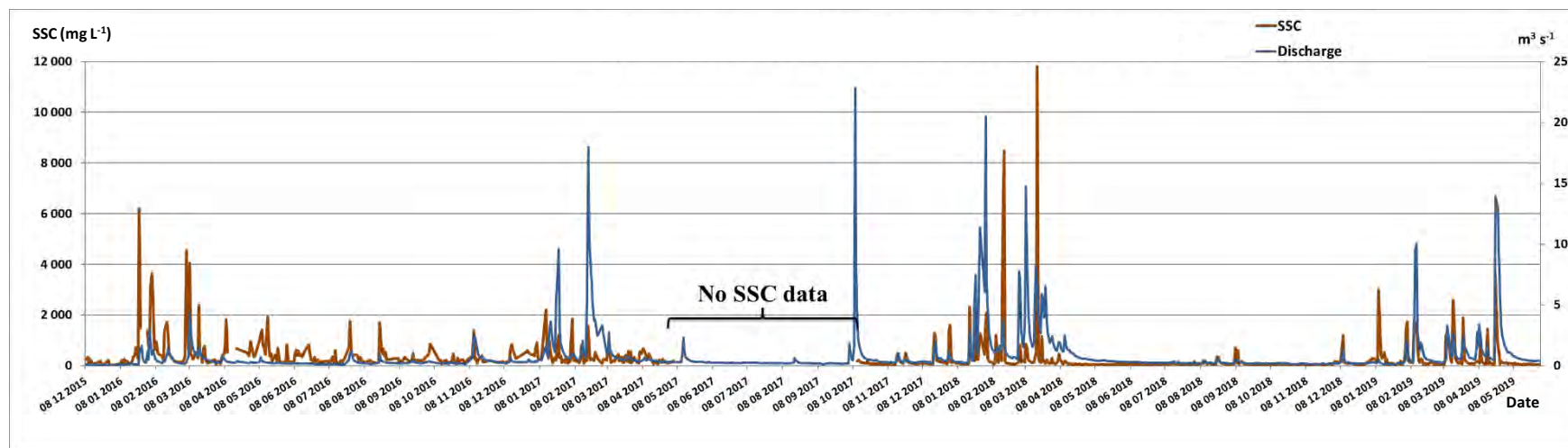


Figure 7-9: Daily SSC and discharge 08 12 2015 - 31 05 2019 at Gqukunqa

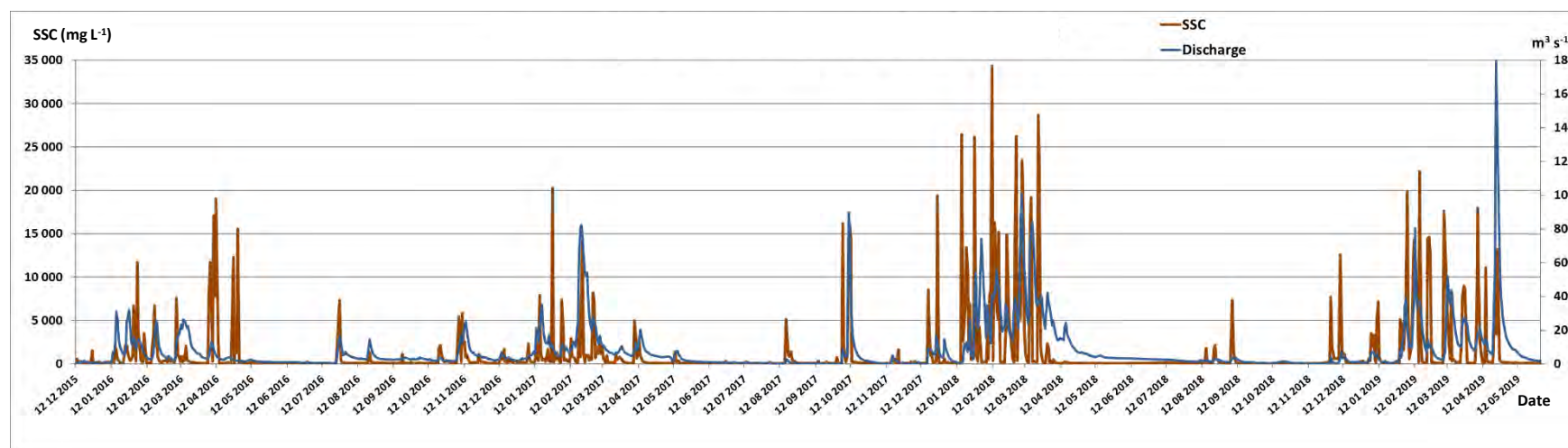


Figure 7-10: Daily SSC and discharge 12 12 2015 - 31 05 2019 at Inxu

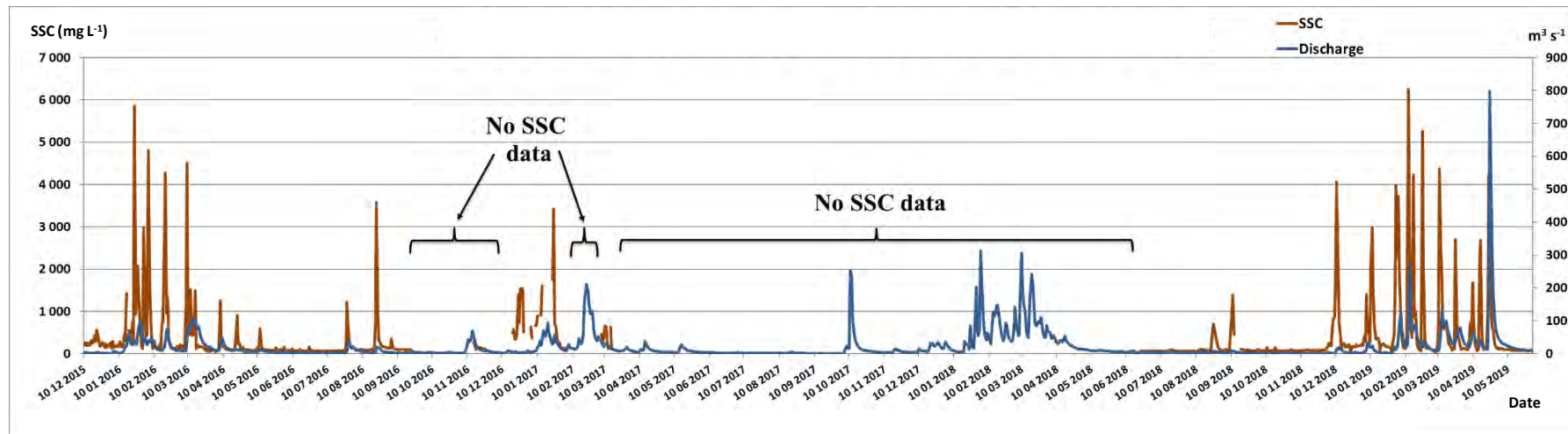


Figure 7-11: Daily SSC and discharge 10 12 2015 - 31 05 2019 at TN2 (Tsitsa at Mbelembushe)

Table 7-2: Number of samples, mean, median, and maximum values for instantaneous SSC and daily time-weighted average SSC

Site Name	Instantaneous SSC				Daily SSC			
	# Samples	Mean (mg L ⁻¹)	Median (mg L ⁻¹)	Maximum (mg L ⁻¹)	# Days	Mean (mg L ⁻¹)	Median (mg L ⁻¹)	Maximum (mg L ⁻¹)
Little Pot at Cornlands	616	122.51	108.59	909.95	285	111.01	108.62	358.51
Tsitsana at Lokishini	1510	801.18	105.76	64796.08	473	379.07	91.28	25799.65
Hlankomo at Makgetheng	1086	154.69	91.22	4645.08	404	107.45	81.93	3273.87
T4 (Tsitsa at The Falls)	2196	250.79	159.38	3862.63	622	188.86	115.06	2788.96
Pot at Vipan Farm	2140	202.21	105.76	2751.12	1032	119.96	92.03	1524.47
Mooi at Maclear	1760	149.70	89.68	4116.73	653	79.74	47.18	1219.02
T3 (Tsitsa at the Gorge)	2954	295.74	121.56	8592.94	1018	159.75	76.21	4901.60
T2 (Tsitsa at Qulungashe Bridge)	2445	488.05	151.60	9297.74	1046	246.57	84.77	7452.82
Gqukunqa at Thambekeni	3208	795.92	370.98	15628.87	890	306.48	120.37	11803.35
Inxu at Junction Ferry	3177	5011.42	955.53	69158.02	1129	1275.28	118.09	34316.74
TN2 (Tsitsa at Mbelembushe)	1956	659.38	236.66	7513.33	686	375.29	115.78	6247.07

Table 7-3: Number of samples, mean, median and maximum values for 15 minute discharge and daily average discharge

Site Name	Instantaneous Discharge				Daily Discharge			
	# Readings	Mean (m ³ s ⁻¹)	Median (m ³ s ⁻¹)	Maximum (m ³ s ⁻¹)	# Days	Mean (m ³ s ⁻¹)	Median (m ³ s ⁻¹)	Maximum (m ³ s ⁻¹)
Little Pot at Cornlands	20546	0.35	0.06	43.08	286	0.35	0.06	4.92
Tsitsana at Lokishini	36956	0.89	0.21	79.35	514	0.88	0.22	24.29
Hlankomo at Makgetheng	37162	0.31	0.22	20.18	517	0.31	0.22	1.99
T4 (Tsitsa at The Falls)	46224	3.23	1.38	55.60	644	3.22	1.39	45.36
Pot at Vipan Farm	91872	3.63	1.31	75.45	1277	3.63	1.32	53.79
Mooi at Maclear	N/A	N/A	N/A	N/A	1251	3.50	0.77	85.5
T3 (Tsitsa at the Gorge)	56054	9.15	3.73	171.95	715	9.74	4.17	154.52
T2 (Tsitsa at Qulungashe Bridge)	91916	14.91	5.18	288.20	1278	14.90	5.27	241.1
Gqukunqa at Thambekeni	91858	0.76	0.27	76.12	1277	0.76	0.27	24.9
Inxu at Junction Ferry	91923	7.93	2.79	203.73	1278	7.92	2.79	179.24
TN2 (Tsitsa at Mbelembushe)	N/A	N/A	N/A	978.75	1269	21.20	6.10	797.19

Figures 7-1 to 7-11 and **Table 7-2** show that the most complete daily SSC datasets from the eleven sites sampled were available at Pot, T2 (Tsitsa at Qulungashe Bridge), Gqukunqa, and Inxu. The bias introduced by calculating SSC from turbidity was evident in the daily SSC values at some sites (e.g., Little Pot **Figure 7-1**, T4 (Tsitsa at the Falls, **Figure 7-4**), and Pot, (**Figure 7-6**). This is examined in more detail in **Section 9.3.2**.

As could be expected, daily mean, median, and maximum SSC values derived from TWMC were lower than those of the instantaneous SSC values (**Table 7-2**). This was due to the averaging of multiple high values that occurred during single flood events with other daily values, thereby skewing the daily SSC dataset towards low SSC values, evidenced by diverging mean and median values. Most notable is the difference in SSC mean / median at Ta (Tsitsana at Lokishini). The maximum SSC values at this site are only slightly lower than those at the Inxu (Instantaneous SSC = 64796.08 mg L⁻¹; daily time weighted mean SSC = 25799.65 mg L⁻¹; **Table 7-2**). However, more than 80% of instantaneous SSC values, and more than 90% of mean daily SSC values, were <500 mg L⁻¹, emphasising the extreme positive daily SSC data skewness at this site.

Discharge data are also typically non-normal and positively skewed (Valkama & Ruth, 2017) and this is apparent from the difference between the mean and median discharge in the study sub-catchments (**Table 7-3**). Mean and median values remained almost identical between instantaneous and daily discharge, due to near-continuous discharge data, whilst maximum discharge values were “smoothed” as expected.

At all sites the magnitude and timing of SSC peaks varied greatly in relation to those of discharge peaks. This marked inconsistency between SSC and discharge peaks suggests the probability of weak relationships between SSC and discharge. In terms of constraining uncertainty in estimated SSLs/SSYs, and particularly for the choice of SSL estimator, the site-specific SSC/discharge relationship is an important consideration (Quilbé et al., 2006). SSC/discharge relationships will be examined in greater detail in **Section 7.3**.

7.3 Suspended sediment load estimator selection

7.3.1 Decision support tree

A time-and-effort balance exists in terms of developing and selecting the optimal estimator, informed by the resulting uncertainty, and constrained by the resources and data available. In this study, a

decision tree based on the findings of Quilbé et al. (2006) was devised that used r^2 as a criteria to guide estimator selection after outliers were removed from the daily SSC and discharge datasets (**Figure 7-12**).

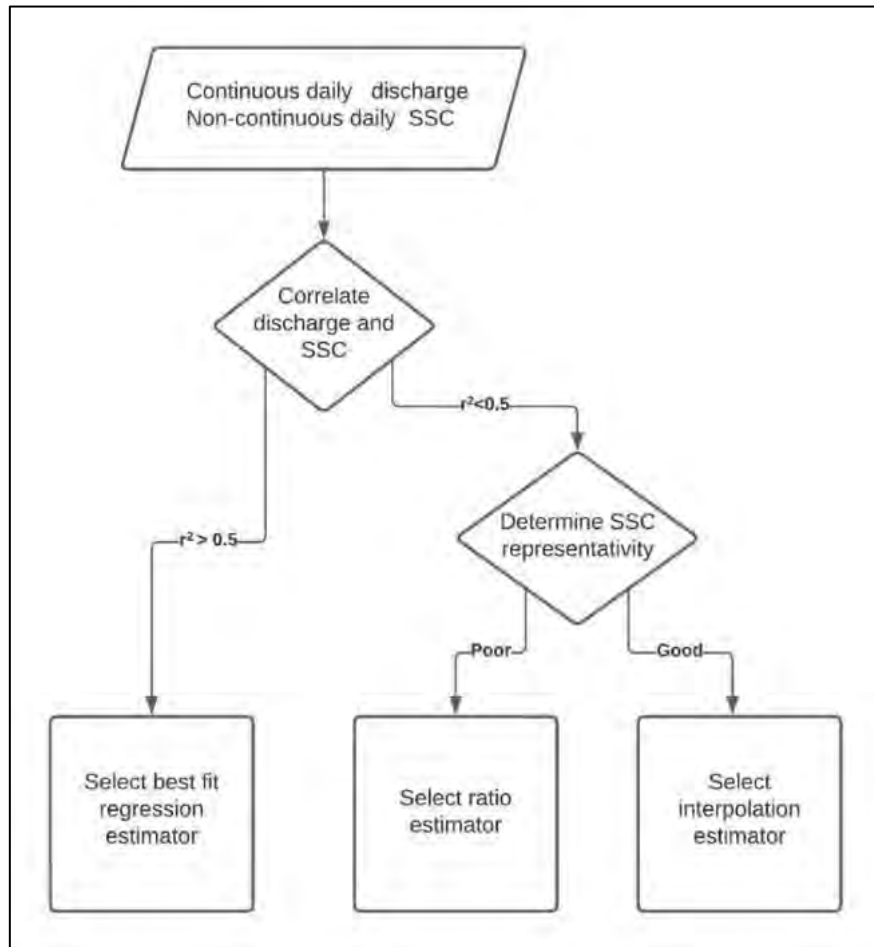


Figure 7-12: Decision-tree for SSL estimator selection, after Quilbé et al. (2006)

7.3.2 Suspended sediment concentration outlier identification and removal

Linear SSC/discharge regression was undertaken at all sites to identify SSC outliers. Due to the skewed nature of the data, low values were not inspected for outlier removal. Where outlying high SSC values were identified, the daily SSC and discharge time series datasets were checked to determine their validity, for example whether they were supported by a chronological series of daily SSC values, and/or closely associated with flood flows. Values that were determined to be non-valid were removed as outliers. **Figures 7-13 to 7-23** show the linear regression of untransformed daily SSC and discharge data at each site. Potential outliers revealed by the regression are indicated by red circles.

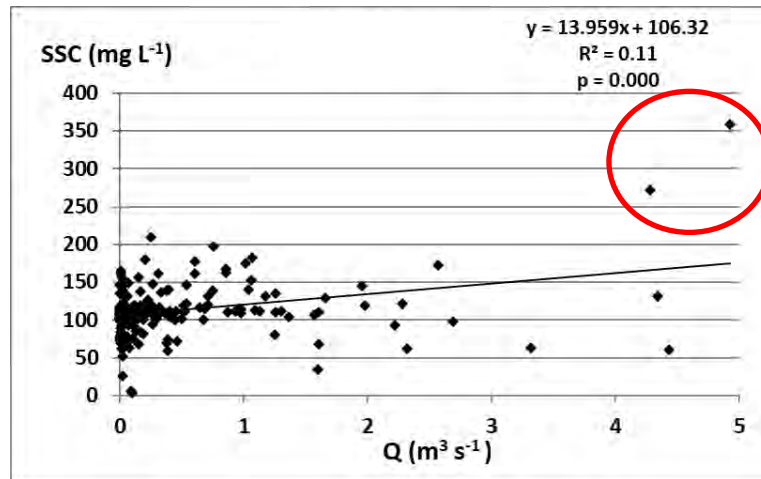


Figure 7-13: Correlation of all daily SSC and discharge data at Little Pot 30 12 2015 – 11 10 2016. The red circle indicates potential outliers.

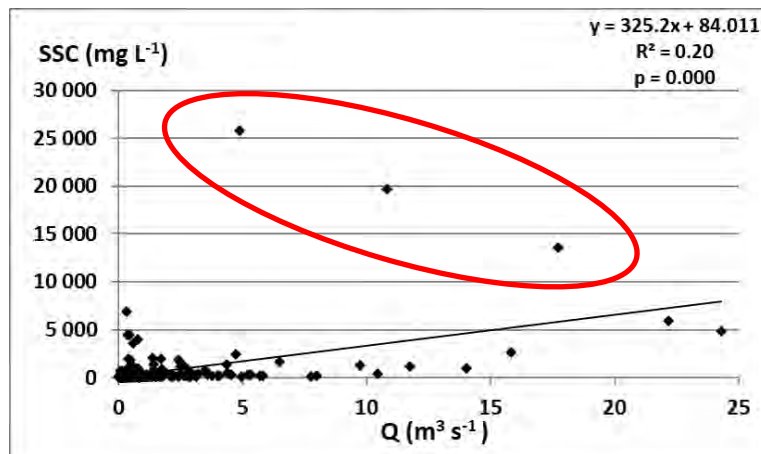


Figure 7-14: Correlation of all daily SSC and discharge data at Tsitsana at 05 12 2015 – 30 04 2017. The red circle indicates potential outliers.

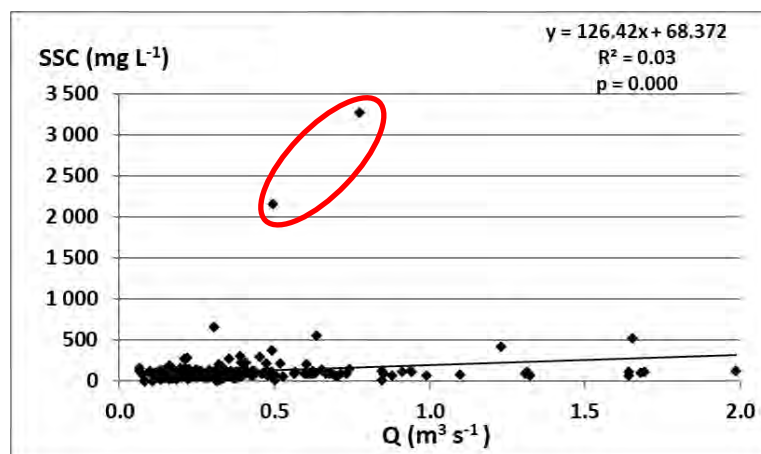


Figure 7-15: Correlation of all daily SSC and discharge data at Hlankomo 04 12 2015 – 03 05 2017. The red circle indicates potential outliers.

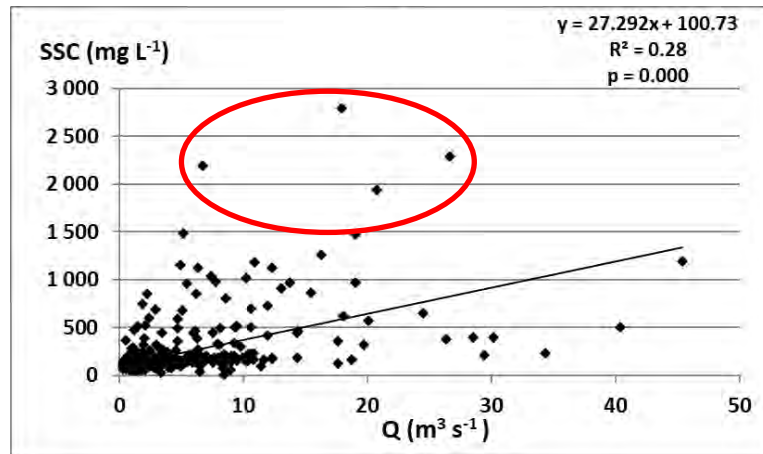


Figure 7-16: Correlation of all untransformed daily SSC and discharge data at T4 (Tsitsa at The Falls) 09 12 2015 – 12 09 2017. The red circle indicates potential outliers.

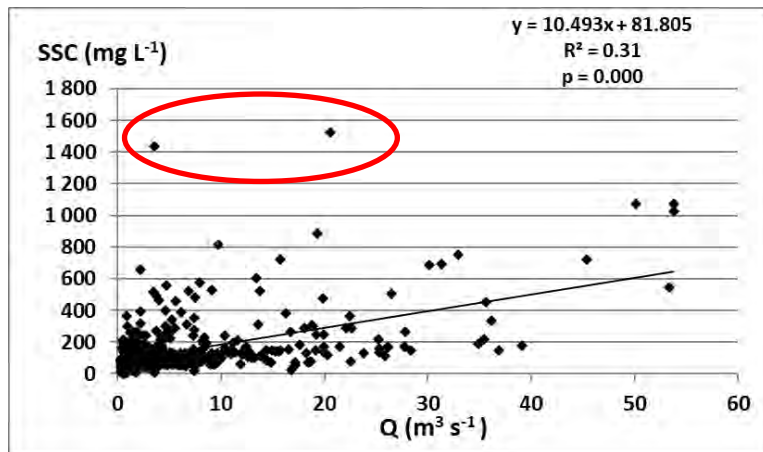


Figure 7-17: Correlation of all untransformed daily SSC and discharge data at Pot 05 12 2015 – 31 05 2019. The red circle indicates potential outliers.

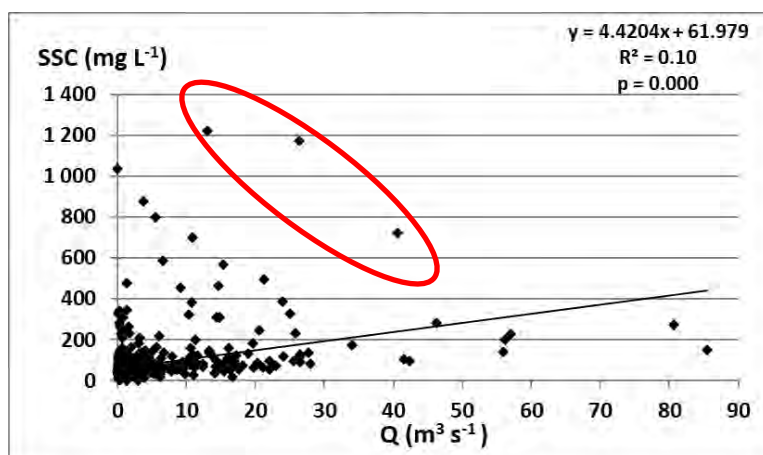


Figure 7-18: Correlation of all untransformed daily SSC and discharge data at Mooi 12 12 2015 – 31 05 2019. The red circle indicates potential outliers.

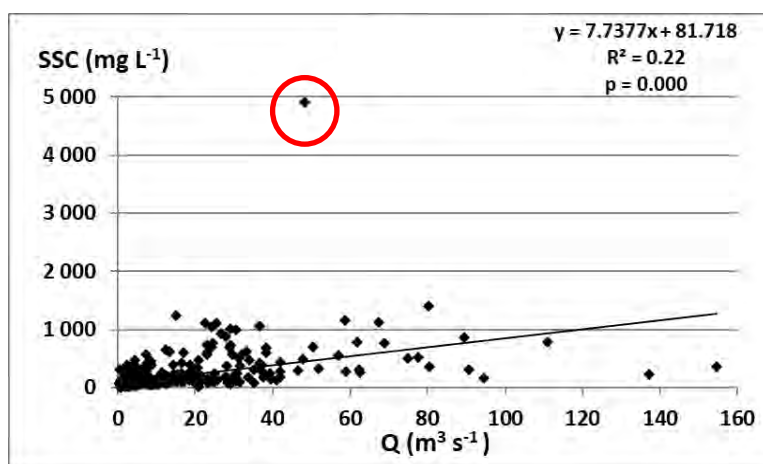


Figure 7-19: Correlation of all untransformed daily SSC and discharge data at T3 (Tsitsa at the Gorge) 02 12 2015 – 26 03 2019. The red circle indicates potential outliers.

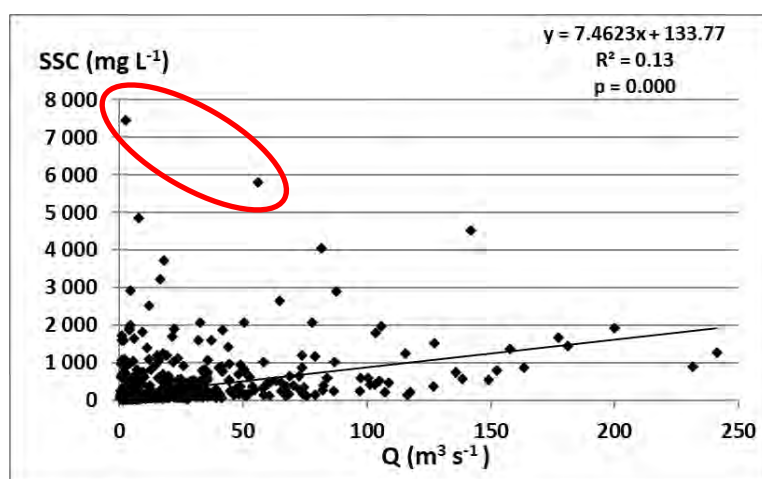


Figure 7-20: Correlation of all untransformed daily SSC and discharge data at T2 (Tsitsa at Qulungashe Bridge) 03 12 2015 – 31 05 2019. The red circle indicates potential outliers.

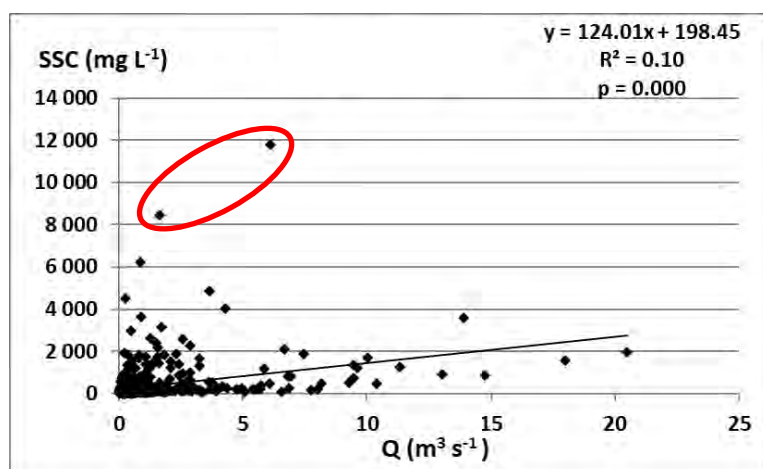


Figure 7-21: Correlation of all untransformed daily SSC and discharge data at Gqukunqa 08 12 2015 – 31 05 2019. The red circle indicates potential outliers.

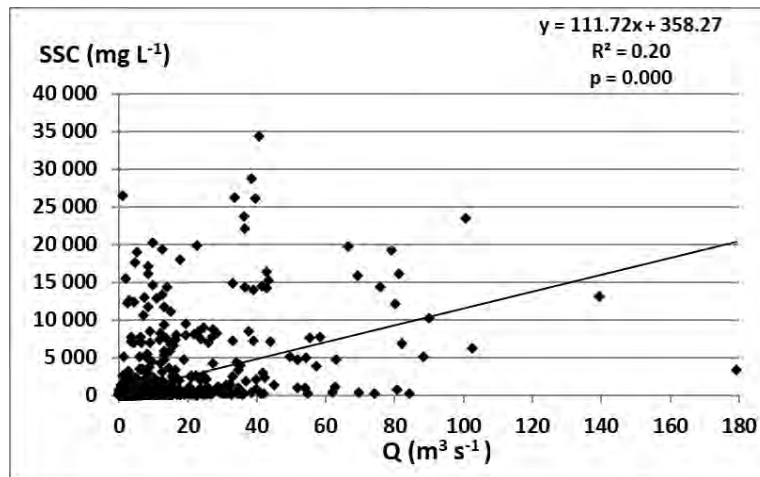


Figure 7-22: Correlation of all untransformed daily SSC and discharge data at Inxu 12 12 2015 – 31 05 2019. The red circle indicates potential outliers.

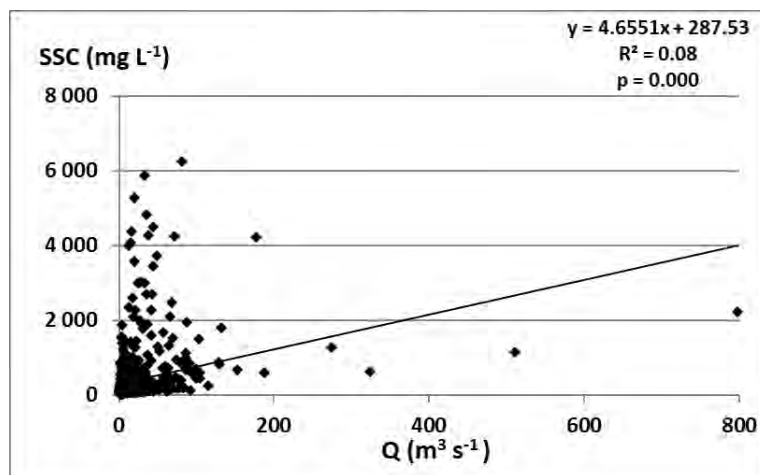


Figure 7-23: Correlation of all untransformed daily SSC and discharge data at TN2 (Tsitsa at Mbelembushe) 10 12 2015 – 31 05 2019. The red circle indicates potential outliers.

Potential outliers were identified at all monitoring sites except at Inxu and TN2 (Tsitsa at Mbelembushe) and were reviewed by comparing the datapoints with proximal data in the daily timeseries. Taking T4 (Tsitsa at the Falls) as an example, the following review of the four potential SSC outliers at that site firstly demonstrates why outlier identification and removal based only on visual inspection and selection of high value SSC data points has the potential to lead to SSL/SSY underestimation. Secondly, it confirms the causes of the weak SSC/discharge relationships suggested by the daily timeseries in **Figures 7-1 to 7-11** and shown by the correlations in **Figures 7-13 to 7-23**.

Although the highest instantaneous SSC values had already been “smoothed” by averaging to daily values, **Figure 7-16** still revealed four high SSC values that lay above the main SSC data grouping and

had relatively low discharge values. The SSC and discharge data for these four points are plotted as timeseries in **Figure 7-24 A, B, C, D**.

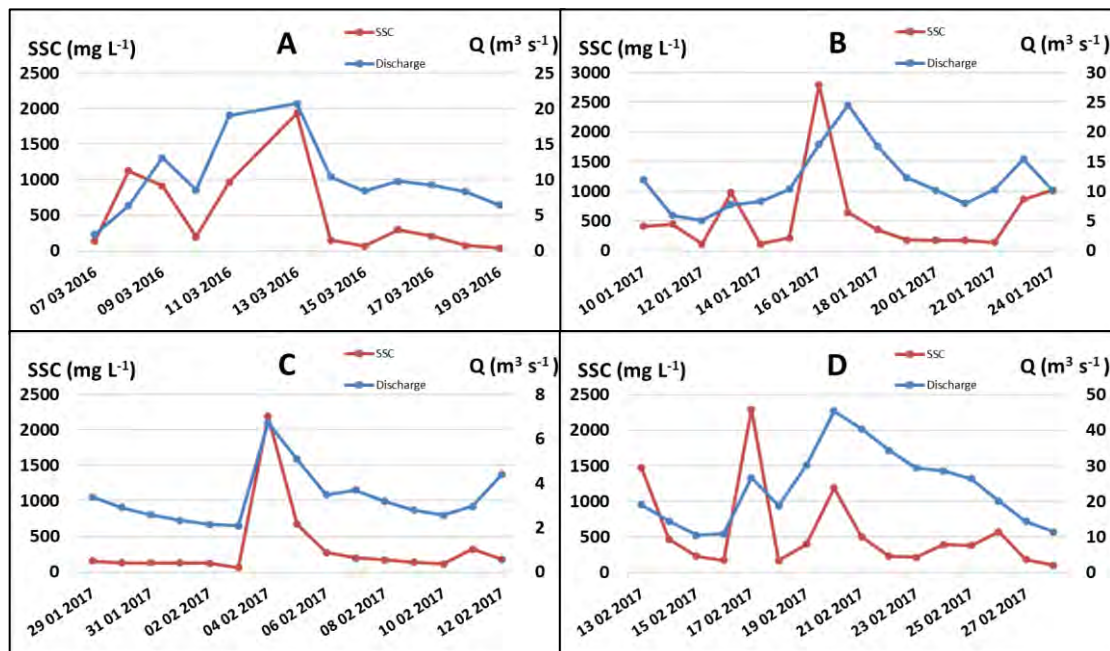


Figure 7-24: SSC and discharge timeseries for four potential outliers (A, B, C, D) at T4 (Tsitsa at the Falls) 07 03 2016 – 28 02 2017)

The SSC peaks in **Figure 7-24 A** to **D** were all associated with discharge peaks, and were therefore considered to be valid, and were not removed as outliers. Notably, however, the SSC peaks in **Figure 7-24 A, C**, and **D** coincide with discharge peaks, but the SSC peak precedes the discharge peak in **Figure 7-24 B**, whilst sediment exhaustion is evident in the low second SSC peak in **Figure 7-24 D**. These examples of hysteresis illustrate a source of weak SSC/discharge relationships.

As expected, SSC was higher on the rising limbs and at the peaks than on the falling limbs of the hydrograph, due to sediment exhaustion (Malutta et al., 2020), but as seen in the timeseries for all sites (**Figures 7-1** to **7-11**) the relationship between SSC and discharge was inconsistent: SSC peaks for **Figure 7-24 A** and **C** are similar ($1935.14 \text{ mg L}^{-1}$ and $2187.96 \text{ mg L}^{-1}$) but the associated discharge peaks are not ($20.70 \text{ m}^3 \text{ s}^{-1}$, and $6.73 \text{ m}^3 \text{ s}^{-1}$). The daily SSL at **A** is 3461 t day^{-1} whilst at **C** it is 1272 t day^{-1} , i.e., a difference of 2189 t day^{-1} . A more extreme example of sediment exhaustion and its effect on the SSC/discharge relationship is provided by the Pot River in early October 2017 (**Figure 7-25** and **Table 7-4**).

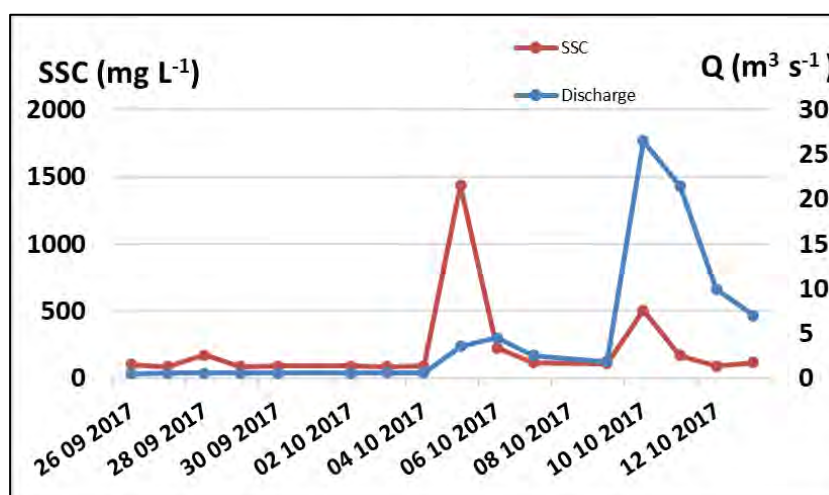


Figure 7-25: A first flush event followed by sediment exhaustion at Pot River (October 2017)

Table 7-4: Date, daily discharge, SSC and SSL for 4 to 13 October 2017 at Pot River

Date	Discharge (m³ s⁻¹)	SSC (mg L⁻¹)	Daily SSL (t day⁻¹)
04 10 2017	0.64	88.53	8
05 10 2017	3.57	1435.09	124
06 10 2017	4.55	224.85	19
07 10 2017	2.54	115.92	10
09 10 2017	1.84	108.99	9
10 10 2017	26.49	505.42	44
11 10 2017	21.45	170.18	15
12 10 2017	9.94	89.60	8
13 10 2017	7.03	117.57	10

Here, the relatively low ($\sim 3.6 \text{ m}^3 \text{ s}^{-1}$) first flood flow of the 2017 – 18 wet season was apparently sufficient to flush the sediment that had accumulated during the preceding dry season i.e., from June 2017. This resulted in an SSC peak of 1435 mg L^{-1} and a daily load of 124 t day^{-1} on 5 October. This SSC peak displayed clockwise hysteresis relative to the discharge peak of 6 October ($4.55 \text{ m}^3 \text{ s}^{-1}$) and was flagged as a potential outlier in **Figure 7-17**. Five days later, a discharge of $26.49 \text{ m}^3 \text{ s}^{-1}$ (which was the fourth largest of the 2017 – 18 wet season) produced a coincident sediment peak of only 505.42 mg L^{-1} . This data pair fell within the main grouping in **Figure 7-17**. The resulting load was 44 t day^{-1} .

Table 7-5 provides the date, SSC value, and status of the potential outliers, based on the SSC and discharge daily time-series data illustrated by **Figures 7-1 to 7-11**.

Table 7-5: Date, SSC value, and status of potential outliers revealed by Figures 7-13 to 7-23.

Site	Date	Daily SSC (mg L ⁻¹)	Status	Outlier? (Y/N)
LP	19 01 2016	358.51	Associated with Q peak 19 01 2016	N
	24 01 2016	271.22	Associated with Q peak 24 01 2016	N
Ta	13 02 2017	25799.65	Associated with Q peak 12 02 2017	N
	16 02 2017	19649.82	Associated with Q peak 16 02 2017	N
	22 02 2017	13594.97	Associated with Q peak 20 02 2017	N
H	21 01 2016	3273.87	Associated with Q peak 21 01 2016 and supported by 24 samples	N
	23 01 2016	2159.03	Not associated with Q; single sample	Y
T4	13 03 2016	1935.14	Associated with Q peak 13 03 2016	N
	16 01 2017	2788.96	Associated with Q peak 17 01 2017	N
	04 02 2017	2187.96	Associated with Q peak 04 02 2017	N
	17 02 2017	2290.95	Associated with Q peak 17 02 2017	N
P	10 01 2017	1524.47	Associated with Q peak 10 01 2017	N
	05 10 2017	1435.09	Associated with Q rise 05 10 2017	N
M	27 01 2016	721.92	Not associated with Q; single sample	Y
	11 03 2016	1219.02	Associated with Q rise 11 03 2016 and supported by 2 samples	N
	15 03 2016	1171.75	Associated with Q peak 15 03 2016	
T3	18 02 2017	4901.60	Associated with Q rise 17 02 2017	N
T2	09 12 2018	7452.82	Associated with Q rise 08 12 2018	N
G	17 02 2018	8467.99	Associated with Q peak 16 02 2018 and supported by 17 samples on 16 & 17 02 2018.	N
	18 03 2018	11803.35	Associated with Q peak 17 03 2018	N
I			No outliers identified	
TN2			No outliers identified	

Only two of the 20 potential outliers needed to be removed. Despite the apparent scatter of the correlated data, the remainder were each supported by a rise or a peak in discharge, and/or by more than one SSC value.

7.3.3 Exploratory suspended sediment concentration/discharge correlations

Daily SSC/discharge was correlated at all sites using an untransformed power regression, to determine if $r^2 > 0.5$ i.e., if more than 50% of variance in the relationship was explained by discharge, thereby allowing discharge to be accepted as a predictor of SSC. Log₁₀ transformation was applied if untransformed $r^2 < 0.5$, and the data were stratified to give a subset of only the upper 25% of discharge, and a subset of only wet season data (1 October – 31 May). If $r^2 = < 0.5$, then regression estimators

(i.e., sediment rating curves) were rejected (as per **Figure 7-12**), the proviso being that the same estimator must be used for all monitoring sites and years to enable comparison (Quilbé et al., 2006). As noted in **Section 3.7.1** it is known that the approach taken to estimating daily SSL and to estimating annual SSL impacts the bias, precision and accuracy of the resulting SSL (Walling & Webb, 1985; Lee et al., 2016; De Girolamo et al., 2018).

The MS Excel workbook containing the SSC/discharge correlations for T2 (Tsitsa at Qulungashe Bridge) as an example is included as **Appendix 10. Table 7-6** summarises the SSC/discharge r^2 for untransformed, $\log_{10}$ transformed, and stratified data, at all sites. In all cases r^2 was <0.5 even though correlations were statistically significant, therefore rating curves based on the regression of SSC and discharge were rejected in favour of a ratio estimator (as per **Figure 7-12**).

Table 7-6: SSC/discharge r^2 for untransformed, $\log_{10}$ transformed, and stratified data

Site Name	Untransformed r^2	$\log_{10}$ transformed r^2	Upper 25% of discharge r^2	Wet season r^2
Little Pot at Cornlands	0.11 (n= 285)	0.008 (n= 285)	0.10 (n = 74)	0.12 (n = 163)
Tsitsana at Lokishini	0.20 (n=473)	0.32 (n=473)	0.18 (n = 119)	0.19 (n= 357)
Hlankomo at Makgetheng	0.03 (n=404)	0.07 (n=404)	0.003 (n = 103)	0.02 (n = 313)
T4 (Tsitsa at The Falls)	0.28 (n = 622)	0.33 (n = 622)	0.14 (n = 159)	0.26 (n = 407)
Pot at Vipan Farm	0.31 (n = 1032)	0.22 (n = 1032)	0.21 (n = 255)	0.30 (n = 725)
Mooi at Maclear	0.10 (n = 630)	0.17 (n = 630)	0.06 (n = 201)	0.10 (n = 545)
T3 (Tsitsa at the Gorge)	0.22 (n = 614)	0.42 (n = 614)	0.07 (n = 156)	0.21 (n = 497)
T2 (Tsitsa at Qulungashe Bridge)	0.13 (n = 1046)	0.28 (n = 1046)	0.11 (n = 266)	0.12 (n = 776)
Gqukunqa at Thambekeni	0.10 (n = 890)	0.18 (n = 890)	0.05 (n = 270)	0.09 (n = 691)
Inxu at Junction Ferry	0.20 (n = 1129)	0.31 (n = 1129)	0.10 (n = 297)	0.20 (n = 830)
TN2 (Tsitsa at Mbelembushe)	0.08 (n = 686)	0.32 (n = 686)	0.02 (n = 164)	0.08 (n = 469)

The relationships between discharge variability and SSC variability are examined in more detail in **Section 9.2.3**.

7.4 Suspended sediment load and yield estimation

7.4.1 Estimator selection

Daily SSL was calculated as the product of time weighted mean daily SSC and daily discharge (**Section 3.7.1**). Based on the findings of **Chapter 7.3**, a ratio estimator was selected that weighted daily SSL by annual discharge to give annual SSL ($t \text{ yr}^{-1}$, Equation 7-2 (Quilbé et al., 2006)).

Equation 7-2: $\left(Total\ SSL = \overline{CQ} \frac{\mu_q}{\bar{Q}} n \right)$

Where:

$\overline{CQ}$ = Mean daily load (g m⁻³)

$\bar{Q}$ = Mean discharge of sampled days (m³ s⁻¹)

μ_q = Mean of all daily discharge measurements for the year (m³ s⁻¹)

n = number of samples

Annual SSY (t km⁻² yr⁻¹) was determined by dividing SSL by catchment area. The catchment areas were based on the quinary catchment boundaries that had initially been digitised at a scale of 1:50 000 using 20 m contour lines and spot heights as part of a WRC project to standardise approaches to eco-hydrological responses in South Africa (Schulz et al., 2011). Differences in catchment area of <1% were found when compared with later estimates that were made using a Shuttle Radar Topography Mission (SRTM) DEM (Rademeyer & van der Spuy, 2012).

Where at least three annual values were available, the variability of SSL (and by extension SSY) at each monitoring site was determined using %CV. Whilst more data points are preferable to determine %CV, the availability of a maximum of four years' SSL data meant that other methods of expressing variability would be no more robust. Mean SSY was determined from all years that annual SSYs were available (see **Table 7-7**), which varied between sites.

A correlation analysis was applied to mean SSY and catchment area to determine if the relationship was scalable, which would allow catchment area to be used as a predictor of SSY and to inform catchment management decision-making. A correlation analysis was also applied to SSY and mean discharge, although discharge had already been shown to be a poor predictor of SSC (**Section 7.3.3**).

7.4.2 Annual suspended sediment loads and yields

The MS Excel workbook containing the SSL estimates for T2 (Qulungashe Bridge) as an example is included as **Appendix 11**. **Table 7-7** summarises annual and mean SSL and SSY; the Q ratio, and annual SSL/SSY %CV using all available data at all monitoring sites.

Table 7-7: Annual and mean SSL, SSY; Q ratio, and SSL/SSY %CV

Site and catchment area (km ²)		2015 - 16	2016 - 17	2017 - 18	2018 - 19	Mean SSL (t yr ⁻¹)	Mean SSY (t km ⁻² yr ⁻¹)	CV SSL/SSY (%)
LP 75	SSL (t yr ⁻¹)	2 145	N/A	N/A	N/A	N/A	N/A	N/A
	SSY (t km ⁻² yr ⁻¹)	29	N/A	N/A	N/A			
	Q ratio	0.91	N/A	N/A	N/A			
Ta 135	SSL (t yr ⁻¹)	5 849	95 351	N/A	N/A	50 600	375	N/A
	SSY (t km ⁻² yr ⁻¹)	43	706	N/A	N/A			
	Q ratio	0.93	0.96	N/A	N/A			
H 64	SSL (t yr ⁻¹)	1 655	991	N/A	N/A	1 332	21	N/A
	SSY (t km ⁻² yr ⁻¹)	26	15	N/A	N/A			
	Q ratio	0.96	1.01	N/A	N/A			
T4 607	SSL (t yr ⁻¹)	45 505	47 738	N/A	N/A	46 713	77	N/A
	SSY (t km ⁻² yr ⁻¹)	75	79	N/A	N/A			
	Q ratio	1	0.99	N/A	N/A			
P 432	SSL (t yr ⁻¹)	23 334	34 082	28 286	20 104	26 451	61	20
	SSY (t km ⁻² yr ⁻¹)	54	79	65	47			
	Q ratio	0.95	0.97	1.08	1.02			
M 306	SSL (t yr ⁻¹)	37 970	13 047	13 860	12 618	19 374	63	55.5
	SSY (t km ⁻² yr ⁻¹)	124	43	45	41			
	Q ratio	0.82	0.56	1.86	0.87			
T3 1550	SSL (t yr ⁻¹)	97 723	120 189	N/A	N/A	108 956	70	N/A
	SSY (t km ⁻² yr ⁻¹)	63	78	N/A	N/A			
	Q ratio	0.99	0.98	N/A	N/A			
T2 1881	SSL (t yr ⁻¹)	174 734	199 668	417 387	238 599	257 597	137	36.9
	SSY (t km ⁻² yr ⁻¹)	93	106	222	127			
	Q ratio	1.11	0.87	1.02	1.06			
G 204	SSL (t yr ⁻¹)	15 774	11 737	29 709	15 264	18 121	89	37.9
	SSY (t km ⁻² yr ⁻¹)	77	58	146	75			
	Q ratio	0.84	0.81	0.78	1.05			
I 1452	SSL (t yr ⁻¹)	342 849	395 724	2 094 703	1 103 793	984 267	678	71.9
	SSY (t km ⁻² yr ⁻¹)	236	273	1443	760			
	Q ratio	0.93	0.99	1.02	0.89			
TN2 4285	SSL (t yr ⁻¹)	484 459	262 417	N/A	685 169	477 348	111	36.2
	SSY (t km ⁻² yr ⁻¹)	113	61	N/A	160			
	Q ratio	1.01	1.33	N/A	0.95			

7.4.3 Annual suspended sediment load and yield variability

Statements of variability need to accompany reported annual or mean SSLs/SSYs for the Tsitsa River catchment so that catchment managers can accommodate it in their decision-making. Except at Pot, interannual variability was high, particularly at Tsitsana, Mooi, and Inxu. **Figure 7-26** shows annual SSL for all sites 2015 – 2019 whilst **Figure 7-27** shows %CV for sites where at least 3 years of data were available.

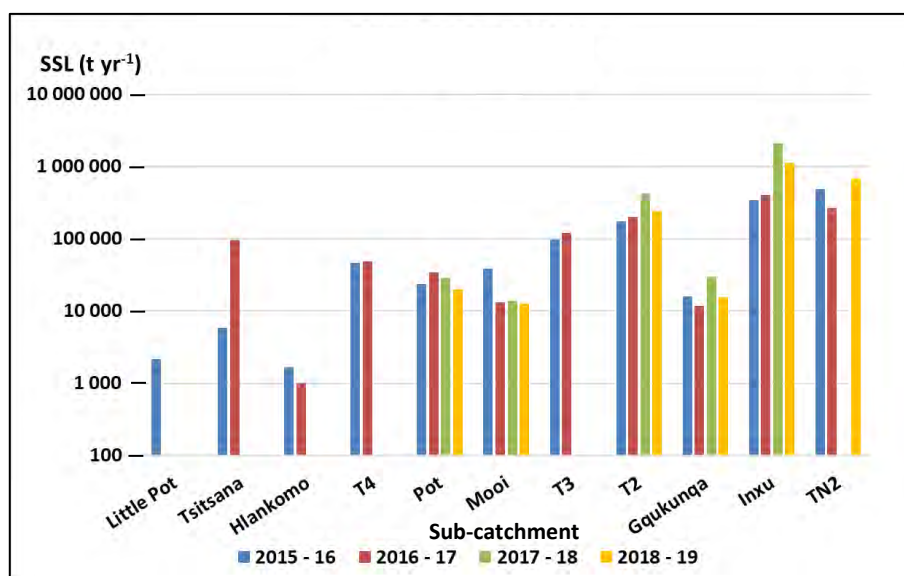


Figure 7-26: Annual SSL for all sites 2015 - 2019

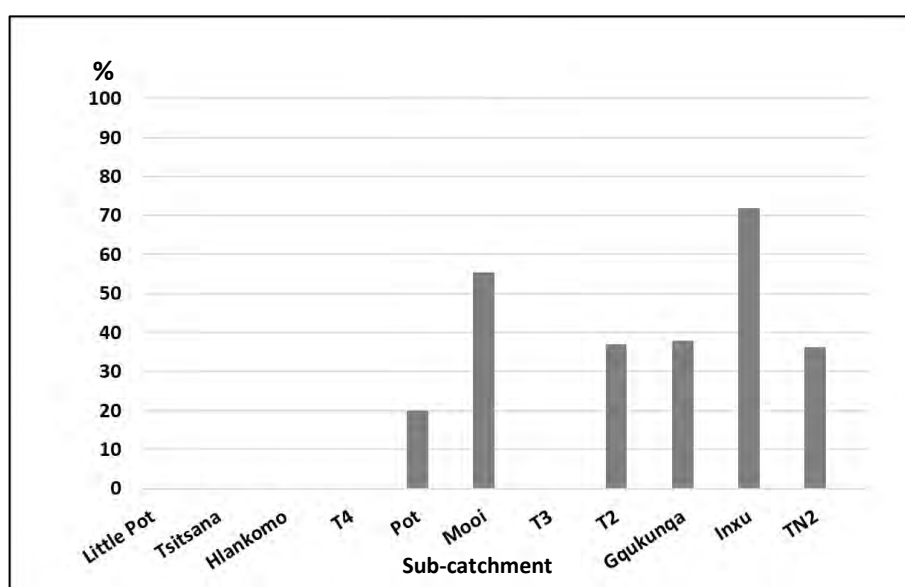


Figure 7-27 Percentage coefficient of variation at sites with >3 annual SSLs available

Inter-annual SSL/SSY variability exceeded 30%CV at all sites except Pot. The variability of the Inxu was approximately twice that of T2 (Tsitsa at Qulungashe Bridge), which represents the Tsitsa above their

confluence. Inter-annual variability in general, and of the Tsitsana in particular, is discussed further in Section 9.2.3.

7.4.4 The Q ratio as an indicator of uncertainty

Figure 7-28 shows the ratio of sampled discharge to annual discharge, i.e., the “Q ratio” at all sites. The Q ratio is derived from Equation 7-2 and expresses sampling effectiveness across the range of discharges that occurred each year. The black lines highlight ratio values of 0.8 and 1.2, i.e., an arbitrary 20% boundary selected for comparison of results.

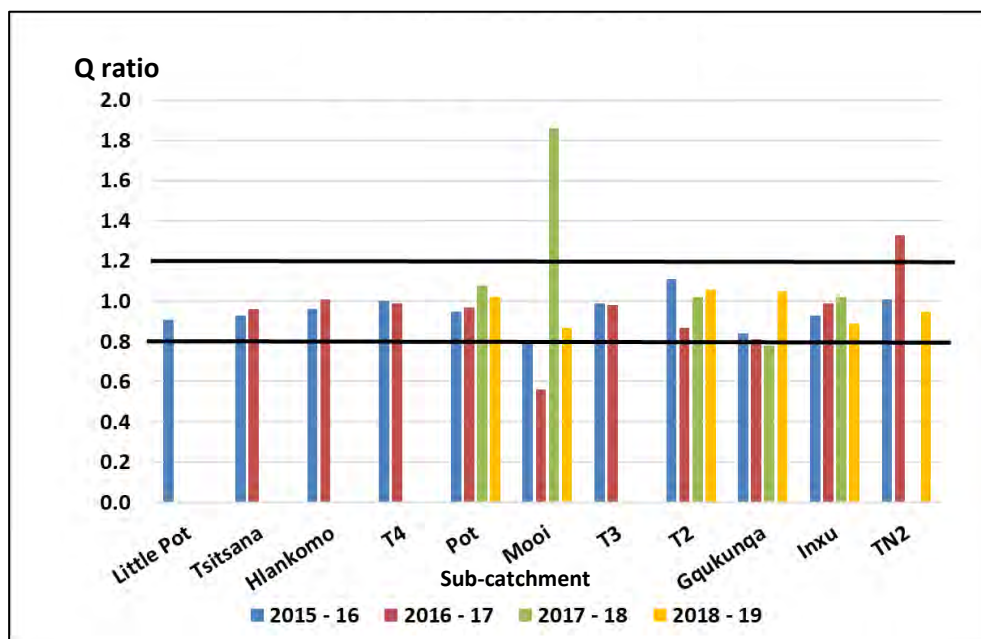


Figure 7-28: Ratio of sampled to annual discharge (Q ratio) 2015 – 2019. The black lines highlight ratio values of 0.8 and 1.2, i.e., an arbitrary 20% boundary selected for comparison of results.

The Q ratio was generally between 0.8 and 1.2, except at Mooi (2016 – 17: 0.56, 2017 – 18: 1.86) and TN2 (Tsitsa at Mbelembushe, 2016 – 17: 1.33). This supports the contention that citizen technician sampling during daylight hours provided SS data representative of the range of flows. It was most often between 0.8 and 1.0, i.e., most high flows were sampled at least once but low flows may have been under-represented by sampling, achieving the aim of the flood-focused sampling campaign.

Mooi. The compensatory effect of the Q ratio on SSL estimation was strongly apparent at Mooi for 2016 – 17 and 2017 - 18. In 2016 – 17 the Q ratio of 0.56 compensated for the lack of sampling during the June to October 2016 low flow period (Figure 7-5). Reciprocally, most of the high flows between January and mid-April 2018 were missed (Q ratio = 1.86).

TN2 (Tsitsa at Mbelembushe). The Q ratio for 2016 – 17 was high (1.33), compensating for the poor sampling that took place at this site during this year (**Figure 7-11**). Most low flows between late September and mid-December 2016 were not sampled, and most significantly, the largest flood series of that year, (from the beginning of February to mid-March 2017) was not sampled.

7.4.5 Mean suspended sediment load

Figure 7-29 graphs the mean SSL for all the sub-catchments using the available data 2015 – 2019 at each site (see **Table 7-7**), whilst **Figure 7-30** presents these data as a schematic diagram.

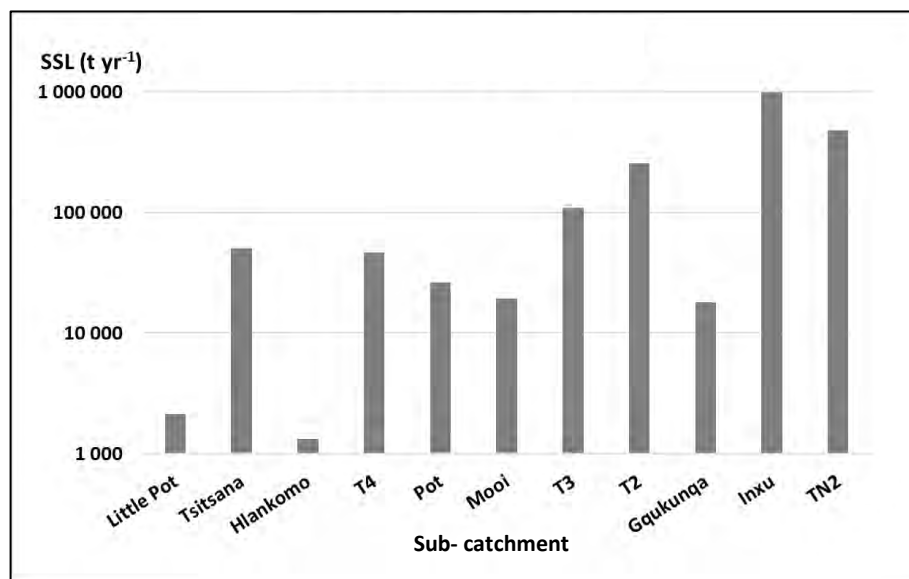


Figure 7-29: Graph of mean SSL using available years for all sub-catchments 2015 – 2019

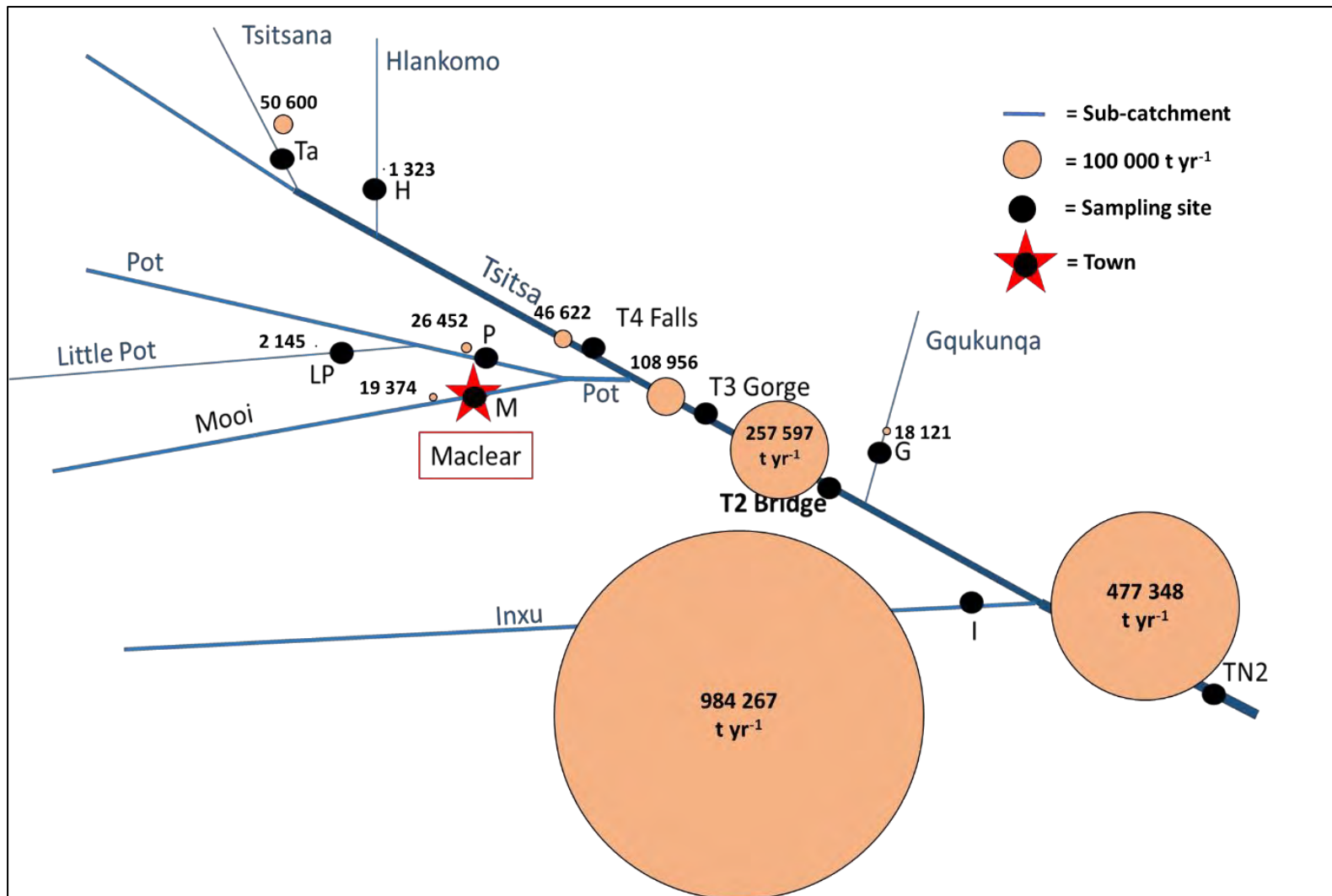


Figure 7-30: Schematic diagram of mean SSL using available years for all sub-catchments 2015 – 2019. The circles are proportionally representative of SSL (t yr⁻¹)

All catchments had a mean SSL > 1 000 t yr⁻¹ (**Figure 7-29**). As expected, mean SSL generally increased on the main stem of the Tsitsa River, probably due to the dispersive soils found in the middle and lower parts of the catchment: SSL doubled downstream between sites on the main stem from T4 (Tsitsa at the Falls) to TN2 (Tsitsa at Mbelembushe, **Figure 7-30**). Only Little Pot and Hlankomo had SSL of < 10 000 t yr⁻¹, but these values were based on one and two years of data respectively. The uncertainty for these two catchments was relatively high, but their importance in terms of SS contribution to the downstream catchment was low. The high and variable SSL at Tsitsana is examined in **Section 9.2.3**. The Inxu catchment was of obvious importance as the major SS contributor with a mean SSL of ~1 000 000 t yr⁻¹, approximately four times the contribution from the Tsitsa catchment upstream of their confluence (i.e., SSL from T2 (Tsitsa at the Qulungashe Bridge) combined with that of Gqukunqa). Bed deposition due to the gentler gradient in the 36 km between the Inxu confluence and the sampling site at TN2 (Tsitsa at Mbelembushe) may have accounted for the ~50% reduction in SSL from Inxu to TN2. However, the mean value for TN2 did not include data for 2017-2018, a year in which high loads were estimated for T2 (Tsitsa at Qulungashe Bridge), Gqukunqa, and Inxu.

7.4.6 Mean suspended sediment yield

SSY is typically used as a metric for comparing catchment soil erosion, although this assumes the unlikely scenario of a spatiotemporally constant SDR (Walling, 1983). Dividing/normalising SSL by catchment area to derive SSY (t km⁻² yr⁻¹) nevertheless allows comparison between catchments, years, and results from different studies. **Figure 7-31** graphs the mean SSY 2015 – 19 (from **Table 7-7**), whilst **Figure 7-32** presents these data as a schematic diagram.

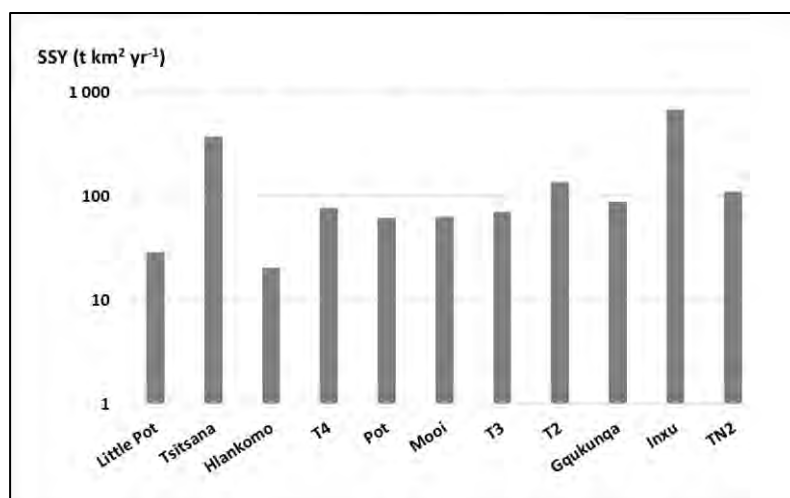


Figure 7-31: Graph of mean SSY using available years for all sub-catchments 2015 – 2019

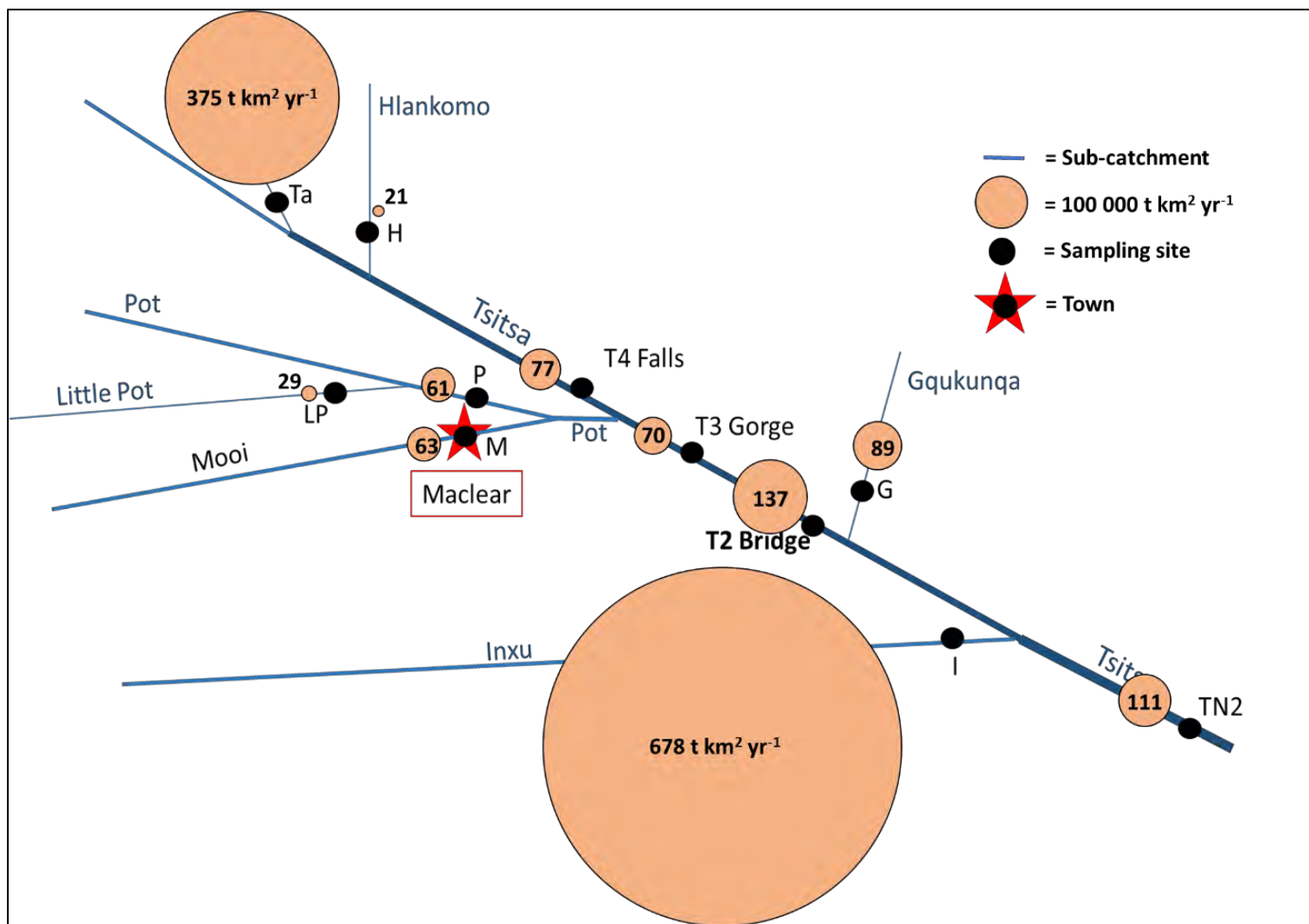


Figure 7-32: Schematic diagram of mean SSY using available years for all sub-catchments 2015 – 2019. The circles are proportionally representative of SSY ($\text{t km}^{-2} \text{ yr}^{-1}$)

SSY for Little Pot ($29 \text{ t km}^{-2} \text{ yr}^{-1}$) was relatively low, as could be expected for a near-pristine headwater catchment with only Hlankomo ($21 \text{ t km}^{-2} \text{ yr}^{-1}$) transporting slightly less sediment per unit area. Tsitsana ($375 \text{ t km}^{-2} \text{ yr}^{-1}$) and Inxu ($678 \text{ t km}^{-2} \text{ yr}^{-1}$) were again anomalously high, given that SSY for the entire Tsitsa catchment above the confluence with the Inxu was $\sim 250 \text{ t km}^{-2} \text{ yr}^{-1}$. As the most downstream site, the SSY estimated for TN2 (Tsitsa at Mbelembushe) integrated the estimated SSY for the entire $\sim 4900 \text{ km}^2$ catchment. While acknowledging the missing 2017 – 18 data, this ($111 \text{ t km}^{-2} \text{ yr}^{-1}$) is the value that will be compared with average SSY estimates from other studies of the same area (**Section 9.2.3**).

7.5 Summary: The uncertainty associated with SSL and SSY estimation (Objective 2)

TWMC was used to compensate for variable SS sampling intervals when deriving daily SSC from measured and calculated SSC. This approach is associated with less uncertainty than using the arithmetic mean. Daily mean, median, and maximum SSC values derived from TWMC were lower than for instantaneous SSC. Daily discharge data were similarly affected (here using simple averaging without introducing further uncertainty, due to the near-continuous data). The marked inconsistency between SSC and discharge peaks suggested weak relationships between SSC and discharge. Of the eleven sites for which data were collected, only Pot, T2 (Tsitsa at Qulungashe Bridge), Gqukunya, and Inxu had near complete daily SSC data sets that represented the range of natural uncertainty that occurred during the full study period.

SSC and discharge displayed significant but weak, ($r^2 < 0.5$) relationships at all sites: Discharge-weighted ratio estimation was therefore selected as an SSL estimator in preference to rating curves. The resulting Q ratio, and the variability between annual SSLs/SSYs were used at this stage as preliminary measures of uncertainty. The predominant Q ratio of between 0.8 and 1.2 showed that citizen technician sampling during daylight hours had generally provided discharge-representative SSC data.

Mean SSL was $> 1\,000 \text{ t yr}^{-1}$ for all sub-catchments (**Figure 7-29**), and generally increased down the main channel of the Tsitsa River catchment. SSL for the Inxu River was $\sim$ four times that measured for the similarly sized effective catchment at T2 (Tsitsa at Qulungashe Bridge). Mean SSY ranged from $21 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Hlankomo sub-catchment to $678 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Inxu sub-catchment, while annual SSY ranged from $15 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Hlankomo sub-catchment (2016 – 17) to $1443 \text{ t km}^{-2} \text{ yr}^{-1}$ for the Inxu sub-catchment (2017 – 18). This exceeded Vanmaercke et al.'s (2014) range for South

Africa ($0 \text{ t km}^{-2} \text{ yr}^{-1}$ – $890 \text{ t km}^{-2} \text{ yr}^{-1}$), but was within the range for southern Africa ($0.4 \text{ t km}^{-2} \text{ yr}^{-1}$ – $3132 \text{ t km}^{-2} \text{ yr}^{-1}$). Interannual SSL/SSY variability (expressed by %CV) was high, particularly at Tsitsana, Mooi, and Inxu, while variability was very high between the two annual SSL available for Tsitsana, making predictions based on these results very uncertain. The relative uncertainty associated with estimated SSLs/SSYs is examined in greater detail in **Section 9.2.3**.

8 The effect of stratifying and decimating daily suspended sediment concentration data on the precision of annual suspended sediment loads and yields (Objective 3)

8.1 Overview

Chapters 3 and **5** assessed, where possible, the natural and epistemic uncertainty that was due to sampling and monitoring approaches; spatiotemporal discharge and SSC data coverage; and discharge and SSC data quality. **Chapters 6** and **7** assessed, where possible, the uncertainty associated with calculating SSC from turbidity; calculating daily SSC from irregular values; and estimating SSLs/SSYs for all sites based on the resulting daily discharge and SSC data. This chapter investigates the effect of using stratified and limited data on the precision of SSL/SSY estimation (**Table 8-1**). The purpose was to provide insight into the precision associated with the approach to temporal sampling taken in this study, and to inform the spatiotemporal design of future CT-based, flood focused direct sampling programmes in resource scarce regions.

Table 8-1: Objective 3 actions, methods, and outputs

Objective 3	Investigate the effect of using stratified and limited data on the precision of SSL estimation
Action	a) Estimate sub-catchment SSL and SSY using limited datasets b) Compare with SSL estimated from complete daily SSL datasets.
Method	a) Stratify the complete daily SSL dataset using discharge, and seasonal limiting b) Decimate the complete daily SSL dataset using permutations of weekdays. c) Estimate limited SSL and SSYs d) Compare limited SSLs and SSYs with those estimated from complete daily SSL datasets
Output	Statements of the effects of limited sampling on SSLs/SSYs precision

8.2 Input data

Sampling frequency, record length, and data representativeness are three of the factors influencing epistemic uncertainty (i.e., precision) associated with SSL/SSY estimation (Walling & Webb, 1981; Walling & Webb, 1985; Horowitz, 1997). Gqukunqa, Pot, Inxu and T2 (Tsitsa at Qulungashe Bridge) were selected for precision analysis from the eleven monitoring sites established in 2015. These four sites had near-complete daily discharge and SSC datasets for the entire project period (**Table 5-4**). They also represented the targeted high flows (**Table 5-5**). In other words, data from these monitoring sites comprised the most complete record of the natural variability that had occurred throughout the project period.

Of these four sub-catchments, Pot and Gqukunqa were relatively small catchments (<450 km²), whilst the Inxu and T2 (Tsitsa at Qulungashe Bridge) catchment were relatively large (>1400 km²). The Pot sub-catchment represented the upper part of the Tsitsa River catchment (typified by private and commercial land-tenure coincident with less erodible soils), whilst the remaining three sub-catchments represented the middle and lower part of the Tsitsa River catchment, where predominantly communal tenure and land-management practices were coincident with highly dispersive duplex soils and widespread gully erosion (**Figure 2-22** and **Figure 2-18**). These differing characteristics would allow consideration of the effects of catchment area and of biophysical and anthropogenic factors on SSL/SSY precision and spatiotemporal sampling programme design.

8.3 High discharge sampling

The extent to which high discharges were sampled at each of the four sites was described in **Section 5.7.1.3** and summarised in **Table 5-5**. Days where SS sampling took place during the site period were matched by date to the highest 1%, 5%, and 20% of daily discharges, to determine if sufficient high-discharge sampling had taken place to allow discharge-limited stratification.

8.4 Limiting the suspended sediment load data

The complete daily SSL datasets at each site were stratified and decimated. Precision was assessed by comparing annual SSLs estimated using stratified and decimated SSL datasets with the “complete” annual SSLs estimated from complete datasets. **Appendix 12** comprises the Excel spreadsheet showing SSL data limiting at Gqukunqa.

8.4.1 Data stratification

Daily SSL datasets at each site were stratified in two ways: according to daily discharge, and according to season. The discharge-limited subsets were restricted to data collected during the highest 20% of daily discharge, to emulate sampling only during high water conditions. The seasonally-limited subsets were restricted to data collected between 1 October and 31 May, to emulate sampling only during the wet season. The resulting discharge-limited and seasonally-limited annual SSLs were expressed as a percentage of the complete annual SSLs. Annual variation of the complete and limited annual SSLs at each site was assessed using %CV (n=4).

8.4.2 Data decimation

Daily SSLs in the complete dataset were decimated to emulate the effect of sampling only on certain days of the week. Decimation was achieved by sorting the daily SSLs using the days of the week, and calculating all the SSLs resulting from the permutations of restricting sampling to between 1 and 6 days per week. For example, the seven subsets for one day per week comprised Mondays; Tuesdays; and so on. The 21 subsets for two days per week comprised Mondays + Tuesdays; Mondays + Wednesdays; Mondays + Thursdays; and so on. The variation in the resulting SSLs was analysed using %CV, and also expressed as a percentage of complete annual SSL, to determine the maximum sampling interval that would constrain the resulting difference in SSL to <20%.

8.5 Results

8.5.1 Representativeness of sampled high discharges

The MS Excel workbook containing the data stratification and decimation for T2 (Tsitsa at Qulungashe Bridge) as an example is included as **Appendix 12**. The site period SSC coverage and the percentage of the highest 20% of flows that were sampled at each site are summarised in **Table 8-2** (taken from **Table 5-5**).

Table 8-2: Percentage of daily high discharge sampled at each site (from Table 5-5)

	Total temporal SS coverage (%)	Discharges < =1%			Discharges >1%<5%			Discharges>5% <20%		
		Q days	SS days	% Q days sampled	Q days	SS days	% Q days sampled	Q days	SS days	% Q days sampled
Pot	81.4	12	10	83.3	51	42	82.4	255	201	78.8
T2	82.2	12	12	100.0	51	37	72.5	255	209	82.0
Gqukunqa	69.8	12	9	75.0	51	46	90.2	255	221	86.7
Inxu	89.7	12	11	91.7	51	48	94.1	255	235	92.2

Sampling coverage of the highest 1% of discharges was above 75%, whilst between 78% and 92% of the highest 20% of discharges were sampled. This reaffirmed that the aim of flood-focused sampling was achieved at these sites, and indicated that sufficient high-discharge samples had been taken to allow data stratification based on the highest 20% of daily discharge.

8.5.2 Data stratification

The complete annual SSLs, discharge-limited annual SSLs, and seasonally-limited annual SSLs are summarised in **Table 8-3**, with their means and %CVs. Note that SSL for 2015-16 remained the same

because the study began at the beginning of the wet season i.e. in December 2015. The difference between complete and stratified annual SSLs is shown as a percentage in **Figure 8-1**.

Table 8-3: Complete, discharge-limited and seasonally-limited SSL with mean SSL and %CV SSL

Site (area, km ²)	Dataset	SSL 2015 – 16 (t yr ⁻¹)	SSL 2016 – 17 (t yr ⁻¹)	SSL 2017 – 18 (t yr ⁻¹)	SSL 2018 – 19 (t yr ⁻¹)	Mean SSL (t yr ⁻¹)	Inter- annual CV SSL (%)
P (432)	Complete SSL	23 334	34 082	28 286	20 10	26 451	20.0
	Top 20% Q	30 191	43 282	33 687	25 517	33 169	19.7
	Wet season	23 334	37 633	28 380	22 456	27 951	21.6
T2 (1881)	Complete SSL	174 734	199 668	417 387	238 599	275 597	36.9
	Top 20% Q	218 952	247 022	537 348	298 455	325 444	38.6
	Wet season	174 734	215 248	371 762	257 479	254 806	28.9
G (204)	Complete SSL	15 774	11 737	29 709	15 264	18 121	37.9
	Top 20% Q	19 793	13 774	37 748	21 069	23 096	38.5
	Wet season	15 774	12 177	30 975	17 896	19 206	36.9
I (1452)	Complete SSL	342 849	395 724	2 094 703	1 103 793	984 267	71.9
	Top 20% Q	342 204	599 413	2 577 824	1 308 700	1 207 035	71.8
	Wet season	342 849	447 352	2 045 947	1 167 439	1 000 897	68.1

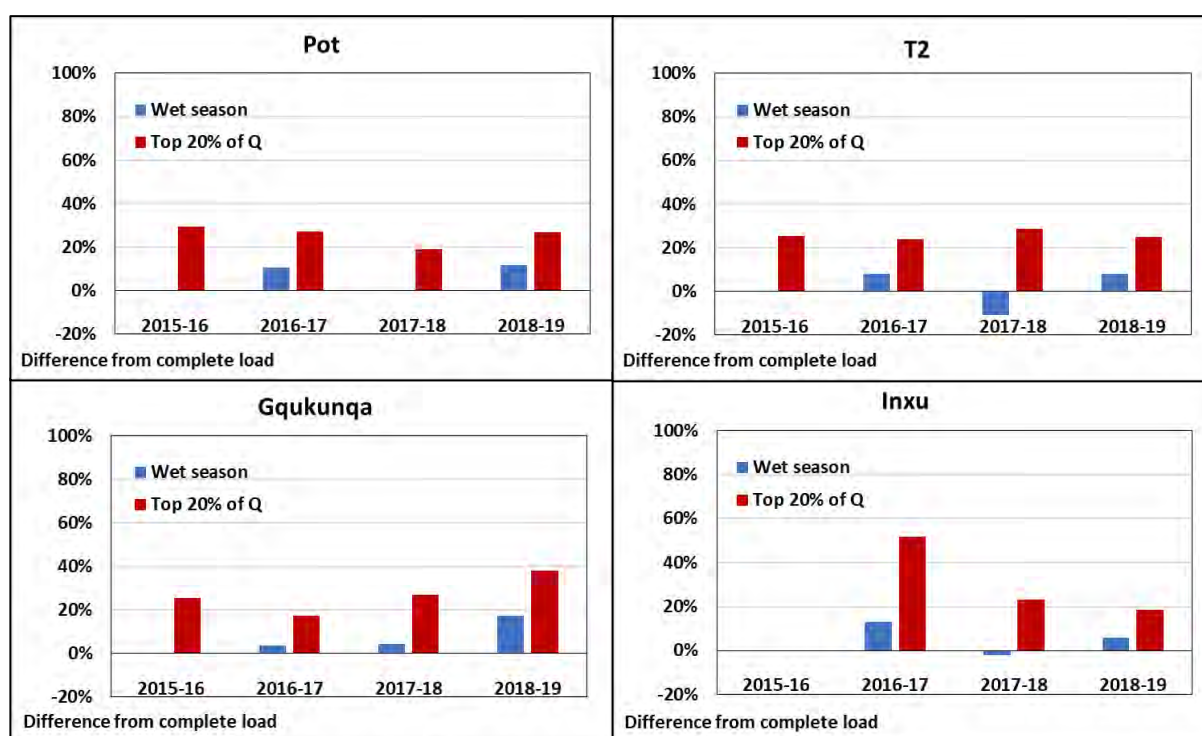


Figure 8-1: The percentage difference from complete annual SSL: SSL estimated from the highest 20% of discharge only (red bars), and from wet season data only (blue bars), at the four study sites 2015 - 2019

Discharge-limited SSLs were always greater than complete SSL, typically by ~25% except at Inxu for 2015 – 16 (-0.19%), Gqukunqa for 2016 – 17 (17%), Inxu for 2016 – 17 (51%), and Gqukunqa 2018 -19 (38%). The difference between the interannual variability of complete SSL and of discharge-limited SSL was inconsistent, but minor ($\pm 2\%$, as expressed by %CV).

The differences between seasonally-limited SSL (1 October – 31 May) and complete SSL were less, but inconsistent, ranging between -11% to +8%. Interannual variability as expressed by %CV increased slightly at Pot (+1.6%) but decreased at the other sites, notably by -3.8% at Inxu and -8% at T2. These results suggest that sampling could be restricted to wet season flood flows with the expectation that the resulting annual SSLs would be over-estimated but within ~25% of those that would be estimated from year-round sampling. The implications of this are discussed in **Chapter 9.3**.

8.5.3 Data decimation

The variation within each set of SSLs was expressed as %CV, indicating the precision resulting from different sampling frequencies ranging from one to six samples per week. The variation in SSLs derived from the 21 sets of decimated data are compared with the mass of the complete annual SSL in **Figure 8-2**.

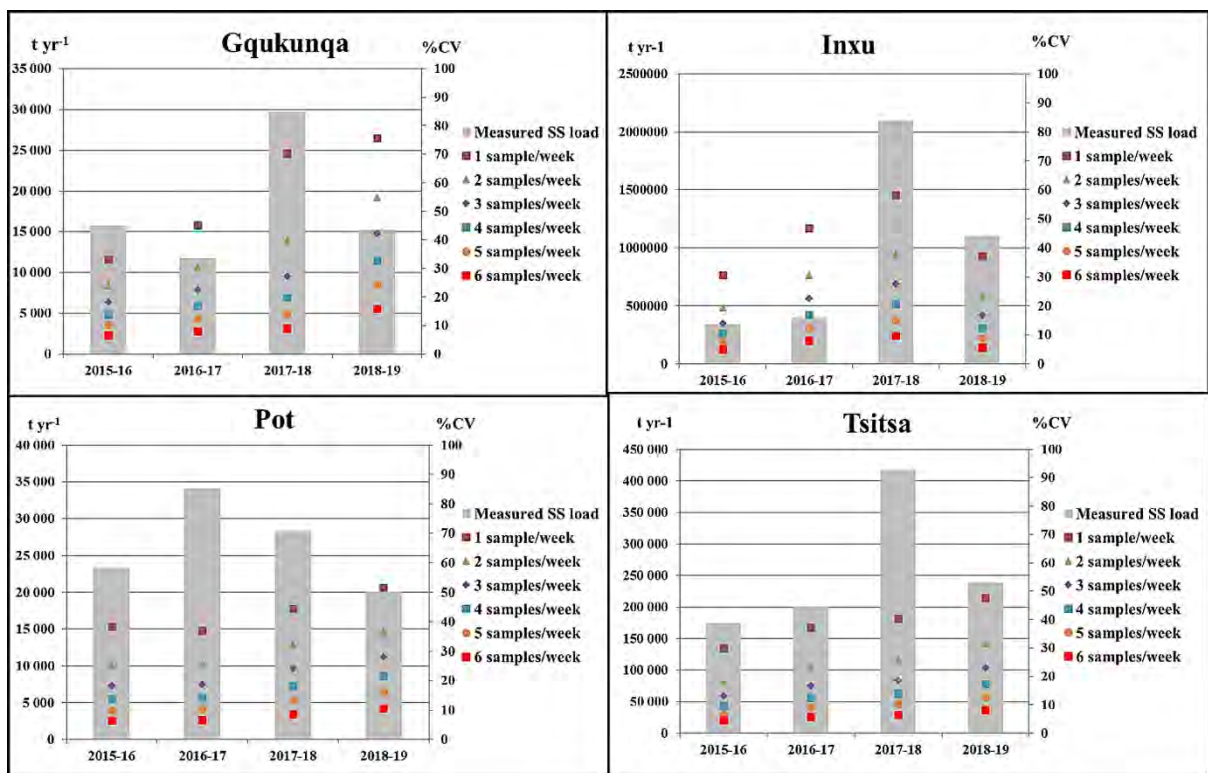


Figure 8-2: The effect of sampling frequency on the variability (expressed as %CV) of SSL at the four study sites. Columns represent the mass of complete annual SSL.

SSL precision improved as expected when sampling was more frequent, or in other words, when epistemic uncertainty was constrained and natural variability was better represented (Walling & Webb 1981, 1985). SSL variability was inversely related to sample frequency and, less obviously, to catchment area: In the Gqukunqa, sampling needed to be undertaken for six days per week to achieve <20 %CV for SSL, for Pot five days per week, for the Inxu four, and for the Tsitsa three days per week. These results suggest that sampling frequency could be reduced to fewer days per week in larger catchments with the expectation that the resulting annual SSLs would be within ~20% of those that would be estimated from daily sampling. The implications of this are discussed in **Chapter 9.3**.

8.6 Summary: the effect of limited data on suspended sediment loads and yields

The complete SSL datasets for the Gqukunqa, Pot, Inxu and T2 (Tsitsa at Qulungashe Bridge) sub-catchments were used to benchmark the effects on annual loads of limiting the SSL data by stratification based on discharge, and decimation based on sampling frequency. Discharge-limited SSL was typically 25% more but interannual variability was almost the same, and similar for all catchments ($\pm 2\%$), suggesting that sampling could be restricted to wet season flood flows. Seasonally-limited SSL (1 October – 31 May) differed inconsistently (-11% to +8%), but interannual variability was greater, and was less consistent between catchments (+1.6% to -8%). Discharge-limited sampling was less accurate but more precise than seasonally-limited sampling. The sampling frequency required to maintain precision (<20%CV) was inversely related to catchment area suggesting that sampling frequency could be reduced to fewer days per week in larger catchments. These findings contribute to the discussion of future sampling design in **Section 9.3.3**.

9 The uncertainty associated with suspended sediment load and yield estimation for catchment management decision-making in inaccessible, ungauged, and resource-limited catchments

9.1 Introduction

This study investigated the implications of the uncertainty in SSC data gathered by citizen technicians for catchment management decision-making in inaccessible, ungauged catchments with limited resources, through the following objectives (**See Section 1.4.1**):

Objective 1: Identify and assess (where feasible) sources of uncertainty associated with the input SSC data in terms of its spatiotemporal coverage and data quality.

Objective 2: Estimate the project period measured SSLs and SSYs for each sub-catchment with, where feasible, an assessment of the sources and extent of the uncertainty in the estimate.

Objective 3: Investigate the effect of stratifying and decimating daily SSC data on the precision of SSL/SSY estimates.

Objective 4: Evaluate the current approaches to SS monitoring and SSL/SSY estimation, and suggest modifications to the sampling programme to reduce uncertainty in SSY estimation in inaccessible and ungauged catchments where resources are limited.

This chapter presents the key findings that came from achieving **Objectives 1 to 3**, discusses them in the context of published research and the limitations of the study, and identifies priorities for future research. Firstly, the uncertainty associated with input data and the project period SSLs/SSYs are examined (**Objectives 1 and 2**). Secondly, the approach taken to SS monitoring and SSL/SSY estimation is evaluated, and suggestions are made for optimising scarce resources to support catchment management decision-making (**Objectives 3 and 4**). Lastly, opportunities for further research are suggested.

9.2 The uncertainty associated with suspended sediment load and yield estimates (Objectives 1 and 2)

9.2.1 Input discharge data (Objective 1)

Key finding

Temporal discharge coverage at ten of the eleven sites was >99.8%, but discharge estimation was inadequate. The associated natural and epistemic uncertainty was likely significant, but the combined error was not quantified.

Discussion

In contrast to their northern hemisphere counterparts, many catchments in South Africa are ungauged, whilst data from DWS gauging weirs can be unreliable (Kapangaziwiri et al., 2012). The pressure loggers that were installed in the nine previously ungauged sub-catchments withstood extreme flows that carried large woody debris (i.e. alien invasive trees felled in the riparian zone). Due to their small size and unobtrusive, firmly anchored placement, they were not vandalised or stolen. The project period hydrological variability/natural uncertainty at eight of the nine stage-monitoring sites was well represented, and there now exists a database of near continuous stage measurements and calculated discharge for these catchments from 1 December 2015 – 31 May 2019. The pressure loggers and barologgers were still in situ at time of writing and were last downloaded in October 2023, which will allow the hydrological variability to be better understood through the collection of more data (Merz & Thielen, 2005).

Two loggers failed consecutively at T3 (Tsitsa at the Gorge), resulting in only 55.9% coverage. The logger was installed on a dolerite dyke that traversed the riverbed: lightning is suspected to have been responsible for logger failures at this site. That said, pressure loggers are recommended as a cost-effective and reliable way to acquire near-continuous stage data in similar, remote, ungauged areas.

Di Baldassarre & Montanari (2009) examined the uncertainties associated with using HEC-RAS to calculate discharge and noted that discharge observations, and parameter uncertainties (e.g., Manning's "n") could contribute significant error. In the Tsitsa River catchment, only one to six flow measurements were taken per site as input to the HEC-RAS rating curves that were used to calculate discharge from the stage data. This major inadequacy was due to the cost of travelling to the 500 km distant catchment from the research base, and the logistical difficulties in accessing sites. Where flow was measured, the reaches were non-uniform and affected by the transport and deposition of mobile,

sandy bedload, and the water levels were typically < 1 m due to safety considerations, and because hydrological fieldwork was carried out in the dry, winter months to allow access to the pressure loggers in order to download the data. The flow-monitoring site on the Inxu River (**Figure 9-1**) provides an example of these conditions in a sand-bed river, while the Gqukunqa shows contrasting but equally non-ideal flow measuring conditions where a dolerite dyke forms the riverbed (**Figure 9-2**).

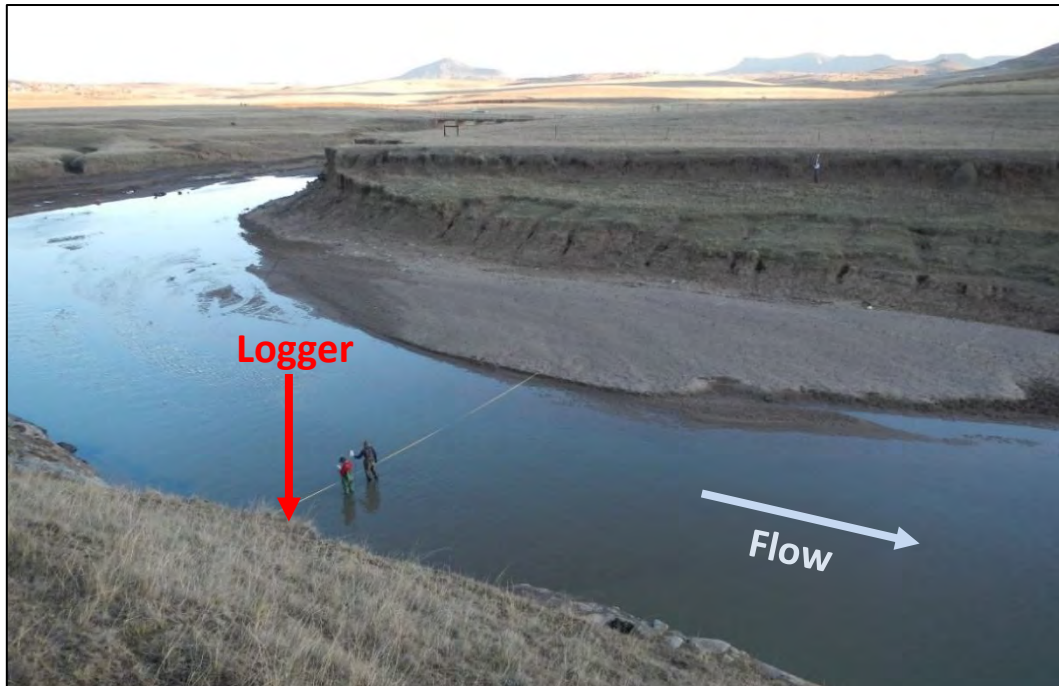


Figure 9-1: The flow measuring site on the Inxu River

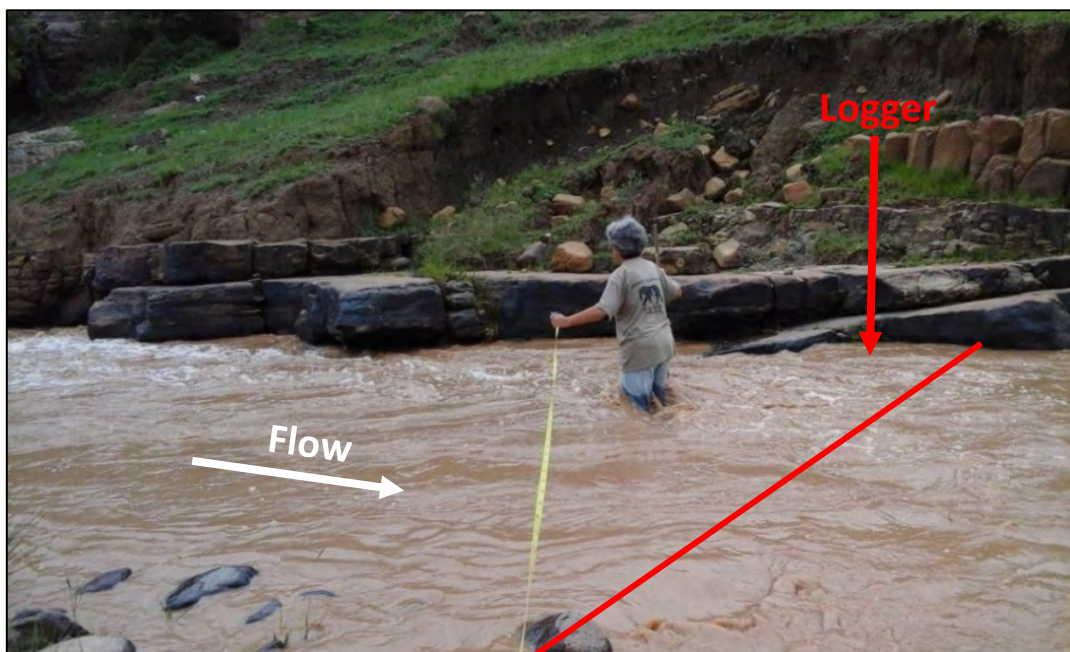


Figure 9-2: The flow measuring site on the Gqukunqa River. The red line indicates the flow measurement cross-section

These circumstances were inadequate compared with the recommended twelve to fifteen measurements per site, taken through the range of flows (Braca, 2008), with the dearth of flow measurements contributing to data scarcity. This is a not uncommon challenge in developing regions, and even where established national-level monitoring programmes are in place (Gordon et al., 2004) (Renouf et al., 2005). The straight, stable reaches with a length of at least five times the mean channel width, uniform water slope, depth, and velocity, channel geometry and roughness required to constrain natural uncertainty (Gordon et al., 2004) were not available close to SSC monitoring sites, or indeed in most parts of the Tsitsa River catchment (**Appendix 2**). Flow measurements are typically $\pm 20\%$ in error (Gordon et al., 2004): this margin of epistemic uncertainty was likely to have been exceeded due to non-uniform reach conditions, negatively impacting the resulting rating curves (Di Baldassarre & Montanari, 2009).

The rating curves that were used to calculate discharge from the stage data were developed from these few, mainly low-flow discharge observations. The resulting error associated with calculated discharge was unknown, but likely to be high, particularly at high flows where no measured data were available and channel controls at different stages were unknown (Di Baldassarre & Montanari, 2009). There were too few observed discharge data to allow drop-out cross validation to establish the RMSE of the resulting stage/discharge relationships. Using Manning's 'n' and channel-width coefficients as calibration variables to develop the curves in HEC-RAS added further unknown error to high flow estimation (Reistad et al., 2007; Di Baldassarre & Montanari, 2009).

The error associated with DWS discharge data provided for T3H009, (Mooi at Maclear) was also unknown, but probably high. Only 12% of the project period record was classified by DWS as "Good, edited data. 86% was classed as "edited and checked, still unaudited", and the remainder as "unreliable". From personal observation, this weir underwent cycles of siltation and dredging, which would significantly and negatively affect the reliability of the DWS rating curve for that site (**Figure 9-3 A and B**).

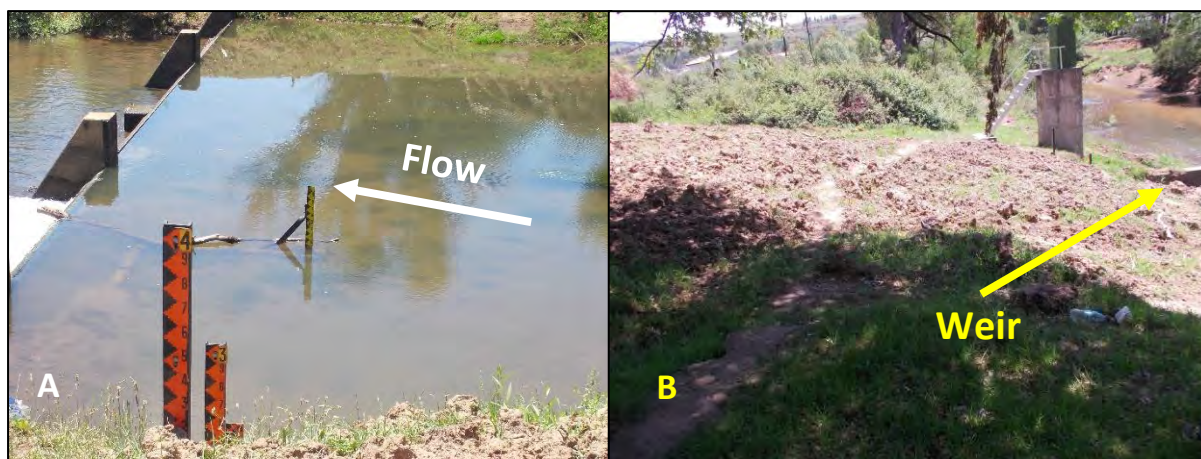


Figure 9-3: DWS gauging weir T3H009 (Mooi River) showing (A) siltation and (B) dredging

Only the data from DWS gauging station T3H006 near TN2 (Tsitsa at Mbelembushe) was 99% good, edited data (**Table 5-9**). This uncertainty and its implications for the resulting SSLs/SSYs must be conveyed to researchers and catchment policy and decision-makers as guidance for future studies and as a caveat accompanying the study outcomes.

The uncertainty associated with scarce hydrological data is a recognised problem in southern Africa (Kapangaziwiri et al., 2012). It could be constrained by restricting future SSL/SSY estimation to catchments with functional DWS gauging stations. As seen at T3H009, however, maintenance of gauging weirs is declining in South Africa. In ungauged catchments, SSC monitoring programme designs and budgets must be structured to ensure sufficient field visits and appropriate equipment to safely achieve the twelve to fifteen recommended direct flow and stage measurements per site, particularly during high flows. However, the uncertainty related to flow-measurements in non-uniform channels with changing bedforms would persist (Di Baldassarre & Montanari, 2009). Hydrological modelling calibrated using reliable DWS gauging weir data and using available rainfall data as input could supplement these measures (Kapangaziwiri et al., 2012). Recommendations for alternative approaches to discharge estimation are discussed further in **Section 9.3.3**.

Key Finding

The Tsitsa River catchments exhibit high interannual, annual, and seasonal hydrological variability.

Discussion

The daily discharge time series for each site exhibited a strongly seasonal pattern and revealed sub-catchment scale inter-annual variability (**Figure 2-17**). The response of the Tsitsa River sub-catchments

to precipitation was “flashy”, with annual R-B Index values ranging between 0.24 and 0.54 (**Table 2-3**). To the author’s knowledge, the R-B Index has not previously been applied to South African rivers, yet it may have significant value, providing a first insight into the variability of project-length discharge records that are typically too short to allow flood frequency, flow duration, and flood magnitude indices to be derived (Olden & Poff, 2003).

Hydrological variability is an important source of natural uncertainty (Walling, 1977b; Schumm, 2005), and has been strongly linked to SSC variability, particularly in arid and semi-arid areas where long drought periods may be terminated by extreme floods (Fryirs & Brierley, 2012). Although a sub-humid rather than semi-arid catchment, the study area (in common with large parts of South and southern Africa) is otherwise typified by this description. Determining the R-B Index provides some insight into catchment-scale SSC variability in South Africa (Onwuka et al., 2021). As such, it is recommended that discharge data collection should commence prior to an SSC sampling campaign, and that the R-B Index of sub-catchments should be determined to inform spatiotemporal design and SSC sampling frequency for the proposed study catchments. SSC/discharge relationships are examined in **Section 9.2.3**.

9.2.2 Input suspended sediment concentration data (Objective 1)

Key finding

SSC monitoring sites were active for differing periods of time, with record lengths ranging from 316 to 1278 days.

Discussion

Of the eleven SSC monitoring sites established, only four (Pot, Mooi, T2 (Tsitsa at Qulungashe Bridge) and Inxu) achieved > 70% project period coverage. This was due to early discontinuation, and/or to citizen technician sampling inconsistency (discussed as the next key finding). The relatively unimpacted 75 km² Little Pot was expected to have low annual SSLs/SSYs against which to compare others (**Chapter 2**, study area). Sampling was discontinued here in early October 2016, allowing one annual SSL/SSY to be estimated: extremely low turbidity values (91% of samples were <20 ntu) confirmed that Little Pot would contribute very little to downstream SSL and funding for SSC monitoring was curtailed in May 2017. Sampling at Tsitsana and Hlankomo was discontinued to reduce costs and allow unchanged sampling intervals at the remaining sites. Sampling at T4 (Tsitsa at the Falls) stopped in September 2018 when the personal safety of the citizen technician was compromised.

Two annual SSLs/SSYs were estimated for Little Pot, Tsitsana, Hlankomo and T4 (Tsitsa at the Falls). These sites were therefore “poor” by Vanmaercke et al.’s (2014) criteria for record length, although according to Walling et al. (2007), Tsitsana, Hlankomo and T4 (Tsitsa at the Falls) were “good” (**Table 3-4** and **Table 3-5**). In practical terms, the short SSC record lengths limited the potential to assess inter-annual SSL/SSY variability at these sites, and to meaningfully compare their results with those that fully represented the project period.

Key finding

SSC sampling took place on more than 80% of the days that sites were active, and target high flows were sampled more than 78% of the time at nine of the eleven sites.

Discussion

Maximising SSC sampling coverage of flood flows was a major goal of the project, but the relative contribution of low flows to SSL/SSY in the Tsitsa River sub-catchments was not known, and possibly significant. Temporal sampling programme design therefore aimed to ensure consistent (i.e., daily to sub-daily) low-frequency low-flow sampling, and high-frequency flood-flow sampling.

The impact of site-specific reduced and inconsistent SSC sampling coverage (**Figure 5-6**) on the epistemic uncertainty of the resulting SSLs/SSYs was expected to be high. However, **Table 5-5** shows that (except at Mooi and TN2), the CT-based manual flood-focused sampling approach successfully captured most (78% to 97%) of the highest 20% of flows that occurred while each site was active.

Although some days were missed, these were typically low flow/low SSC days, due to the incentive of citizen technician payment and sampling frequency protocols: the citizen technicians knew that they could make substantially better earnings in a period of hours during a flood than over several days of low water sampling. They were (as planned in the sampling programme design) therefore motivated to sample during the target high SSC flood flows.

Key finding

Project resources were disproportionately allocated to collecting and analysing low SSC samples.

Discussion

In a project framing of resource and data scarcity, it is important to prioritise the collection of data that are essential to answering the research questions. As noted in the previous section, winter dry season sampling was suspected to be of limited importance, but the contribution of low flow/low SSC samples to the estimation of annual SSL/SSY was unknown and might have been substantial, particularly if snowmelt had been a significant contributor of sediment.

As expected, the discharge data were heavily skewed towards low flows (**Figure 2-17**). Consequently, even though some of these samples were missed, almost half the SSC data collected had low values (i.e., turbidity <200 ntu, **Table 6-2**, Subset 1). Collecting these samples was necessary to this research, but the new knowledge resulting from data stratification and decimation (**Chapter 8.5**) showed that focusing on wet-season sampling only would be a more efficient allocation of financial and human resources in future projects that aimed to estimate SSLs and SSYs in similar areas.

Laboratory analysis and data processing of samples containing large amounts of sediment required fewer steps and less time than those with very little sediment. The evaporation method was geared towards samples with high SSC (**Table 6-2**, Subset 2) producing consistent results for these samples (**Figure 5-7**, precision analysis), but evaporation had to be used for the sub-set of samples with turbidity measurements ranging from 0-999 ntu in order to obtain the required SSC/turbidity data pairs (**Table 6-2**, Subset 3). Hence, the uncertainty associated with calculating SSC for samples <200 ntu from measured turbidity was relatively high (**Figure 5-7**).

Additionally, event-related changes in sediment particle size and other properties produce non-unique SSC/turbidity relationships (Minella et al., 2008). Ramothello (2021) found that not only did particle size distributions change through flood events, but also that early season floods had a different particle size range than late season floods, at T4 (Tsitsa at the Falls) and at TN2 (Tsitsa at Mbelembushe). This could add significant uncertainty to the SSC/turbidity relationships. The research by Ramothello (2021) was also a first indication that the assumption of homogenous SSC distribution throughout the channel cross-section of South African rivers (Msadala et al., 2010) may be incorrect. This is examined in more detail later in **Chapter 9.5**.

In future, vacuum filtration may be a preferred option to determine SSC for low discharge samples with low SSC, if the number of such samples is reduced. The contribution to SSL/SSY of low SSC samples is discussed in the next section, together with approaches to optimise scarce resources by reducing the number of low SSC samples collected and analysed.

9.2.3 Estimating project period suspended sediment loads and yields (Objective 2)

Key finding

Discharge variability explained less than 30% of SSC variability, even for stratified data.

Discussion

This finding was foreshadowed by the visual inspection of daily SSC and discharge timeseries (**Figures 7-1 to 7-11**). Weak SSC/discharge relationships were suggested by the marked offset (i.e., positive and negative hysteresis) of SSC and discharge peak values at all sites. This was confirmed by coefficients of determination (i.e., r^2) that were mainly below 0.3 for regressions of untransformed and log transformed SSC/discharge data, and for discharge-limited and seasonally-limited datasets (25% exceedance discharge and wet season, respectively). Neither the extent of SSC variability nor its weak relationship to catchment hydrology had been quantified for the Tsitsa River sub-catchments prior to this study, nor, with one exception, are they published for other South African catchments. The exception is the similar findings reported for the Umfolozi River in the province of Kwa-Zulu Natal, i.e., also located on the East coast of South Africa, to the north of the Eastern Cape (Grenfell & Ellery, 2009).

There are three consequences of this finding. Firstly, sediment rating curves cannot be used to estimate SSLs in (East coast) South African rivers. Secondly, SSC variability in the Tsitsa River catchment is more strongly influenced by factors such as sediment availability, sediment particle size, land use and sediment sources, and catchment connectivity, rather than by discharge variability. Thirdly, SSC/discharge relationships require further study in the southern hemisphere in general and in southern Africa in particular to determine the patterns and causes of hysteresis.

Where strong ($r^2 > 0.5$) SSC/discharge relationships are found, often from near-continuous, and less hydrologically variable data, sediment rating curves are usually the most accurate and precise method of estimating SSL (Walling, 1977a; Walling, 1977b; Walling & Webb, 1981; Asselman, 2000; Horowitz, 2003, 2008; Gao, 2008; Kuhnert et al., 2012). A sediment rating curve expresses the empirical relationship between SSC and discharge (Walling & Webb, 1981). It allows both historic and predictive

SSLs to be estimated from discharge data, (Walling, 1977b), particularly in undeveloped catchments such as the Tsitsa River catchment where stationarity can be assumed within the limitations of climate change (Fryirs & Brierley, 2012). A discharge-weighted ratio estimator was selected in order to constrain the further epistemic uncertainty that would accrue from rating curves, and the computational bias that would result from an averaging estimator. Ratio estimators require daily SSL as input, and so cannot be used predictively (Quilbé et al., 2006): SSLs/SSYs can only be determined for the Tsitsa River sub-catchments for the sampling periods at each site.

Low sampling frequencies would increase the uncertainty associated with SSLs estimated using discharge-weighted ratio estimators (Vanmaercke et al., 2012), but the resulting Q ratios were typically between 0.8 and 1.2 (**Table 7-7**), indicating that discharge ranges had been adequately represented by sampling. Where Q ratios were outside these bounds, SSLs/SSYs were associated with greater uncertainty

Discovering the weak relationship between SSC and discharge in the Tsitsa River catchment raises the question of the specific causes. This, unfortunately, was outside the scope of this project, but is firmly highlighted as an important area for further research based on the SSC data now available. The results of such studies will inform catchment management decision-making, for example regarding land restoration interventions and the feasibility and design of proposed impoundments.

Most hysteresis research has focused on the northern hemisphere. Malutta et al. (2020) found only two Australian and three African studies in their state of the art review of 71 hysteresis analysis papers that focused on quantifying sediment dynamics (Malutta et al., 2020). Studies indicate that hysteresis and variable SSC/discharge relationships throughout flood hydrographs are linked to episodic sediment supply, or “pulses”, due to seasonal and event-based cycles of erosion, transport and deposition, antecedent rainfall conditions, and sediment availability or exhaustion (Walling, 1974; Gao, 2008). Locally, some research has been undertaken in a similar catchment to determine the effects of catchment connectivity on sediment transport (Van der Waal & Rowntree, 2018). In the Tsitsa River catchment, soil erosion risk has been determined (Le Roux & van der Waal, 2020), as well as the *potential* for sediment production from gullies (Pretorius et al., 2016), but studies have thus far failed to investigate either the magnitude or the variability of sediment delivery ratios, particularly for the prevalent gullies that are associated with the dispersive soils associated with Tarkastad Formation mudstones. The episodic production, transport and deposition of material in one large gully in the

Inxu catchment was linked to erosive rainfall events (Le Roux et al., 2022), but determining the extent and frequency with which gullies in the Tsitsa River catchment generally act as sources of, and/or conduits for sediment delivery to channels, is a critical area of further research.

Key finding

Inter-annual SSL/SSY variability was high.

Discussion

High inter-annual SSL/SSY variability makes predictive statements difficult and, by extension, increases risk when informing catchment management decisions (Vanmaercke et al., 2012). Even for the four sites with the most complete records, and for which uncertainty can be better assessed, longer SS data records are required to better determine SSY trends and calculate reliable means, bearing in mind that the inter-annual variability of SSLs/SSYs can range from 6%CV to 300%CV. Vanmaercke et al. (2012) based this statement on a study of northern hemisphere rivers, noting that limited data were available from which to determine the range of inter-annual variability and assess the uncertainties associated with mean SSYs derived from differing record lengths. Although this study adds SSL/SSY data from South African rivers to the global body of knowledge and demonstrates variability, the short record length precludes meaningful *analysis* of the inter-annual variation. SSLs/SSYs have not yet been estimated post 31 May 2019, although SSC and discharge data were collected until 31 March 2023. Once available, these additional data may provide an improved overview of inter-annual variability.

In addition to the requirement for further research into sediment supply and transport associated with gullies, investigations of catchment characteristics and processes *sensu* Mills & Bathurst (2015) and Gannon et al. (2022) are required to identify the sediment sources, pathways and storages that result in the extreme spatiotemporal SSL/SSY heterogeneity in the Tsitsa River catchment. However, an examination of the SSC and discharge data (see **Figure 7-2**, daily SSC and discharge) and of SSLs (**Table 7-7**) at Tsitsana provides a possible explanation for SSL/SSY variability at that site that may have wider applicability to other sub-catchments, and which highlights the limits of the inferences that can be drawn from SSLs/SSYs.

The SSL at Tsitsana for 2016 – 17 was seventeen times greater than for 2015 – 16 (a difference of 89 502 t yr⁻¹) for this 135 km² headwater catchment. The 2015 – 16 and 2016 – 17 peak loads at Tsitsana were associated with a series of small floods in January 2016, and a far larger series of floods

in February 2017 (**Figure 7-2**). The peak SSC values from 2016 – 17 were investigated as outliers and found to be valid (**Section 7.3.2**). **Figure 9-4** shows daily SSC, SSL, and discharge for the two flood series. Note that there is an order of magnitude difference in the y-axis for SSC and SSL whilst the y-axis for discharge is the same in both graphs.

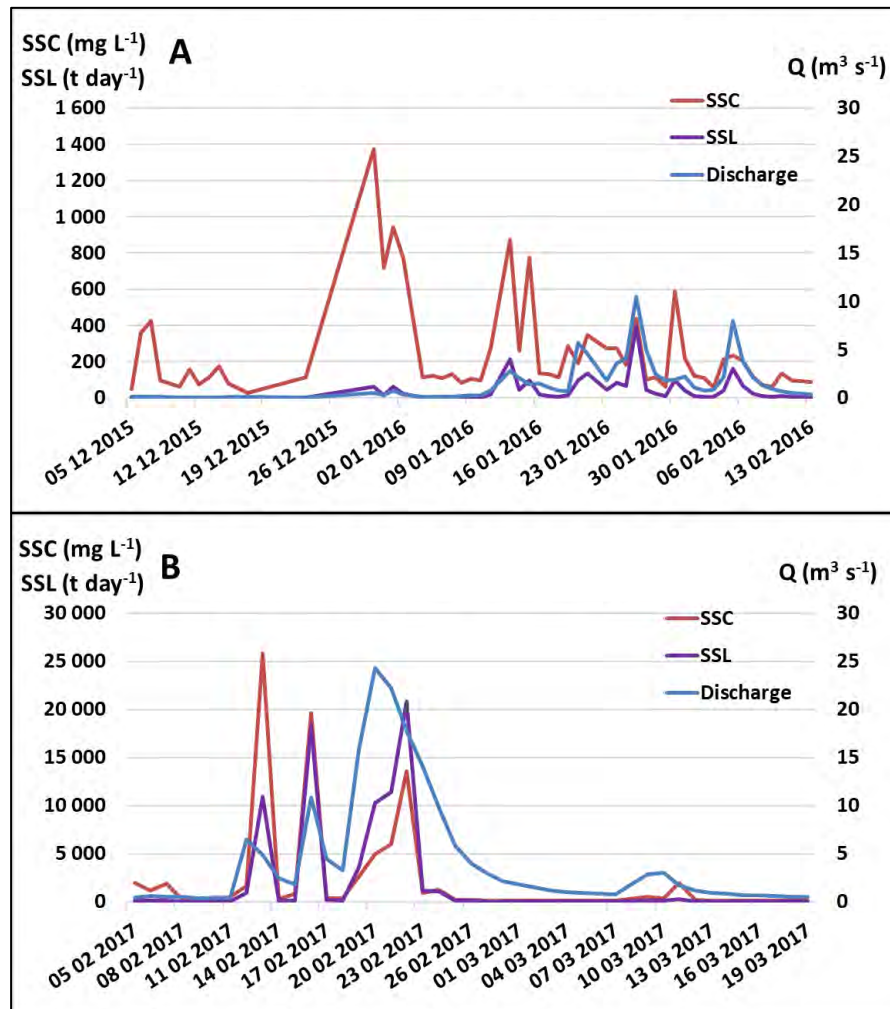


Figure 9-4: Daily SSC, SSL, and discharge at Tsitsana (A) 05 12 2016 – 13 02 2016, (B) 05 02 2017 – 07 03 2017

Figure 9-4 A and B show that SSC and discharge peaked at virtually the same time. Average discharge for the two years was similar (0.77 and $0.91 \text{ m}^3 \text{ s}^{-1}$ respectively), but while the peak flows were approximately twice as high in 2016 – 17, the peak SSC for 2016 – 17 was greater by more than an order of magnitude.

Definitively linking SSL to catchment characteristics and processes is outside the scope of this study, and is an important area of further research that can now be addressed following the evaluation of

the SSC data. However, bank erosion is a possible source of the sediment that could contribute to high SSL and inter-annual variability (**Figure 9-5** and **Figure 9-6**).

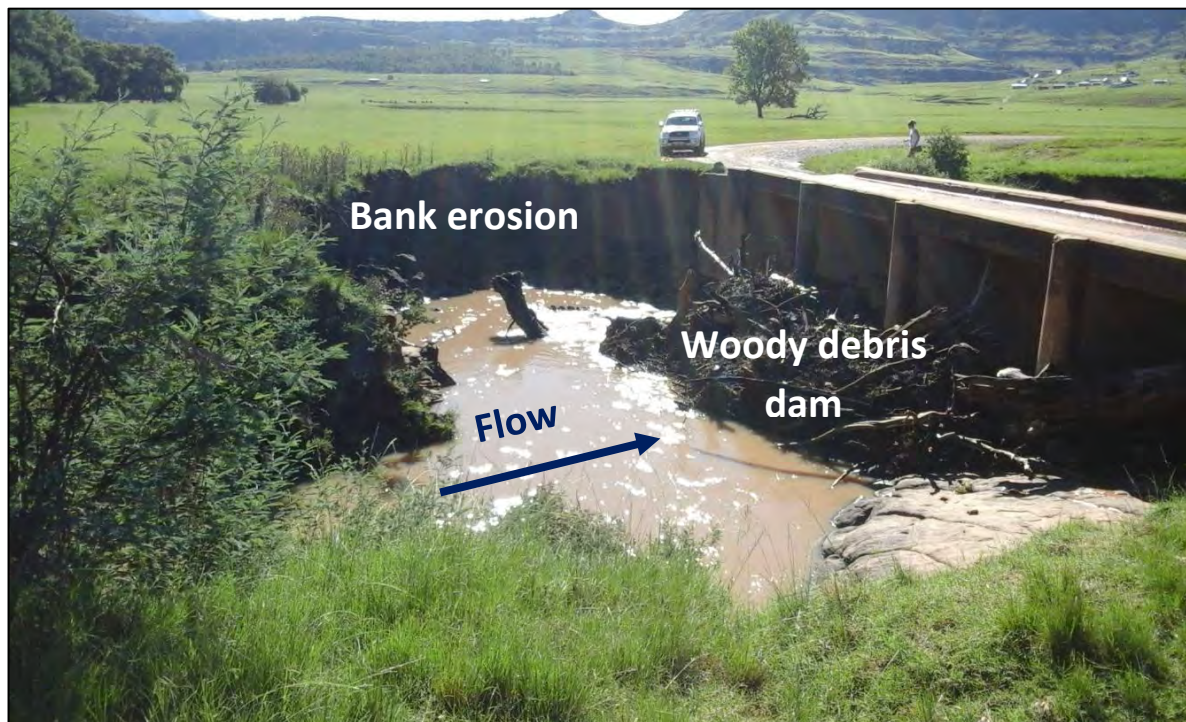


Figure 9-5: Photograph of woody debris dam and associated bank erosion 100 m upstream of the sampling site at Tsitsana

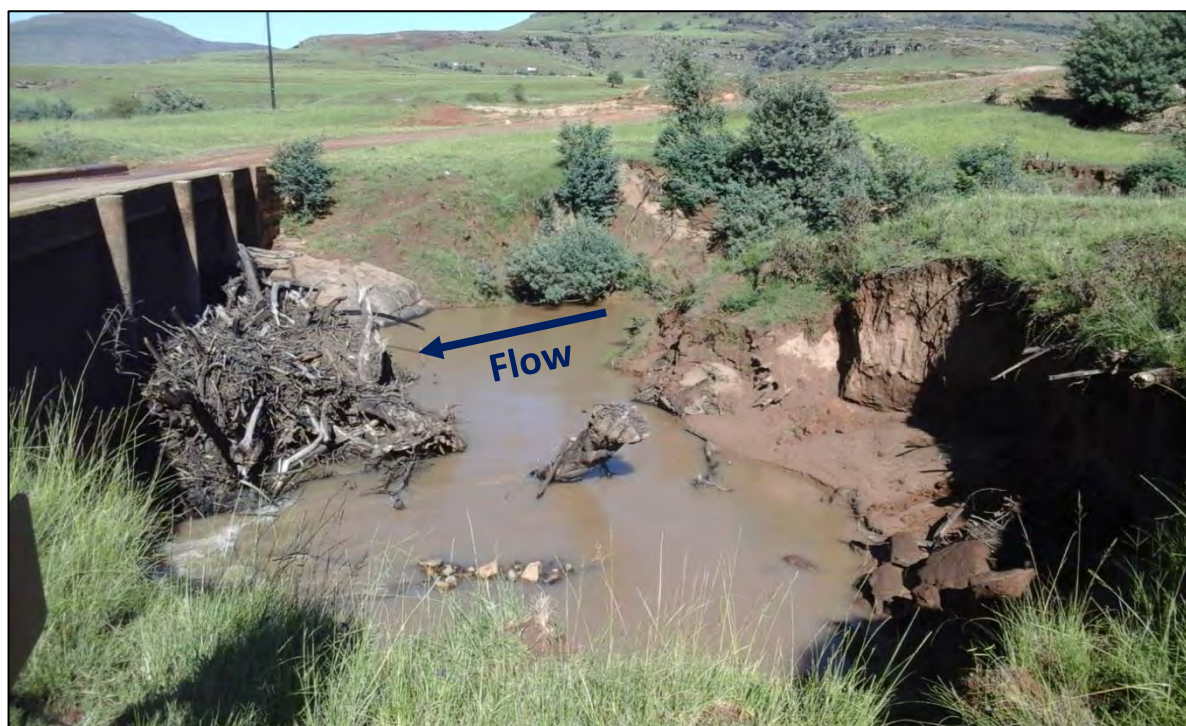


Figure 9-6: Photograph foregrounding the bank erosion 100 m upstream of the sampling site at Tsitsana

The bridge shown in **Figure 9-5** and **Figure 9-6** is located ~100 m upstream of the Tsitsana sampling site. The woody debris came from the upstream clearance of riparian alien invader tree species and accumulated at the bridge during preceding high flows, forming a dam. The resulting high, turbulent water caused extensive bank undercutting upstream of the bridge, causing episodic mass failure of the bank and introducing large volumes of sediment to the channel during the rising phase of the flood. High concentrations of SS would have been monitored at the sampling site when the debris dam was overtopped, decreasing during the falling limb as the dam impeded flow causing upstream deposition.

Similar debris dams with associated bank erosion were frequently observed throughout the Tsitsa River catchment during the project period. The effects may have been much more pronounced at Tsitsana compared for example with Hlankomo, Little Pot, or Gqukunga where there are also bridges upstream of the sampling site, perhaps due to a combination of proximity to the bridge and other catchment characteristics. An extended sampling period and further research would be needed to determine whether this wide interannual variation is characteristic of this site.

Key finding

There was a tendency for sub-catchment scale SSY to increase down the Tsitsa River catchment but there was no clear relationship with catchment area

Discussion

There is no “rule of thumb” inversely relating SSY to catchment area, even though this trend does occur in some settings (Mills & Bathurst, 2015). The complex interactions of the drivers and controls of sediment supply, transport and deposition vary over time and space within catchments, and particularly between catchments. This applies not only to the transport of eroded material *to* the channel (Walling, 1983; Richards, 2002), but also to the suspension and deposition of sediment and bank erosion *in* the channel .

In the Tsitsa River catchment (**Section 7.4.6**, Mean SSY), there was no significant relationship between mean SSY and catchment area when all sites were included (**Figure 9-7A**), and a weak ($r^2 = 0.44$), borderline significant ($p = 0.050$), positive relationship was observed when the obvious “outliers” Tsitsana and Inxu were removed (**Figure 9-7B**). Catchment area was therefore not a good predictor of SSY. The next key finding provides further insight into the catchment characteristics that appear to

exert a greater influence on SSY than does catchment area.

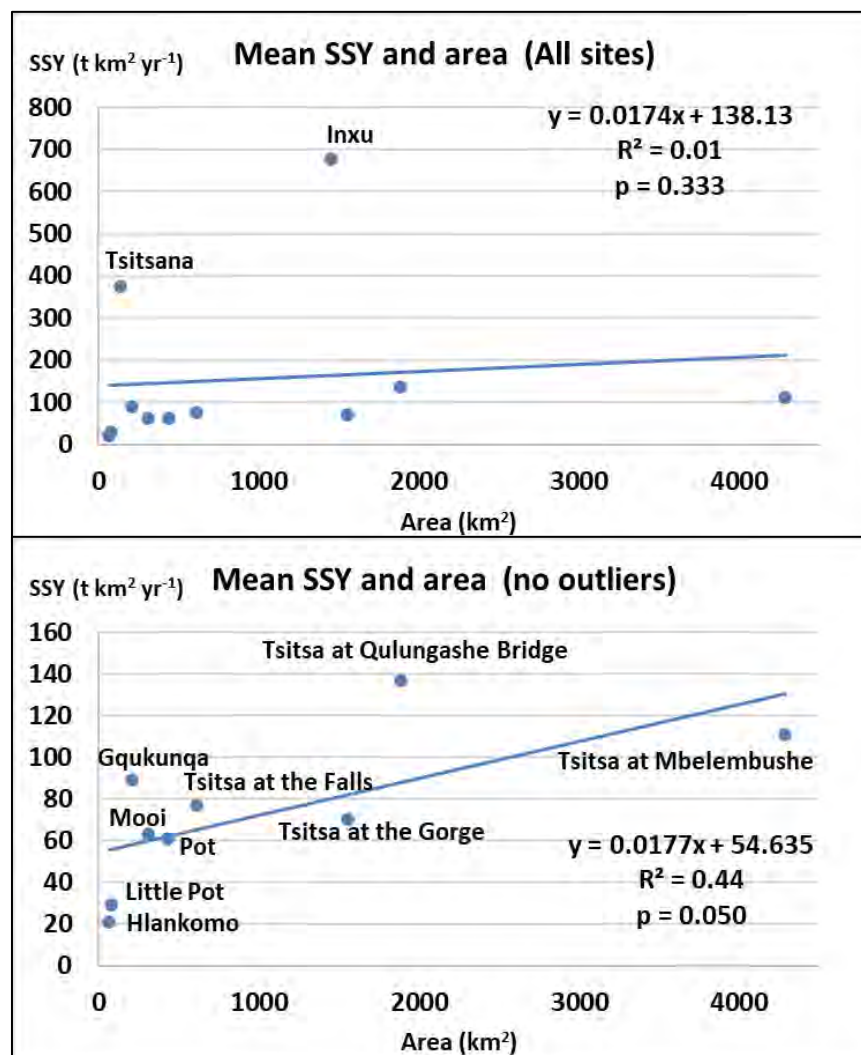


Figure 9-7: Relationship between mean SSY and catchment area for all sites (A) and excluding Tsitsana and Inxu (B)

Key finding

Geology, land tenure, and SSY were spatially related

Discussion

At catchment scale, land tenure is spatially related to geology and soil type in the Tsitsa River catchment (**Section 1.2**). A study limited to Pot, T2 (Tsitsa at Qulungashe Bridge), Gqukunga, and Inxu linked these characteristics to SSY (Bannatyne et al. (2022), included as **Appendix 9**). The lowest SSY was estimated for Pot sub-catchment, which was representative of the commercial and privately-owned farming and plantation area of the less erodible upper Tsitsa River catchment. Higher SSYs

were estimated at T2 (Tsitsa at Qulungashe Bridge), Gqukunqa, and Inxu, that were representative of the lower parts of the catchment that included the communal areas where dispersive soils and extensive gullying occurred. This trend was confirmed when all sub-catchments were included in the analysis. The topography of the headwater (upper) sub-catchments is steeper than that of the middle and lower parts of the catchment (**Table 2-1**). However, relatively low SSYs of between $61 \text{ t km}^{-2} \text{ yr}^{-1}$ and $77 \text{ t km}^{-2} \text{ yr}^{-1}$ were estimated at the upper catchment sites (other than at the Tsitsana), i.e., Pot, Mooi, Hlankomo, T4 (Tsitsa at the Falls) and T3 (Tsitsa at the Gorge). The sites in the lower catchment (i.e., T2 (Tsitsa at Qulungashe Bridge), Gqukunqa, Inxu, and TN2 (Tsitsa at Mbelembushe) had relatively high SSY i.e., above $89 \text{ t km}^{-2} \text{ yr}^{-1}$. In other words, catchment area and topography appeared to be less closely related to SSY than geology, soil type, and land tenure.

A confluence-based sediment tracing and source apportionment study using bed-sediment resuspension (Bannatyne et al. (2024) **Section 4.5.5**) also showed that the Tsitsana, Gqukunqa, and Inxu sub-catchments contributed relatively significant proportions of SS to the catchment downstream of their confluence, whilst the Little Pot, Pot and Mooi sub-catchments contributed significantly less than the main stem of the Tsitsa at that point. However, the tracing study apportioned a far greater contribution to the Hlankomo, and proportionally far less to the Inxu, than indicated by the estimated SSLs for these sub-catchments. With these exceptions, the results of the SS sampling programme were similar to those of the tracing study, with the caveat that the tracing results were based on a single sampling effort using sediment re-suspended from the river bed (Bannatyne et al., 2024).

Key finding

Limiting data to the wet season or the highest 20% of flows resulted in <20% loss of SSL/SSY precision

Discussion

Seasonally limiting the data collected at the four sites with complete records (**Section 8.5.2**) showed that removing data collected in the dry season between 30 June and 30 September each year (i.e., the low discharge samples) typically resulted in an over-estimation of less than ~15% (**Figure 8-1**). The number of samples collected and analysed would have been reduced by ~11 000 (assuming most samples <200 ntu were collected in the dry season, **Table 6-2**). This would have reduced the number of 1000 km, 4-day trips to pick up samples from the field, relieved pressure on the laboratory workers,

and shortened the time needed for sample analysis, data processing, and the finalisation of results. The substantial cost-savings would have been available to maintain or even extend the spatial and/or temporal scope of the project.

Focusing exclusively on flood sampling (emulated by stratifying the data and estimating SSYs from only the top 20% of flows) resulted in greater over-estimation, i.e. between ~20% and ~25% for most years and sites (**Figure 8-1**). Adopting a strategy of sampling only the highest flows would have again reduced the number of samples collected and analysed, again benefitting project efficiency. Further, sampling in larger catchments could be restricted to fewer days per week without loss of precision (**Figure 8-2**), thereby optimising survey costs.

Restricting sampling to the wet season flood flows could be an appropriate strategy to optimise both study costs and SSL/SSY precision. The implications of adopting this strategy are discussed in **Section 9.3.3**.

Key finding

Mean SSY for the Tsitsa River catchment is comparable with estimates from other African studies

Discussion

The review by Vanmaercke et al. (2014) provided the most recent data against which to compare the SSY estimated in this study with SSYs derived from other African studies (**Figure 4-4** and **Table 4-1**). Broadly, SSY estimated for the Tsitsa River catchment in this study ranged from 15 t km⁻² yr⁻¹ at Hlankomo for 2016 to 1443 t km⁻² yr⁻¹ at Inxu for 2018. This is well within the range of 0.4 t km⁻² yr⁻¹– 3132 t km⁻² yr⁻¹ reported for southern Africa but exceeds the range of 0 t km⁻² yr⁻¹– 890 t km⁻² yr⁻¹ for South Africa reported by Vanmaercke et al. (2014). Msadala et al. (2010) reported a range of 94 t km⁻² yr⁻¹ to 1509 t km⁻² yr⁻¹ for Region 7 (Eastern Cape) in general, which is similar to the range of SSYs estimated for the Tsitsa River catchment.

Key finding

Mean SSY was comparable with SSY estimates from reservoir studies, but not with modelled estimates

Discussion

Several studies have modelled SSY for the Tsitsa River catchment above TN2 (Tsitsa at Mbelembushe, **Section 4.5.2**) The results of these studies and the approaches that they used are summarised in **Table 4-5**. The uncalibrated modelled SSYs vary considerably from each other, and from the average SSY of $111 \text{ t km}^{-2} \text{ yr}^{-1}$ estimated by this study for TN2 (**Table 7-7, Figure 7-32**). At sub-catchment scale, SSY derived by other researchers are summarised in **Table 9-1** and compared with SSY from this study (in brackets).

Table 9-1: A comparison of estimated sub-catchment SSY from other studies with measured SSY from this study (in brackets)

Catchment	Approach	SSY $\text{t km}^{-2} \text{ yr}^{-1}$ (this study)	Reference
Little Pot	SWAT with GIS	200 – 599 (29)	Le Roux et al. (2015)
Tsitsana		200 – 599 (43 - 706)	
Hlankomo		200 – 599 (15 - 26)	
T4 (Tsitsa at the Falls)		600 – 1 099 (75 - 79)	
Pot		200 – 599 (47 – 79)	
Mooi (above Maclear)		0 – 199 (41 – 124)	
T3 (Tsitsa at the Gorge)		600 – 1 099 (63 – 78)	
T2 (Tsitsa at the Qulungashe Bridge)		2 100 – 4 999 (93 – 222)	
Gqukunqa		2 100 – 4 999 (58 – 146)	
Inxu		100 – 4 999 (236 – 1443)	
Tsitsa River catchment average		500 (111)	
Inxu (2016 -17)	Direct suspended sediment sampling	550 (273)	Nyamela (2018)
Inxu (2016 – 17)	MUSLE	5000 (273)	Gwapedza et al. (2021)

Nyamela (2018) undertook the only other study that relied on measured data, using the same input discharge and SSC data as this study. The shorter period for which discharge data were available may have impacted Nyamela's (2018) estimated SSL/SSY, as the smaller number of directly measured flow data increased the uncertainty related to the discharge rating curve. The high 2017 SSY for Tsitsana ($706 \text{ t km}^{-2} \text{ yr}^{-1}$) from this study falls within the modelled range of Le Roux et al. (2015), as do the SSY for all years for the Inxu. Generally, however, the results of Le Roux et al. (2015) were an order of magnitude greater than the SSY estimate from this study, as is the estimate for the Inxu by Gwapedza et al. (2021). At T4 (Tsitsa at the Falls) and Gqukunqa, the upper limit of Le Roux et al.'s (2015) modelled range is two orders of magnitude greater than the measured SSY from this study.

There is no in-channel water storage infrastructure in the Tsitsa River catchment from which to estimate average annual SSL/SSY for direct comparison with the results of this study. Comparisons can, however, be made with the Mt Fletcher Dam in the nearby Thina catchment, the Welbedacht Dam in the Orange Free State (**Section 4.3**), and the five dams from Msadala et al.'s (2010) Region 7 sediment yield prediction area, that are closest to the Tsitsa River catchment (**Figure 9-8**).

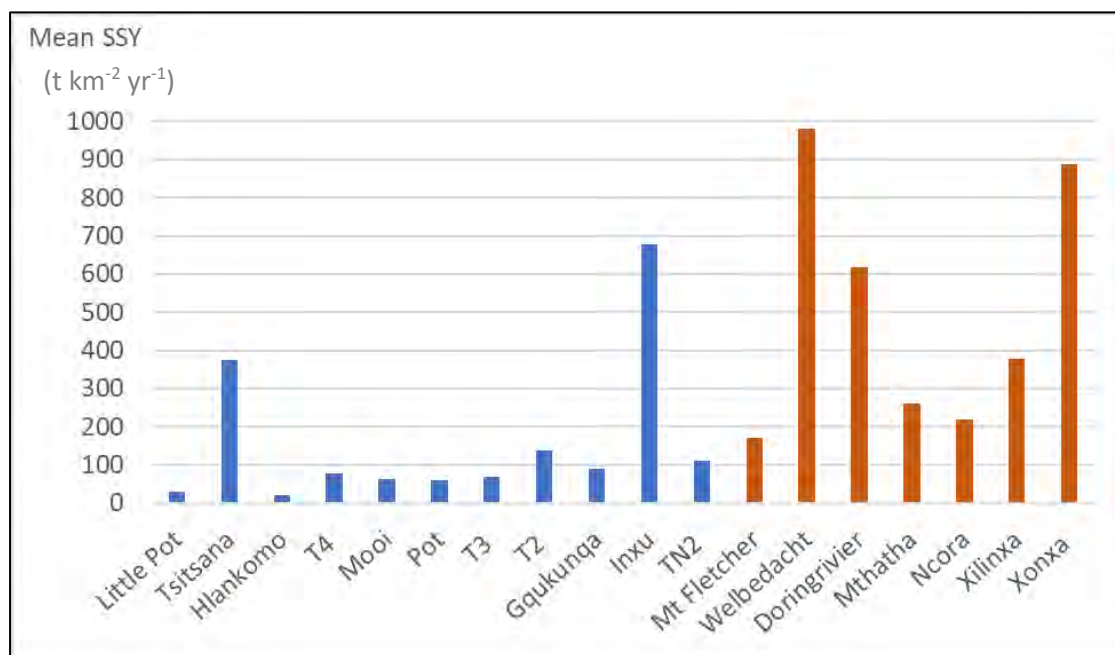


Figure 9-8: Mean SSY for the Tsitsa sub-catchments (blue) and selected reservoir studies (brown)

Similar climate, geology, soils, demography, and land use support the comparison of the mean SSY of $170 \text{ t km}^{-2} \text{ yr}^{-1}$ estimated from sedimentation of the Mt Fletcher dam with the annual SSYs of $43 \text{ t km}^{-2} \text{ yr}^{-1}$ and $706 \text{ t km}^{-2} \text{ yr}^{-1}$ estimated by this study for the Tsitsana catchment. The 70% storage loss for

the 500 000 m³ capacity Mt Fletcher dam between 2008 and 2012 indicated an average annual SSL of 131 250 t yr⁻¹ for the 771 km² catchment, assuming 100% trap efficiency. It is likely, however, that trap efficiency was low and that the mean SSY is under-estimated (Pers. comm. B van der Waal).

Welbedacht Dam (**Section 1.1**) lies in an area characterised by long droughts and extreme floods. Catchment geology is broadly similar to that of the Tsitsa River catchment (DWA, 2009). Situated near Wepener in the Orange Free State to the northwest of Lesotho, the Welbedacht Dam lost 95% of its initial storage capacity in the first 45 years of operation (Basson et al., 2022). Mean annual SSY for the 15 285 km² catchment was estimated as 981 t km⁻² yr⁻¹ (Basson et al., 2022). This exceeds the mean SSY from any sub-catchment of the Tsitsa River catchment, although annual SSY was estimated at 1443 t km⁻² yr⁻¹ for the Inxu River catchment (2018 – 19) and 706 t km⁻² yr⁻¹ for the Tsitsana (2016 – 17). The mean annual SSY estimated for five dams situated closest to the Tsitsa catchment (Doringrivier, Mthatha, Ncora, Xilinxha, and Xonxa dams, **Table 4-2**) ranged between 219 t km⁻² yr⁻¹ and 888 t km⁻² yr⁻¹ (Msadala et al., 2010), whilst mean annual SSY for the Tsitsa sub-catchments were lower, ranging from 21 t km⁻² yr⁻¹ to 679 t km⁻² yr⁻¹. (**Table 7-7**).

SSYs that are available from reservoir studies in other areas such as the karoo (e.g., Foster et al., 2005; Foster et al., 2012) and the Kruger National Park (e.g., Baade et al., 2012; Reinwarth et al., 2019; Miller et al., 2022) are not directly comparable as the catchment characteristics that drive and control sediment availability and transport differ markedly from and between these areas.

Key finding

Data and SSL/SSY uncertainties could be described but not quantified

Discussion

It was not possible to empirically determine the error associated with estimating the Tsitsa River catchment SSLs/SSYs (i.e., error could not be reported using units of measurement such as m³ s⁻¹ or t yr⁻¹). The greatest degree of (unknown) error was associated with the discharge calculations, and was assumed to be constant for all sites. Ideally, more discharge measurements, particularly of higher flows, needed to be undertaken, to reduce the uncertainty of stage/discharge rating curves and the resulting modelled discharge. This was not feasible within the constraints of safety considerations and

human, technical and financial resource availability. Alternative approaches to discharge calculation are discussed in **Section 9.3.3**.

Practical indicators of uncertainty for SSC data were record length, the percentage of high SSC samples (i.e., Subset 2), overall sample coverage, sample coverage of high flows, and, for SSLs/SSYs, the Q Ratio (sample coverage of the range of flows). Interannual variation, where available, was an indicator of SSL/SSY variability and predictability. **Table 9-2** collates the data associated with uncertainty indicators for the period that each site was active.

Table 9-2: Collated indicators of SSY uncertainty at each site

Site Name	High SSC samples (% of samples per site)	Q Ratio				Record length (years)	SSL/SSY %CV	Site period sample coverage (%)	Site period high flow Coverage (%)
		2015 - 16	2016 - 17	2017 - 18	2018 - 19				
Little Pot	9	0.91	N/A	N/A	N/A	1	N/A	99	95
Tsitsana	26	0.93	0.96	N/A	N/A	2	N/A	94	92
Hlankomo	19	0.96	1.01	N/A	N/A	2	N/A	78	77
T4	34	1.00	0.99	N/A	N/A	2	N/A	97	96
Pot	19	0.95	0.97	1.08	1.02	4	20	81	80
Mooi	14	0.82	0.56	1.86	0.87	4	56	52	60
T3	31	0.99	0.98	N/A	N/A	2	N/A	80	91
T2	34	1.11	0.87	1.02	1.06	4	37	82	81
Gqukunqa	57	0.84	0.81	0.78	1.05	4	38	70	87
Inxu	55	0.93	0.99	1.02	0.89	4	72	90	92
TN2	46	1.01	1.33	N/A	0.95	3	36	54	45

Subjectively, the summarised indicators allowed uncertainty to be compared between sites by applying criteria and scores for each indicator, while treating discharge uncertainty as a constant. All criteria were assumed equal, i.e., no weightings were applied. Suggested subjective criteria and scores are summarised in **Table 9-3** and applied in **Table 9-4**, which is sorted according to the resulting uncertainty score.

Table 9-3: Subjective criteria and scores for uncertainty indicators

Criteria	Good	Average (and SSY present)	Poor
High SSC samples	>40%	30 – 39%	<29%
Q Ratio	± 0.10	± 0.11 – 0.20	>± 0.21
%CV*	<25	>26 -40	>41
Sample coverage	>89%	70 – 88%	<69%
High flow coverage	>89	70 – 88%	<69%
Score	+2	1	-2

* Q ratio and %CV was scored 0 for missing years/insufficient data

Table 9-4: Monitoring sites sorted according to subjective uncertainty scores

Site Name	High SSC samples (% of samples per site)	Q Ratio				Record length	SSL/SSY %CV	Site period sample coverage %	Site period High flow Coverage %	Score
		2015 - 16	2016 - 17	2017 - 18	2018 - 19					
Inxu	2	2	2	2	1	4	-2	2	2	15
Pot	-2	2	2	2	2	4	2	1	1	14
T2	1	1	1	2	2	4	1	1	1	14
Gqukunqa	2	1	1	-2	2	4	1	1	1	11
T4	1	2	2	0	0	2	0	2	2	11
T3	1	2	2	0	0	2	0	1	2	10
Tsitsana	-2	2	2	0	0	2	0	2	2	8
Hlankomo	-2	2	2	0	0	2	0	1	1	6
Little Pot	-2	2	0	0	0	1	0	2	2	5
TN2	2	2	-2	0	2	3	1	-2	-2	4
Mooi	-2	1	-2	-2	1	2	-2	-2	-2	-8

Although subjective, a standardised approach to comparing relative uncertainty can guide managers and researchers in terms of the relative confidence with which they can use the SSLs/SSYs for each site and/or year.

9.3 Evaluating the approach taken to suspended sediment monitoring and suspended sediment load and yield estimation (Objectives 3 and 4)

9.3.1 Introduction

Natural resource monitoring programmes, like the systems they aim to measure, have drivers, controls, and responses. The driver of this research was the need, expressed by government officials

and researchers, for reliable sampled SSL/SSY data for the Tsitsa River catchment. Controls included limited budget, lack of background information, distance from site, and challenging biophysical and socio-economic conditions. The response was an eight-year¹³, CT-based, flood-focused, directly-sampled SSC monitoring programme in nine previously ungauged and two gauged sub-catchments of the Tsitsa River catchment.

The success, limitations, and learnings of the monitoring programme are evaluated here according to three themes:

- Output: New knowledge about soil erosion and sediment transport (previous section),
- Programme design: Sampling, laboratory analysis, and SSL/SSY estimation; and
- Benefits: to science, management, and communities (this section)

9.3.2 Existing programme design

This study confirmed that due to flashiness, and other sources of SSC variability in small catchments, short sampling intervals (~15 to 20 minutes) and daily monitoring are required to monitor the rapid changes in SSC. To derive the most reliable SSLs and SSYs without any changes to the approach means that sampling is probably best restricted to catchments >200 km², and laboratory analysis to samples with turbidity >200 ntu. Uncertainty in the resulting SSLs/SSYs increased greatly, particularly below the latter threshold. Where possible, record length should be prioritised over spatial coverage to allow inter-annual variability to be assessed.

Employing local residents as citizen technicians to use pole-and jar samplers from the river-bank provided precise data for the target high-SSC samples, and resulted in most target high flow events being sampled at least once, in all catchments. However, most samples were taken at low discharges, contributed little to annual SSL/SSY estimation; and had a high degree of uncertainty. Reducing the number of low-discharge, <200 ntu samples collected and analysed, without loss of data, requires changes to the sampling protocols. If the number of samples requiring analysis is reduced, changes can, in turn, be made to laboratory protocols. Modifications to the sampling and laboratory protocols are suggested in the next section.

¹³ 2015 – 2023, of which 2015 – 2019 were the subject of this thesis.

9.3.3 Future programme design

9.3.3.1 Sampling

The outcomes from **Objective 3** showed that discharge-limiting and seasonally-limiting SSC sampling to the wet season and/or the highest 20% of flows resulted in a minor loss of precision and would drastically reduce the number of redundant, low water samples taken. However, there are other important considerations in the design of CT-based sampling programmes in rural, socio-economically depressed areas. Flood-focused, more frequent sampling relies on the citizen technician observing the “trigger”, i.e., a rise in water level. In rural South Africa it is not feasible to expect voluntary observations, and in practice it is difficult to administer a payment system with partial rates for partial actions (i.e., sometimes take a river observation but no sample, other times take a river observation and one or more samples). Secondly, suspending dry season sampling would result in a disruptive break in citizen technician earnings. In those circumstances, citizen technicians would be compelled to seek other income, which would likely entail migrating to an urban area due to the lack of employment opportunities in the Tsitsa River catchment (Calmeyer & Muruven, 2015). Sampling programme continuity was maintained throughout the dry season by allowing citizen technicians to take one sample per day. This reduced sampling costs while still providing basic income, and the potential for any infrequent dry season higher flows (due to snow melt or isolated rainfall events) to be sampled (Bannatyne et al., 2022). Further, it is not, in real time, possible to restrict sampling to only the highest 20% of discharges, but only to select these samples during analysis. A site-specific stage as a trigger for flood sampling could only be set (*somewhat* reliably) if sufficient hydrological data were available to undertake a flood flow analysis. Under- or over-estimating the trigger stage would lead to over-sampling or loss of important SSC data. The next section examines approaches to limiting the resources directed towards samples with little sediment, by empowering citizen technicians to use additional technology.

9.3.3.2 Technology

In this study, oven evaporation provided precise SSC results for samples above 500 ntu (**Figure 5-7**), whilst stratifying the data by removing the samples taken at low discharges had little effect on annual SSLs/SSYs (**Table 8-3**). To optimise the use of resources and improve SSC precision, a hybrid approach that adds in-field turbidity testing to the SSC sampling protocol is suggested. Turbidity measurements would replace sampling up to a project-specific (in terms of cost and SSY precision) turbidity threshold, above which direct sampling would commence. Low-water monitoring could be undertaken directly

using hand-held turbidity probes, or even clarity tubes (Graham et al., 2023). Alternatively, citizen technicians could be trained to use bench equipment such as the Eutech TN-100 meter to test samples at the riverbank or at their home: samples below the turbidity threshold would be recorded and discarded, samples above the turbidity threshold would be taken to the laboratory for SSC analysis. Regularly collecting paired SSC samples and turbidity measurements, and using vacuum filtration instead of oven evaporation to analyse samples <500 ntu would likely improve the SSC/turbidity relationships used to calculate SSC from turbidity for samples containing little sediment. In these scenarios, a rise in water level remains the trigger for more rapid flood sampling, and monitoring would be reduced from the wet season minimum of twice per day to once per day in the dry season.

Equipment costs would be offset by the redirection of resources previously allocated to low SSC samples. Hand-held turbidity probes with integral data loggers for use in open channels, though relatively expensive, are cheaper than their installed counterparts. Bench turbidity testing equipment is cheaper than hand-held probes, though more complex to use. Clarity tubes require consistent technique and repeated calibration to provide precise SSC values. The success of this approach would depend firstly on the aptitude of individual citizen technicians to appropriately use the equipment and to recognise the threshold value to commence sampling SSC. Secondly, payment structures would need to accommodate the use of both approaches and ensure compliance with the appropriate protocols, including the collection of calibration samples. As with the use of any equipment (including mobile phones), the personal safety of the citizen technician is the primary concern.

An acoustic backscatter SSC probe (LISST-ABS) was successfully installed at DWS gauging weir T3H006 close to TN2 (Tsitsa at the N2 Bridge) as part of this study (**Section 5.3**), but no data were collected, due to lightning strikes: the gauging weir was located on a dolerite dyke. If financial and technical resources allow the purchase, installation, calibration, and maintenance costs, an installed probe would provide an independent calibration of monitored SSC data. However, due to extreme, debris-laden discharges, and the prevalence of theft and vandalism in South Africa, probes can only be safely installed at existing DWS gauging weirs that are already equipped with electrical infrastructure and secure housings for data logging and telemetric instrumentation.

Since the inception of this research, advances have taken place in the field of data capture and storage using mobile phones and digital forms. A number of platforms other than ODK (Anokwa et al., 2009) now exist that offer improved user interfaces and allow users to access some results and metrics

ahead of formal data processing/analysis. These platforms should be investigated and incorporated into future sampling programme design.

Using alternative technology such as acoustic doppler current profiling (ACDP), and unmanned aerial vehicles (UAVs) to measure discharge may address safety and accuracy concerns (Cai et al., 2022), but may be too expensive in developing regions. However, remote sensing approaches are available that for example allow stage-discharge rating curves to be constructed using a DEM, river bathymetry, and Landsat TM imagery, with discharge then calculated from the inundation area-river stage relationship (Pan et al., 2016). The uncertainty associated with such methods relates to the accuracy of the input data. Remote sensing approaches may offer an accessible, affordable alternative to physical discharge measurement that could support a range of catchment management decisions in addition to the estimation of SSL and SSY.

9.4 Benefits from the study

Prior to this study, contemporary SSLs/SSYs for South African catchments relied largely on uncalibrated modelled estimates, or on dam sedimentation studies. This study was commissioned, at national government level, to add input SSC and discharge data and the resulting SSLs and SSYs to the body of South African soil erosion and suspended sediment transport knowledge. This aim has been achieved for 2015 - 2019, and the resulting SSLs/SSYs will be made available to DFFE in report format, accompanied by the assessment of uncertainty described earlier. SSLs/SSYs 2019 – 2023 will be available once estimated from the available data. The resulting overall record length (interrupted by Covid 19) approached eight years, i.e., beyond the “good” record length recommended by Vanmaercke et al. (2014).

Some findings regarding the SSLs/SSYs have been published (Bannatyne et al. (2022), included as **Appendix 9**). Once SSL/SSY estimation for 1 June 2019 – 31 March 2023 is complete, all data will be made publicly available via an online interactive Web-GIS platform with daily sediment observation data, metadata and accompanying reports, hosted by a DFFE-approved entity. ~45 000 SSC data points will then be available for eleven sub-catchments with record-lengths from 1 to 8 years. To the author’s knowledge, there is no other recent, directly sampled, sub-daily timestep SSC database approaching this record-length for any catchment on the African continent, despite the clear need for such data to inform water resource and land management decisions in the context of population growth and

climate change. This will be a critical resource for calibrating and validating modelled SSYs in South Africa and will support the areas of critical further research that became evident during this study (summarised in **Section 9.5**).

Although construction of the Ntabelanga and Lalini Dams has been mentioned as imminent in most Presidential State of the Nation addresses since 2014, to date the Mzimvubu Water Project has not progressed beyond the planning stage. The results of this study may yet inform the operational design of this much discussed water resources infrastructure.

Achieving the sampling project goals by employing local people to use locally-accessible, affordable, and appropriate equipment means that the sampling programme used in the Tsitsa River catchment is adaptable to other resource-scarce regions. This approach is already being applied as part of a two-year United Nations Development Programme Global Environment Facility (UNDP-GEF) sediment transport monitoring project coordinated by the Limpopo Watercourse Commission (LIMCOM). This project, currently in the inception phase, aims to engage citizen scientists to carry out SSC sampling as per the protocols described in **Section 5.4**, in tributary catchments and the main stem of the Limpopo River, in Botswana, Zimbabwe, South Africa and Mozambique. The aim is to strengthen the capacities of these States and the LIMCOM Secretariat to support Integrated Water Resource Management implementation at the basin level by building capacity to enable SSC monitoring in a transboundary context.

The communal areas of the Tsitsa River catchment where most of the citizen technicians lived are typified by high levels of unemployment (**Section 2.4**), and a heavy reliance on land-based livelihoods that are dependent on the provision of ecological goods and services (Calmeyer & Muruven, 2015). The earnings from sampling activities had a direct benefit for the citizen technicians and their families, not only in terms of income, but also because the citizen technicians could remain at home rather than leave to look for employment outside the area. The citizen technicians gained new skills and experience through their sampling work which would later be helpful in securing further employment. Additionally, some used their earnings as “seed money” for other sources of income such as catering, sewing, or building (Bannatyne et al., 2017).

At a broader level, citizen science is becoming an expected approach to both data gathering and community empowerment (i.e., the democratisation of science) in South Africa (Rowntree et al., 2018; Adelle, 2019). Engaging local residents directly with research and implementation related to the

management of their natural resources is particularly important in rural areas like the Tsitsa River catchment, where livelihoods are closely linked to ecological goods and services (Rowntree et al., 2018; Cockburn et al., 2018; Itzkin et al., 2021; Weaver et al., 2023). It was a DFFE- specified outcome of the Tsitsa Project (of which this study was part), to ensure the sustainability of related land management initiatives by empowering local community members and their leadership to exercise their agency effectively in decision-making fora (Rowntree et al., 2018; Cockburn et al., 2018). The CTs, other citizen scientist, community members, and traditional leaders participated in capacity-building interventions organised by the Tsitsa Project. This enabled them to actively engage in multi-stakeholder governance workshops where strategies for sustainable land management initiatives were co-created, and actions relating the construction of the proposed Ntabelanga and Lalini dams were discussed (Cockburn et al., 2018; Weaver et al., 2023, **Section 1.3.1**). The citizen technician approach to SSC sampling contributed directly to the resulting individual and community benefits of the Tsitsa Project.

9.5 Further research

The R-B Index should be determined for rivers in other hydroclimatic regions of South Africa, and compared with the findings of other indicators that have been used to characterise hydrological regimes in this country. Additionally, investigations are required into the relationships between rainfall patterns, volumes, and erosivity, and surface and sub-surface flows, to determine the influence on flashiness in South African rivers. The results of these investigations will assist with monitoring programme and water resources infrastructure design, and may inform SSL/SSY variability in the Tsitsa River catchment.

Northern hemisphere researchers maintain that sediment characteristics throughout channel cross-sections and over time may be heterogenous, and related to changes in sediment sources, for example throughout storms (Walling et al., 2000; Minella et al., 2008; Regüés 2013). The representativeness of the riverbank sampling approach adopted in this study is endorsed by Msadala et al.s' (2010) claim that most SS transported by South African rivers is clay and silt (i.e., < 63 μm) and therefore homogenously distributed throughout the channel cross-section. This claim has not been confirmed, and Ramothello's (2021) research indicates that particle size distributions change not only through flood events but also seasonally in the Tsitsa River catchment. Further research is required to determine the width and depth related patterns of particle size distributions over time and through a

range of stages. Ramothello's (2021) investigation was limited to four events at two sites. Further research that includes rainfall data analysis and sediment source tracing is needed to link event-scale SSC/discharge relationships to factors such as rainfall events of varying erosivity, antecedent conditions, and sediment sources in the sub-catchments of the Tsitsa River to improve our understanding of sediment dynamics in this catchment.

Neither the research described in this thesis nor the confluence-based sediment tracing study (**Section 4.5.5**), sought to identify sediment sources at finer than sub-catchment scale, except for considering the probable contributions of bank erosion to SSLs/SSYs in the Tsitsana catchment (**Section 9.2.3**) Further research is needed, with particular reference to gully sediment contributions and transport, to identify and, where possible, map the characteristics and processes influencing soil erosion, transport, and deposition. This is needed to inform more effective prioritisation and targeting of appropriate mitigation and rehabilitation measures, as well as to provide insight into inter-annual SSL/SSY variability. For example, without the knowledge that riparian processes were probably major contributors to high SSYs in the Tsitsana catchment, false assumptions could be made about the hillslope erosion status, resulting in less effective use of funding. Specifically, if the principal aim was to reduce the risk of excessive siltation of water resources and downstream impoundments, resources may be misdirected if interventions were solely focused on reducing sheet, rill, or even gully erosion. Such intervention would support local land-based livelihoods, but attempts to limit dam siltation should emphasise, (or at least include) riparian zone management and routine monitoring of bridges in the wet season to report and remove woody debris accumulations.

Confluence-based suspended sediment tracing and source apportionment has the potential to be used in combination with modelling and direct measurement, given its ability to provide an alternative and considerably cheaper reconnaissance method of identifying key tributaries responsible for sediment delivery (Bannatyne et al., 2024). This approach warrants repeating in the Tsitsa River catchment, as well as further investigation and validation in other remote, data-scarce catchments, perhaps followed up with a combination of source-type and confluence-based source finger-printing, for example *sensu* Walling et al. (1999) and Collins et al. 2017). Lastly, this study focussed on suspended sediment. Observably, the vast movement of sand-sized particles that form much of the bedload is a significant feature of the Tsitsa River catchment that has not been addressed by this study. Bedload contributions to the total load can vary greatly depending on rainfall regimes, particle sizes and channel morphology (Millares & Moñino, 2018) but this can be difficult or technically demanding

to estimate in sand bed rivers (Latosinski et al., 2017; Valyrakis et al., 2022) and has not been investigated in the Tsitsa River catchment. This is a crucial area of research if the sedimentation of the proposed Ntabelanga and Lalini Dams are to be accurately predicted (**Figure 9-9**) which may need to be estimated indirectly, for example through an investigation of flood plain particle size composition (He & Walling, 1998; Mahon & McElroy, 2018).



Figure 9-9: The mobile, sandy bed of the Inxu River

9.6 Conclusion

This study has shown, for the first time, that innovative, locally-appropriate sampling and analysis strategies result in precise SSC data, confirming that they can be adapted for use in other resource-scarce regions, with benefits not only for natural resource managers and scientists, but also for employment and capacity building for people living in the study area. The investigation of uncertainty and favourable comparison with SSYs estimated from reservoir studies has demonstrated the applicability of this SSC sampling programme to southern African conditions, and highlighted the challenges of acquiring reliable discharge data. The CT-based, flood-focused approach to SSC sampling and laboratory analysis described in this thesis can confidently be advocated to decision-makers mandated to undertake natural resource management. The results of this study can inform the operational design of water resources infrastructure associated with The Mzimvubu water project.

10 References

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