# Developing a Citizen Technician Based Approach to Suspended Sediment Monitoring in the Tsitsa River Catchment, Eastern Cape, South Africa

## THESIS

Submitted in fulfilment of the requirements for the Degree of

MASTER OF SCIENCE

of

RHODES UNIVERSITY

by

LAURA JOAN BANNATYNE

March 2018

Supervisors: Professor Kate Rowntree and Dr Bennie van der Waal

# Abstract

Suspended sediment (SS) in channels is spatiotemporally heterogeneous and, over the long term, is known to be moved predominantly by flood flows with return periods of ~1 – 1.5 years. Flood flows in the Tsitsa catchment (Eastern Cape Province, South Africa) are unpredictable, and display a wide range of discharges. Direct, flood-focused SS sampling at sub-catchment scale was required to provide a SS baseline against which to monitor the impact on SS of catchment rehabilitation interventions, to determine the relative contributions of sub-catchments to SS loads and yields at the site of the proposed Ntabelanga Dam wall, and to verify modelled SS baselines, loads and yields. Approaches to SS sampling relying on researcher presence and/or installed equipment to adequately monitor SS through flood flows were precluded by cost, and the physical and socio-economic conditions in the project area.

A citizen technician (CT)-based flood-focused approach to direct SS sampling was developed and implemented. It was assessed in terms of its efficiency and effectiveness, the proficiency of the laboratory analysis methods, and the accuracy of the resulting SS data. A basic laboratory protocol for SSC analysis was developed, but is not the focus of this thesis.

Using basic sampling equipment and smartphone-based reporting protocols, local residents at eleven points on the Tsitsa River and its major tributaries were employed as CTs. They were paid to take water samples during daylight hours at sub-daily timestep, with the emphasis on sampling through flood flows. The method was innovative in that it opted for manual sampling against a global trend towards instrumentation. Whilst the management of CTs formed a significant project component, the CTs benefitted directly through remuneration and work experience opportunities.

The sampling method was evaluated at four sites from December 2015 – May 2016. The CTs were found to have efficiently and effectively sampled SS through a range of water levels, particularly in the main Tsitsa channel. An acceptable level of proficiency and accuracy was achieved, and many flood events were successfully defined by multiple data points. The method was chiefly limited by the inability of CTs to sample overnight rises and peaks occurring as a result of afternoon thunderstorms, particularly in small tributaries. The laboratory process was responsible for some losses in proficiency and accuracy. Improved laboratory quality control was therefore recommended. The CT-based approach can be adapted to other spatial and temporal scales in other areas, and to other environmental monitoring applications.

# 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.

Name: Laura J Bannatyne

Student number: G13F4066

Signed:

## Acknowledgments

A proverb supposedly of African origin declares that it takes a village to raise a child. Having solemnly declared this “child”, this work, to be my own, I further declare with profound gratitude that several villages have contributed towards its development. Without the input and support of every person who is named here, and quite a few more who are not, this endeavour could not have progressed beyond infancy.

**Funding**

The South African Department of
Environmental Affairs: Chief Directorate
Natural Resource Monitoring

**NLEIP project management**

Michael Braak
Michael Powell

**Academic**

Prof Kate Rowntree: Supervisor
Dr Bennie van der Waal: Supervisor
Dr Art Horowitz
Prof Ian Foster
Dr Simon Pulley

**Administrative and technical support**

Geography Department, RU
Environmental Science Department, RU
Karen Milne
Abe Ngoepe
Nosiseko Mtati
Zanele Max Mase
Brian Clarke
Deidre Fouche
Glyn Armstrong
Sakhi Singata
John Landman
Mthunzi Gumede

**ODK and KoBo**

Dr Alta de Vos
Dr Cynthia Annett

**Translation**

Monde Ntshudu

**Field and laboratory assistance**

Namso Nyamela
Vuyo Ntamo
Marco Trimalley
Nicholaus Huchzermeyer
Pippa Schlegel
Camille Trollope
Mateboho Raleketwa
Danuta Hodgson

**Land owners**

Craig Sephton
Dallas Sephton
PG Bison
Pip Roberts
Mr Hopewell
Angie and Adie Badenhorst
Tsitsana Clinic
Andrew MacFarlane

**Citizen technicians**

Anavuyo Nobala

Alfred Booi

Mildred Gebenga

Khangelani Xeketwana

Vuyiseka Marawu

Ncediswa Saunders

Babalwa Nqweniso

Khanyisa Nogaga

Adie Badenhorst

Theo Wenner

Manisa Ndawo

Siphamandla Nobese

Sinethemba Musada

**And especially…**

To my darling husband Brian, for *everything* from tea to sanity.

To my amazing children, for inspiration.

To Jim, for planting seeds during all those long-ago Sunday mornings.

To Kate, for unfailing support, insight, walks, and friendship.

To Bennie, for unrelenting focus, practicality, and coffee.

To Namso, for stir-fry, fellowship, and fresh perspectives.

To Vuyo, Nosi and Zanele, for keeping it running like clockwork.

To Angie and Adie, for a second home and family at The Falls.

And of course to Art, for reminding me where to look for sympathy.

# Table of contents

## Acronyms and abbreviations

| | |
|---|---|
| CRBM | Conceptual River Basin Model |
| CV | Coefficient of variation |
| DEA | Department of Environment Affairs |
| DWS | Department of Water and Sanitation (formerly DWAF: Department of Water Affairs and Forestry) |
| EC | Electrical conductivity |
| EFT | Electronic Funds Transfer |
| GPS | Global positioning system |
| ISO | The International Standardisation Organisation |
| iSPOT | A biodiversity-mapping project |
| LISST-ABS | An acoustic backscatter suspended sediment probe manufactured by Sequoia Scientific, Inc, Belleville, Washington, USA |
| NEMA | National Environmental Management Act (Act No. 108 of 1998) |
| NLEIP | Ntabelanga and Lalini Environmental Infrastructure Programme |
| NRM | Natural Resource Management |
| ntu | Nephelometric turbidity units |
| NWA | National Water Act (Act No. 36 of 1998) |
| ODK | Open Data Kit |
| SAPAB | South African Bird Atlas Project |
| SASS | South African Scoring System |
| SDR | Sediment delivery ratio |
| SS | Suspended sediment |
| SSC | Suspended sediment concentration |
| TDS | Total dissolved solids |
| SWAT | Soil and Water Assessment Tool |
| TDS | Total dissolved solids |
| UK | United Kingdom |
| USA | United States of America |
| USGS | United States Geological Survey |
| USLE | Universal Soil Loss Equation |
| WRC | Water Research Commission |

## Symbols and units of measurement

| | |
|---|---|
| < | Less than |
| > | Greater than |
| ~ | Approximately |
| = | Equal |
| % | Percentage |
| °C | Degree Celsius |
| g | gramme |
| ha | hectare |
| km | kilometre |
| $km^2$ | Square kilometre |
| L | litre |
| M | metre |
| $m^3/s$ | Cubic metre per second (Cumec) |
| mg/L | milligramme per litre |
| mm | millimetre |
| t | tonne |
| t/ha | tonne per hectare |
| yr | year |

## Equations

# Tables

# Figures

## Plates

# Appendices

## Appendix 1: Data

1. Efficiency and effectiveness.xlsx
2. Balance calibration and negative standard error.xlsx
3. Triple analysis.xlsx

4 Water level range.xlsx

## Appendix 2: Citizen Technician administration and training documents

### Appendix 2.1 Administration

1 CT info and aptitude.docx

2 CHECKLIST1 CT training and contracting.docx

3 CHECKLIST2 Site visit.docx

4 CT contract.pdf

5 Payment intervals.docx

6 Invoice template.xls

7 Payments tracking.xlsx

8 Airtime and data tracking .xlsx

### Appendix 2.2 Training

9 Safety training.pdf

10a Baseline sampling.pdf

10b Baseline samplingXhosa.pdf

11a Flood sampling.pdf

11b Flood samplingXhosa.pdf

# 1 INTRODUCTION

## 1.1 Background

The relationship between suspended sediment (SS) and discharge is non-linear, dynamic, and variable within channels (Petts, Foster 1985; Horowitz 2013) and across a range of temporal and spatial scales (Fryirs 2013). It is influenced both by discharge and sediment availability (Knighton 1984) with antecedent conditions affecting these factors. Flood flows dominate sediment movement (Wolman, Miller 1960; Gordon et al. 2004; Horowitz 2010). This spatiotemporally heterogeneous relationship between SS and discharge has profound implications for monitoring programme design (Gordon et al 2004). SS sampling regimes must accommodate these uncertainties and be responsive to floods in order to generate representative data from which SS loads and yields can be predicted with an acceptable level of confidence (Horowitz 2013). This can be particularly challenging in catchments that experience unpredictable high and flood flows.

## 1.2 Motivation for research

The catchment of the Tsitsa River (a tributary of the Umzimvubu River) in the Eastern Cape Province of the Republic of South Africa (**Figure 4**) is severely affected by soil erosion, with large areas underlain by dispersive soils and subject to gullying (Le Roux et al. 2008a; Le Roux et al. 2008b; Msadala et al. 2010; Le Roux, Weepener 2015). Land use practices such as overgrazing and frequent fires may have exacerbated the problem (Gordon et al. 2013).

Community based land restoration initiatives in the area are being coordinated to the tune of R450 million by the Department of Environment Affairs (DEA) Natural Resource Management (NRM) programme, under the auspices of the Ntabelanga and Lalini Environmental Infrastructure Programme (NLEIP). These restoration initiatives aim to improve the sustainability of local livelihoods which rely heavily on catchment ecological infrastructure, and have provided additional employment opportunities associated with specific interventions. NLEIP is given urgency by the proposed construction of the Ntabelanga and Lalini Dams on the Tsitsa River (BKS (Pty) Ltd 2010) by the Department of Water and Sanitation (DWS).

Modelled sediment yields of up to 22.5 t/ha·yr at the Ntabelanga dam wall site have caused concern that the lifespan of the proposed Ntabelanga Dam may be significantly reduced through siltation (BKS (Pty) Ltd 2010; Le Roux, Weepener 2015). However, studies based on dam sedimentation rates in similar catchments (Msadala 2010) suggest that rates of 3 to 6 t/ha yr may be expected, implying possible under or over-estimation of catchment sediment yields depending on the estimation method employed.

Dispersive soils and highly gullied areas, sub-optimal catchment land use practices, and the high degree of catchment connectivity may be significant factors impacting the SS load estimates for the Tsitsa River catchment (Le Roux, Weepener 2015). The relative contribution of sub-catchments to overall SS yield in the Tsitsa River catchment as a result of these factors is as yet undetermined.

Direct monitoring of discharge and SS was recommended (Le Roux, Weepener 2015) to provide sub-catchment-scale SS load and yield data to assist DEA with the prioritisation of community-based land restoration interventions, and to determine the relative contributions of sub-catchments to the SS yield of the Tsitsa River catchment at the site of the proposed Ntabelanga Dam. Such data would serve as a baseline against which to benchmark the long-term impact of catchment restoration efforts on SS load and yield.

## 1.3 Problem statement

A cost effective and practical SS monitoring programme was required to provide data from which to estimate the relative contributions of sub-catchments to the overall SS impact on the proposed Ntabelanga and Lalini Dams. **Chapter 3** provides a detailed description of the study area, but an overview of some of the pertinent characteristics is given here to highlight challenges associated with SS sampling in the Tsitsa River catchment.

The Tsitsa River catchment lies 550 km from the research base at Rhodes University, and covers an area of approximately 4 000 km$^2$. Many parts of the catchment are topographically rugged and difficult to access. These factors, coupled with time constraints, precluded sufficient catchment-wide presence of researchers to ensure consistent sampling of the high flows that are known to move the bulk of sediment (Gordon et al 2004). Rivers in the area are flashy, with a wide range of discharges and unpredictable flood flows. Woody debris loads (**Plate 1**) due to clearance of riparian alien invader tree species can be significant and cause damage to instream structures.

**Plate 1: Bridge on the Tsitsa River near the upper Tsitsa Falls showing the accumulation of woody debris**

Large parts of the study area lie within the communal areas of the former Transkei homeland areas, where unemployment rates are typically high whilst education levels, household incomes and job opportunities are low (Hodgson 2017). As in South Africa as a whole, there is a high risk of equipment theft and vandalism. In more developed and urbanized countries such as New Zealand, the United Kingdom (UK), United States of America (USA), and European countries, manual sampling approaches have, due to labour costs, largely been superseded by approaches based on the use of automated SS monitoring and sampling equipment (Wren et al. 2000, Kuhnle 2013; Ballantine 2015). However, budget constraints and the risk of equipment loss precluded the catchment-wide use of expensive, typically imported instruments and automated samplers in the Tsitsa catchment (Bannatyne et al 2017).

An alternative to both continuous researcher presence and to a fully instrumented approach was therefore required in order to implement the recommended flood-focused, catchment-wide direct SS sampling campaign. Engaging local residents to take samples had been done (albeit on a much smaller scale) in the nearby Thina catchment (van der Waal 2015). This approach offered an effective solution to the problem which would also satisfy the requirements of job creation under this government funded programme. Further, it offered an opportunity to develop an approach to environmental monitoring that could be adapted to other catchments as well as to other sampling and monitoring applications. However, the challenge of ensuring procedural compliance and data quality control at multiple remote sites in a distant catchment was a significant one, and was coupled with concerns regarding management of and support to samplers. A robust, low-cost and uncomplicated means of sampling, quality assurance and administration was required.

Achieving adequate spatial and temporal SS monitoring of the Tsitsa River catchment over a timeframe of several years would result in several thousand whole water samples requiring analysis. As with the sampling method, a robust, low-cost and uncomplicated means of laboratory analysis was required.

Once a citizen technician (CT)-based approach was selected, designed and implemented, a critical evaluation of the method and resulting data was required in terms of its efficiency, effectiveness, proficiency, and precision, as compared with other accepted approaches.

## 1.4 Research aim

The aim of the project was to design, implement and evaluate a scientifically valid and locally appropriate CT-based approach to SS monitoring for the Tsitsa River catchment. A basic laboratory protocol was developed for SSC analysis, but is not the primary focus of this thesis.

## 1.5 Research objectives

1) Design a flood-focused SS monitoring programme for the Tsitsa River catchment;

2) Develop and implement a CT-based approach to flood-focused SS sampling in accordance with the monitoring programme design;

3) Develop and implement appropriate laboratory processes for the determination of SS concentration;

4) Assess the efficiency of the resulting SS sampling methods.

5) Assess the effectiveness of the resulting SS methods.

6) Assess the proficiency of the analysis methods and the precision of the resulting SS data.

*Efficiency* pertains to the overall number of samples taken, relative to the number of opportunities for sampling. *Effectiveness* pertains to the improvement in data for high flow events that can be attributed to the collection of multiple “flood” samples, relative to data that would have accrued from twice-daily “baseline” sampling. *Proficiency* pertains to the loss of data from collected samples during laboratory analysis. *Precision* pertains to data variability, in terms of SSC results from replicate samples.

Additionally, since SSC data will be used in conjunction with discharge to determine SS load and yield, the range of water levels (a surrogate for discharge) at which SS samples were taken at each site provides a further criterion for ascribing confidence levels to the SSC data produced by the CT-based direct SS sampling programme.

## 1.6 Structure of the thesis

**Chapter 1** has framed the research project by identifying the circumstances that prompted and drove the research activities, and the challenges which shaped the approach and activities undertaken in order to achieve the desired outcomes.

**Chapter 2** is a review of existing research, providing the scientific basis on which the research project was built, and identifying the need for data and information.

**Chapter 3** describes the attributes of the study area, providing the environmental and socio-economic context for the research.

**Chapter 4** describes the design, development and implementation of the CT-based approach to direct SS sampling and laboratory analysis undertaken for the Tsitsa River catchment.

**Chapter 5** identifies points of uncertainty throughout the SS sampling and analysis programme, and describes the methods used to evaluate the sampling approach and resulting data in terms of efficiency, effectiveness, proficiency and precision.

**Chapter 6** presents the results of this critical evaluation.

**Chapter 7** discusses the outcomes, constraints and limitations of the CT-based approach to direct SS sampling, with reference to the research aims and objectives, and in light of accepted norms for SS data as derived from a range of sampling approaches. Recommendations for further research and development regarding the CT-based approach for direct SS sampling are made.

**Chapter 8** presents the conclusions of the research study.

# 2 LITERATURE REVIEW

## 2.1 Introduction

This chapter examines the scientific basis for the design and implementation of the flood focused Citizen Technician (CT)-based suspended sediment (SS) sampling programme in the Tsitsa River catchment.

The study of catchment sediment yield occupies the nexus of climate, land, and water, integrating the principles of open-channel hydraulics, fluvial geomorphology, and hydrology, and applying them at a range of spatial and temporal scales to the catchment as an open system (Thorndycraft et al. 2008). SS monitoring needs to accommodate the variability of flows and SS concentrations resulting from these conditions, within the bounds of time, budget, and human resources (Wren et al. 2000).

There is a global dearth of SS load and yield data (Walling, Fang 2003; Cohen et al. 2014). In a study aiming to quantify global riverine SS fluxes, Cohen et al (2014) stated that sediment load delivery to the oceans is measured in fewer than 10% of rivers globally, and that this figure is decreasing (Cohen et al. 2014). Syvitski and Milliman (2007) noted that the estimation of global sediment delivery to the oceans is complicated by short-term monitoring programmes of variable quality (Syvitski, Milliman 2007), echoing McLennan's (1993) concern that early estimates were based on sporadic sampling that did not account for flood flows and sampling locations were often upstream of depositional floodplains (McLennan 1993). Anthropogenically influenced rates of both positive and negative change in global SS yields, due to not only increased soil erosion but also increased impoundments, remain difficult to monitor and predict at global scale (Walling, Fang 2003; Syvitski, Milliman 2007).

In South Africa, Rooseboom (1992) provides an historical overview of sediment transport in rivers and reservoirs spanning six decades. Ad hoc SS sampling took place as early as 1919, with regular daily sampling by the then Department of Water Affairs starting around 1928 and focusing on major drainage areas such as the Orange, Tugela and Pongola catchments. The Mzimvubu catchment was not included in this programme. Daily sampling continued until around 1971 when decadal sediment surveys of existing reservoirs took precedence over manual sampling due to the relative ease and limited cost of the former, versus the time and effort involved with collecting, transporting and analysing the latter. The longest continuous daily record from this time is for the lower Orange River at Prieska and Upington (Rooseboom, Lotriet 1992).

Sediment yield maps based largely on sampled data were produced by Midgely in 1952, Schwartz and Pullen in 1966, and Rooseboom in 1978 (Rooseboom, Lotriet 1992).

Rooseboom's 1992 update of his earlier map relies on reservoir sediment surveys, as does the related 2010 work of Msadala et al (2010).

New sediment yield estimates in South Africa, particularly at large catchment scale (e.g. for the Olifants River catchment in Limpopo, the Blood/Buffalo River catchment in Kwa-Zulu Natal, and the Tsitsa catchment in the Eastern Cape), are mainly limited to those predicted from modelling and GIS-based soil erosion and loss studies (Le Roux et al. 2008a; Le Roux et al. 2008b; Le Roux, Weepener 2015). Smaller scale, short term studies have been based on direct sampling, e.g. in the Mfolozi River in KwaZulu Natal (Grenfell, Ellery 2009), or on a combination of observation and calculation of sediment transport, e.g. that of the Sabie River in Mpumalanga (Heritage, van Niekerk 1995).

Medium to long-term SS studies are required both globally and nationally to address gaps in the understanding of not only the catchment processes of erosion, transport and deposition, but also to be able to predict SS loads and yields across a range of scales for social, environmental, and engineering purposes.

## 2.2 Factors determining catchment sediment yield: A critical assessment of research approaches and their findings

### *The evolution of suspended sediment research*

The study of SS dynamics lies within the field of fluvial geomorphology, which seeks to understand, describe, and quantify river channel forms, processes, and behaviours across a range of scales (Dollar 2004). Modern quantitative approaches to fluvial geomorphology which could be approximated in the laboratory and monitored in situ (Sack, Orme 2013 p 32; Wohl 2014) supersede traditional descriptive or qualitative approaches. Froude, Manning, Gilbert, Rubey, Leighly, Hjulström and Bagnold, amongst others, developed mathematical and statistical principles describing the physical properties of particles and fluids at rest and in motion (Sack, Orme 2013 p 17).

These principles gave researchers such as Horton, Strahler, Leopold, Schumm, Wolman, Wischmeier, and Walling amongst others the basis on which to study the movement of sediment across a range of temporal and spatial scales. The development of concepts such as stream order (Horton 1945; Strahler 1952), time and spatial scale hierarchies (Schumm, Lichty 1965), flood frequency and geomorphic work (Wolman, Miller 1960), erosion factors (Wischmeier, Smith 1978), sediment budgets (Slaymaker 2003), sediment delivery ratios, (Walling 1983; Parsons et al. 2006; Walling, Collins 2008), sediment tracing and dating (Walling 2005), and catchment connectivity (Fryirs 2013), occurred in response to the need to identify sediment sources, and to estimate sediment loads and yields.

SS sampling methods are reviewed elsewhere in this section, but suffice to mention here that in line with general technological advancement since the mid-20th century, the emphasis for SS data collection at both reach and catchment scale has tended in many countries to have shifted from a reliance on manual direct water sampling to the more widespread use of instruments such as automated pump samplers for discrete sampling, and fixed probes for continuous monitoring (Wren et al. 2000; Hicks, Gomez 2003). In the latter case the monitoring of turbidity as a surrogate is common.

The estimation of SS loads and yields has evolved over time to include the routine use of satellite imagery (e.g. land cover, gully size, soil type, slope, etc.,) as an input to computer models based on erosion equations. These provide a powerful research tool for estimating and predicting SS sources, loads and yields (Merritt et al. 2003; Le Roux, Weepener 2015). The analysis of cores from the sediment deposits trapped in reservoirs, lake bottoms and other sediment stores in the landscape also provides a means to compare long-term catchment sediment yields on a national (Rooseboom, Lotriet 1992; Msadala et al. 2010), and local scale allowing historic SS loads and yields to be related to other time-based climate, hydrological, and catchment land-use records (Foster et al. 1990; Ambers 2001; Foster, Rowntree 2012). The outputs from both these approaches, however, should be calibrated and/or verified using data from monitoring programmes (Le Roux, Weepener 2015).

As with other fields of study, the ability to undertake and disseminate the findings of fluvial geomorphological research has been greatly enhanced by incremental advances in communications and imaging technology. Likewise, ever-increasing personal and institutional computing power supports the collection, management and analysis of large data sets in support of complex stochastic models (Wohl 2014). Coupled with cellular and satellite communication networks, this capability allows the immediate and continuous transmission of time, date and geo-stamped quantitative and qualitative data from study sites to research centres in real-time for management and analysis purposes (Bannatyne et al. 2017).

One outcome of such advances is that the original quite narrow geographic focus of research into fluvial geomorphology has expanded from its beginnings in the USA, UK, and some European countries. Researchers in regions such as South America, the Indian subcontinent, Africa and Australasia gained electronic access to research findings, bringing them up to date with the state of global knowledge (Wohl 2014) and providing a platform for them to contribute their findings to the body of knowledge.

It has thus become apparent that due to differing climatic, geological, and even socio-economic conditions, the “typical” approaches to collecting data and conceptualising fluvial geomorphological models that were developed by American and European researchers do not necessarily fully accommodate the sediment dynamics and channel/catchment interrelationships found in other parts of the world (Wohl 2014). Alternative approaches to data collection and analysis must therefore be developed that more fully accommodate the conditions found in such areas.

### *Drivers for research*

The drivers of research focusing on SS have shifted over the past 70 or so years, in response to societal concerns regarding landscape and the environment (Wohl 2014).

Early impetus for research came from the requirements of agriculture and engineering hydrology for monitoring and control of erosion and transport/deposition respectively (Sack, Orme 2013 p 88). More recently, pressure on water resources has prompted the development of integrated approaches to catchment research and management (Wohl 2014), which typically place the fluvial geomorphologist within a transdisciplinary team looking at soil erosion, transport, and deposition in the context of social, economic and environmental interactions at catchment scale (Dollar 2004). Often driven by the need to determine sources of sediment and related contaminants (Owens 2005), the outcomes of such research guide or prioritise local interventions that attempt to identify, accommodate, and mitigate catchment-wide processes and impacts. Recognising the social, economic and environmental nexus represented by sediment yield, Owens (2005) emphasised that such research should include actions such as risk assessments and cost benefit analyses in consultation with stakeholders and with reference to the appropriate legislative frameworks.

In South Africa, as elsewhere in the world, the requirements of a national legislative framework for environmental protection, such as the National Water Act (NWA) (Act No. 36 of 1998) and the National Environmental Management Act (NEMA) (Act No. 108 of 1998), have driven much of the recent research that has added substantially to the understanding of sediment dynamics in this country. In common with other countries where sustainable rural livelihoods and food security are closely linked to the ecosystem services offered by natural resources, SS studies in South Africa are also strongly driven by concerns regarding landscape degradation and subsequent soil loss (Le Roux, Weepener 2015) as well as the threat to instream biodiversity (Gordon et al. 2013)

### *Soil erosion factors*

As noted, concerns around agricultural productivity, topsoil loss and food security for growing populations prompted (particularly American) researchers in the 1940s to focus on the problems of agricultural soil erosion and loss (Wischmeier, Smith 1978). As a result, the Musgrave equation was developed from the study of plot-scale slope, soil, and crop management processes (Lloyd, Eley 1952) for use in agricultural soil loss abatement programmes. From this, Wischmeier and Smith (1978) developed the Universal Soil Loss

Equation (USLE) as a soil conservation tool, based on the following somewhat simplistic set of factors (or catchment characteristics) which affect sheet and rill erosion:

- Rainfall erosivity;
- Soil erodibility;
- Slope length and gradient;
- Plant cover, and
- The specific erosion control factor (Wischmeier, Smith 1978)

The complexities of erosion, transport and deposition across temporal and spatial scales as noted by Schumm and Lichty (1965), are not accommodated in Wischmeier and Smith's (1958) equation, yet with some modifications these soil erosion factors still lie at the heart of most models intended to estimate and predict sediment load and yield at catchment scale (De Vente, Poesen 2005; Kinnell 2010). To go beyond the confines of USLE in their understanding of the factors affecting catchment sediment yield, researchers needed to address the interlinking problems of time, space, and transport.

### *The issue of scale*

Rivers as systems have both history and geography: they change over time and space (Schumm 2005). Owens (2005) stated that the river basin or catchment is "the fundamental unit of study in hydrology and fluvial geomorphology" (Owens 2005 p 201). However, a layering of temporal and spatial scales occurs in the catchment process-response setting, which therefore must be accommodated in research programme design and data interpretation. The temporal and spatial scale encompassed by research activities should therefore be tailored to the temporal and spatial scale at which catchment variables or processes operate (Schumm 2005).

Schumm and Lichty (1965) described the temporal and spatial framework which guides current fluvial systems research. Expanding Davis' theory of the erosion cycle through their hierarchical concept of cyclic, graded and steady time, Schumm and Lichty (1965) linked these timescales to spatial scales and to the factors, controls, or variables (described earlier) determining catchment sediment yield. In this model, the number of dependent variables decreases with temporal and spatial scale.

At cyclic, or geological erosional cycle time, time itself as well as the initial relief and geological attributes and climate of the system are considered to be independent variables. Slope length and gradient, drainage network and hillslope morphology, vegetation type and cover, discharge and catchment sediment yield are the dependent variables being determined at this large spatial scale. The classification of South Africa into geomorphic provinces (Partridge et al. 2010) is an example of studies focusing on cyclic time-scale processes: Opening descriptions of research study areas tend to be scaled at the level of cyclic time.

In graded time, channel self-adjustment (dynamic equilibrium) takes place at the spatial scale of system components. Intrinsically, the time period over which this occurs is irrelevant, as is the initial topography. All other variables are independent, except the morphology of the hillslope and channel network, together with discharge and catchment sediment yield. The geomorphological classification of rivers (Rowntree et al. 2000) exemplifies work focusing on graded timeframes. The SS sampling programme described in this thesis is framed within graded time, at the spatial scale of the sub-catchment.

Steady time, like steady hydraulic flow, exists when no variables are dependent other than hydraulics, discharge and sediment yield. SS sampling through a flood event illustrates the concept of steady time. **Figure 1** (Schumm, Lichty 1965) illustrates the relationship between cyclic, graded and steady time.

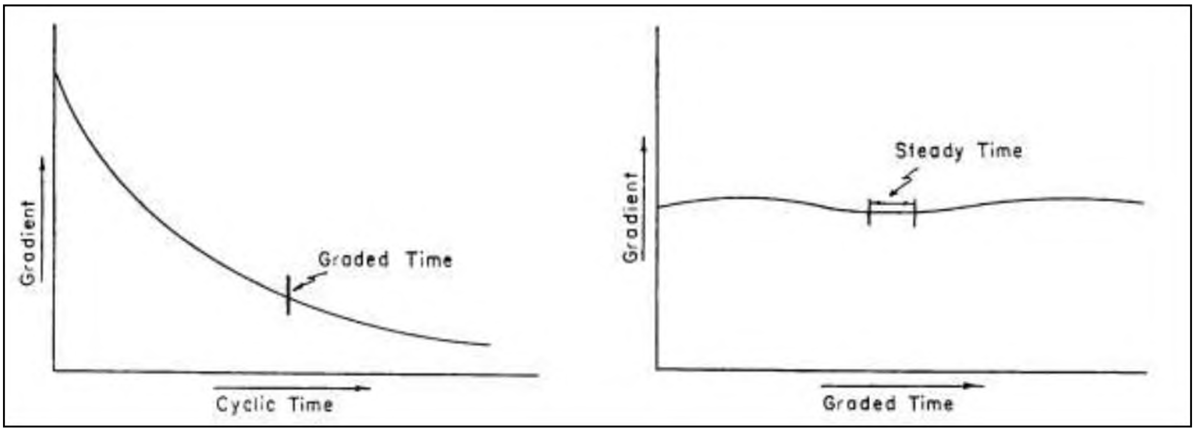


**Figure 1: The relationship between cyclic, graded and steady time using channel gradient as the dependent factor** (Schumm, Lichty 1965)

Knighton (1984) expanded this framework somewhat with definitions of long, medium, short, and instantaneous time (Knighton 1984), noting that measurements of discharge and sediment yield over instantaneous time (<$10^1$ years) may not be representative of the system as a whole. Short ($10^1$ – $10^2$ years) periods provide the most significant and representative observational timeframes to define the long-term controls and relationships operating at sub system or reach scale (Knighton 1984).

Although an “instantaneous” time-span (<$10^1$ years) is used in this thesis to illustrate the development of the CT-based SS sampling approach, the full monitoring programme is expected to span five to ten years in terms of DEA funding allocations, falling within Knighton’s (1984) definition of “short”.

### *Catchment processes*

Precipitation falling within a catchment's boundaries drains towards its channel network, transporting sediment via the movement of water through the catchment (Owens 2005). Catchment sediment yield is the total eroded material at the outlet of the catchment, expressed as volume/area/time (De Vente, Poesen 2005). Research into the spatiotemporal complexities of sediment movement through catchments has been a strong and recurrent theme of fluvial geomorphology (Vercruysse et al. 2017), in pursuit of the ability to estimate or predict catchment sediment yield from the quantitative analysis of catchment characteristics and processes.

Wolman (1977), and later Walling (1983), noted that defining gross erosion to sediment delivery ratios (SDR) remained problematic, and that an improved understanding of catchment erosion, transport and storage mechanisms remained a major research goal (Wolman 1977; Walling 1983). This still remains the case (Vercruysse et al. 2017).

Walling (1983) conceptualised catchment sediment delivery as a "black box" in which the "nature, extent and location of the sediment sources, relief and slope characteristics, the drainage pattern and channel conditions, vegetation cover, land use and soil texture" (Walling 1983 p 211) were amongst the complex and interrelated geomorphological and environmental factors that influenced the catchment sediment delivery ratio (SDR).

In this seminal 1983 review, Walling (1983) identified a temporal and spatial paradox, framing the "sediment delivery problem" in terms of uncertainties in quantifying catchment processes taking place over concurrent and varying temporal and spatial scales. Walling (1983) stated that whilst sediment transport in plots and small catchments tended to occur at the temporal scale of individual storm events which are best characterised by Wischmeier and Smith's (1978) USLE, sediment transport in large catchments typically occurred at the scale of annual runoff regimes, modified by seasonal plant cover patterns. Walling (1983) further noted that in large catchments, most eroded material is stored for long periods as alluvium in valley systems, and for shorter periods in channel forms, contributing to temporal discontinuity when this stored sediment is remobilised e.g. by land use change, or by channel shifting. Further, only small areas of catchments might respond to individual storm events. These observations revealed uncertainties in terms of the estimation of timescales and volumes of sediment being transported, and rendered problematic the characterisation of a catchment with a single SDR (Walling 1983).

Harvey (2002) noted that Brunsden and Thorne's (1979) concept of the "coupling" (or connectivity) of hillslopes and channels took place across local and zonal (or regional scales), and that spatial and temporal scales were linked (Harvey 2002) Temporal scales ranged from individual events to geological time (Harvey 2002), echoing Schumm and

Lichty's (1965) steady to cyclic time concepts. Well-coupled or connected systems more readily and rapidly transmit the effects of anthropogenic, climatic or tectonic change (such as the transmission of sediment) throughout the system than those which were poorly coupled, or "buffered" (Harvey 2002).

Owens (2005) reviewed what he termed Conceptual River Basin Models (CRBMs) which attempt to account for sources, pathways and stores of sediment within catchments and to quantify catchment sediment transport in terms of sediment budgets. Owens (2005) noted that CRBMs should conceptualise components as follows in order to better represent the internal sediment dynamics of a catchment:

- Key environments as subsystems;
- Sources of sediment;
- Sediment pathways as interrelationships; and
- Storage elements, including residence time (Owens 2005).

Echoing Walling's (1983) and Harvey's (2002) assertions regarding scale, Owens (2005) noted the complexities associated with identifying these sediment components, as they occur and operate at a variety of scales throughout a catchment (Owens 2005).

Fryirs (2013) drew on the by now comprehensive body of work to refine conceptual models for the determination of catchment sediment yield to better accommodate the layered temporal and spatial scales at which catchment processes take place (Fryirs 2013). Fryirs envisioned a catchment "sediment cascade" in terms of:

- components;
- connectivity;
- the thresholds, switches, and blockages in terms of which linkages may be made or broken; and the
- framework of temporal and spatial scaling in which these exist.

In her approach to understanding and quantifying the internal sediment dynamics of catchments, Fryirs (2013) adopted the concept of the "jerky conveyor belt" (Ferguson 1981) to describe the cascade of sediment through the catchment, asserting that sediment spends more time in storage than in transport. Fryirs found that sediment stores may be active or passive, depending on whether they are laterally, longitudinally or vertically linked to fluvial transport processes, or whether they are blocked by e.g. valley constrictions, buffered by e.g. riparian zones, or blanketed by e.g. cobble armouring.

The use of contemporary techniques such as mapping, tracing, and dating of catchment components, linkages, and switches allows the definition of the temporal and spatial framework of potential sediment cascades (Fryirs 2013). Recognition of the sensitivity of these defined catchment sediment transport processes provides insight to the ease with which links within the sediment cascade would be “switched” on or off according to the magnitude and/or frequency of climatic, tectonic or anthropogenic drivers.

In the Tsitsa catchment, Le Roux (2015) noted that soil erosion and mapping work which had indicated high erosion potential had taken little or no account of such sediment cascades and as such as offered insufficient insight into sediment movement or yield (Le Roux 2015). Le Roux (2015) recognised that typical soil erosion modelling approaches based on sheet and rill erosion factors could not accommodate the prevalence of gully erosion and the high degree of connectivity found in the Tsitsa catchment, and would under-estimate sediment loads and yields from the quaternary catchments in the Tsitsa River system. Le Roux (2015) integrated remote sensing and modelling into a GIS approach over a five-year timeframe to provide an improved estimation of sediment loads and yields between 2007 and 2012. Although the overall estimated average yield was 5 t/ha yr, estimated yields ranged at sub-catchment scale from 1 t/ha yr in headwater catchments to 25 t/ha yr for the catchment at the proposed outlet of the Ntabelanga Dam. This represented the firmest estimation to date and incorporated catchment-specific factors such as land cover, slope, soil type, connectivity, and gully growth. Nevertheless, Le Roux (2015) cautioned that these parameters were dynamic and their values not absolute, and noted not only that such catchment characteristics and processes would vary within each sub-catchment, but also that overall they were not fully understood.

The results of the integrated GIS approach were therefore still subject to uncertainty, leading Le Roux to recommend further research including identifying areas at risk of gully erosion, generating estimated sediment yield based on a range of gully development scenarios, and also to monitor discharge and sediment over the long term (Le Roux, 2015).

### *Conclusions*

Despite advances in technology to monitor, analyse and disseminate information and data regarding SS dynamics, and regardless of the evolution of conceptual models, SS transport still remains something of a black box (Vercruysse et al. 2017). Whilst emphasising timescales rather than the determination of yield in their review of SS dynamics, Vercruysse et al. (2017) nevertheless concluded that researchers have “*not sufficiently addressed the temporal complexity of sediment transport processes, which is limiting our ability to disentangle the hydro-meteorological, catchment, channel and anthropogenic drivers of suspended sediment*” (Vercruysse et al. 2017). Thus, computer models incorporating soil loss equations to determine erosion rates, and GIS mapping to identify sources and pathways, still provide results which are intrinsically uncertain, cannot properly accommodate the complexities of sediment cascades, and which require verification of their modelled SS load and yield results using data derived by other means, e.g. reservoir studies and direct monitoring (Le Roux, Weepener 2015).

The direct SS monitoring programme undertaken in the Tsitsa River catchment was planned and implemented due to these uncertainties in modelled results and inconsistencies with reservoir studies. In contrast to these approaches it aimed to directly measure SS loads and yields. The results could in turn be used to calibrate and verify modelled outputs, reducing the uncertainty regarding the relative contribution of sub-catchments to overall SS yield at the proposed Ntabelanga dam wall.

## 2.3 The relationship between suspended sediment and discharge

### *Introduction*

This section examines sediment/discharge relationships that result from the nature of SS, and the spatial and temporal variability of suspended sediment concentration (SSC) and loads. The scientific basis for a spatially and temporally representative SS sampling programme is thereby established with reference to the design of the CT-based approach in the Tsitsa River catchment.

SS load is a function of SSC and discharge. Average daily SS load can be expressed by

$$\boldsymbol{Q_s = 0.0864\, Q_D c_t} \qquad \textbf{Equation 1}$$

where:

$Q_s$ = SS discharge (tonnes/day);

$Q_D$ = average daily discharge ($m^3/s$); and

$c_t$ = daily SSC (parts per million or mg/L) (Gordon et al. 2004), with the factor 0.0864 converting seconds to days and milligrams to tonnes.

Discharge is the main driver of sediment transport capacity in a river (Petts, Foster 1985 p110), whilst sediment availability is a strong control on sediment concentration and load (Knighton 1984). Flood events are responsible for the bulk of sediment movement (Collins, Walling 2004), in terms of which Wolman and Millar (1960) stated that flows with an average return period of ~1 year typically move the largest proportion of sediment, with storm discharges with a <5 year return period moving 90% of sediment in many rivers (Wolman, Miller 1960). Gordon et al (2004) note that variations in sediment load are greater in rivers in semi-arid than in humid regions, and that short periods of high flow may be responsible for the majority of sediment moved (Gordon et al. 2004). Horowitz (2010) noted that more than 85% of sediment movement in large rivers (such as the Mississippi) was associated with flood flows and that this percentage could be higher in smaller rivers (Horowitz 2010).

Variations in SSC are, however, influenced by factors other than discharge (Walling 1974), with the consequence that SSC/discharge relationships are site-specific, and frequently non-linear. Kuhnle (2013) notes that "*There are still major gaps in the understanding of the processes and prediction of the transport of suspended sediment*" (Kuhnle 2013). In addition to the magnitude and frequency of flows, catchment-scale factors influence SS variability (Vercruysse et al. 2017). SS is also variable throughout the width and depth of channels at the scale of the reach (or monitoring site) (Gordon et al. 2004). These spatial and temporal variations in SS are highly relevant to SS programme design and purpose.

### *The nature of suspended sediment*

Soil particles, once eroded from catchment surfaces, must be transported by water, air, or ice across the boundary between catchment and channel (Knighton 1984; Morgan 2009). Total sediment load in a channel comprises bedload and suspended load (Gordon et al. 2004) as shown in **Figure 2**. Suspended load comprises washload and organic material, together with the suspended component of bedload (Knighton 1984).

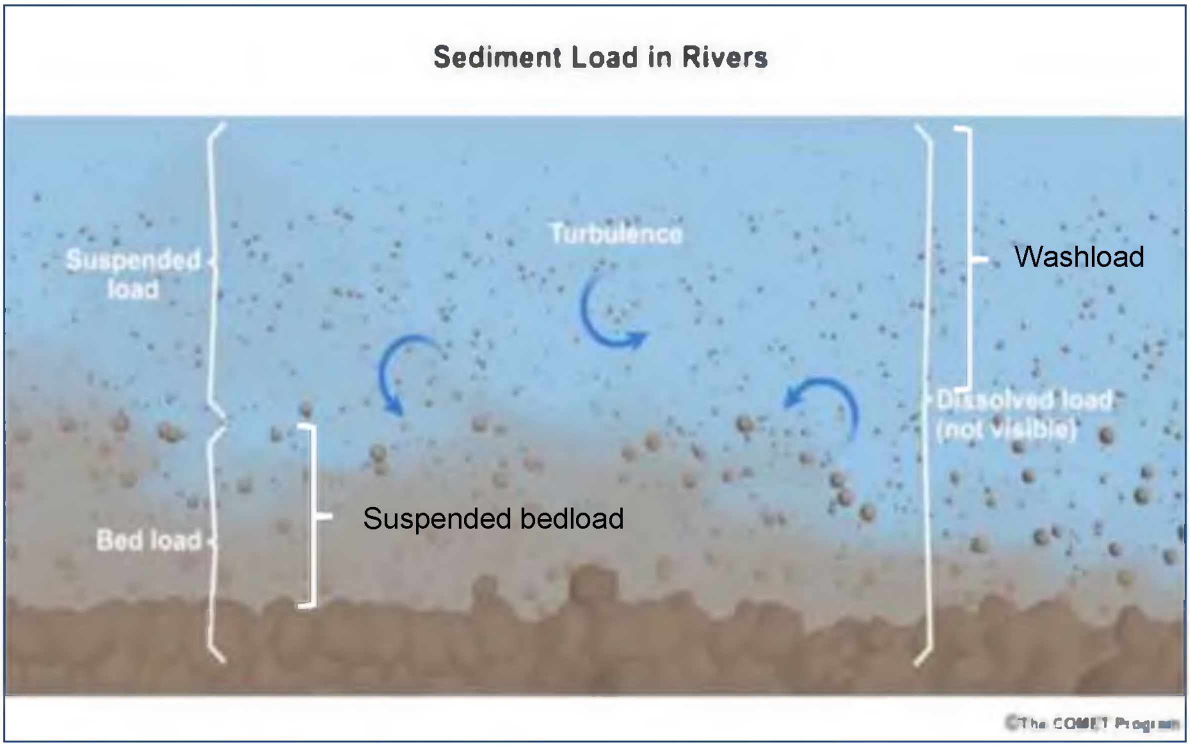


**Figure 2: The components of sediment load** (Lubeck 2015).

In the Tsitsa River catchment, organic and dissolved materials were found to be insignificant components of the total load and are not discussed further (Bannatyne et al. 2017). Neither bedload nor the factors affecting its provenance and transport are considered in this literature review. Firstly, accurate bedload transport rates are extremely difficult to monitor, requiring dedicated equipment and sampling approaches (Petts, Foster 1985 p 108). Secondly, since suspended load dominates total sediment load and globally contributes

~70% of sediment delivered to oceans by fluvial systems (Vercruysse et al. 2017), bedload is unlikely to contribute significantly to the potential sediment-related loss of storage capacity of the proposed Ntabelanga Dam. As a consequence, estimation of bedload was deemed to be beyond the ambit of this research project.

Generally, washload comprises fine silt and clay material (particles <0.064 mm) introduced into the channel from catchment surfaces by overland flow/runoff resulting from precipitation. Fine silt may remain in suspension almost indefinitely, whilst clay can be transported at low velocities/turbulence. Washload is typically limited by the supply of eroded material within the catchment (Knighton 1984) and the occurrence of precipitation events.

Suspended bedload includes sand and finer gravels (particles >0.064 mm) likely to have been eroded or remobilised from the channel bed and banks which require higher velocities/turbulence to become entrained and transported: The amount of > 0.064 mm particles in suspension is limited by the capacity of the river to carry it (Gordon et al. 2004 p 172). Suspended bedload moves above the bed sediments with the washload, settling preferentially when velocity or turbulence is reduced (Knighton 1984). Thus, the highest levels of SSC are found just above the stream bed (Petts, Foster 1985).

### *Spatiotemporal variability of suspended sediment*

#### *Catchment-scale factors*

Early studies proposed a constant local relationship between SSC and discharge (Leopold, Maddock 1953) but with further research this was questioned (Walling 1974), and it is now accepted that SSC: discharge relationships can vary considerably both temporally and spatially within and between rivers (Wood 1977). In their review of the multiscale drivers of temporal SS in rivers, Vercruysse et al (2017) highlight its spatiotemporal non-linearity, and attribute this at catchment scale to the complex feedback mechanisms affecting soil erosion and transport thresholds/processes (Vercruysse et al. 2017). **Figure 3** (with permission Elsevier License Number 4238740766100) draws on the work of Harvey (2002) and Fryirs (2013) to illustrate the spatial inter-relationships between catchment characteristics such as climate, vegetation, land use and practice, slope and geology (layer a), coupling and connectivity influenced by blockages, boundaries and blankets (layer b), and the transport capacity of the fluvial system (layer c), which in turn are subject to change over time.

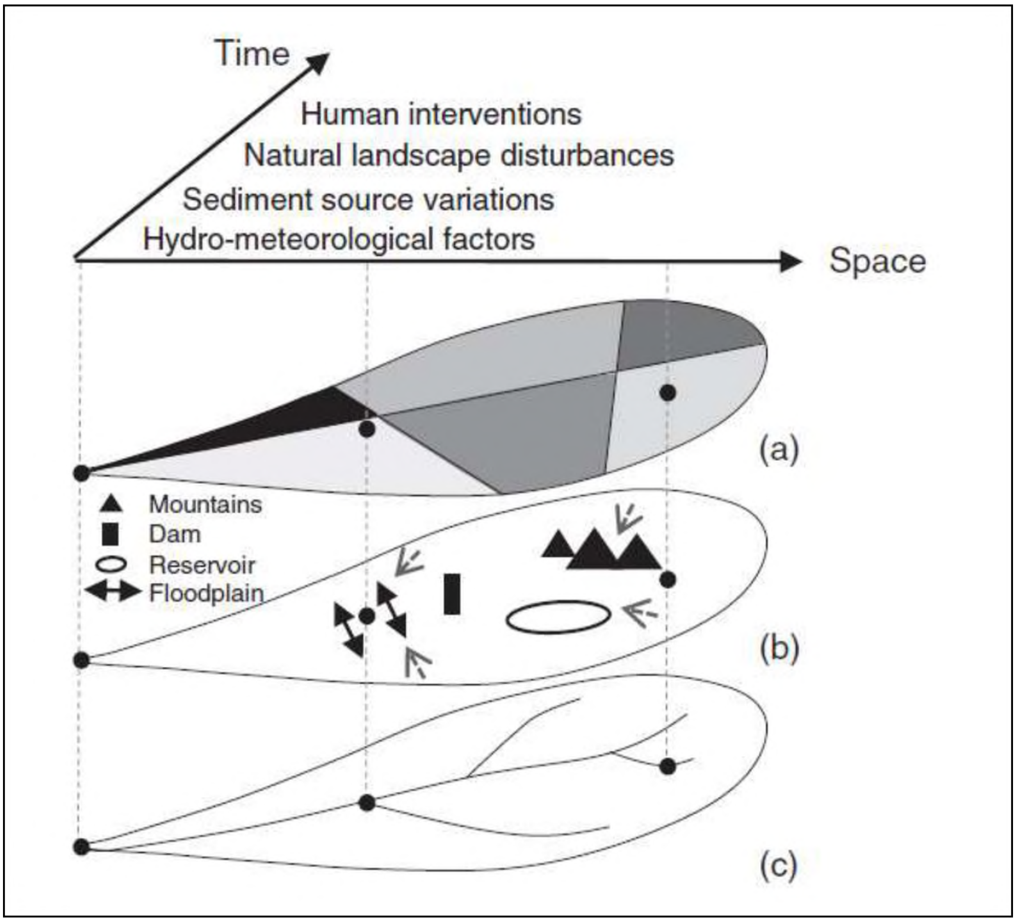


**Figure 3: Catchment scale drivers of SS variability** (Vercruysse et al. 2017) **by permission Elsevier**

SSC can therefore vary gradually (over cyclic or graded time) in response to geological or climatic changes, seasonally in response to e.g. annual climate variation, vegetation coverage, or farming practices, or rapidly (in steady time) in response to e.g. rainfall events, mass soil movement events or the effects of a recent fire in the catchment (Gregory, Walling 1974; Petts, Foster 1985; Gordon et al. 2004).

As a consequence of these catchment scale factors, SSC sampled or load determined at any point in a catchment is subject to continuous temporal variation, and will in turn differ from the results of sampling undertaken elsewhere in the catchment at the same time. Sampling programme design must therefore ensure appropriate sampling intervals that will adequately capture these temporal changes, (e.g. short sampling intervals for small flashy rivers, longer intervals in larger catchments) (Wren et al 2000). Appropriate siting of monitoring points within the stream network will allow variations in SS to be attributed to the catchment characteristics under investigation (e.g. the difference in SS yield from paired catchments with different land uses).

### *In-channel factors*

Substantial short-term spatial (width and depth) and temporal variability of SSC and particle size occurs within channels (Horowitz et al. 1990). Finer clay and silt particles (washload) are more likely to be fairly evenly distributed through the depth of a stream, whilst larger, heavier sand-sized grains are typically concentrated nearer the stream bed but are distributed erratically through the water column by turbulence and stream velocity (Gordon et al. 2004 p 172; Horowitz 2013). As noted, variations in the silt and clay fractions of suspended load are typically influenced by supply, whilst variation in larger particles is typically influenced by the flow rate.

Sediment erosion, transport, and deposition rates vary through time along the length, across the width, and through the depth of the channel. For example, the inside and outside bends of meanders experience different shear stresses (and therefore erosion and deposition rates); undercutting/mass movement, often during flood events, may spontaneously introduce large quantities of material into a channel (Robert 2003). Downstream of confluences, SSC may vary laterally due to the presence of sediment rich inflow from tributaries (Kuhnle 2013). Material from the channel bed and banks is an important source of SS (Robert 2003) and is composed of a heterogeneous mix of grain sizes. Thus, together with fine washload, SS particle size is typically heterogeneous (Robert 2003). Mobilisation, entrainment and transport of particles within the channel depend on highly localised flow intensity conditions working on this range of particle sizes. Forces include shear stress, drag, and turbulent velocity fluctuations in response to changes in stream power, channel shape and depth, obstructions such as boulders, debris dams, or infrastructure, and channel roughness due to coarse bed material or vegetation. This is illustrated by Horowitz et al. (1990) who sampled six rivers in the USA to compare the results of detailed depth and width integrated sampling, pump sampling and grab sampling. Substantial short-term (i.e. 20-30 minutes) and spatial differences were found in the resulting SSC data even when streams were in steady-state stage and discharge conditions (Horowitz et al. 1990).

The implication of this is that a SS sample taken at a single point in space and time (e.g. by a sampler standing at the bank and sampling at a constant depth below the surface) is unlikely to be representative of the channel cross-section at the monitoring point, even if an isokinetic sampling vessel is used (Wren et al 2000) (i.e. one that by its design does not alter the concentration of water and sediment flowing into the vessel compared with that flowing at that point in the river). Taking a depth-integrated sample in which the sampling vessel is filled by drawing it through the entire water column improves representivity, but such samples must be regularly calibrated by sampling the stream cross section as a whole using width and depth integrated sampling (Wren et al 2000).

### *The influence of flood events on sediment/discharge relationships*

SSC varies throughout flood flows, depending on whether the supply of sediment is limited during an event in the case of fine sediment from catchment surfaces, or whether the power of the stream to transport sediment is limited as in the case of coarser sediment from the channel bed and banks (Gordon et al. 2004). These variations can result in the SSC and discharge peaks being offset throughout the flood time period, which is expressed graphically as leading/clockwise (SSC peaks first) or lagging/anticlockwise (SSC peaks last) hysteresis (Williams 1989).

Williams (1989) described and categorized the relationships between SSC and discharge in single hydrological events. The following paragraphs, unless otherwise referenced, are informed by his work.

By analysing the ratio between SSC and discharge (Q) over time through flood hydrographs, Williams defined five classes of SSC: Q relationship, namely single-valued relationships; clockwise and anticlockwise hysteretic loops, a combination of single-value and loop, and a combination of clockwise and anticlockwise loops, i.e. the figure-8 relationship (Williams 1989).

Class 1, a single line relationship, describes a situation where SSC and Q rise and fall at the same rate through the hydrograph, peaking simultaneously. The SSC: Q ratio on the rising and falling limb is identical. Williams (1989) noted that this may be an uncommon occurrence, offering only Wood’s example from the River Rother (West Essex, UK), of the circumstances under which such a relationship might exist, i.e. where the flood is of insufficient length to cause sediment exhaustion (Wood 1977).

Class 2, a leading hysteresis or clockwise loop typically (though not exclusively) occurs when the SSC peak precedes the peak in discharge at the sampling point. Williams (1989) suggested such data are produced when either sediment exhaustion or armouring occur during the early part of a flood.

Williams (1989) proposed three lagging hysteresis scenarios in which the SSC: discharge ratio would plot as a Class 3, anticlockwise loop. In the first, the discharge peak from the flood source might, in many rivers, arrive at the measuring point more quickly than that of the SSC peak since the former travels at wave speed whilst the latter would travel at mean flow velocity. The difference in arrival time would increase with downstream distance from flood source to sampling site. Secondly, highly erodible soils coupled with prolonged erosion through the course of the flood would produce lagging hysteresis as more sediment became available and entrained over time. Thirdly, variability of sediment supply and precipitation within the catchment could result in the observation of lagging hysteresis, presumably at a measuring point with a large and complex catchment, and using data compiled over a series of events.

In contemplating Classes 4 and 5, which are characterised by combinations of the SSC: discharge relationships already described, the scenarios which might produce such plots become increasingly complex and subject to a wide-ranging mixture of controls and variables. In conclusion, the following apt statement by Williams (1989) summarises the inherent intricacy of the SSC: discharge relationship:

*"(SS)C-Q relations are influenced by precipitation intensity and areal distribution, runoff amount and rate, floodwater travel rates and travel distances, spatial and temporal storage-mobilization-depletion processes of available sediment, and sediment travel rates and distances. The potential mix and interrelations of these and other variables present a formidable challenge to predicting the type and magnitude of C-Q relation for a particular site and occasion*" (Williams 1989)

Sampling through both limbs of the flood hydrograph improves the possibility of capturing both leading and lagging hysteresis and thus being able to infer sediment sources from the results.

Rapid or catastrophic inputs of material associated with major precipitation, flood or tectonic events can be followed by a "relaxation period" as the system adjusts to such inputs, as for example reported by Hicks and Basher (2008) in their study of large (>50 year) storm events and recovery periods in the Motueka River catchment, South Island New Zealand. Hicks and Basher (2008) found that SSC levels decreased over time and downstream as sediment exhaustion and riparian stabilisation took place (Hicks, Basher 2008). Horowitz (2010) reported similar findings in the Mississippi River in the aftermath of the 1993 flood, noting that this is due to a reduction in sediment availability rather than a decline in discharge (Horowitz 2010).

### *Conclusions*

The dynamic and variable relationship between SS and discharge has profound implications for monitoring programme design. In order to allow the estimation and prediction of SS loads and yields with a reasonable degree of confidence, SSC monitoring programmes need to accommodate: the dynamic spatiotemporal variation of SSC across a range of scales; the dominance of flood flows in terms of sediment movement; and the non-linear relationship between SSC and discharge. Low flows are likely to contribute little to overall SS loads and yields, and can be routinely sampled on a calendar basis. However, the often unpredictable high and flood flows associated with the majority of SS movement must be the focus of a successful sampling programme, which should be responsive enough to water level rises to ensure sampling of the rising limb, peak and to a lesser extent the recession of the hydrograph, through as many flood events as possible. Monitoring through the highest flows in the study period allows the establishment of a robust site-specific relationship between SSC and water level, and the estimation of peak discharge sediment loads for higher flows with longer (e.g. >2 year) return periods that may not have been experienced within the study period. Such high discharges are required for example in planning scenarios, or model calibrations.

Placing monitoring points upstream of confluences allows comparison between catchments and hence insight into the effects of catchment characteristics on SSC, such as land cover or gullied areas. At reach scale, the representivity of point sampling needs to be calibrated by width and depth integrated sampling at a range of discharges, to accommodate in-channel SSC variation.

## 2.4 Advantages and limitations of suspended sediment monitoring methods

### *Introduction*

This section reviews the accepted methods for collecting representative SS data, and examines their advantages and limitations. These 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; Hicks, Gomez 2003; Kuhnle 2013), including those which monitor surrogates such as turbidity or visual clarity.

SS data may be extremely costly and difficult to acquire, with a reduced expectation of accuracy if flood flows are not captured (Wren et al. 2000). SS monitoring method, design, and implementation is influenced by: the data required to answer the relevant research questions; the time, budget, and human resources available; and the physical, hydrological, and socio-economic attributes of the study area (Wren et al. 2000). This inevitably leads to a compromise between the monitoring undertaken and the degree of accuracy and confidence in the resulting data, given the impracticality of fully capturing the spatiotemporal heterogeneity of SS at a monitoring point. Wren et al (2000) categorised the available field techniques for SS measurement as follows:

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

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

### *Manual and automatic sampling*

Historically, most SS sampling campaigns relied on manual sampling (Ballantine 2015), whereby water samples were collected by hand for later SSC analysis or turbidity measurement, and/or where hand-held equipment such as turbidity meters, Secchi disks or clarity tubes were used to measure in-channel turbidity or visual clarity.

Manual samples can be taken on a fixed or flexible (e.g. flood-responsive) schedule by a relatively unskilled operator, and do not require a power source or fixed housing. The equipment used can be relatively low cost and unsophisticated, comprising either open vessels for grab sampling or simple isokinetic samplers for depth-integrated sampling through the water column. Operators can adjust their position at the sampling site in response to flow and bank conditions, and point or depth-integrated samples can be taken without the operator entering the water. No fixed power supply or housing is required, removing these limitations from sample site selection. Consistency of results relies heavily on operator training and compliance, albeit at a relatively low technical level (Bannatyne et al 2017). The training and administration of personnel is a significant commitment which is ongoing throughout a manual sampling programme (Bannatyne et al 2017), but which is likely to produce acceptably consistent and accurate SS data (See **Chapter 6**).

However, unless the person responsible for sampling remains permanently near the sampling point and is thus available to notice and monitor flood flows, SS loads and yields may be under-estimated (Horowitz 2013). Access to and proximity of the sampling site for the operator is therefore a limitation on sample site selection. Further, safety considerations at night and during dangerous weather and/or flow conditions potentially limit flood flow sampling. Due to this requirement for near-continual but still limited operator presence, the manual sampling method has been described as labour intensive, expensive, inconvenient, difficult and hazardous (Kuhnle 2013) not only in comparison with contemporary instrumented approaches, but also due to the cost of laboratory sample analysis (Ballantine et al. 2015). This “first world” view may however be less pertinent in 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). Isokinetic depth-integrated sampling allows a more representative sample to be taken throughout channel depth, although it under-represents the small area of suspended bed sediments below the vessel inlet point (Gordon et al. 2004). Accuracy depends on the operator using the correct transit rate to prevent over-filling the vessel during sampling (Gordon et al. 2004).

Passive (and pump) point and rising-stage samplers (i.e. automatic samplers) comprise medium-cost installed equipment that, like manual sampling, 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).

Whilst automatic samplers reduce to an extent the dependency on operator presence, they still require regular emptying, servicing and maintenance (Kuhnle 2013). 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.

In common with manual sampling, representivity must be achieved 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).

Manually monitoring turbidity and visual clarity as a surrogate for SSC can be done in-channel or on extracted samples. The same advantages and disadvantages pertain as with manual sampling, with the added benefit that laboratory analysis is not required (Ballantine et al 2015), but the additional constraint that robust relationships between turbidity, visual clarity and SSC can be difficult to accurately establish (Ballantine, 2015). Further, turbidity meters typically do not cope with very high sediment conditions, requiring sampling and SSC analysis still to be undertaken (Bannatyne et al 2017).

### *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 continuous acquisition of SS data. Fixed instruments offer consistent and accurate results from 24-hour monitoring, and avoid reliance on and training/ administration of operators. Although they may require skilled installation, set-up, and maintenance, they require little ongoing support once this is done, beyond occasional download of stored data if not continuously sent electronically or via the cellular network to off-site storage.

A range of sensors and probes are manufactured which use either optical turbidity as a surrogate for SS, or measure SS by acoustic or optical backscatter, or laser diffraction. These instruments range from sophisticated to highly sophisticated, with associated vulnerability to malfunction. All require secure placement and a permanent power supply, and all are thus 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 due to cost, typically reducing the spatial coverage of a programme (Wren et al, 2000; Kuhnle 2013). Most require periodic servicing and maintenance due to e.g. biofouling of sensors.

Additionally, few such instruments are manufactured and/or repaired in South Africa which experiences a weak currency value against those of the typically 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 such instruments require calibration at least against local conditions and particle sizes, and typically against 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).

### *Conclusions*

The choice of sampling method has profound implications for the design and implementation of a SS sampling programme. Choice of method is subject to a range of spatiotemporal and socio-economic limitations, and offers a reciprocal range of benefits. “Plug and play” installed instrumentation has the attraction of avoiding the significant training and administrative burden associated with manual sampling methods, cost being the significant drawback. Manual sampling requires a high level of support, yet in the South African context offers a relatively affordable method of acquiring acceptable SS data that has tangible benefits not only to the research programme, but also to the communities within which such research is being undertaken. The efficacy of the CT-based approach to direct SS sampling is the focus of this thesis.

## 2.5 Public engagement with environmental monitoring

### *Introduction*

This section examines the concept of involving members of the public in gathering scientific data, an approach foundational to the design of the SS sampling programme in the Tsitsa catchment. The nature, history, and evolution of public or citizen engagement with science are reviewed, and the roles and responsibilities of those involved are described within the context of structured scientific research. The benefits and limitations of the voluntary activities of "citizen scientists" are contrasted with the more business-like employment of "citizen technicians" in the Tsitsa River catchment.

### *Citizen science*

Typically, "citizen science" is the term routinely applied to the component of a scientific research project that involves data observation and recording by people outside the formal research team (Silvertown 2009). Other interchangeable terms include community based monitoring (Whitelaw et al. 2003; Conrad, Hilchey 2011) and networked or crowd science (Vallabh et al. 2016).

The term "citizen scientist" is widely applied to members of the public who collect data or make observations that contribute to a scientific study (Bonney et al. 2009). Paradoxically, however, many researchers are at pains to distinguish between citizen scientists and their "professional counterparts" (Silvertown 2009) by describing the former as "not…necessarily even scientists" (Cohn 2008); as "amateurs" or "nonscientists" (Trumbull et al. 2000); in some cases as "non-professionals", in others as "the affected population" (Dickinson et al. 2012).

However, a primary assertion made by researchers almost without exception is that regardless of the extent of their role, *citizen scientists are volunteers* (Trumbull et al. 2000; Cohn 2008; Bonney et al. 2009; Conrad, Hilchey 2011; Crall et al. 2011; Roy et al. 2012). Roy et al. (2012) defines citizen science broadly as "*the involvement of* volunteers *in science*" (Roy et al. 2012) and more concisely as "Volunteer *collection of biodiversity and environmental information which contributes to expanding our knowledge of the natural environment, including biological monitoring and the collection or interpretation of environmental observations*" (Roy et al. 2012).

### *The growth of citizen science*

Despite the recent coining of the term (Silvertown 2009), citizen science is not a new phenomenon, either globally or in South Africa. In terms of public collaboration with scientific projects, the often-cited Audubon Christmas Bird Count in the USA has been in existence since 1900, whilst in South Africa the River Health Monitoring programme for example has been operating for more than 20 years (Vallabh et al. 2016). Examples of robust citizen science-based projects active in South Africa include the simplified version of the South African Scoring System (SASS) aquatic bio-monitoring tool known as mini-SASS, the South African Bird Atlas Project (SAPAB), and iSPOT, a biodiversity-mapping project, amongst many others (Vallabh et al. 2016).

The recent national and global increase in the number and variety of citizen science projects may be attributable in part to the reduced cost of data collection offered by this approach Furthermore, citizen science projects have become easier to implement as advances in and improved access to communications and information technology facilitate participation in and feedback from such projects, allowing for example the capture and transfer of images and other information. Silvertown (2009) notes that social media such as FaceBook, Twitter, and Flickr are being widely used in conjunction with resources such as GoogleMaps, Wikis, internet web-pages and You Tube to facilitate citizen scientist input and capacity building as access to home computers and mobile phone networks becomes more and more widespread (Silvertown 2009). Additionally there is an increasing number of customised applications being developed, such as the Open Data Kit (ODK) platform (Anokwa et al. 2009) utilised in the Tsitsa River catchment SS sampling programme.

In the USA and UK the requirement by funding agencies such the National Science Foundation and the Natural Environment Research Council respectively for scientific outreach and capacity building have provided compelling motivation for involving the public in scientific work (Silvertown 2009). In South Africa, DEA's equally firm commitment to job creation for poverty alleviation and sustainable rural livelihoods both motivated and enabled the involvement of local residents in the collection of SS samples and other environmental observations in the Tsitsa River catchment (Bannatyne et al. 2017).

### *The continuum of citizen science*

Citizen science projects have been carried out across a range of disciplines, including space, earth, environmental, social-ecological and health sciences (Vallabh et al. 2016), for purposes on a spectrum from purely educational to hypothesis-driven research (Roy et al. 2012). Such projects offer a range of involvement and agency to non-professionals. Whilst typically remaining volunteers and being perceived as distinct from the "professional" scientists, the actions and involvement of so-called citizen scientists may thus vary considerably depending on the type, purpose, and scope of the project. Their involvement may be as limited as the submission of observations to a database, or as far-reaching as formal involvement with management and governance (Whitelaw et al. 2003). Bonney et al. (2009) categorise such projects by the degree of citizen involvement as follows:

- Contributory projects, designed by professional scientists with citizens suppling observations and data,
- Collaborative projects, designed by professional scientists but informed by citizen input to problem solving, data analysis and information dissemination,
- Co-created projects, where citizens and professional scientists are jointly responsible from problem identification and framing, data collection, analysis, information dissemination and feedback of the findings into mitigation actions (Bonney et al, 2009).

Roy et al. (2012) add the further scenario whereby citizens undertake all aspects of a scientific study without the direct involvement of professional scientists.

### *Benefits of citizen science*

Silvertown (2009) states that whilst some citizen science projects are designed for the benefit of citizen scientists, and some for the benefit of the project, the best are designed for the benefit of both (Silvertown 2009). Dillon et al. (2016) envision citizen science at the nexus of science and society, with the potential for significant socio-ecological civic benefits (Dillon et al. 2016). In all cases the nature of the benefit should be understood as a project goal by all parties.

Benefits to the non-professional participants include individual benefits such as a feeling of involvement, personal capacity building, and contact with experts in the field of interest. Sustainable community benefits include using knowledge and data accruing from citizen science projects to empower communities to lobby for and effect socio-economic and environmental change (Whitelaw et al. 2003). For the research team, citizen science allows a larger number of participants to provide data, and thus the collection of more data over a wider range than would otherwise be possible (Bonney et al. 2009). Silvertown (2009) goes as far as to assert that citizen science is a *requirement* for large scale environmental science.

Silvertown (2009) notes that citizen science projects can promote science as a worthy recipient of public funding to taxpayers, arguing that public (i.e. taxpayer) participation in scientific projects will foster their appreciation and understanding of science (Silvertown 2009). The participatory hydrology and sediment monitoring project facilitated at field scale by Kongo et al. (2010) in the Potshini catchment of KwaZulu Natal is an example of a project co-designed and implemented to provide decision-support information directly useful to all stakeholders (Kongo et al. 2010).

### *Constraints of citizen science*

A citizen scientist-based approach is not without its challenges. Perceptions of data quality have improved over time, but quality assurance of data collected by citizen scientists remains of utmost importance, particularly when the information gathered is to be used in support of environmental management actions and policy decision making (Sheppard, Terveen 2011). To this end, precise and uncomplicated data collection protocols are essential (Bonney et al. 2009) and clear criteria and best practice must be used to define, measure, implement, and maintain the quality of the data collected (Sheppard, Terveen 2011). An obligation for supportive supervision and tight data quality control is placed on the researcher, which requires substantial time and commitment throughout the project (Kongo et al. 2010).

### *Conclusions*

Citizen science is an established, accepted, and increasingly valuable approach to scientific data collection which is supported by advances in communications and computing technology, and has a range of benefits for all role-players. The approach to public involvement for data gathering in the SS monitoring programme undertaken in the Tsitsa catchment embraced many salient features of citizen science, such as involvement of local residents, use of communications technology, development of simple and rigid data-gathering protocols, and imposition of rigorous quality control. It was, however, distinct from the accepted model of citizen science in certain significant aspects.

Firstly, the members of the public who collected the SS samples were not volunteers, and their motivation and benefit was almost exclusively financial. The term “citizen technician” was therefore adopted in preference to that of “citizen scientist”. Secondly, whilst offering capacity-building related to the activities being carried out, this project made no provision for certain key attributes of typical citizen science projects, such as community problem identification, decision making and information sharing in a context relevant to participants’ lives and daily activities.

# 3 THE STUDY AREA

## 3.1 Introduction

This chapter places the study in its socio-economic and bio-physical context, thereby informing the basis for decision-making regarding the development of a locally-appropriate SS sampling method.

## 3.2 Location

The study area comprises the catchments of the Tsitsa River and its tributaries upstream of the proposed Ntabelanga and Lalini Dams. The Tsitsa River is a tributary of the Umzimvubu River. **Figure 4** is a locality map of the study area showing the main watercourses and catchments of the proposed Ntabelanga (darker shading) and Lalini (lighter shading) Dams, in relation to gullied areas (Le Roux, Sumner 2012) and the Umzimvubu River.

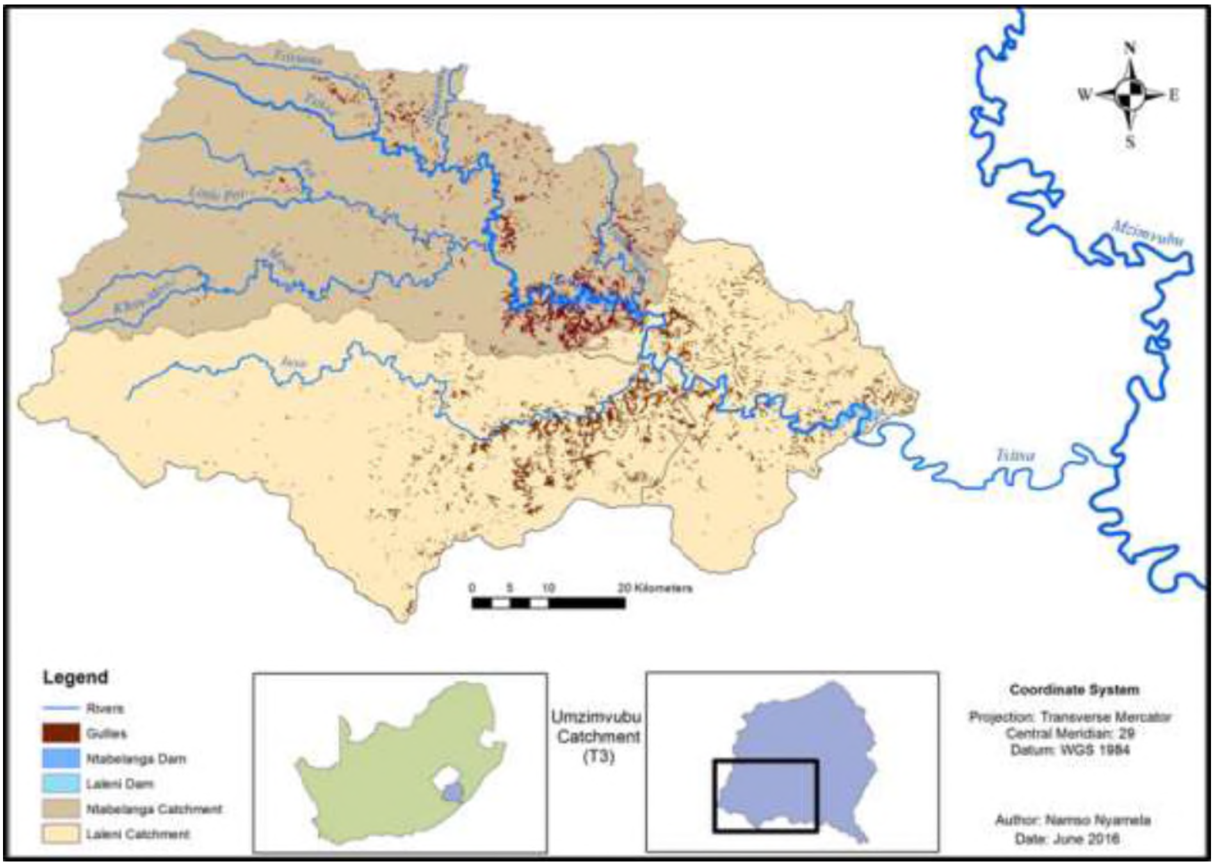


**Figure 4: Study area with major rivers, gullied areas, and catchments of the proposed Ntabelanga and Lalini dams.** (Bannatyne et al. 2017)

The towns of Maclear and Tsolo lie within the study area. Much of the Tsitsa River catchment lies in the communal areas of the former Transkei homeland as depicted in **Figure 5** where the majority of the population resides in low-density rural villages, often situated on the mid-slopes of hillsides (**Plate 2**).

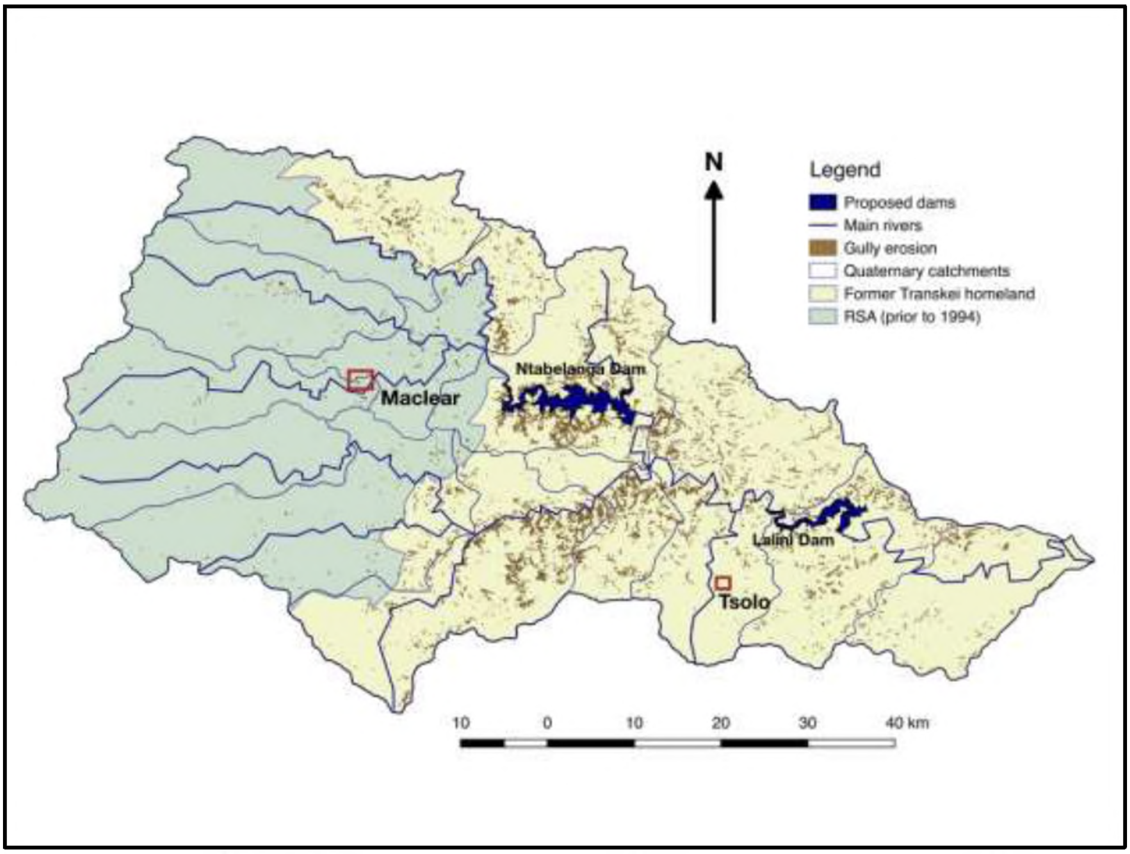


Figure 5: The Tsitsa River catchment showing the former Transkei boundary, settlements, major rivers, gullied areas, and the site of proposed Ntabelanga dam (KR Rowntree)

Plate 2: A typical study area landscape in the Gqukunqa River catchment

## 3.3 Socio economics

The catchment restoration and natural resource monitoring components of DEA-NRM's NLEIP form part of the South African Government's job creation programme (Fabricius et al. 2016 p i). This initiative is directed towards poverty alleviation, particularly in rural areas, with an emphasis on providing employment opportunities for women and the youth (<30 year-olds). The socio-economic status quo of the Tsitsa River catchment is relevant to the decision to employ local residents as CTs. The information in this section is drawn from the work of Hodgson (2017), which was largely based on data gathered during the 2001 and 2011 South African National Population Census, and from DWS Report No PWMA 12/T30/00/5314/3, i.e. the scoping report of the Environmental Impact Assessment for the Mzimvubu Water Project by Calmeyer and Muruven (2015).

Calmeyer and Muruven (2015) describe the Mzimvubu River catchment (of which the Tsitsa River catchment forms part) as "*one of the poorest and least developed regions in the country*" (Calmeyer, Muruven 2015 p v). They summarise the socio-economic profile of the area as follows:

- "*A majority of Black Xhosa speaking people;*
- *More women than men;*
- *A high proportion of children under 15 years and people over 65 years;*
- *Population densities up to 110 people/km2;*
- *HIV prevalence amongst antenatal women of up to 29.3%;*
- *Unemployment rate up to 35%;*
- *Very low or negative population growth*" (Calmeyer, Muruven 2015 p xiii).

Hodgson (2017) found that most of the ~45 000 residents described their race group as "Black African". Fewer than 600 described their race group as "White", and a similar number described themselves as "Coloured". First language use followed this pattern, with most people speaking isiXhosa: fewer than 1 000 and 2 000 people respectively reported English or Sesotho as their first language, with the former mainly resident in Maclear or the commercial farmlands, and the latter living to the north of the study area towards the border with Lesotho (Hodgson 2017). Out-migration underlies the fall in total population numbers from ~56 000 to ~45 000 during the period 2001 – 2011, fuelled by a strong drive to seek better employment opportunities and living conditions (Hodgson 2017).

The majority of Black African people resided either in rural villages or in the township near Maclear, whilst the majority of White people lived in the suburbs of Maclear or on commercial farms (Hodgson 2017).

Fewer (~5000) people in 2011 reported that they had received no schooling whatsoever than in 2001 (~8500). However, despite overall increases in the number of people receiving or completing primary and secondary schooling between the censuses, fewer than 3000 people across the catchment reported in 2011 that they had completed secondary schooling, whilst only ~1100 reported experiencing any form of higher education.

More people described themselves as employed and fewer as unemployed in 2011 than in 2001. However, total employment figures remained extremely low, with only 5652 people of the 22 020 people aged between 18 and 65 (i.e. ~25%) reporting in 2011 that they were employed.

These figures apparently point to improvements since 2001 in both educational and employment levels amongst the people of the Tsitsa River catchment. However, Hodgson (2017) notes firstly that the driver behind the positive trend in education and employment figures may be due to employment via government initiatives such as small scale collective farming and “Working for” projects and, secondly, that areas with infrastructure clusters such as hospitals and police stations are also employment clusters, and *inter alia* of recipients of people with secondary and higher education.

In summary, the picture painted by Calmeyer and Muruven (2015) and Hodgson (2017) confirms that job creation is a necessary and appropriate strategy in the Tsitsa River catchment, and that the opportunity to earn money whilst remaining in the area has the potential to make significant beneficial impacts on residents’ livelihoods.

## 3.4 Topography

The Tsitsa River rises in the Drakensberg Mountains, in the Great Escarpment geomorphic province, and flows through the Southeastern Coastal Hinterland geomorphic province (Partridge et al. 2010) to its confluence with the Umzimvubu River. Elevations in the study area range from 2 730 m in the Drakensburg in the north-east, to ~600 m towards the confluence with the Umzimvubu (Le Roux, Weepener 2015). The topography of the study area is typically hilly to rolling with steep escarpment zones in the headwaters and middle catchment.

Once free of its Drakensberg headwaters, the Tsitsa River may be described as a mixed alluvial/bedrock river, typically with a sandy bed except where dolerite dykes or sills are evident. Instream vegetation is generally absent, with riparian vegetation dominated by alien invader tree species. In many places, channels are deeply to very deeply incised in alluvial plains, and may be locally characterised by flood benches, meanders and ox-bow lakes. Below the Tsitsa Falls waterfall to a point upstream of the inlet to the proposed Ntabelanga Dam, the Tsitsa River passes through a deep and largely inaccessible gorge as it crosses the middle escarpment. The Pot River, having been joined by the Mooi River, converges with the Tsitsa River within this gorge.

The presence of the gorge, together with the steep and unstable bank conditions typical of the alluvial reaches of channels, restrict access to and impact on the availability of safe, accessible sampling sites throughout the catchment.

## 3.5 Climate

The climate of the Tsitsa River catchment has been described variously as sub-tropical (Iliso Consulting (Pty) Ltd 2015), sub-humid (Le Roux, Weepener 2015), and warm-temperate (Mucina, Rutherford 2006). Given its altitudinal range the catchment traverses a range of climate types (Mucina, Rutherford 2006). Iliso Consulting (2015) report 749 mm in the lower catchment area as measured at Tsolo whilst Le Roux and Weepener (2015) put mean annual rainfall in the upper parts of the catchment at 1327 mm.

Mean annual rainfall at Maclear is highly variable, as shown in **Figure 6,** in which Moore (2016) demonstrates that it ranges from a low of 503 mm in 1992 to a high of 1144 mm in 2000, with an average of 824 mm. Mucina and Rutherford (2006) note a ~23% coefficient of variation in mean annual rainfall for the area.

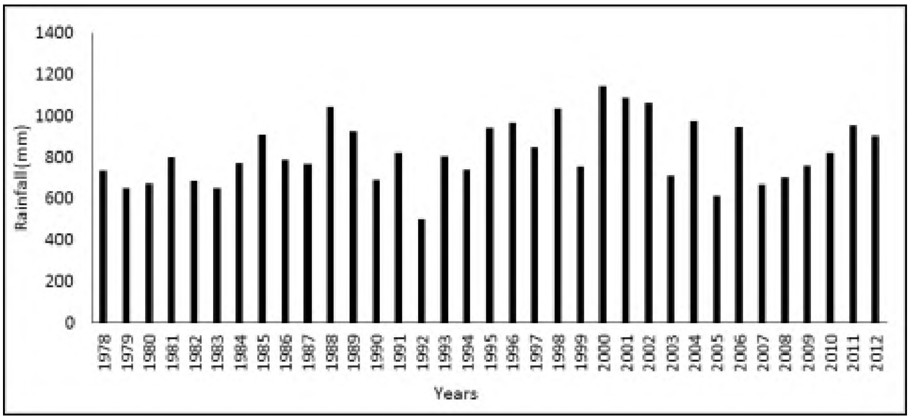


**Figure 6: Annual rainfall (mm) at Maclear 1978 – 2012 (**(Moore 2016)

The study area experiences summer rainfall (Mucina, Rutherford 2006) between October and March as depicted in **Figure 7** (Moore 2016)**,** often in the form of afternoon thundershowers (Mucina, Rutherford 2006).

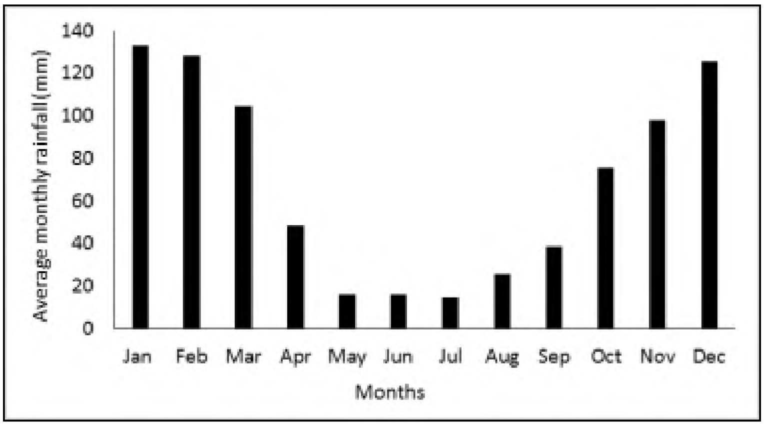


**Figure 7: Average monthly rainfall at Maclear 1978 – 2012** (Moore 2016)

Both rainfall and temperature peak in January with a monthly average of ~130 mm and ~20°C respectively. The driest and coldest month is July, with a monthly average rainfall and temperature of ~13 mm and ~0 °C respectively (Mucina, Rutherford 2006 p 416). Snowfalls can be expected during the winter months in the upper part of the catchment, and may occur in other parts (Mucina, Rutherford 2006).

As with precipitation, river flows are highly variable. Mean annual water levels 1951 – 2016 are depicted in **Figure 8** which illustrates mean water levels ranging between 0.1 m to 3.5 m. It should be noted that the highest flows would be far greater than this, given that the gauge is overtopped beyond the highest level shown. This variability introduces uncertainties into the estimation of flood durations, particularly in ungauged catchments, which in turn can impact on the effectiveness of the temporal flood sampling design. Furthermore, the annual variability implies that a study spanning a relatively dry period is unlikely to provide data representative of the higher flows that can be expected in future, and may lead to under-estimation of SS loads and yields. The maximum water level of 1.2 m recorded during the study period lies within the lower end of the record amongst flows with a return period of less than 2 years.

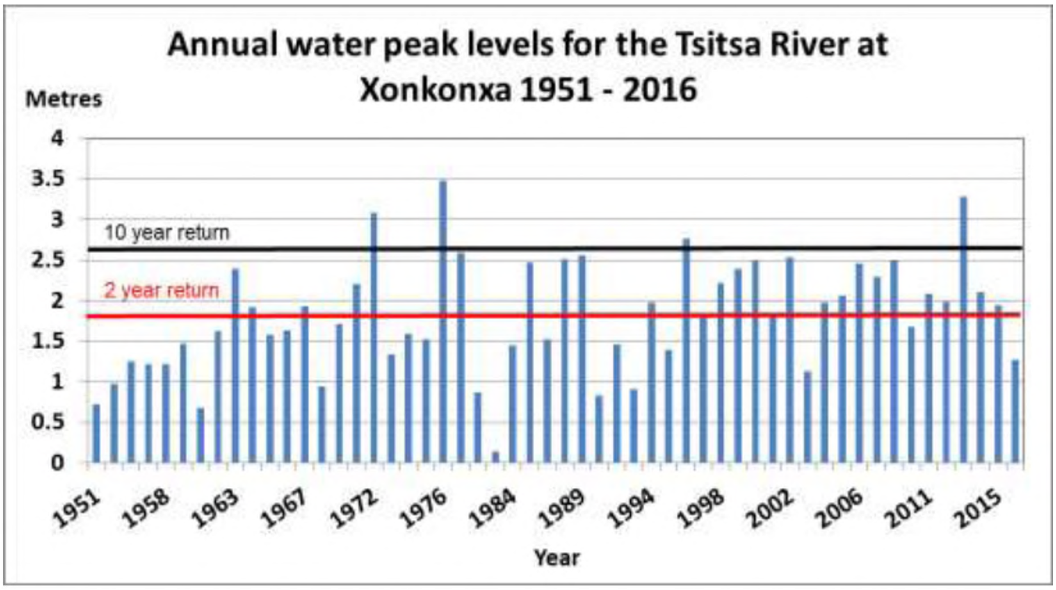


**Figure 8: Mean annual water level for the Tsitsa at Xonkonxa 1951 - 2016**

## 3.6 Geology and soils

The study area is underlain by the Tarkastad Subgroup and the Molteno and Elliot Formations of the Karoo Supergroup, which are succeeded towards the headwaters of the catchment by the Clarens Formation. Drakensberg Group basalt caps the sequence, whilst intrusive dolerite sills and dykes occur throughout the catchment (Le Roux, Weepener 2015).

Soils that develop on the Tarkastad Subgroup are particularly vulnerable to the formation of soil pipes and subsequent gullying (Le Roux, Weepener 2015) as shown in **Plate 3**.

**Plate 3: A gully network in the Tsitsa River catchment** (Iliso Consulting (Pty) Ltd 2015)

## 3.7 Vegetation and land cover

The study area is typified by grassland (**Figure 9)** with areas of both commercial and indigenous/alien invader forests, and agriculture (**Figure 10)** on both private and communal land. Land use practices such as continuous grazing and frequent burning are thought to exacerbate soil loss and result in high SS loads (Madikizela et al. 2001; Gordon et al. 2013; van der Waal 2015).

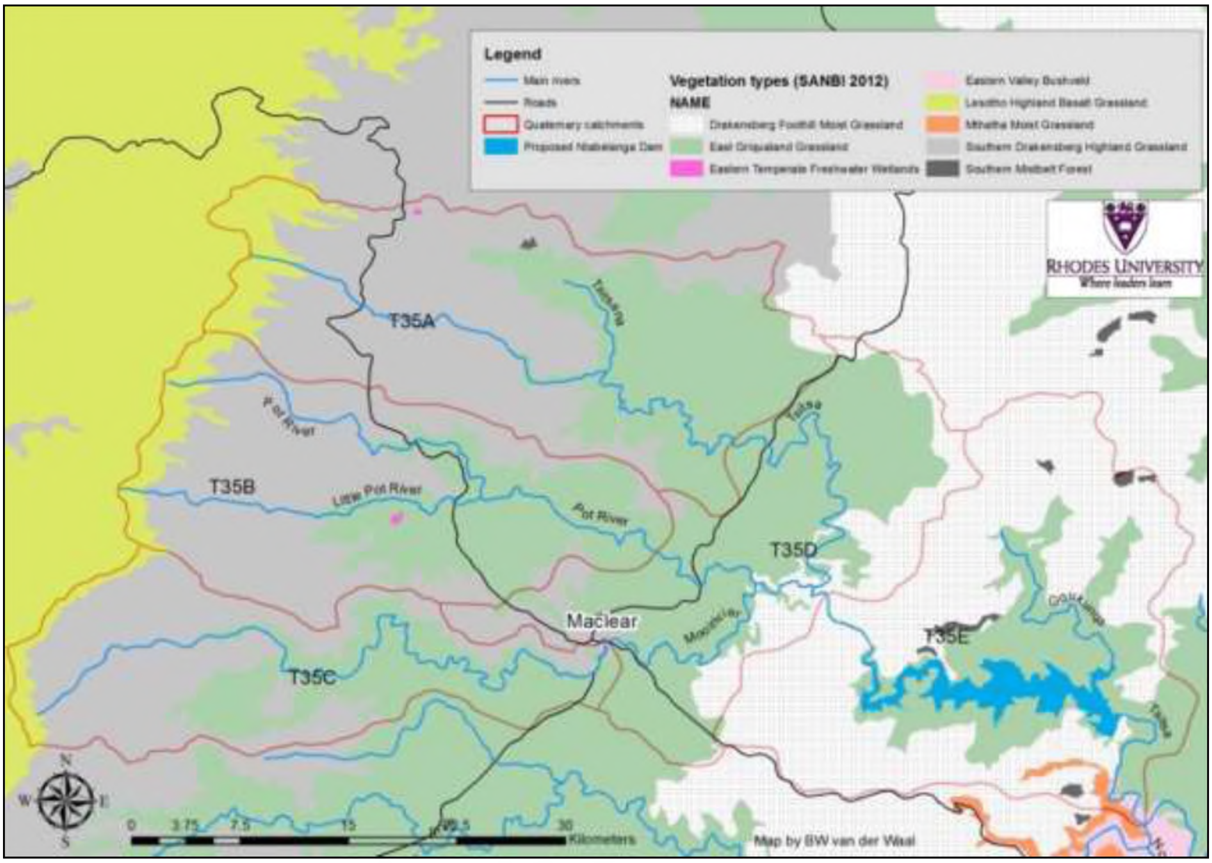


**Figure 9: Natural vegetation in the Tsitsa River catchment (B vd Waal)**

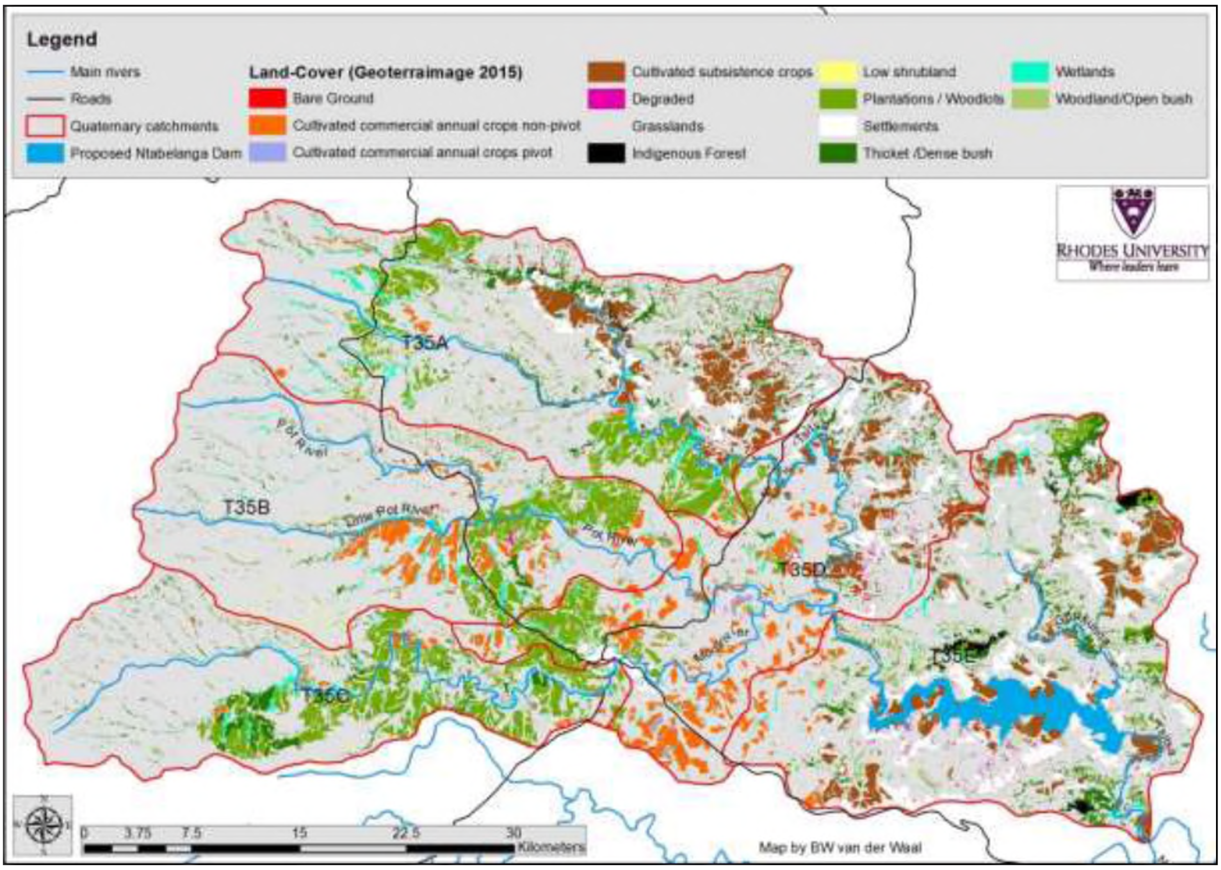


**Figure 10: Land cover in the Tsitsa River catchment (B vd Waal)**

**Figure 10** illustrates the dominance of particular land covers in certain sub-catchments. For example, plantations/woodlots, together with cultivated commercial crops are seen to be important land covers in the Pot and Mooi catchments, whilst grasslands and cultivated subsistence crops dominate in the Tsitsana, Hlankomo and Gqukunqa catchments.

## 3.8 Suspended sediment data

In common with much of South Africa there is very little SS data for the Tsitsa River. Short-term, calendar-based studies have attempted to correlate catchment conditions to sediment input to channels (Gordon et al. 2013) and to establish baseline water quality conditions including levels of SS (Madikizela, Dye 2003).

A recent WRC study (Le Roux, Weepener 2015) reported modelled sediment yields ranging from 1 t/ha·yr in upstream catchments to 22.5 t/ha·yr at the proposed dam wall site. Much of the catchment was modelled as having sediment yields in the region of 2-5 t/ha/yr, as shown in **Figure 11**.

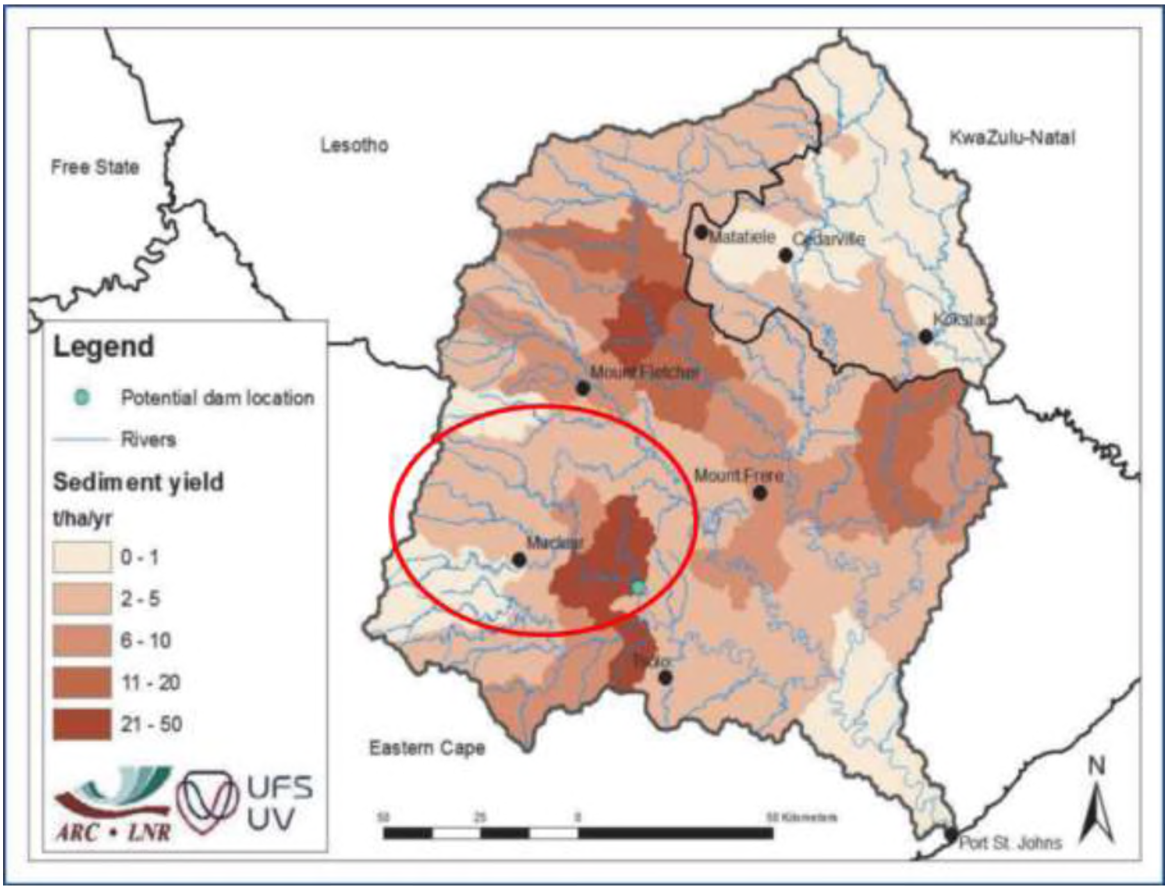


**Figure 11: Modelled sediment yield for the Mzimvubu catchment** (Le Roux, Weepener 2015).

Sediment surveys carried out by DWS and presented in (Msadala et al. 2010) for the Umtata Dam on the Umtata River, the Ncora on the Tsomo River, and the dam on the Caledon River in Lesotho may be broadly compared in terms of their catchment geology and land use with the proposed Ntabelanga Dam. Extrapolating the findings of Msadala et al. (2010) to the Tsitsa catchment upstream of the proposed Ntabelanga Dam wall suggests somewhat lower annual SS yields than those predicted by Le Roux, Weepener (2015), as indicated in **Table 1**, evidencing the uncertainty associated with these findings and pointing to the need for direct measurement of SS.

**Table 1: Comparison of SS yields from the findings of Le Roux 2015 and Msadala et al. 2010**

| Dam | Drainage region | River | Sediment yield (t/km$^2$/yr) | Sediment yield (t/ha/yr) | Catchment area (km$^2$) | Source |
|---|---|---|---|---|---|---|
| Ntabelanga | T | Tsitsa | ~2300 | ~5.00 | ~2000 | Le Roux 2015 |
| Ncora | S | Tsomo | 219 | 2.19 | 17775 | Msadala et al. 2010 |
| Umtata | T | Mthatha | 262 | 2.62 | 882 | Msadala et al. 2010 |
| Caledon River in Lesotho | D | Caledon | 1141 | 11.41 | 934 | Msadala et al. 2010 |

## 3.9 Conclusions

In conclusion, the study area lay in a remote part of one of South Africa's least developed provinces, with high levels of unemployment and low levels of education. Many livelihoods were closely tied to ecological infrastructure and services, which particularly in the communal areas were negatively impacted by poor, dispersive soils. Local residents in the communal areas had few employment opportunities, but due to poor educational background, typically lacked the capacity for technical tasks. Difficult access for researchers to some parts of the area, together with the need for safe access to monitoring sites within easy walking distance of the CTs' homes, also impacted the design of the sampling programme. The variable, unpredictable, and often extreme nature of flows was a further challenge to monitoring programme design. The uncertainties associated with existing SS yield at the site of the proposed Ntabelanga Dam underlines the need for direct SS monitoring in the Tsitsa River catchment.

# 4 SAMPLING PROGRAMME DESIGN AND FIELD AND LABORATORY PROTOCOLS

## 4.1 Introduction

This chapter describes the design and implementation of the CT-based direct SS sampling programme and associated laboratory protocol. Building on the approach taken on a much smaller scale by van der Waal in the Thina catchment (van der Waal 2015) it was decided to use the flexible combination of communication, data reporting and compliance-checking offered by software-enabled smartphones, and to develop an approach that would involve local residents as CTs. This would allow routine “baseline” sampling at a sub-daily time step, and optimise the opportunities for frequent sampling through flood flows, whilst providing job opportunities in line with the aims of the NLEIP programme (Bannatyne et al. 2017).

The SS sampling programme described here was developed from February 2015, and implemented from mid-December 2015 when funding from DEA for payment the CTs became available. The sampling activities described in this thesis took place between December 2015 and July 2016. The programme is ongoing with the intention of continuing data collection until at least April 2018. By that time, one partial and three full wet seasons (October – March) will have been sampled, approaching a “short” (Knighton 1984) study timeframe.

## 4.2 Sampling and laboratory protocol design and development

A significant component of the research activity associated with the early part of this study focussed on designing the combination of sampling equipment and protocols required to overcome the challenges inherent to the design of the CT-based approach. These activities are contextualised throughout the remainder of this chapter and included:

- Incorporating accepted water-related safety procedures (such as the correct use of a personal flotation device and self-rescue techniques) into the safety training and material given to the CTs,
- Researching smartphone specifications in the light of the GPS, memory, and camera requirements for information gathering and transmission,
- Researching, selecting and setting up appropriate platforms i.e. Open Data Kit (ODK) and KoboToolbox for enabling standardised smartphone data recording, transmission and storage,
- Estimating quantities, sourcing and purchasing appropriate equipment and consumables including lifejackets, smartphones, clarity tubes, sample jars, crates, waterproof phone pouches, and water purification pills,

- Developing appropriate safety training and sampling training materials (written in English and also provided in isiXhosa) to ensure procedural compliance and quality control (See **Appendix 2**),
- Designing and overseeing the manufacture of customised basic sampling equipment including pole-and-jar samplers and 2-litre milk bottle/fishing weight water samplers,
- Developing a system of electronic and hardcopy forms and spreadsheets for tracking and collating sample, data and analytical information throughout the sampling and analysis process (See **Appendix 2**),
- Developing an administrative system (including for example an equipment register, and checklists for field visits and resupply of consumables) for the management and support of CTs, including payment for samples collected (See **Appendix 2**),
- Developing straightforward laboratory procedures for turbidity and SSC analysis based on accepted analysis methods.

## 4.2 Spatial framework

The direct SS sampling programme was intended to determine the relative contribution of sub-catchments to the overall SS yield from the Tsitsa River catchment to the proposed Ntabelanga and Lalini Dams. The spatial design emulated that used in the River Exe UK by Collins and Walling (2004) whereby monitoring sites in tributaries were positioned upstream of confluences in order to “isolate” and monitor the upstream catchment.

The assumption was made that characteristics including slope, land use, connectivity, rainfall, etc. would influence SS load and yield of sub-catchments and sections of the main Tsitsa River, as described in **Chapter 2.2**. From the work of Le Roux (2015) it was for example known that predominant land uses included plantation forestry in the Mooi catchment, communal areas in the Hlankomo and Gqukunqa catchments, and private stock farms in the Little Pot catchment, and that highly gullied and degraded areas existed proximal to the Tsitsa River between the gorge and the Qulungashe Bridge (Le Roux, Weepener 2015). A desk study was undertaken in early 2015, based largely on 1:50 000 topographic sheets. The major tributaries and their sub-catchments were identified and potential monitoring sites selected upstream of their confluences. Potential sites were also chosen on the main channel above and below the gullied areas around the proposed Ntabelanga Dam, and at the outlet of the research catchment close to the DWS gauging weir at Xonkonxa. This was followed up by a field visit in which each of the proposed sites was assessed for its suitability for CT-based SS sampling. Eleven SS monitoring points were thus selected, as shown in **Figure 12.**

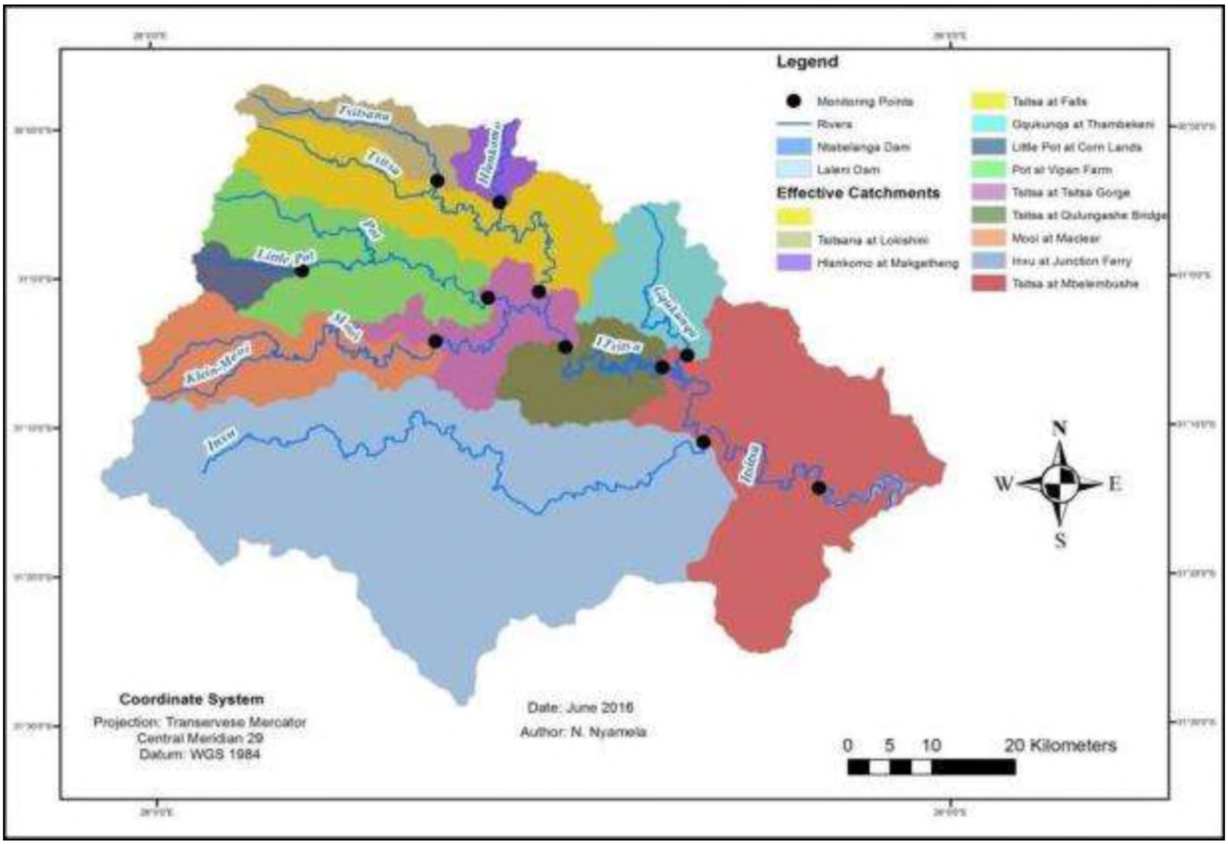


**Figure 12: Monitoring sites and their catchments on the Tsitsa River and its tributaries** (Bannatyne et al. 2017).

At local scale, proximity to settlements upstream of confluences was the main influence on the coarse positioning of monitoring sites, followed by researcher access to the area of the site. Monitoring site locations were refined at the reach scale by the availability of at least one person to be employed as a CT, by the distance from their dwelling to an access point on the channel with safe bank conditions at all water levels, and by the presence of competent bedrock for the attachment of a pressure transducer to measure water level and to provide a stable cross-section for discharge measurements. A stable cross section was also required for width and depth integrated SS sampling for the calibration of the depth-integrated "point" samples collected by the CTs.

Most of the sites, with the exception of the Tsitsa at Tsitsa Gorge (see **Figure 12**), were relatively easy to access, albeit mainly by narrow dirt roads. At several sites whilst the sampling site was close to the CT's dwelling, the pressure transducer and flow-gauging site was located some distance away due to the absence of suitable bedrock at the sampling site (e.g. at the Inxu and Pot Rivers, as shown in **Plate 4** and **Plate 5**). Pressure transducers were not installed at the Mooi sampling site or on the Tsitsa at Mbelembushe due to the proximity of DWS gauging weirs which would supply discharge data.

Plate 4: Babalwa Nqweniso at her sampling site on the Inxu River at Junction Ferry: close to her home but unsuitable for installing a pressure transducer or for flow gauging due to the sandy cross section

Plate 5: The flow-gauging site on the Pot River at Vipan, showing the stable bedrock channel: the sampling site closer to the CT's home has no suitable outcrop for attachment of the pressure transducer

Placement of the most downstream monitoring site at the outlet of the study area, on the Tsitsa at Mbelembushe (see **Figure 12**) was close to to the location of the DWS gauging weir at Xonkonxa, both in order to be able to use the DWS discharge data measured at the weir, and to allow comparison with a LISST ABS acoustic backscatter SSC probe which was to be installed at this weir, with the permission and collaboration of DWS. Funding delays meant that, following bench set-up and calibration in consultation with DWS officials, the probe was only installed in the gauging weir in mid-September 2016, i.e. not coincident with the reporting period of this thesis. It was destroyed by a lightning strike in early November 2016 during the first high-water event following its installation, after less than two months of recording.

## 4.3 Temporal framework

### *Seasonality*

As noted, the wet season (as measured at Maclear) in an average year runs from October to April (See **Figure 7**) (Moore 2016). Funding for the payment of CTs was received from DEA in mid-December 2015, following which twice-daily baseline sampling was undertaken continuously. Due to the relatively dry El Nino conditions, floods occurred mainly during January and February 2016, with sporadic floods occurring in March and April. An isolated period of heavy rain and snow-fall also triggered floods in late July 2016 (Bannatyne et al. 2017).

### *Baseline sampling*

CTs were paid to take baseline samples twice a day. The CTs were expected to take these samples each morning after dawn and before 11h00, and each afternoon after 14h00 and before dusk, so that samples would preferably be taken at close to ~12 hourly intervals, and not clustered around mid-day (Bannatyne et al. 2017). It is important to note that for safety reasons, sampling was restricted to daylight hours. CTs were forbidden to sample during the hours of darkness, or during dangerous weather (e.g. lightning) or river (i.e. very high flow) conditions.

Baseline sampling was intended to provide insight into base flow conditions in the dry season, but importantly the required presence of the CT at the river each morning and afternoon meant that they were more likely to observe a rise in water level i.e. the trigger for the commencement of flood sampling. In the wet season, baseline sampling would provide data continuity between periods of flood sampling and possibly catch the first part of an unobserved late afternoon rise, or provide insight into recession limb SSC in a falling river.

### *Flood sampling*

The design of the temporal monitoring framework was primarily influenced by the well-established fact that SS yield is dominated by flood events (Gordon et al. 2004; Horowitz

2013). Sampling programme design therefore emphasised hydrology-based sampling (i.e. through flood events) against a background of calendar-based sampling (i.e. at scheduled intervals).

Since catchment size tends to control flood duration, floods are likely to be attenuated over longer periods in larger catchments, and to be smaller and "flashier" in smaller catchments (Gordon et al. 2004). It follows that sampling needed to be undertaken at shorter intervals in smaller catchments where change in discharge and SSC occurred more rapidly (Horowitz 2013).

The aim of the flood sampling framework was to sample frequently through both limbs of the flood hydrograph in order to define SS load and the timing and magnitude of SS peaks. CTs were given a clear flood sampling trigger (i.e. water rise or upstream storm in small catchments) and specific duration (i.e. 20 samples taken at catchment-specific intervals). Flood sampling could continue in sets of 20 samples throughout daylight hours, and even resume the following day if water levels remained high and/or rising.

Flood duration predictions for the Mooi at Maclear (306 km$^2$) and the most downstream monitoring point on the Tsitsa at Xonkonxa (4285 km$^2$) were estimated using available DWS discharge data. Estimates for the remaining, ungauged catchments were made based on these calculations and the assumption that high-flow event duration increases with catchment size. Conversely, high-flow events in smaller catchments would be more "flashy", i.e. with faster responses to precipitation and shorter flow durations (Gordon et al. 2004). Specific sampling intervals were then derived for each monitoring point that would allow twenty consecutive samples to effectively represent the hydrograph (including the recession limb) of those "workhorse" floods that in a typical year would move most of the SS (Wolman, Miller 1960). As noted in **Chapter 3.5** uncertainties intrinsic to these estimations were due to the highly variable rainfall (Moore 2016) and thus discharges, particularly in the previously ungauged catchments**. Table 2** summarises the catchment size, flood durations and resulting sample intervals at the eleven monitoring points.

**Table 2: Catchment area, estimated flow duration and sampling intervals for flood flows at Tsitsa River catchment monitoring sites**

| Site name | River name | Catchment area (km$^2$) | Flood duration (hours) | Sample timing (flood duration/2)/20 |
|---|---|---|---|---|
| Cornlands Farm | Little Pot/Upper Pot | 75 | 1-3* | 10 mins |
| Lokashini | Tsitsana | 135 | 1-6* | 15 mins |
| Makgetheng | Hlankomo | 64 | 1-3* | 10 mins |
| Tsitsa Falls | Tsitsa | 607 | 6-56* | 1st 10 samples: 30 mins,<br>2nd 10 samples: 1 hour |

| | | | | |
|---|---|---|---|---|
| Maclear | Mooi | 306 | 6-48 | 1st 10 samples: 30 mins<br>2nd 10 samples: 1 hour |
| Vipan Farm | Pot | 432 | 6-56* | 1st 10 samples: 30 mins<br>2nd 10 samples: 1 hour |
| Tsitsa Gorge | Tsitsa (Ntabelanga Dam inlet) | 1550 | 12-60* | 1st 10 samples: 45 mins,<br>2nd 10 samples: 1.5 hours |
| Qulungashe Bridge | Tsitsa (near Ntabelanga Dam Wall) | 1881 | 12-60* | 1st 10 samples: 45 mins<br>2nd 10 samples: 1.5 hours |
| Thambekeni | Gqukunqa | 204 | 1-8* | 15 mins |
| Junction Ferry | Inxu | 1452 | 12-60* | 1st 10 samples: 30 mins<br>2nd 10 samples: 1 hour |
| Mbelembushe DWS weir at Xonkonxa | Tsitsa (study area outlet) | 4285 | 24-60 | 1st 10 samples: 1 hour<br>2nd 10 samples: 2 hours |

*estimated

### *Triplicate sampling*

Establishing the level of precision of the sampling method was challenging due to the spatiotemporal heterogeneity of SS in a river channel (Horowitz 2013) and the absence of an alternative means of benchmarking SSC at most sites. Replicate sampling was used to overcome this uncertainty. Three samples were taken in quick succession once per week, effectively achieving a replicate sample (dubbed “Triple samples”) that would be used to determine the margin for error occurring during the laboratory analysis of the samples (Horowitz, 2013). **Plate 6** shows the sample photograph from an ODK form of a triple sample. Note that the jars have the same sample number, but are labelled ‘a’, ‘b’, and ‘c’.

**Plate 6: Sample photograph from an ODK record showing a “triple” sample, denoted by the same sample number plus ‘a’, ‘b’, ‘c’**

## 4.4 Monitoring programme inception

### *Suspended sediment sampling*

The pole-and-jar samplers were designed for depth-integrated isokinetic sampling, meaning that the sample jar was filled by the power of the moving water and collected the particles that were in suspension at that time with minimum deflection of the stream flow and subsequent change in pressure (Horowitz 2013). They were of basic design, and cheap to make, comprising a 2 m wooden pole and a milled silicon head assembly with a jar lid fixed inside. With eleven sites, the need for some spare items, and budget constraints, low cost equipment was important. The samplers were made at Rhodes University's workshops using standard tools and equipment, and most repairs (e.g. detached sample pole heads, loose tubing) could be undertaken by the CTs themselves in the field using for example wire or silicon sealer. **Plate 7** depicts the pole sampler in use, with a close-up of the head assembly featuring a fixed jar lid into which the sample jar is secured.

**Plate 7: The wooden pole sampler in use showing the head assembly and sample jar** (Bannatyne et al. 2017)

In line with accepted norms, a 5 mm aperture inlet pipe in the head of the pole led to the sample jar. An outlet breather tube allowed air to escape from the sample jar (Gordon et al. 2004). The sample vessels were 450 ml in volume, which was considerably smaller than ideal: a 1 litre sample volume is recommended for suspended sediment concentration (SSC) >100 ppm, and up to 10 litres for expected SSC of <20 ppm (Gordon et al. 2004 p 107; Horowitz 2013). In addition to a sample vessel of this volume and weight being impossible to handle in a manual sampling situation, it was known from a previous short-term study in the Tsitsa that very high SSC could be expected during target flood events (Madikizela et al. 2001), thus offsetting the practical and logistical implications of larger samples aimed at lower SSC (Gordon et al. 2004).

CTs took a depth integrated point sample as far as it was possible to reach from the river bank. The sampling jar was lowered as near to the bed as it was safe to reach, without stirring up bottom sediments, and raised through the water column without completely filling the jar.

Algae growth in the sample jars was controlled by adding a water purification pill containing 17 mg sodium dichloroisocyanurate to each jar. According to the manufacturer, this amount should release sufficient chlorine to effectively treat 1 litre of water to potable standard. The sample jars were then stored indoors away from direct sunlight until collection.

Visual clarity estimates were made using a GroundTruth clarity tube (Ringwood 2016). This gave the CTs an indication of how SS changed through time and provided additional information as a check on laboratory SSC analysis. To fill the tube, the CTs were trained to collect a representative two-litre water sample by throwing a weighted plastic milk bottle into the river whilst keeping hold of the attached string (**Plate 8**). After sinking and filling, the bottle was pulled back whilst avoiding dragging the neck of the bottle across any sand or mud. The contents were swirled and poured into the clarity tube. CTs estimated visual clarity on a scale of 90 = clear, 1 = opaque by noting the point on the tube at which a Secchi disk, pulled towards them using a magnet, becomes visible, as shown in **Plate 8**.

**Plate 8: Visual clarity estimation using a weighted milk-bottle and GroundTruth clarity tube**

### *Hydrological monitoring*

The SS data collected by the CTs will be used at a later date estimate SS loads based on SSC and discharge, from which catchment sediment yields required by the DEA-NRM project will then be determined. A hydrological monitoring network was therefore set up at the sediment monitoring sites. The water level data are used in this thesis to relate sample collection to the hydrograph shape, and will be used later to determine discharge at each site.

At all the sites described in **Section 4.2**, other than those located near a DWS gauging weir, Solinst model 3001 pressure loggers in protective iron cages were installed in July 2015 to continually log water depth/stage. The iron cages were held in place on rock outcrops with three expansion bolts, protecting them from damage from mobile bedload as well as camouflaging them somewhat to prevent theft and vandalism. **Plate 9** shows a pressure transducer in its housing firmly attached to bedrock at a monitoring site.

**Plate 9: A pressure transducer (inset) in its steel housing attached to bedrock at a monitoring site in the Tsitsa River catchment**

Pressure transducers were typically placed close to a bank rather than in the channel thalweg to allow them to be located more easily and removed annually during dry-season low water for download. Barometric loggers were installed in houses at two locations in the catchment to allow compensation of the pressure transducer data for barometric pressure.

Although not directly pertinent to the thesis aim, each site was surveyed using either a Geomax Zenith 10 differential global positioning system (GPS), or a Topcomm Total station. Transects upstream, downstream, and through the location of the pressure logger were surveyed, together with surface water slope. The survey data provided a baseline to determine any changes in bed morphology during the wet season, and in conjunction with water depth and velocity allowed discharge calculations to be made using the velocity area method (Gordon et al. 2004). Flows have been measured by the researcher using a Marsh-McBirney Flo-Mate 2000 flow meter at all sites through a range of water levels, starting in July 2015.

### *Installation of rain gauges*

Five autographic rain gauges were installed throughout the project area in support of the sampling programme (although not pertaining directly to this study), to provide data on rainfall variability (Bannatyne et al. 2017).

## *Identification, recruitment and training of citizen technicians*

### *Questionnaires, training material, and contracts*

In preparation for identification, selection, training and administration of CTs, a suite of documents including questionnaires, contracts, safety training material and sampling training material covering the use of both the equipment and the ODK/smartphone interface were developed by the researcher. Some of this material had safety and legal connotations and required careful development in consultation with subject matter experts, whilst all of it was foundational to the thorough and successful inception of CT activities. These documents are to be found in **Appendix 2**.

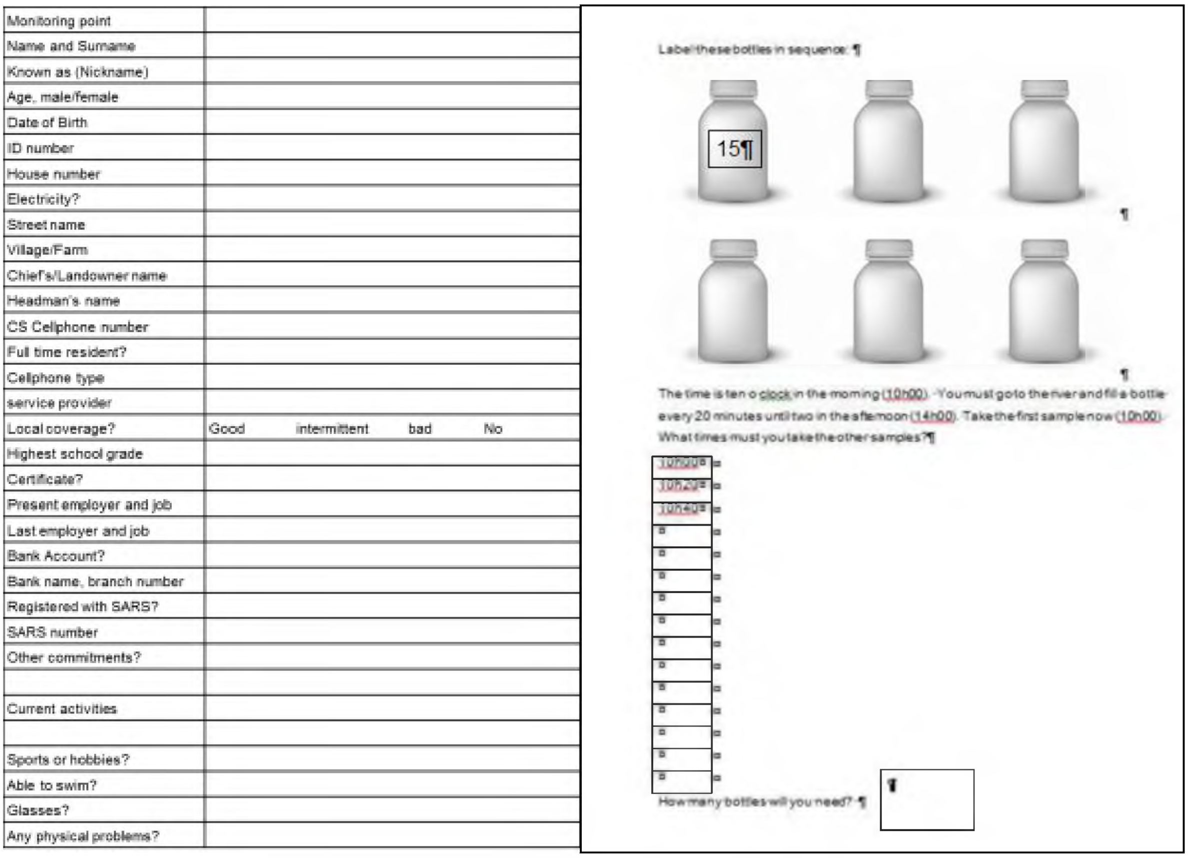
### *Identification of potential CTs*

Prior to the establishment of the monitoring sites, local traditional authority leaders and/or landowners had been notified of researcher presence in the area and had been asked for permission to proceed. Some offered assistance in identifying potential CTs, whilst others insisted in selecting people themselves. In other cases the identification of potential CTs was left entirely to the researcher, in which case people who lived close to the monitoring sites were approached directly.

Challenges encountered during this part of the project included the location of dwellings relative to the proposed monitoring sites, and the availability of people to become CTs: On privately-owned farms, for example, there were few people dwelling or working close enough to the sampling site who were not already fully employed by the farmer. In communal areas, villages were not always close to proposed sampling sites. Sometimes, where dwellings were close to a sampling site, there were few people who felt willing to become involved as CTs. In these cases it was necessary either to engage a person who lived further than the ideal easy walk from the sampling site, or to shift the sampling site slightly up or downstream of the proposed area to accommodate the potential CT.

### *Recruitment*

Unless the potential CT was pre-selected by either the local traditional leadership or a private landowner, the recruitment process often began with an informal conversation between the researcher and a person who had been approached based on the locality of their dwelling. Occasionally the researcher was approached by a person living nearby, for example whilst surveying a monitoring site. The possibility of working as a CT having been discussed and positively received, the potential CT was given a form to complete with their contact details and a basic aptitude test (**Figure 13**). From this, the person's grasp of English, ability to read and write, use a smartphone, tell time, count, and plan a flood sampling event could be established, along with information such as the strongest cellular network in the area, and the availability of electricity for charging. A person who struggled to complete the form (as distinct from a person who perhaps asked some questions for clarity) would be unlikely to cope with working in isolation to carry out the tasks required of a CT. Wherever possible, a CT and a “stand-in” were recruited to ensure continuity when the CT would, inevitably, be absent for short periods (Bannatyne et al. 2017).



| | | | | |
|---|---|---|---|---|
| Monitoring point | | | | |
| Name and Surname | | | | |
| Known as (Nickname) | | | | |
| Age, male/female | | | | |
| Date of Birth | | | | |
| ID number | | | | |
| House number | | | | |
| Electricity? | | | | |
| Street name | | | | |
| Village/Farm | | | | |
| Chief's/Landowner name | | | | |
| Headman's name | | | | |
| CS Cellphone number | | | | |
| Full time resident? | | | | |
| Cellphone type | | | | |
| service provider | | | | |
| Local coverage? | Good | intermittent | bad | No |
| Highest school grade | | | | |
| Certificate? | | | | |
| Present employer and job | | | | |
| Last employer and job | | | | |
| Bank Account? | | | | |
| Bank name, branch number | | | | |
| Registered with SARS? | | | | |
| SARS number | | | | |
| Other commitments? | | | | |
| | | | | |
| Current activities | | | | |
| | | | | |
| Sports or hobbies? | | | | |
| Able to swim? | | | | |
| Glasses? | | | | |
| Any physical problems? | | | | |

Label these bottles in sequence: ¶

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

| |
|---|
| 10h00 |
| 10h20 |
| 10h40 |
| |
| |
| |
| |
| |
| |
| |
| |
| |
| |
| |
| |

How many bottles will you need? ¶

**Figure 13: CT details and aptitude test form**

## *Safety training*

The personal safety of the CTs was the foremost concern at all times, not only whilst undertaking sampling but also whilst approaching and leaving their sites. CTs were not allowed to sample at night (and were in fact advised to be back at home by nightfall) and were forbidden under any circumstances to enter the water for sampling purposes, even at very low water. Similarly, they were not allowed to sample when bank or weather conditions were dangerous. In that way, the CTs were never required to decide for themselves whether or not it was safe to work. The use of a lifejacket at all times was insisted upon, and the correct manner of putting on and securing the lifejacket was covered thoroughly during safety training.  Self-rescue techniques for floating and using currents to assist with exiting the river safely were also explained. Awareness of potentially changing bank and river conditions, the need for and correct use of the lifejacket, prohibition on the use of alcohol and the presence of children during sampling activities, and the safe handling of equipment were all covered during safety training. The personal safety training leaflet is included in **Appendix 2**.

### *Sampling training*

Once safety training was complete, CTs were trained to collect SS samples and geo-referenced photographic, numerical and descriptive data. A training guideline document in both English and isiXhosa was given to each CT and used as the basis for training and to keep as a reference. The training guideline is included in **Appendix 2**.

Customised Open Data Kit (ODK) forms loaded onto smartphones provided guidance and information capture at each step in the process (Bannatyne et al. 2017). The different time protocols for baseline and flood sampling were explained, emphasising the trigger (rise in water level) at which they should change from twice-daily baseline sampling to rapid flood sampling at the catchment-specific intervals summarised in **Table 2**.

### *Suspended sediment sampling equipment*

The CTs were provided with basic water sampling equipment and sufficient consumables to last until the next support visit, estimated according to the seasonal likelihood of flood sampling. This comprised:

- A smartphone;
- A waterproof touch-sensitive phone pouch with lanyard;
- A power-bank;
- A two-metre wooden isokinetic pole-and-jar sampler;
- Between three and six crates of fifty 450 ml plastic sampling jars with lids;
- Between three and six boxes of fifty “chlorine” (sodium dichloroisocyanurate) pills;
- A two-litre plastic milk bottle with lead fishing weights;
- A GroundTruth clarity tube;
- Stationery (pen, pencil, eraser, notebook, ruler, permanent marker);
- Rubber boots and a rain-suit.

The smartphones were GPS enabled with Android operating-systems and the ODK software loaded. Airtime and data bundles for the appropriate networks were supplied.

### *Open Data Kit and KoBo Toolbox*

ODK was selected to in place of manual recording and paper forms for the collection and transmission of data from the field to the research base in Grahamstown. ODK (Anokwa et al. 2009) was developed to enable users in developing countries to easily and cheaply collect, transmit, store, and use data via smartphones and a computer-based suite of tools and applications. ODK Collect forms are loaded to a smartphone to guide field data collection, and to send data through the mobile network to ODK Aggregate, a collecting database. This online database is hosted by Google and allows data to be exported to other platforms for mapping and analysis.

KoBo Toolbox (Harvard Humanitarian Initiative 2016), a similar platform, was used for creating the forms. The smartphones were enabled for data collection using the workflow depicted in **Figure 14**, with each smartphone linked to its own ODK Aggregate database for data collection.

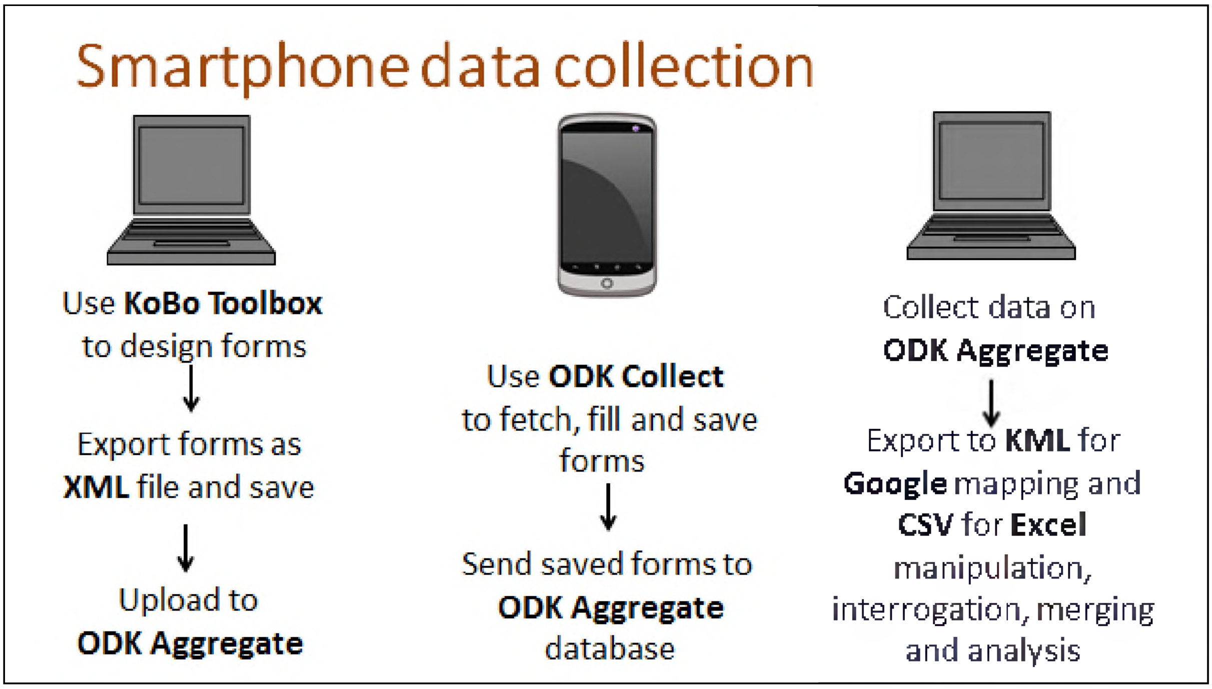


**Figure 14: Process flow for form design, upload, use, saving, and sending to database (Bannatyne et al. 2017).**

KoBo Toolbox provides a user-friendly platform for developing appropriate questions and constructing forms prior to publishing them to the smartphones. **Figure 15** is an example of question “building” using KoBo Toolbox.

METADATA:START TIME, END TIME, DEVICE ID, USERNAME, SIM SERIAL, SUBSCRIBER ID, PHONE NUMBER

* Who is sampling?

Main — Value: Main

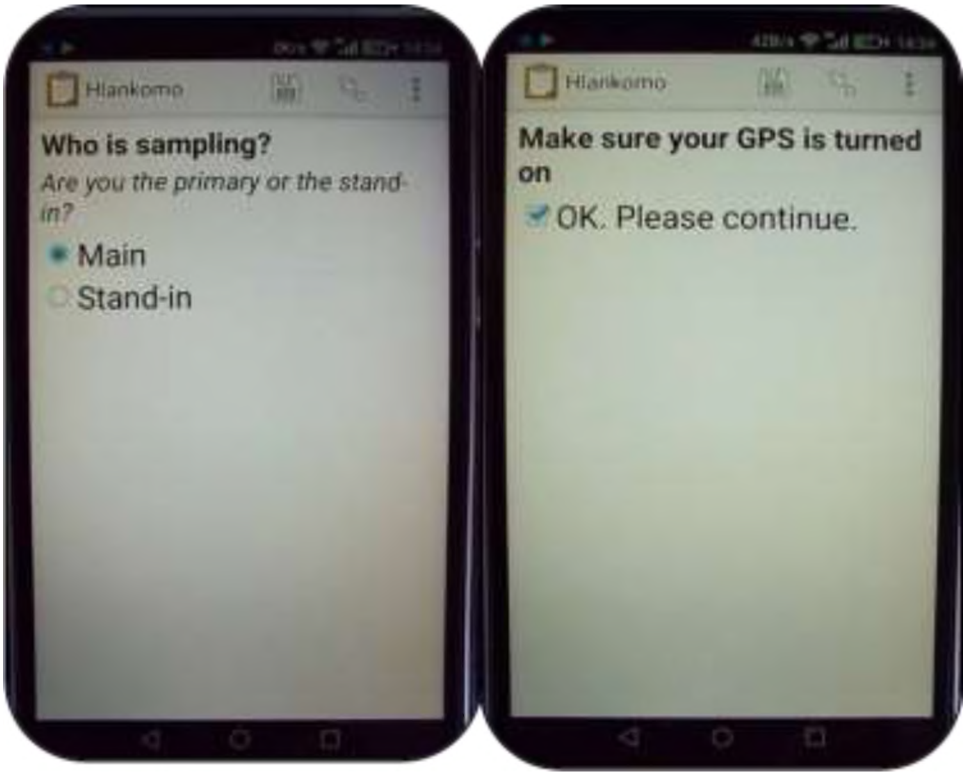
Stand-in — Value: Stand_in

+ Click to add another response... — Value: AUTOMATIC

* Make sure your GPS is turned on

**Figure 15: An example of question building during form design in KoBo Toolbox**

**Figure 16** shows two of the questions that are part of the ODK Collect form used to guide CTs to take SS samples.



**Who is sampling?**

*Are you the primary or the stand-in?*

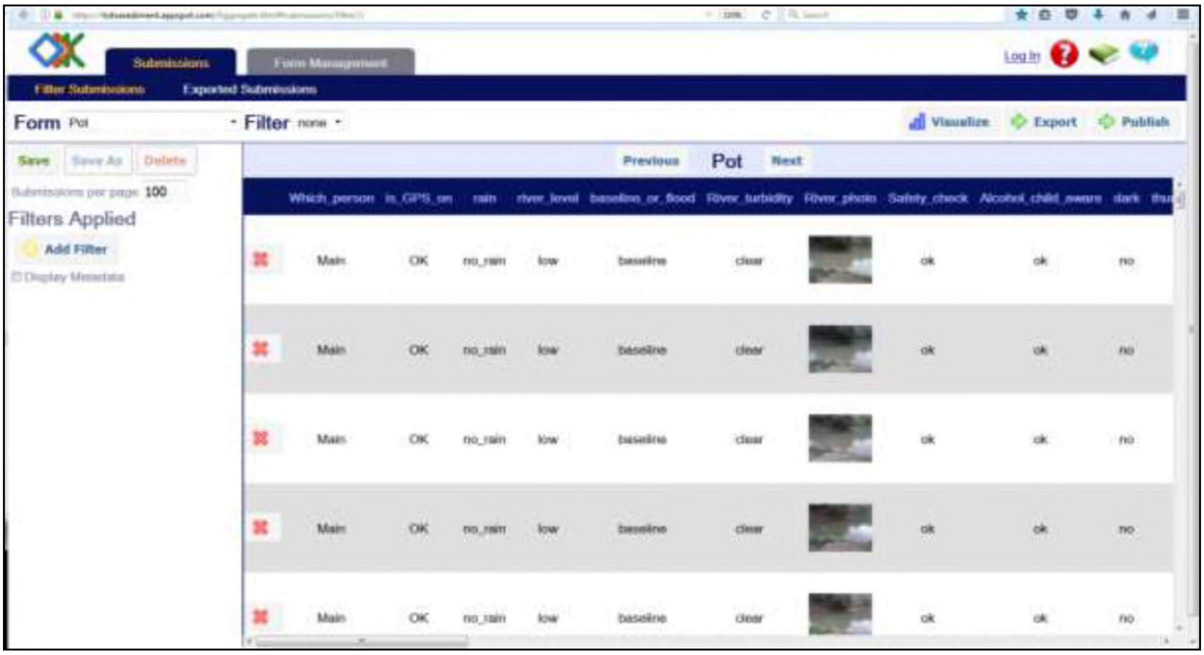
● Main
○ Stand-in

**Make sure your GPS is turned on**

☑ OK. Please continue.

**Figure 16: Questions in the ODK Collect form as they appear on the smartphone**

**Figure 17** shows part of the ODK Aggregate database for the Pot River, with some recorded information and the river photo. Each record represents one form, and one sample taken.



Form Pot
Filter none

Submissions per page 100

| Which_person | is_GPS_on | rain | river_level | baseline_or_flood | River_turbidity | River_photo | Safety_check | Alcohol_child_aware | dark |
|---|---|---|---|---|---|---|---|---|---|
| Main | OK | no_rain | low | baseline | clear |  | ok | ok | no |
| Main | OK | no_rain | low | baseline | clear |  | ok | ok | no |
| Main | OK | no_rain | low | baseline | clear |  | ok | ok | no |
| Main | OK | no_rain | low | baseline | clear |  | ok | ok | no |
| Main | OK | no_rain | low | baseline | clear |  | ok | ok | no |

**Figure 17: Part of the ODK Aggregate database showing recorded information and river photo for the Pot River**

## 4.5 Monitoring programme implementation

### *Suspended sediment sampling by citizen technicians*

CTs were were guided through their sampling protocol by the ODK form loaded onto their smartphones (detailed below). Note that:

- Strictly speaking, no “floods”, as defined as bank-full discharges (Beven, Carling 1989), occurred during the study period. The term “flood” is used to indicate any high-flow event, which should have been “flood” sampled by CTs, i.e. rapidly sampled having been triggered by an observed rise in water level to achieve detailed sampling through the rising limb and flood peak.
- An asterisk* denotes that the CT cannot proceed until the question has been answered or acknowledged.
- The bullet points denote the alternative answers available for using a radio button (see **Figure 16**).

==============================================================

Form metadata recorded: Start time; end time; Device ID; Username; SIM serial; subscriber ID; Phone number.

**Who is sampling?*Are you the main or the stand-in?**

- Main
- Stand-in

**Make sure your GPS is turned on***

- OK

**Is there rain?***

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

**What is the river level like?***

- Low
- Medium
- High

**Is this a baseline or a flood sample?***

- Baseline
- Flood

**What does the water look like?***

- Clear
- A bit muddy
- Very muddy

**Take a photo of the river*** (Phone records date and time to photograph)

**You must do a safety check. You need to be close to the river but away from the bank.***

- I understand and agree

**You may not go to the river if you have been drinking alcohol or if you have a child with you***

- I understand and agree

**Is it dark?***

- Yes
- No

**Is there thunder or lightning?***

- Yes
- No

**Is the riverbank washing away or slippery?***

- Yes
- No

**Is the river very high or over the banks?***

- Yes
- No

(If "yes" to any of the preceding 4 questions then)

**You have noticed a safety hazard. You should only sample when you can answer "No" to all the safety questions!**

- I understand and agree

**You must be wearing your lifejacket properly***

- I understand and agree

**GPS your sampling point*Use GPS function to record your coordinates**

- latitude (x, y °)
- longitude (x, y °)
- altitude (m)
- accuracy (m)

**Take a 2 litre water sample from the river and fill the clarity tube***

- OK

**Take a clarity tube reading***

**Take a second clarity tube reading***

**Take a last clarity tube reading***

**Label a sample jar***

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

- OK

**Put a chlorine pill in the jar and put the lid on***

- OK

**Take a photo of the sample***

**Thank you!! You have completed your sample. Please name and send the form.***

- OK

============================================================

Using touch-screen technology and multiple choice-style selections meant that minimal typing was required. Because each section of the form required a response and was recorded on the database, the form not only captured data and information but also ensured safety awareness and compliance with sampling protocols. As a backup, the CTs also recorded sample dates, times, and basic information in a notebook (Bannatyne et al. 2017).

The date- and time-stamped photograph of the river was always taken from the same point, which was typically somewhat distant from and above the monitoring point. This was to encourage the CT to properly observe the river before approaching, for example, a dangerously high river to reach their "customary" spot. The photograph always captured the same view, including "tell-tales" identified during training, such as large rocks, gravel bars, or in-stream vegetation, to indicate river level and allow researchers to confirm the level from the research base in Grahamstown. In this way CTs could be called or messaged to begin or stop flood sampling, and river level could be checked retrospectively if there was doubt as to whether flood sampling had been undertaken at an inappropriate (low/not rising) river level when baseline sampling would have been sufficient. **Plate 10** shows low and high water at a monitoring point, illustrating the use of telltales to confirm water depth.

**Plate 10: Photographs of the Tsitsa River at The Falls from ODK forms, showing the use of "telltales" to determine low and high water depth at the monitoring site**

The CTs were trained to take the photograph of the sample jar so that the sample number was clearly visible. Since this photograph was time and date stamped all this information was captured without the CT needing to record it, thus avoiding mistakes or even deliberate time errors. The sample photograph also allowed a real-time, superficial comparison of SS at the time of sampling, which could be correlated with the clarity tube readings (Bannatyne et al. 2017). **Plate 11** shows samples photographed at low and rising water, showing less and more SS respectively. Note that the CT has indicated a flood sample with an "F" preceding the sample number on the second jar.

**Plate 11: Photographs of samples from ODK forms, showing the label and varying SS at low and high water respectively**

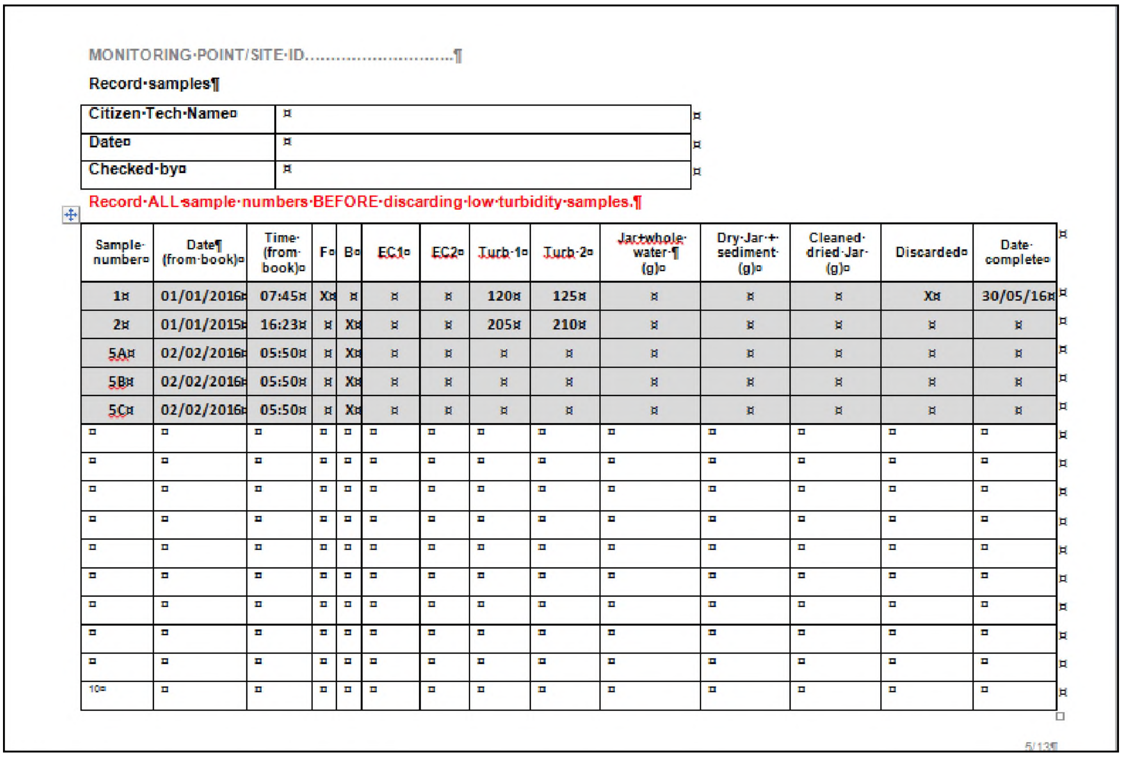
The times when the form was opened and closed were recorded as metadata on the ODK Aggregate database. Completed forms were saved to the smartphone memory and, ideally, transmitted to the receiving database immediately after collection using the cellular network. Information sent from the Tsitsa River catchment to the database was immediately available to researchers in Grahamstown. Where connectivity issues occasionally delayed or even prevented the transmission of forms, they were routinely downloaded to a field computer during the administrative visit.

### *Management and administration of citizen technicians*

#### *Field administration*

Field visits were undertaken by the researcher and a field assistant at three- to five-week intervals in order to collect the SS samples and to download the saved forms from the smartphones as a back-up to the ODK Aggregate database. These visits provided opportunities to provide support to the CTs, resupply jars, chlorine pills and other consumables, check and if necessary replace damaged equipment, review sampling technique and protocols, and resolve any quality-control or performance issues that had emerged. If serious or repeated problems were apparent, (such as smartphone, airtime or data abuse) a system of first, second and final written warnings was followed. Issuing a first written warning typically resolved the situation.

The samples taken since the last visit were unpacked from their crates and laid out in numerical order, usually in a room of the CT's house. This was done to physically check for duplicate and missing numbers and to count the number of baseline, flood and triple samples taken. The sample numbers were then entered onto the data forms which would be used to record results during laboratory processing, and checked against the numbers and times written in the CT’s notebook. An example of a laboratory data processing form is shown in **Figure 18**.



MONITORING POINT/SITE ID.............................

**Record samples**

| | |
|---|---|
| Citizen Tech Name | |
| Date | |
| Checked by | |

Record ALL sample numbers BEFORE discarding low turbidity samples.

| Sample number | Date (from book) | Time (from book) | F | B | EC1 | EC2 | Turb 1 | Turb 2 | Jar+whole water (g) | Dry Jar + sediment (g) | Cleaned dried Jar (g) | Discarded | Date complete |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 01/01/2016 | 07:45 | X | | | | 120 | 125 | | | | X | 30/05/16 |
| 2 | 01/01/2015 | 16:23 | | X | | | 205 | 210 | | | | | |
| 5A | 02/02/2016 | 05:50 | | X | | | | | | | | | |
| 5B | 02/02/2016 | 05:50 | | X | | | | | | | | | |
| 5C | 02/02/2016 | 05:50 | | X | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | |

5/13

**Figure 18: Example of a data form on which sample numbers are recorded in the field and results are added in the laboratory**

The ODK forms were downloaded from the smartphone to a field computer. Sample numbers, as well as sampling times and frequencies were again checked to rule out gaps in sampling, as well as speed or batch sampling, and to ensure that the number of samples and ODK instances tallied, and that no data had been lost. The smartphones were erased once the ODK forms were downloaded and checked.

During conversations with the CTs, and guided by the requirements of a field visit protocol form (included in **Appendix 2**), any problems that had been noticed by the researcher via the ODK Aggregate database or with the samples present were discussed. Similarly any difficulties experienced by the CT were brought forward. Equipment, consumables such as chlorine pills, airtime, data, and stationery were checked and replaced if necessary.

### *Remuneration*

Timely and precise remuneration of the CTs was important for the method to be sustainable and to maintain trust and a positive working relationship with the CTs. The CTs were paid R 20 (~$ 1.50, ~£ 1.00) per baseline and R 30 (~$ 2.25, ~£ 1.50) per flood sample, initially on a two-weekly cycle, but later moving to monthly pay periods. Contextually, government-administered labour programmes which are active in the area, such as Expanded Public Works Programmes (EPWP), typically pay R 110 (~$ 8.20, ~£ 6.15) per 8-hour day.

On-site researcher presence was not required for payments to take place: The ODK Aggregate database was used to ascertain the numbers of samples taken by each CT, and confirmed by the field administrator by text message to their smartphones. Money was paid by Electronic Funds Transfer (EFT) directly into bank accounts (these details having been gathered as part of CT administration) or else by post office transfer. Where necessary, money was deducted from current or subsequent pay cycles if repeated non-compliance leading to non-payment for certain samples was discovered.

Initially, the administration of the CTs required roughly half to two-thirds of the researcher's time per month. A 4x4 utility vehicle was required to travel to each site and to carry the samples from the study area back to the research base in Grahamstown. During the wet season approximately 800 samples were collected per trip, with a trip typically lasting 7 to 10 days and involving over 2000 km of travelling.

This degree of management activity eventually led to the creation of a field-administrator post and the allocation of 100 hours per month of their time to the research framework. It is likely that this post may be relocated to the Tsitsa River catchment, further meeting the goals of local job-creation and capacity-building in the area.

The Tsitsa Falls Backpackers near Maclear is located within the study area and was used as a research base during field trips. Secure storage facilities were also available there, which allowed spare consumables and equipment to be kept in the catchment between field visits. A monitoring site and a raingauge were also located at Tsitsa Falls.

### *Field processing of samples*

Whilst at the research base, after collecting samples from CTs, the researcher undertook initial sample processing. This entailed turbidity testing and discarding visibly low SS samples in order to reduce the number of samples taken back to the laboratory, and the selection and turbidity testing of a range of "cross-over" samples (see **Figure 19**) to provide the link between turbidity and SSC. This saved time in the laboratory and could typically be achieved between visits to CTs.

### *Data products*

Both quantitative and qualitative data were generated by the sampling programme. Quantitative data accruing from the sites comprised:

- Visual clarity data,
- Continuous water level data from Solinst pressure loggers,
- Surveyed transects of each site before and after the first wet season
- Discharge data from the DWS gauging stations

Additionally, 5-minute rainfall data were gathered from the five rain gauges installed throughout the catchment. Quantitative data generated from sample analysis comprised:

- SSC derived by evaporation,
- Measured turbidity, and
- Electrical conductivity.

Qualitative information from each site comprised time and date-stamped photographic records of the river and of each sample taken, as well as a weather report. This data, in particular the photographs, gave researchers an up-to-date indication of river stage and SSC (Bannatyne et al. 2017).

### *Additional data collection*

In addition to the data collection described above, data were also collected on discharge, sediment load through width-depth integrated sediment and rainfall. These data were not utilised in the present study but will be made available to the long term sediment monitoring programme.

## 4.6 Laboratory analyses

### *Introduction*

Analysis of SSC to determine SS loads, yields and dynamics was beyond the scope of this study. Likewise, the development of laboratory processes to analyse SSC was necessary from the point of view of longer term research goals, but was not central to the development of the CT-based SS sampling method described in this thesis.

It was anticipated that achieving adequate spatial and temporal coverage of the sub-catchments of the Tsitsa River would produce a large number of SS samples, particularly in the wet season when rapid sampling of frequent floods was expected to take place. Indeed, by July 2016 ~4 000 SS samples and associated information had been received from the eleven CTs. Low cost/high volume laboratory processes were needed to provide scientifically valid data whilst remaining within the time and budget limits of a post-graduate project.

### *Suspended sediment concentration*

Trials were conducted on some of the early high-sediment samples, using a Buchner funnel and various grades of filter paper, to establish a filtration method for SSC analysis as described by Gordon et al. (2004). This approach was abandoned due to a combination of:

- Significant amount of fine particles passing through filter paper;
- High cost of appropriate filter paper;
- Long time taken to filter;
- Difficulties with drying and weighing samples whilst avoiding sample loss and cross-contamination;
- The high number of samples to be processed.

Trials in which a selection of low to high concentration sediment samples were processed using evaporation to dryness and weighing within the original sample jar revealed that the method was more effective for high-sediment samples, since inaccuracies incurred during the process had a greater impact on low-sediment samples.

Turbidity can be measured as a surrogate for SSC (Horowitz 2013). A combined measured turbidity/evaporation approach was developed whereby visibly low-sediment samples, that were likely to measure below 200 nephelometric turbidity units (ntu), were analysed using measured turbidity. Visibly high (>200 ntu) sediment samples were evaporated. A sub-set of "cross-over" samples across a range of turbidities 0- 200 ntu was processed for all sites using both methods, to provide a relationship between turbidity and SSC (Grenfell, Ellery 2009) as illustrated in **Figure 19**.

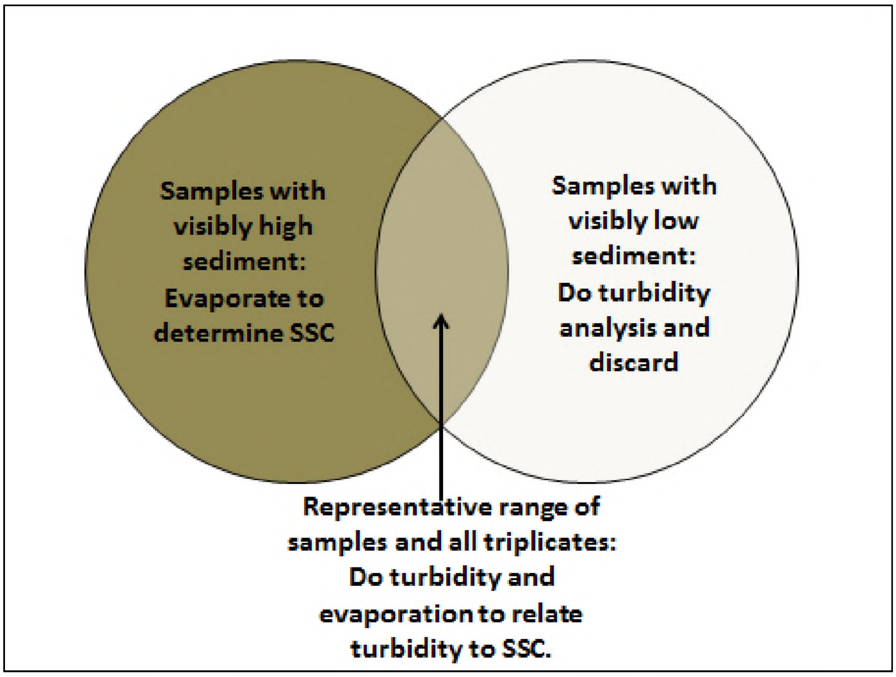


**Figure 19: Sample sub-sets to relate measured turbidity to SSC at each site**

"Triplicate" samples (0-999 ntu) were also processed using both methods. The adoption of this method meant that low-sediment samples other than cross-over and triplicate samples were turbidity-tested and discarded in the field if lower than 200 ntu, greatly reducing the transport and laboratory analysis volumes.

The process flow depicted in **Figure 20** for a combined measured turbidity/evaporation method was adopted:

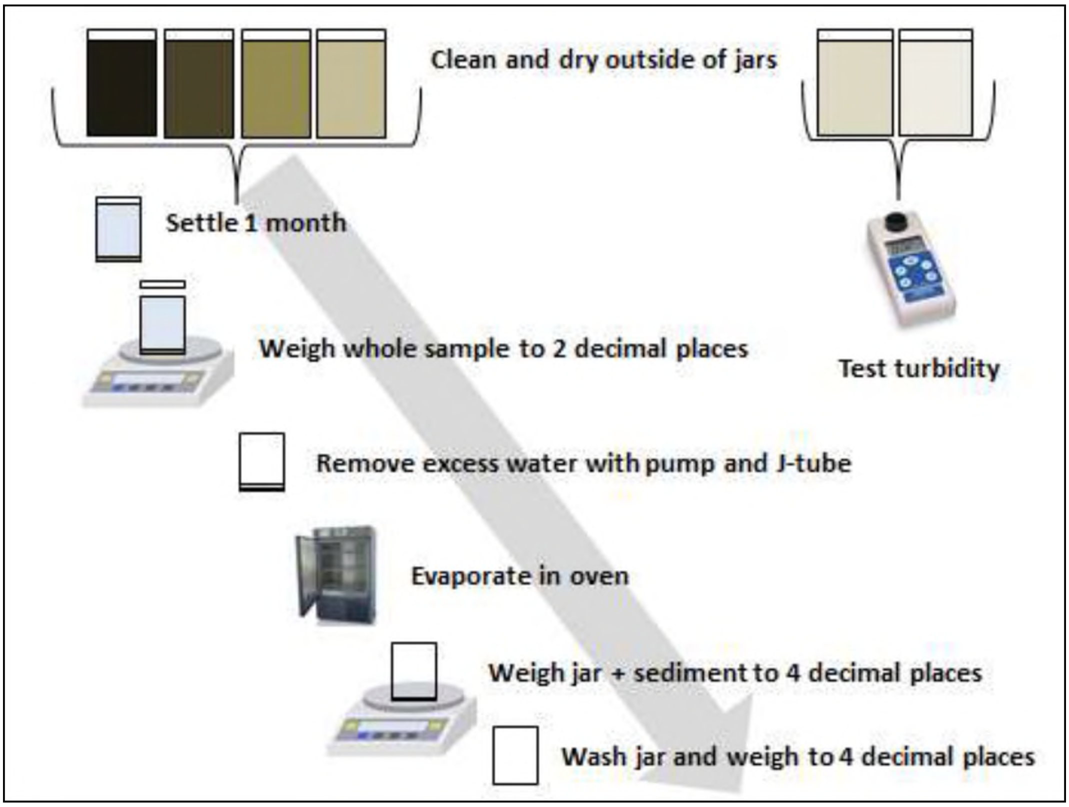


**Figure 20: Laboratory process flow for the determination of turbidity and SSC (Adapted from** (Bannatyne et al. 2017)

The laboratory process flow detailed below was followed to determine SSC at each of the eleven sites:

**(1) Establish turbidity and SSC relationship for each site**

(1a) Select samples with a turbidity range from clear to ~200 ntu and all "Triples" from each site/batch.

(1b) Process these jars for electrical conductivity (EC) and turbidity.

(1c) Process as (3) below.

**(2) Group the remaining samples into visibly low and high turbidity**

(2a) If sediment is visibly very low (~<200 ntu), select for turbidity testing.

(2a i) Test and record turbidity

(2a ii) Discard sample.

(2b) If turbidity is visibly high (~>500 ntu), select process (3), SSC via evaporation.

(2c) If unsure of amount of sediment (~>200 - <500 ntu)

(2c i) Test and record turbidity:

(2c ii) If lower than 200 ntu, discard.

(2c iii) If higher than 200 ntu, proceed as for (3).

**(3) Determine SSC via evaporation**

(3a) Settle sample 4 weeks

(3b) With lid removed, weigh sample jar + sample to 2 decimal places

(3c) Record mass **(a)**

(3d) Siphon off top water from sample jar with a J-tube and discard

(3e) Place sample jar on an ovenproof mat in oven set to 60° and evaporate completely

(3f) Weigh sample jar plus dry sediment to 4 decimal places

(3g) Record mass **(b)**

(3h) Thoroughly wash sediment from sample jar *NB do NOT wipe off label*

(3i) Dry empty sample jar in oven overnight

(3j) Weigh to 4 decimal places

(3k) Record mass **(c)**

(a) – (b) = A: mass of water in g (= volume of water in litres)

(b) - (c) = B: mass of sediment in g

**(4) Compute $C^s$ in mg/ℓ.**

$$\boldsymbol{C^s} = \left[\frac{(\boldsymbol{B})}{(\boldsymbol{A})}\right] \times \mathbf{10^6}$$

### *Turbidity*

Water samples were thoroughly shaken until all settled sediment was mobilised. A 10 ml sub-sample was immediately withdrawn using a 20 ml surgical syringe (moving from bottom to top and across the jar) and placed in a measuring vial previously double-rinsed with distilled water (in the laboratory) or bottled water (in the field). Turbidity was measured using a Eutech TN-100 turbidity meter, as shown in **Plate 12**. Two measurements were taken in this manner for each sample tested.

**Plate 12: Eutech TN-100 turbidity meter** (Eutech Instruments 2015)

### *Total dissolved solids*

Evaporating whole water samples to dryness to determine SSC meant that any dissolved load in the form of salts would be included in the residue after evaporation (Grenfell, Ellery 2009). Electrical conductivity (EC) was measured in samples taken through a range of flows at all sites, and converted to mg/litres total dissolved solids (TDS) as shown in **Equation 2.**

$$\left(\frac{\mu S/cm}{1000}\right) \text{x } 650 \qquad \textbf{Equation 2}$$

This analysis revealed that TDS levels were extremely low (**Table 3**). Given that only ~50 ml of supernatant remained in the jars after siphoning (i.e.~1/10 of the original sample), the volume of dissolved solids would constitute an insignificant proportion of the total volume of sediment remaining after evaporation, particularly in the high-sediment samples which were the focus of this study.

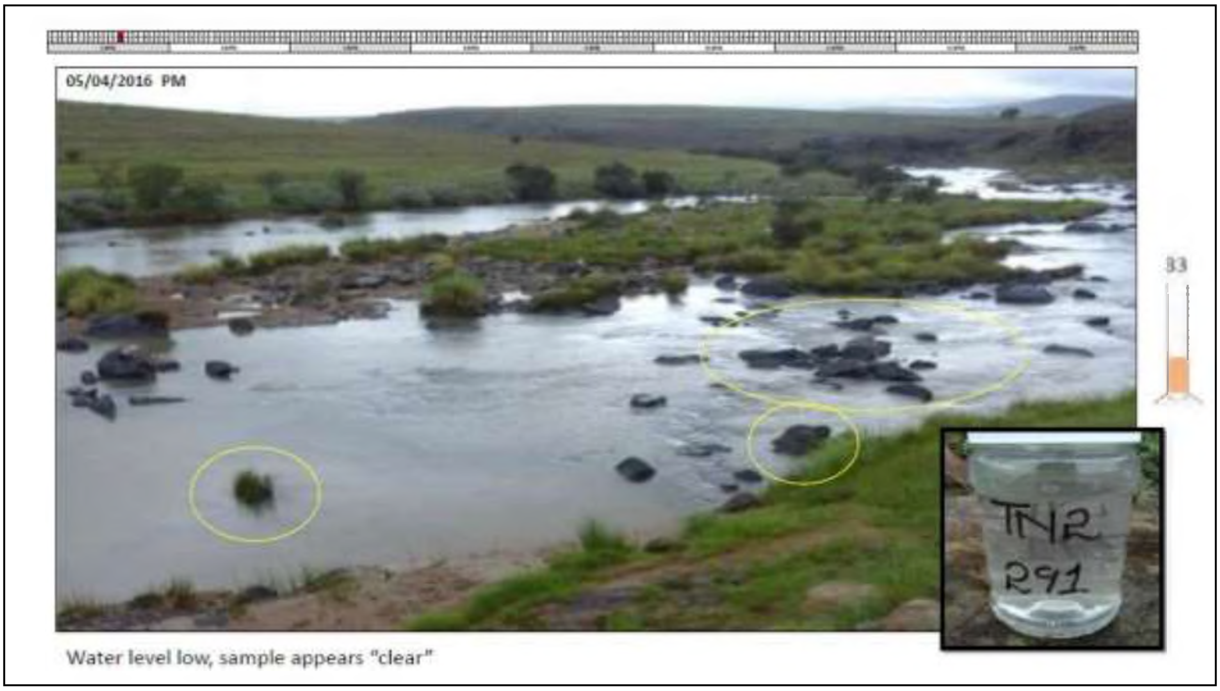
**Table 3: TDS analysis at all SS sampling sites**

| Site | Min (mg/ℓ) | Max (mg/ℓ) | Range (mg/ℓ) | Ave (mg/ℓ) | n |
|---|---|---|---|---|---|
| **Little Pot at Cornlands** | 64.94 | 143.98 | 79.04 | 103.63 | 151 |
| **Tsitsana at Lokashini** | 4.39 | 196.30 | 191.91 | 178.37 | 205 |
| **Hlankomo at Makgetheng** | 16.93 | 176.48 | 159.54 | 90.24 | 133 |
| **Tsitsa at Tsitsa Falls** | 56.52 | 171.60 | 115.08 | 115.65 | 99 |
| **Mooi at Maclear** | 34.32 | 174.20 | 139.88 | 96.57 | 89 |
| **Pot at Vipan Farm** | 27.40 | 133.58 | 106.18 | 106.90 | 134 |
| **Tsitsa at Tsitsa Gorge** | 36.92 | 143.65 | 106.73 | 108.26 | 146 |
| **Tsitsa at Qulungashe Bridge** | 16.90 | 147.23 | 130.33 | 93.66 | 103 |
| **Gqukunqa at Thambekeni** | 34.84 | 243.43 | 208.59 | 146.20 | 93 |
| **Inxu at Junction Ferry** | 9.65 | 188.18 | 178.53 | 127.73 | 97 |
| **Tsitsa at Mbelembushe** | 52.78 | 167.38 | 114.60 | 76.96 | 188 |

### *Qualitative information*

Qualitative information such as photographic records of the river and of each sample taken was available to researchers in Grahamstown in “real time” via the ODK Aggregate database (Bannatyne et al. 2017). **Figure 21 a - j** comprises a series of composite images depicting stages in a flood sequence. The time slider at the top margin provides an indication of the passage of time, a representation of the clarity tube is to the right, and the sample that was taken at that time is inset.

By working through the sequence it is possible to observe the low, clear river (**Figure 21a**) gradually rise and become more turbid (**Figure 21b** and **21c**), then stabilise at that level (**Figure 21d** and **21e**) until SSC peaks (**Figure 21f**) ahead of the first discharge peak (**Figure 21g**) with SSC and level falling back towards the pre-flood level (**Figure 21h – 21j**).


05/04/2016 PM

Water level low, sample appears "clear"

**Figure 21a: Composited qualitative data 05/04/16 (pm), Tsitsa River at Xonkonxa.**

Water level rising, sample less clear

**Figure 21b: 06/04/16 (am)**

Water level rising, sample turbid

**Figure 21c: 06/04/16 (pm).**

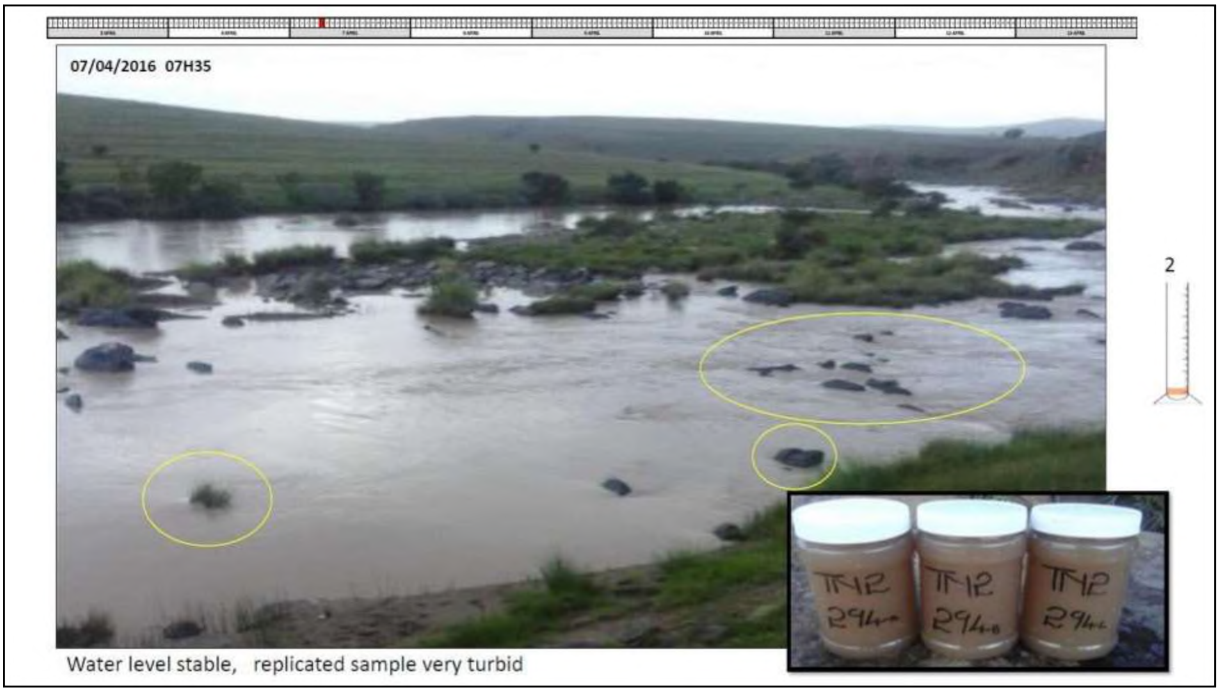
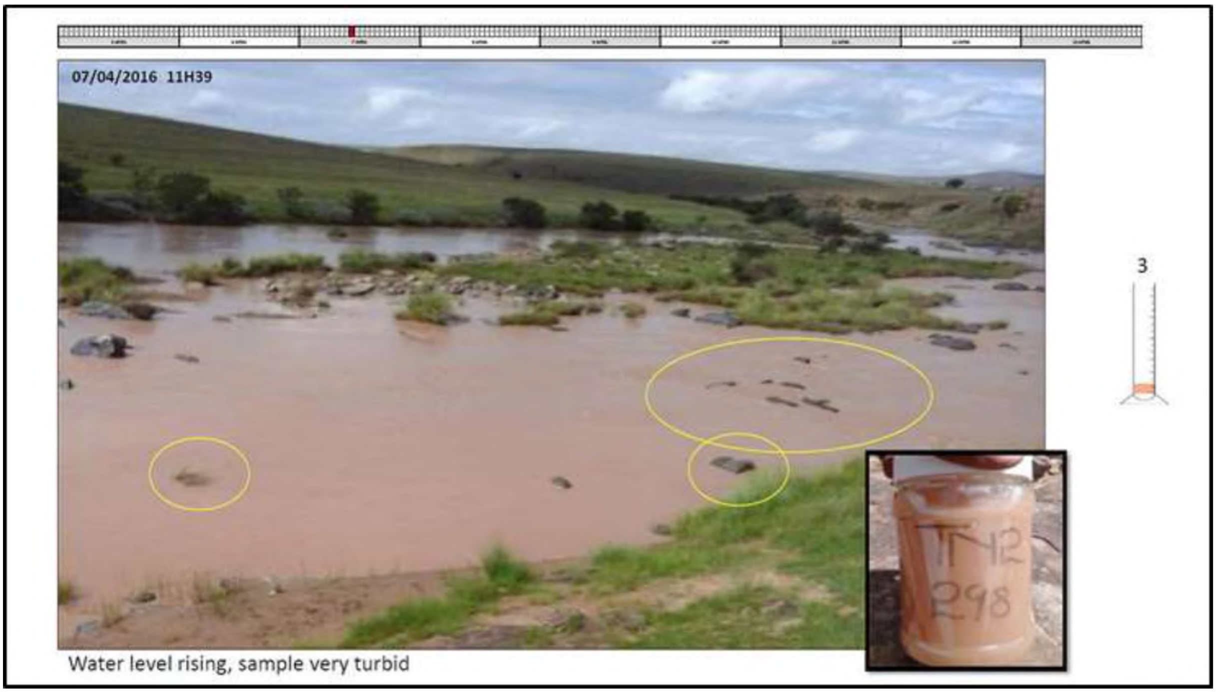


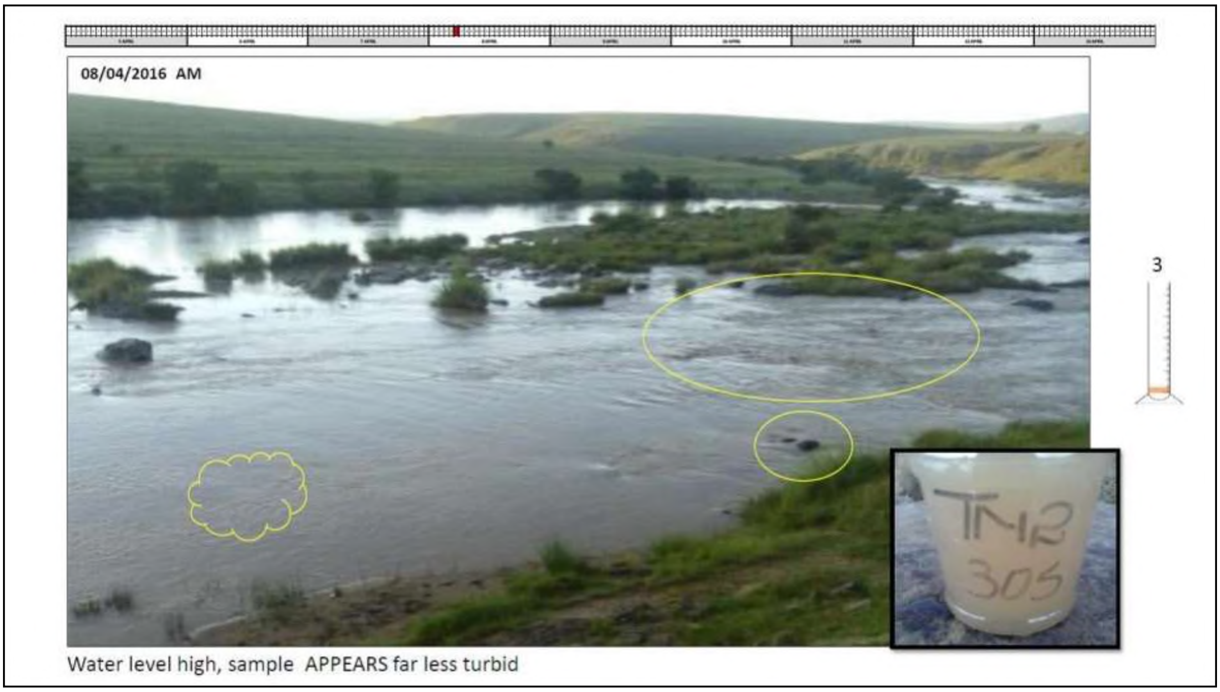
Figure 21d: 07/04/16 (am).

Figure 21e: 07/04/16 (early morning).



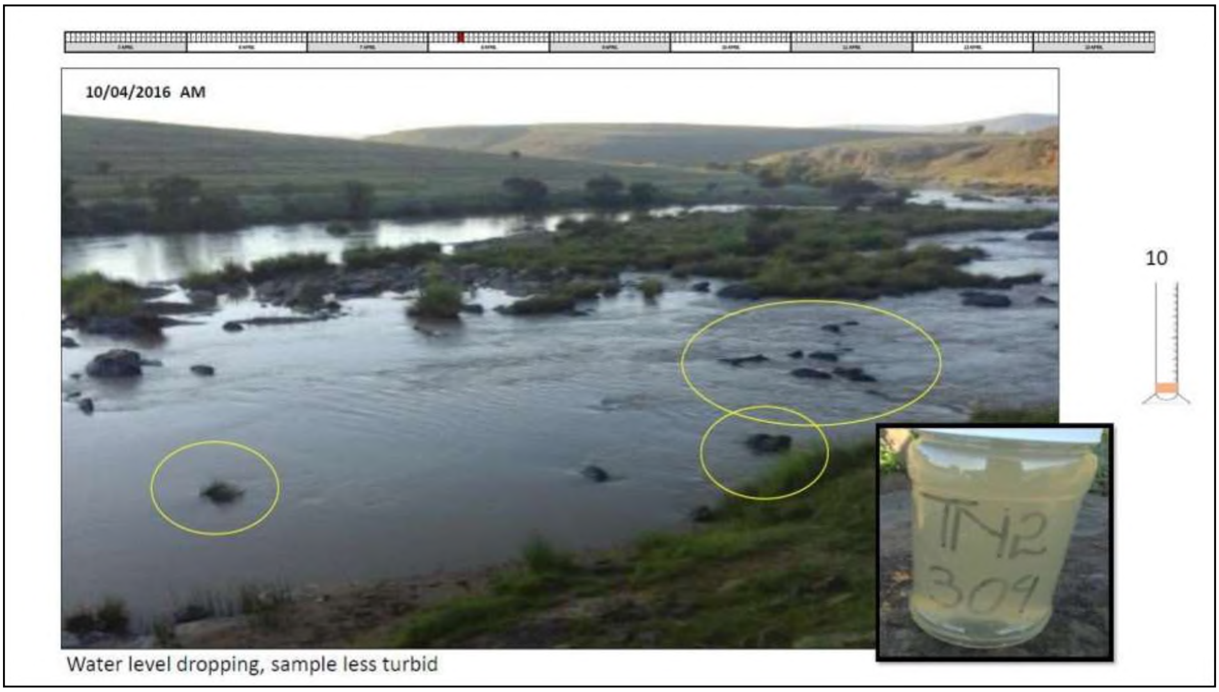
Water level rising, sample very turbid

Figure 21f: 07/04/2016 (mid-day).



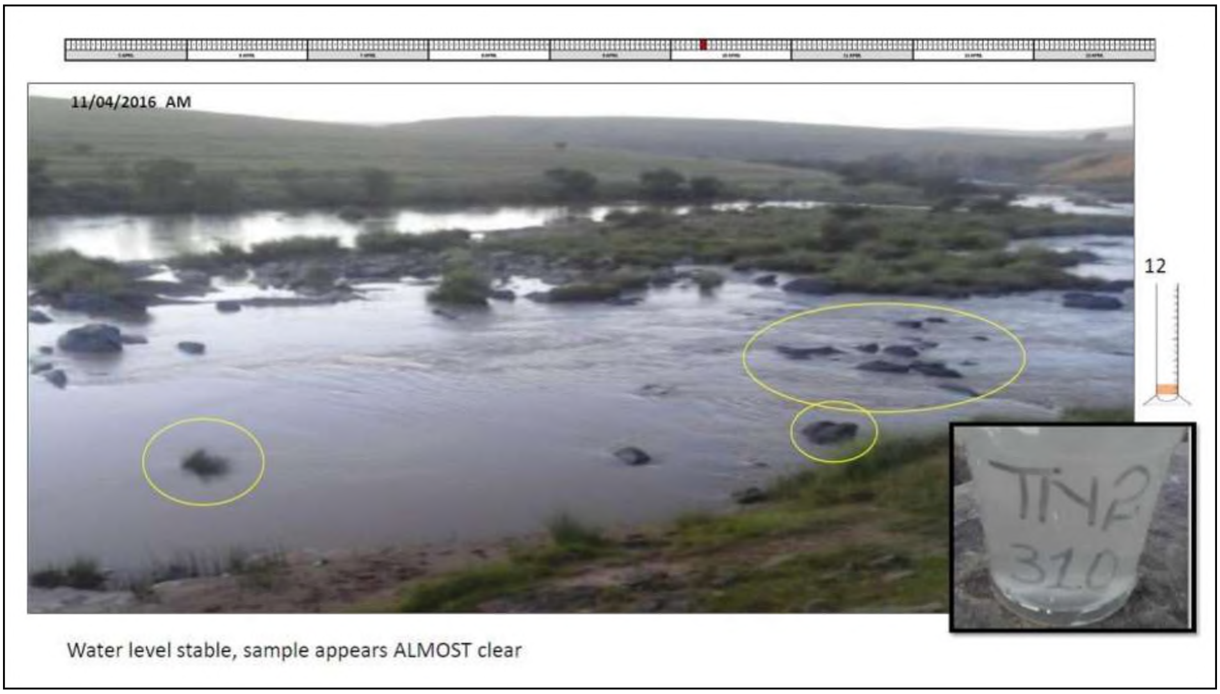
Water level high, sample APPEARS far less turbid

Figure 21g: 08/04/2016 (am)


10/04/2016 AM

Water level dropping, sample less turbid

Figure 21h: 10/04/2016 (am).


11/04/2016 AM

Water level stable, sample appears ALMOST clear

Figure 21i: 11/04/2016 (am).

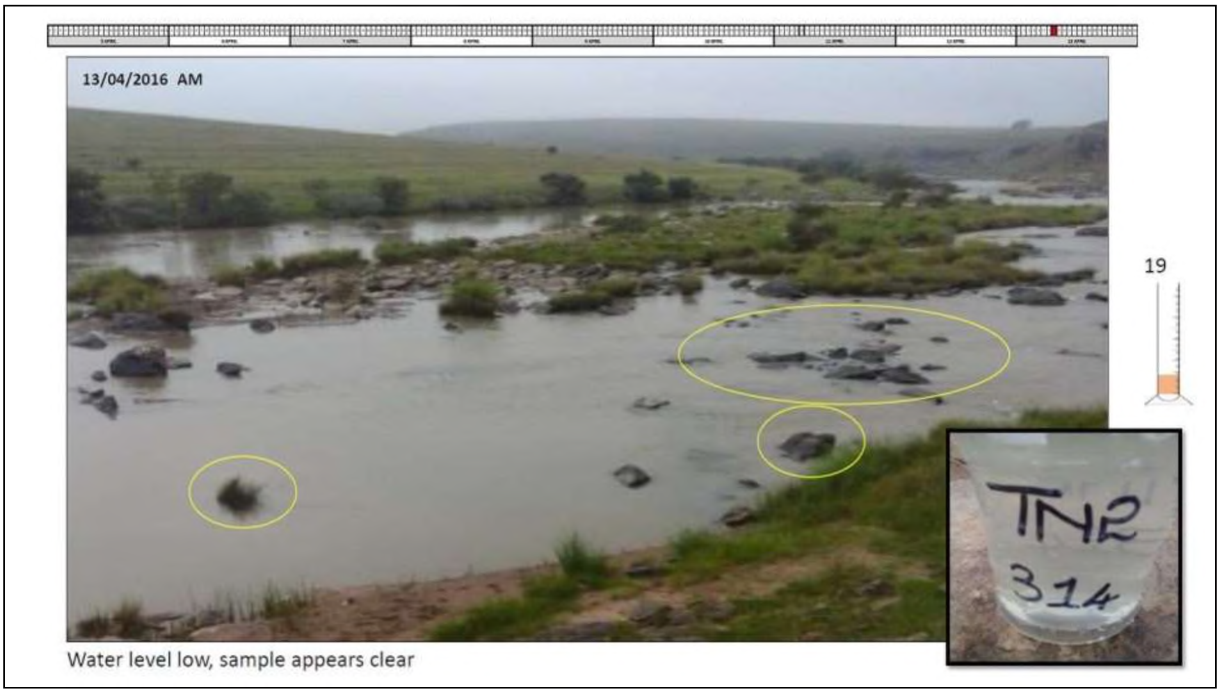


**Figure 21j: 13/04/2016 (am).**

As illustrated, a series of such composites allows a visual interpretation through a flood flow at single or multiple sites. The progression of discharge and sediment through the catchment, identification of one or more hydrological peaks occur, hysteresis of SSC and hydrological peaks can all be visually analysed, together with changes in water and turbidity levels. This record would act as a backup to provide discharge and SS load information in the instance that collected water samples were lost or their analysis delayed.

## 4.7 Conclusion

The design of the CT-based direct SS sampling programme took place within a theoretical framework influenced by:

- The findings and shortcomings of the existing research examined in **Chapter 2.2**,
- The underlying principles of sediment dynamics discussed in **Chapter 2.3**,
- The advantages and drawbacks of the monitoring and sampling methods reviewed in **Chapter 2.4**.

Development and implementation, however, occurred within a practical framework limited by time and budget, and strongly shaped by the real-world challenges (such as communications, distance, quality control, sampling protocol development) encountered at each stage. The foundation for overcoming some of these challenges in order to meet the project aims lay within the potential offered by the citizen science approaches outlined in **Chapter 2.5**, and the adaptation of selected aspects to better fit local conditions. For other challenges, a trial-and-error approach was often required. This meant either developing a tailored solution (for example writing specific training material for sampling protocols and quality control), or modifying the use of something designed for a different purpose to suit the needs of the project (for example using water purification tablets to preserve samples). There was little previous work or literature that could be drawn upon to assist with solving these problems.

The effort required to train, manage, and administer the CTs and to analyse the resulting amount of SSC samples was seriously underestimated and eventually proved to be beyond the capacity of the researcher. This however led to further local benefit in terms of the creation of further employment opportunities for “non-professionals”, i.e. a field administrator and a laboratory assistant.

The aim of the research was thus met in terms of the first three objectives. The design and implementation of a scientifically valid and locally appropriate CT-based approach to SS monitoring for the Tsitsa River catchment, together with a basic laboratory analysis protocol was achieved, and a large amount of detailed quantitative and qualitative data were produced. The following chapter describes the methods used to evaluate the method in terms of its efficiency, effectiveness, proficiency and precision, and to determine the degree of confidence with which the resulting data can later be used to estimate SS loads and yields at the site of the proposed Ntabelanga Dam wall.

# 5 A CRITICAL EVALUATION OF THE CITIZEN TECHNICIAN BASED APPROACH: METHODS

## 5.1 Introduction

The preceding chapters have focussed on the first three research objectives. They have contextualised the research project, outlined the scientific basis for the design and implementation of the sampling programme, demonstrated the need for the SS data, and described the SS sampling and laboratory methods in detail. The purpose of developing and implementing the CT-based direct SS sampling approach was to generate scientifically valid SSC data. This chapter therefore addresses the achievement of the last three research objectives, by describing the methods by which the sampling approach was evaluated, and by which the quality of the resulting data were assessed.Note that the analysis and use of the resulting data, for e.g. the determination of SS loads and yields, lie outside the ambit of this thesis and will form the subject of future research.

As noted, ~4 000 samples had been received from the eleven CTs, providing a wealth of information over the six-month period from December 2015 to June 2016, much of it from previously unmonitored catchments. Whilst both quantitative and qualitative data were generated, the qualitative data produced were not included in the assessment of the sampling method. Assessments of other criteria such as the socio-economic, capacity-building, or environmental awareness impacts of the sampling programme, whilst important in the context of the community-based environmental monitoring, were beyond the ambit of this project. Field data comprised:

- Visual clarity tube data,
- Continuous water level data from Solinst pressure loggers,
- Surveyed transects of each site before and after the first wet season
- Discharge data from the DWS gauging stations,
- 5-minute rainfall data from the five rain gauges installed throughout the catchment.

Data generated from the analysis of SS samples comprised:

- SSC derived by evaporation,
- Measured turbidity,
- EC (found to be inconsequential).

The assessment of quantitative data investigated:

- the extent to which sampling is likely to have resulted in representative SSC data,
- the degree of confidence with which the resulting SSC data can be used to estimate SS loads and yields in the tributary catchments the Tsitsa River catchment, and at the site of the proposed Ntabelanga Dam wall.

## 5.2 Criteria for evaluation

The representivity of the SSC data was assessed by applying the criteria of ***efficiency*** and ***effectiveness***, whilst ***proficiency****,* and ***precision*** were used to infer the degree of confidence achieved by the sampling programme and the resulting data.

- *Efficiency* was assessed in terms of data acquisition. In other words:
    - How many opportunities for baseline and for flood sampling were there?
    - What percentage of the baseline and flood sampling opportunities did each CT achieve?
- *Effectiveness* was assessed in terms of the extra resources invested in the collection of flood samples. In other words
    - Did rapid flood sampling improve the SSC data for flood events, compared with the data derived only from baseline sampling?
- *Proficiency* was assessed in terms of incomplete and negative laboratory results. In other words, were data that had been generated by sampling lost during the laboratory process?
- *Precision* of the SSC data was assessed in terms of the variability of the results from “triple” samples. In other words, how similar were the turbidity and SSC results from three samples that were taken in rapid succession?

The SSC data would ultimately be used in conjunction with discharge to determine the SS load and yield of the Tsitsa River and its tributaries above the site of the proposed Ntabelanga and Lalini Dam walls. Therefore, the range of water levels (a surrogate for discharge range) at which SS samples were taken at each site provided a further criterion for assessing the SSC data produced by the CT-based SS sampling programme.

## 5.3 Site selection

Four of the eleven SS monitoring sites were selected for evaluation. It was assumed that the influences on efficiency, effectiveness, proficiency, and precision would result from a combination of:

- the personality or nature of the CT
- the size of the catchment
- the nature of the river at different sites and over time
- the proficiency of the laboratory evaporation process.

Two CTs who appeared (from the number of samples collected and analysed) to have sampled more consistently and two who appeared to have sampled less consistently were included in the evaluation. "Consistency" was taken to mean that at least one sample was taken on most days throughout the study period.

To contrast the possible influence of catchment and channel size on the resulting data, two sites were chosen on the main Tsitsa River (at Qulungashe Bridge and Mbelembushe), and two on much smaller, but fairly similar tributaries (the Tsitsana River at Lokishini, and the Gqukunqa River at Thambekeni). **Table 4** summarises the details of the sites chosen for evaluation (See also **Table 2**).

**Table 4: Sites evaluated for efficiency, effectiveness, proficiency, and precision**

| **Site name** | **River** | **Catchment size (km$^2$)** | **Flood sampling interval** | **Observed sampling consistency** |
|---|---|---|---|---|
| **Lokishini** | Tsitsana | 135 | 15 mins | More consistent |
| **Thambekeni** | Gqukunqa | 204 | 15 mins | Less consistent |
| **Qulungashe Bridge** | Tsitsa (near Ntabelanga Dam wall) | 1881 | 1st 10 samples: 45 mins<br>2nd 10 samples: 1.5 hours | Less consistent |
| **Mbelembushe** | Tsitsa (study catchment outlet) | 4285 | 1st 10 samples: 1 hour<br>2nd 10 samples: 2 hours | More consistent |

## 5.4 Evaluation of sampling efficiency

As noted, sampling efficiency was evaluated in terms of the number of baseline and flood samples taken relative to the sampling opportunities available.

### *Baseline*

The instances of all baseline samples taken by each CT were used to determine baseline sampling efficiency. Each CT should have taken two baseline samples per day throughout the study period. Efficiency, i.e. the percentage of available baseline sampling opportunities actually taken, was derived using **Equation 3**

$$Percentage\ baseline\ samples\ taken = \frac{number\ of\ baseline\ samples\ taken}{(number\ of\ days)x2} \times \frac{100}{1} \qquad \text{Equation 3}$$

### ***Flood***

#### *Flood sampling opportunities*

In order to determine flood sampling efficiency, it was necessary to identify the flood sampling opportunities at each site, and then determine if *any* (NB: not *how many*) flood samples had been taken close (i.e. within 45 minutes) to the rise and/or the peak of the flood event.

In order to discretise the rises and peaks, and link flood sampling to opportunities, graphs were generated in Excel that depicted all sample instances and water levels over time for each of the four selected sites for the study period of mid-December 2015 to June 2016.

##### *Water level*

With the exception of the Tsitsa at Mbelembushe where data from the DWS gauging weir at Xonkonxa was used, water levels were derived from the pressure transducers installed at each of the selected monitoring sites. Water level data were required to indicate the rises in water levels which were the “trigger” for flood sampling by the CTs, and to indicate the peaks in water levels which were the “target” for the flood focused sampling approach. Discharge will be required in future for the determination of SS loads and yields, but was not required for the evaluation of the CT-based SS sampling approach.

##### *Time*

Sample times were derived from the ODK forms downloaded from each CT’s smartphone. The starting time for each ODK form was assumed to be the time at which each sample was taken. Strictly speaking, sampling time should have been derived from the photograph of each sample, which ought to have been captured as soon as each sample was taken. However, it was both quicker and simpler (and not much less accurate) to use the ODK form start times, as:

- Under normal conditions and according to the sampling protocol, the sample should be taken within ~10 minutes of opening an ODK form;
- All the numeric and text information (including start time) from each ODK form can be rapidly extracted to Excel spreadsheets in batches using the programme ODK Briefcase;
- ODK Briefcase can unfortunately not retain photographs or their time and geo-attributes within the data extracted and batched from each form, storing the photographs separately in an associated folder. Thus, deriving sample times from the photographs would have entailed laboriously accessing each photograph using Windows Explorer in order to transcribe the time.

The water level pressure transducers and the barometric pressure transducers used to compensate them logged total and air pressure respectively at twenty-minute intervals. Time as measured by the pressure transducers was used as the x-axis for all the analytical graphs produced, except at Mbelembushe where time on the x-axis was derived from the six-minute recording intervals from the DWS gauging weir at Xonkonxa weir.

### *Night periods*

Floods that rose or peaked at night were not available as sampling opportunities to the CTs, and needed to be recognised as such in the efficiency and effectiveness analysis. Night periods were defined by ascertaining sunset and sunrise times (Citipedia.info 2017) throughout the year.

### *Flood event selection*

Two levels of high-flow event selection were undertaken at each site using the water level data and graphs. Firstly, a blanket selection of events was made that included ALL water rises and peaks. Rises and peaks occurring at night were distinguished from those occurring in daylight. This left all the potential triggers for flood sampling as perceived by the CTs, who in real-time could not know the eventual duration or amplitude (i.e., the “significance”) of the event they were observing.

Secondly, a subjectively filtered sub-set of “significant” events was selected, comprising those events which from visual analysis of the graphed data were deemed likely to move significant amounts of sediment. Typically, (but not exclusively) these were events separated by a return to near base flow depth, followed by an emphatic rise to a peak of at least twice base flow. **Figure 22** illustrates the first and second level of event selection, with eight significant rises/peaks selected from a total of 20 rises/peaks. Again, this subset of “significant” rises and peaks was divided into “total” and “daylight” rises and peaks.

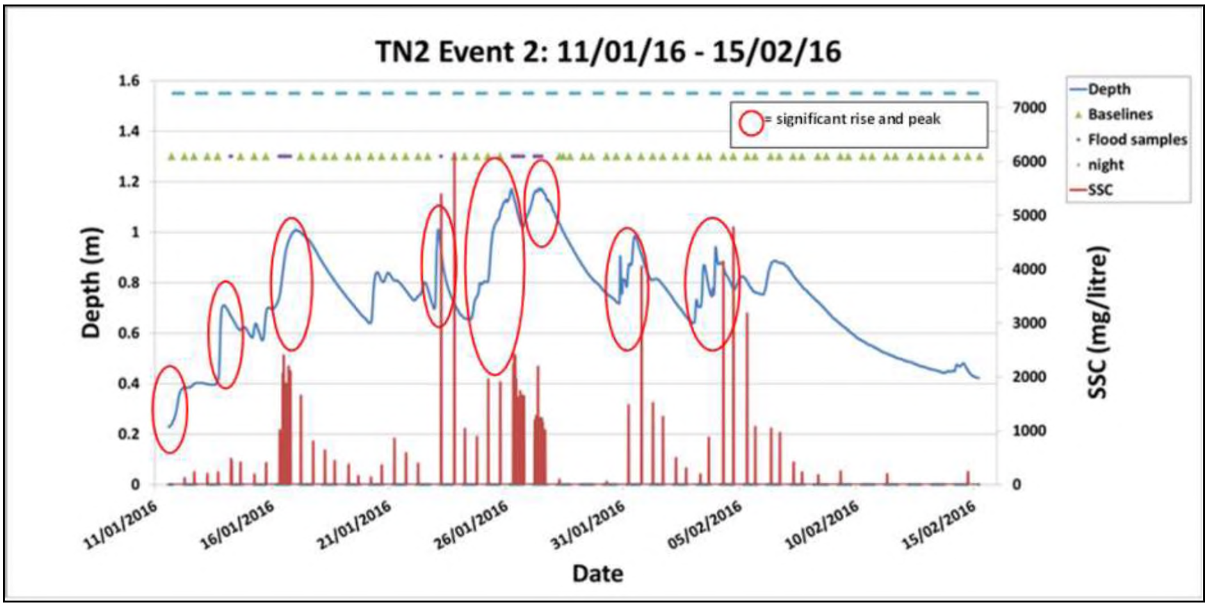


**Figure 22: Graph showing an example of significant rise/peak selection for flood sampling efficiency analysis**

The Excel spreadsheets included in **Appendix 1** contain the relevant data and graphs used during event selection.

### *Analysis*

The resulting flood event opportunities were analysed as follows:

- Total rises sampled
- Daylight rises sampled
- Total peaks sampled
- Daylight peaks sampled
- Significant rises sampled
- Significant daylight rises sampled
- Significant peaks sampled
- Significant daylight peaks sampled

The efficiency of total and significant flood sampling was thereby determined, not only within the limits imposed on the CTs (daylight sampling) but also against the hypothetical performance of a probe or automated sampler that could monitor or sample continuously.

## 5.5 Evaluation of flood sampling effectiveness

As noted, flood sampling effectiveness was evaluated to determine whether flood sampling improved the SSC data collected for flood events. The data collected by flood sampling during water level rises and peaks monitored through flood sampling was compared with that collected by baseline sampling.

### *SSC data*

It was not within the ambit of this study to analyse all the available SSC data for the four selected sites. Only SSC results from visibly high SS samples (>200 ntu) i.e. that had been derived by evaporation rather than from measured turbidity were used: These data could provide sufficient insight into whether periods of high SSC associated with water depth rises and peaks had been more effectively captured by flood sampling than by (default) baseline sampling.

There were two reasons for this. Firstly, the SS sampling method focussed on flood flows: the visibly low SS samples that typically occurred during steady *low* flow conditions (or at the tail end of a flood recession limb) were therefore of less interest. Secondly, using only the SSC results from the evaporation process avoided the introduction of a further degree of uncertainty caused by establishing turbidity/SSC relationship for each site.

### *Analysis*

The effectiveness of flood sampling was analysed firstly by comparing how many "significant" daylight water rises and peaks were monitored by flood sampling, compared with the number monitored by baseline sampling. SSC values were plotted to provide some insight into changing sediment levels during water rises and peaks. From this analysis, the baseline and flood sampling effectiveness (percentages) for the following categories were determined:

- Daylight rises captured by baseline sampling
- Daylight rises captured by flood sampling
- Daylight peaks captured by baseline sampling
- Daylight peaks captured by flood sampling

Secondly, the number of flood samples taken during the significant daylight rises and peaks was determined. This provided insight into whether rapid flood sampling was more effective, i.e. improved the number and definition of flood rises and peaks sampled compared with twice daily baseline sampling.

## 5.6 Proficiency and precision

Since it was not possible to observe the CTs to ensure their compliance with the sampling protocols, their sampling proficiency could not be directly assessed. Proficiency was therefore assessed to determine if potential data that had been generated by sampling was lost during the laboratory process.

The precision of the sampling method as a whole was assessed in terms the variability of SSC data generated from "triple" samples. Comparing the variability of turbidity data with that of the SSC data within triple sample sets gave insight to the precision of the laboratory processes.

### ***Sources of error***

The proficiency and precision of the data was influenced by all steps throughout the entire process of data generation, from the first actions of sampling to the final entry of the last value. Points of uncertainty at which data precision could be affected by major or minor errors existed at every step in the sampling and analysis process, and included:

- Sampling
    - Sample taking
    - Sample storage
    - Sample labelling
    - Sample recording (manual and electronic)
- Analysis
    - Jar washing
    - Sample handling
    - Sample weighing
    - Consistency of analytical techniques
    - Recording of results
    - Balance, turbidity meter, and EC probe accuracy
    - Jar drying
    - Results transcription
    - Computation

Errors could potentially range from minor to major, and be either random or consistent.

### ***Sample taking***

As noted, the ODK forms provided a degree of quality control in terms of sampling timing and location. However, the manner in which the CT took the sample could not be controlled.

- Dipping with an open jar,
- not sampling the full water column (either through sampling too slowly in higher flows and thereby prematurely filling the sampling jar or simply by shallow sampling) or
- stirring bottom sediments whilst sampling

were among several ways in which sampling itself could produce inconsistent minor errors (low flow, when fine sediment is homogenously distributed through the water column) and major errors (moderate to high flow when suspended bed sediments would be variably present in the lower water column) in the data. Occasionally it was possible to detect open-jar dipping, e.g. when debris too large to have passed through the 5 mm inlet aperture in the pole-and-jar sampler (i.e. roots or stones) was found in the sample. The CT was cautioned, and not paid for these samples, which were discarded.

### *Sample storage*

Incorrect storage of samples could occur if:

- Chlorine pills were not added to prevent algal growth
- Jars were not capped properly allowing evaporation and/or leakage during transport.

Both of these would likely lead to a higher apparent SSC, due to organic matter in the first case, and loss of water leading to apparent higher SSC in the latter. Samples with obvious algal growth and those that had leaked were discarded, and the citizen technician was made aware of the problem.

### *Sample labelling*

Early in the sampling programme, some CTs made gross labelling errors including:

- Labelling all samples in a flood sequence with the same number,
- Labelling baseline samples taken in the morning and the afternoon with the same number,
- Starting again at “1” after the first batch of samples was collected.

These errors resulted from misunderstandings during training, and were corrected during subsequent field visits. Other occasional sample labelling errors included:

- Duplicate labels on consecutive samples due to forgetfulness,
- Different sample numbers on each side of the sample jar due to carelessness.

In many cases, the problem was resolved by using the sample photograph and handwriting differences to match the correct jar with the correct time, or by referencing the CT’s notebook. Jars were then re-marked to ensure that results were correctly recorded against the appropriate sample throughout the laboratory process. Unresolved ambiguously labelled samples were discarded. It is possible but unlikely that matching of sample label to results and times was not always done correctly. Skipped sample numbers would not lead to errors.

### *Sample number recording*

CTs occasionally entered the wrong sample number into the ODK form. This was usually revealed as a duplicate or wrong number entry whilst checking the ODK instances and could be rectified against the samples present to ensure that the right data were later attributed to the right sample.

During the laboratory process, errors could have been made in reading the sample number, leading to results being ascribed to the wrong sample. Major errors within and between sites could have occurred in this manner.

### *Jar washing*

Jars were washed on the outside prior to processing when they entered the laboratory. They were washed thoroughly following the evaporation and weighing processes, in order to remove the sediment and re-weigh the clean, dried jars to obtain their tare weight. Minor, random errors in SSC data could have occurred due to the failure to thoroughly remove:

- Dust on the outside of the jar from storing/transport, and/or
- Traces of sediment from the inside of the jar after initial evaporation/weighing.

Additionally, undetected impurities from tap water used for washing could have contributed to minor errors of this nature. Following events such as burst water mains and/or or water outages, the restored water supply was sometimes of poor quality, with sediment having entered the reticulation system. It is possible that this was not detected during one of the two jar washing stages. These errors would be more significant for samples with very low SS.

### *Sample handling*

Cross contamination of samples (sediment from one jar entering another) was unlikely since all laboratory work used the original sample jar. However, it is possible that handling errors occurred, including:

- Spillage whilst opening/moving open jars
- Disturbing settled sediment prior to decanting supernatant
- Dropping jars.

Slightly spilled and disturbed samples would lead to random errors of varying severity in SSC results, whilst major spills and dropped jars would lead to lost samples.

### *Sample weighing*

Whole water samples were weighed to two decimal places, whilst dried jars with sediment and empty dried jars were weighed to four decimal places. Poor weighing technique could contribute to random, major or minor errors through:

- Weighing whilst direct sunlight fell on the balance,
- Not waiting for the balance to “settle”,
- Weighing without closing the balance door.

Reading/recording errors associated with weighing could randomly contribute to major errors in SSC data.

### *Consistency of analytical techniques*

Turbidity was measured by withdrawing two representative samples from each thoroughly agitated jar. This provided two opportunities for technical inconsistency that could lead to errors of varying severity, but at the same time allowed detection and correction of such inconsistencies.

Samples were settled for at least a month before being weighed and decanted prior to oven drying. Longer or, rarely, shorter settling periods may have occurred, which could lead to inconsistency of results. Over-decanting supernatant from high SS samples, or those which were not fully settled would also lead to random errors of varying severity in SSC data.

### *Recording of results*

At all stages of the laboratory process, mis-recorded results could introduce random inconsistencies of varying severity in the resulting SSC values. During analysis of flood samples on smaller channels it was sometimes possible to detect such errors in the series of results of rapid sampling. Baseline samples could typically not be checked in the same way.

### *Balance, turbidity meter and EC probe accuracy*

Inaccuracies with the instruments themselves could lead to consistent, likely minor, errors.

### *Jar drying*

Incomplete drying of evaporated sediment and of cleaned jars, or the effects of atmospheric moisture (or e.g. damp hands) on jars that had been taken from the drying oven, could lead to errors of varying severity in the resulting SSC data. The laboratory itself had no air-conditioning or climate control facilities. Due to the volume of samples it was not possible to maintain continuous moisture control over the samples during laboratory processing.

Further, and significantly, three different drying ovens (one of which was on another floor of the building) of differing sizes and makes were used during this phase of the project, which, together with the necessity to transport jars between laboratories, is likely have led to inconsistencies in the drying process. Colour-changing crystals in the drying ovens and visual inspection were used together with generous drying periods to ensure that evaporated samples and clean jars were fully dried. Initially, jars that had been washed to remove sediment after evaporation were only air dried. Later this was changed: cleaned jars were oven dried and cooled before weighing to determine their tare weight.

#### *Transcription*

Results were manually recorded by the laboratory assistants in hard copy during the laboratory process. Despite frequent double-checking, transcription by the researcher to computer databases could have introduced reading/transcription/finger errors, causing random errors of varying severity in the resulting data.

#### *Computation*

Error/s in the Excel formula used to derive SSC from the values recorded in the laboratory process were unlikely, but had the potential to cause a consistent error in SSC results.

### *Incomplete SSC records*

Due to laboratory process issues leading to one or more missing data values during SSC analysis, some samples returned incomplete SSC records. This erroneous situation was distinct from the case where visibly low-sediment samples were selected for turbidity testing only. Reasons for incomplete SSC records included:

- dropped or spilled jars,
- jars with algae,
- jars that were apparently lost from the laboratory process, and
- failure to record data for a sample.

Incomplete records were derived from the data for the study period by sorting the data on sediment weight values, which revealed extreme results due to missing data. Incomplete records represented a loss in data and reduced laboratory proficiency.

### *Instrument error*

Balance accuracy was assessed by weighing a 100 g test weight to four decimal places on the fine balance. The turbidity meter and EC probe were calibrated according to the manufacturer's specifications by the chief laboratory technician.

### *Negative sediment results*

Negative sediment weight results represented a loss in data and reduced laboratory proficiency. Negative sediment weight results were by default indicative of errors in the laboratory analysis process, since the weight of the sampled sediment should always be positive. The instances of negative sediment weights for each of the four sites were analysed to determine if:

- Negative instances occurred more frequently at certain sites;

- The range and instances of negative results provided an indication of the extent to which precision as a whole could be affected, since a reciprocal, positive range of errors (or "noise") was likely to be both present and undetectable.

The negative instances were isolated by sorting the data for the study period on sediment weight. Negative instances that occurred as a consequence of incomplete records, and from obvious recorded value discrepancies were removed from this analysis. The number and range of remaining negative instances and the percentage of negative to total instances was derived from the remaining dataset.

### *Triplicate sample analysis*

The analysis of the triple sample sets (three samples taken in quick succession, once a week) was used to indicate the precision of the SSC analysis method. As noted, triple sample sets underwent laboratory analysis to determine both turbidity and SSC. Recognising that a degree of natural variability could be expected due to heterogeneous in-channel SSC (Horowitz 2013), the aim of the "triple" analysis was to provide a statistically robust assessment of precision/variation within the sets of triple samples from each site. This would in turn provide an indication of the degree of confidence in the project data.

It is considered standard laboratory practice to undertake routine analysis of duplicated samples as a means of determining precision (Minkkinen 1986; Hyslop, White 2009). The International Standardisation Organisation (ISO) describes precision in terms of the closeness of agreement between replicate measurements (Vim 2004). Rather than prescribe a formula for reporting precision, standard deviation, variance, and CV are suggested (Vim 2004).

Sets of triples including negative and/or incomplete SSC results were excluded from the analysis. The precision of the CT-based SS sampling programme was assessed by deriving the coefficient of variation (CV) for both turbidity and SSC within each remaining set of triples, and comparing the CV for turbidity with the CV for SSC.

Variability for each set of triples was assessed in light of the following assumptions:

1. Natural variability in channel SS at the time of sampling was intrinsic to all results.
2. Turbidity readings were expected be less prone to "introduced" (as distinct from natural) variability/error than SSC values, as there were fewer interactions with the sample and therefore fewer opportunities for error and uncertainty.
3. Within each set of triples, the CV of the turbidity measurements described the introduced error that could be caused by
    a. sampling
    b. one erroneous bench measurement.

4. Within each set of triples, the CV of the SSC results was an expression of cumulative error throughout the entire sampling and analytical process.

Lastly, comparing the CV with the mean turbidity for each set of triples provided insight into whether variability was linked to the amount of sediment present.

### *Water level range*

The estimation of SS loads and yields at the selected sites falls outside the ambit of this study. This was, however, the intended purpose of designing and implementing a scientifically valid and locally appropriate CT-based approach to SS monitoring and laboratory analysis. It is therefore important to gauge whether other requirements for the task of determining SS load and yield in addition to efficiency, effectiveness, proficiency and precision, were met by the method.

As noted in **Chapter 2.2**, the overwhelming majority of sediment is moved during the high flows which are more difficult (or impossible) to sample or which may not actually occur within the study period. It is therefore important to sample SSC through the highest available flood events to allow the establishment of a more robust relationship (within the accepted limitations of such extrapolations). SSC can then be estimated or predicted for those flood events which are known from the hydrological record to occur at intervals too infrequent to physically sample, (e.g. with a >100 year return period), or that are impractical or unsafe to sample if they do occur during the project period (Horowitz 2013).

The range of water levels at which samples were taken by the CTs at each of the four selected sites, together with the maximum recorded water level throughout the recorded period, was therefore determined in order to indicate whether SS loads and yields could confidently be estimated from the resulting data.

# 6 A CRITICAL EVALUATION OF THE CITIZEN TECHNICIAN BASED APPROACH: RESULTS

## 6.1 Introduction

This chapter presents the results of the critical evaluation of the CT-based SS sampling method. Firstly an overview is given of the nature and circumstances of the CT at each of the four sites selected for evaluation, to the extent that it may have impacted on their sampling performance. An analysis of quantitative data in terms of sampling efficiency and effectiveness is then presented as a critical evaluation of CT-based SS sampling. Next, the laboratory proficiency and precision at each of the four sites selected for evaluation is presented. Lastly, the degree of confidence with which the resulting SSC data may be used for the estimation and prediction of SS loads and yields is evaluated, through the analysis of variation within triple samples, and of the range of sampled water levels.

The Excel spreadsheets containing the data summarised and illustrated by the tables and figures in this section are included in digital format as **Appendix 1.**

## 6.2 The citizen technicians

The interpretation of the efficiency, effectiveness, proficiency, and precision of the SSC data is assisted by some insight into the character and circumstances of the people responsible for collecting it. All four of the sites selected for analysis were located in the rural communal areas of the former Transkei homeland, although none of the CTs were pre-selected by traditional authorities. In brief, and without describing the complex socio-economic fabric of gender roles and societal norms, life in communal areas tends to be lived within a traditional, patriarchal framework, influenced by the role of traditional local authorities and against a backdrop of unemployment, low income and poor municipal services (See **Section 3.3**).

### *Tsitsana at Lokishini*

The CT on the Tsitsana at Lokishini was a woman in her late fifties. She was married and therefore responsible for the day-to-day management of her household. She had some church and many immediate family commitments, but no employment outside the home. Few absences and none for more than a day occurred throughout the reporting period. The CT was always present during home visits when samples were collected by the researcher, meaning that any issues associated with sampling tasks could be timeously discussed and resolved. Compliance issues at this site mainly consisted of sample numbering errors. No stand-in CT was available at this site. **Figure 23** shows that consistent, regular baseline sampling (green triangles) was undertaken by the CT on the Tsitsana at Lokishini, with some gaps of a day when baseline sampling did not occur. Several series of flood samples (purple dots) were taken.

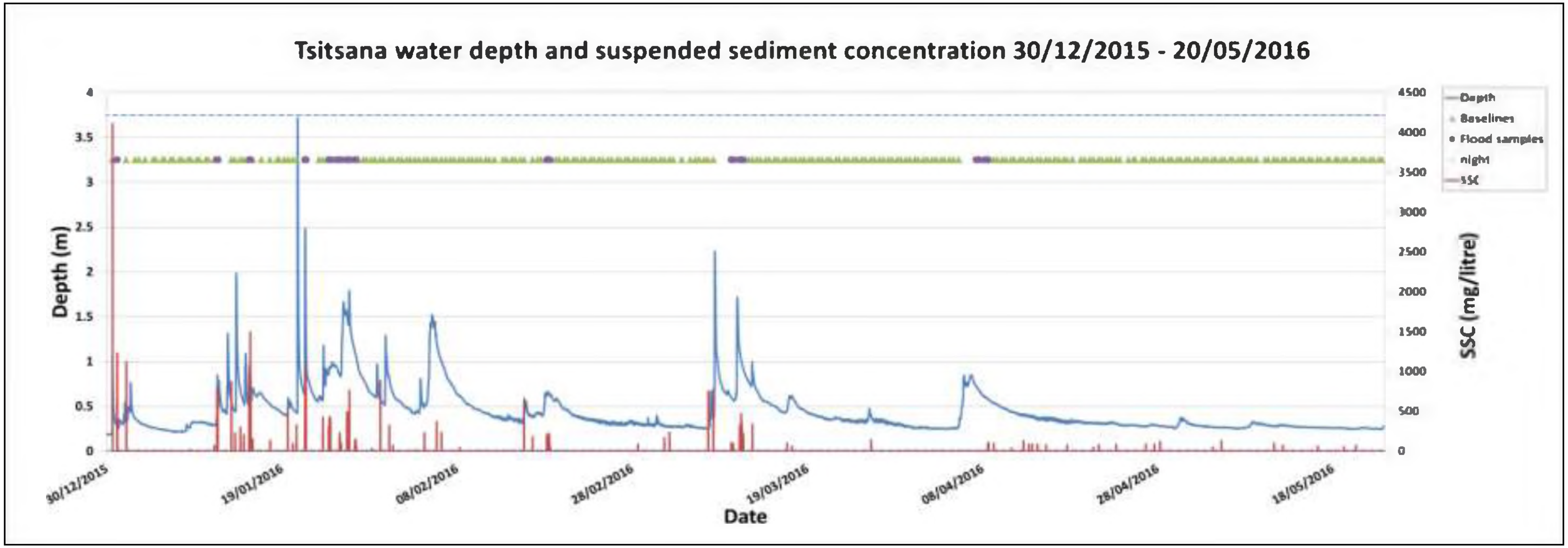


Figure 23: Graph showing water depth, SSC, sample occurrence and night periods for the Tsitsana at Lokishini

### *Tsitsa at Qulungashe Bridge*

The CT on the Tsitsa at Qulungashe was a woman in her early fifties. She was married and therefore responsible for the day-to-day management of her household. She had many community, and some immediate family commitments as well as some part-time employment outside the home. Her father died in January 2016. The personal loss, as well as the responsibilities associated with his funeral and mourning meant that she was unable to undertake sampling for two to three weeks following his death. This CT was not always present during visits when samples were collected by the researcher, meaning that not all issues with sampling tasks could be timeously discussed and resolved. Compliance issues at this site mainly comprised gaps in baseline sampling, and short (fewer than 20 samples) flood sampling sequences. No reliable stand in was available at this site although sampling was occasionally undertaken by others. **Figure 24** shows that whilst baseline sampling (green triangles) was often consistently and regularly undertaken by the CT on the Tsitsa at Qulungashe Bridge, there are several gaps of one or two days throughout the project period, and a two to three-week period at the end of January/beginning of February when baseline sampling occurred sporadically or not at all. Several short series of flood samples (purple dots) were taken.

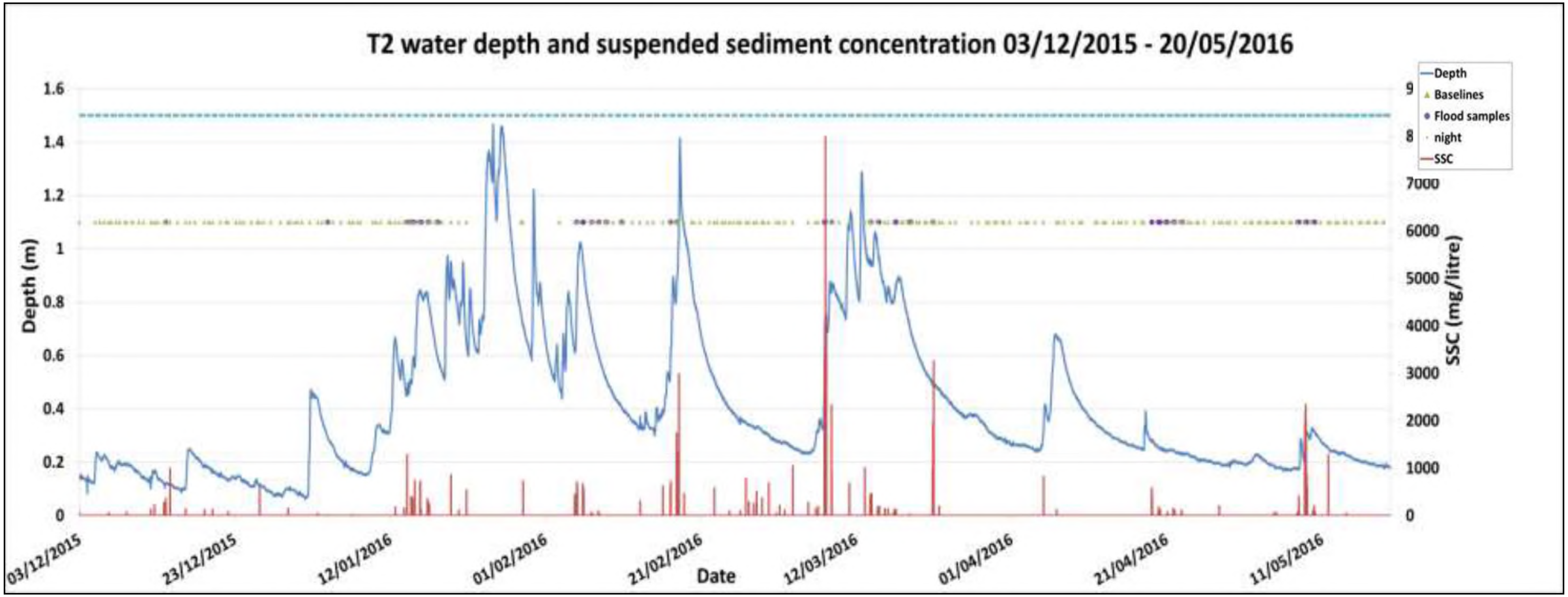


Figure 24: Graph showing water depth, SSC, sample occurrence and night periods for the Tsitsa at Qulungashe Bridge

### *Gqukunqa at Thambekeni*

The CT on the Gqukunqa at Thambekeni was an unmarried man in his early twenties. He lived alone, but close to the homes of his mother and extended family, and had no other work or immediate family commitments. His partner and child lived in Johannesburg. He was frequently absent during visits for sample collection, meaning that recurrent issues with sampling tasks could often not be timeously discussed and resolved. Compliance issues at this site included a pattern of several days' absence following the receipt of payment, misuse of data and airtime allowances, and the theft from his room of a smartphone. No stand-in was available at this site. **Figure 25** shows that baseline samples (green triangles) were often inconsistently and irregularly taken by the CT on the Gqukunqa at Thambekeni. Many gaps of several days to more than a week, when baseline sampling occurred sporadically or not at all, occurred throughout the project period. Many series of flood samples (purple dots) were taken.

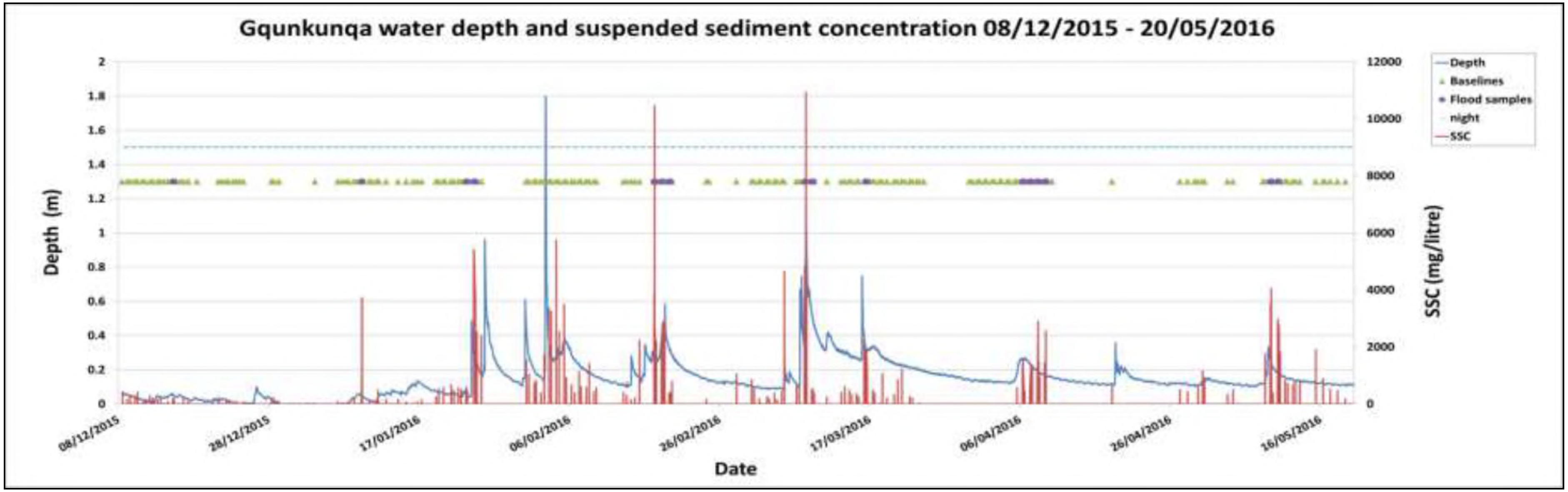


**Figure 25: Graph showing water depth, SSC, sample occurrence and night periods for the Gqukunqa at Thambekeni**

### *Tsitsa at Mbelembushe*

The CT at the Tsitsa at Mbelembushe was an unmarried man in his early twenties. He lived with his mother and immediate family, had no other work, but enrolled for short courses at a local Further Education college. Few absences, and none of more than a day occurred. He was always present during home visits when samples were collected by the researcher, meaning that any problems or difficulties with sampling tasks could be timeously discussed and resolved. There were few compliance issues at this site. No regular stand-in was available although sampling was occasionally undertaken by others. **Figure 26** shows that consistent, regular baseline sampling (green triangles) was undertaken by the CT on the Tsitsa at Mbelembushe, with some gaps of a day when baseline sampling did not occur. Some flood samples (purple dots) were taken.

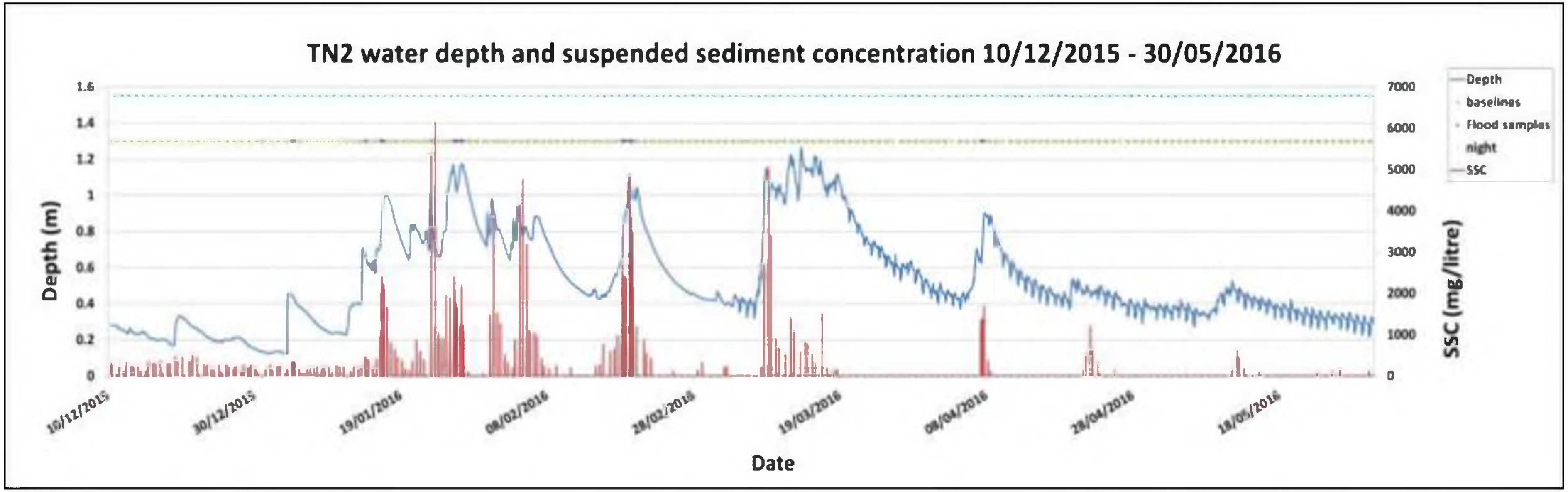


Figure 26: Graph showing water depth, SSC, sample occurrence and night periods for the Tsitsa at Mbelembushe

## 6.3 Baseline sampling efficiency

Baseline sampling was intended to provide regular data, twice daily throughout the project period. Baseline sampling efficiency was analysed using the data represented in **Figure 23, Figure 24, Figure 25** and **Figure 26**. **Table 5** summarises the baseline sampling data for the four sites, which are illustrated in **Figure 27** in terms of the percentage of available opportunities for baseline sampling achieved throughout the recorded period by the CT at each site.

**Table 5: Baseline samples and opportunities at each of the four selected sites**

| Site | Baseline sampling opportunities | Baseline samples taken | Baseline sampling efficiency (%) |
|---|---|---|---|
| **Tsitsana** | 284 | 268 | 94.37 |
| **Gqukunqa at Thambekeni** | 268 | 119 | 44.40 |
| **Tsitsa at Qulungashe Bridge** | 280 | 236 | 84.29 |
| **Tsitsa at Mbelembushe** | 299 | 283 | 94.65 |

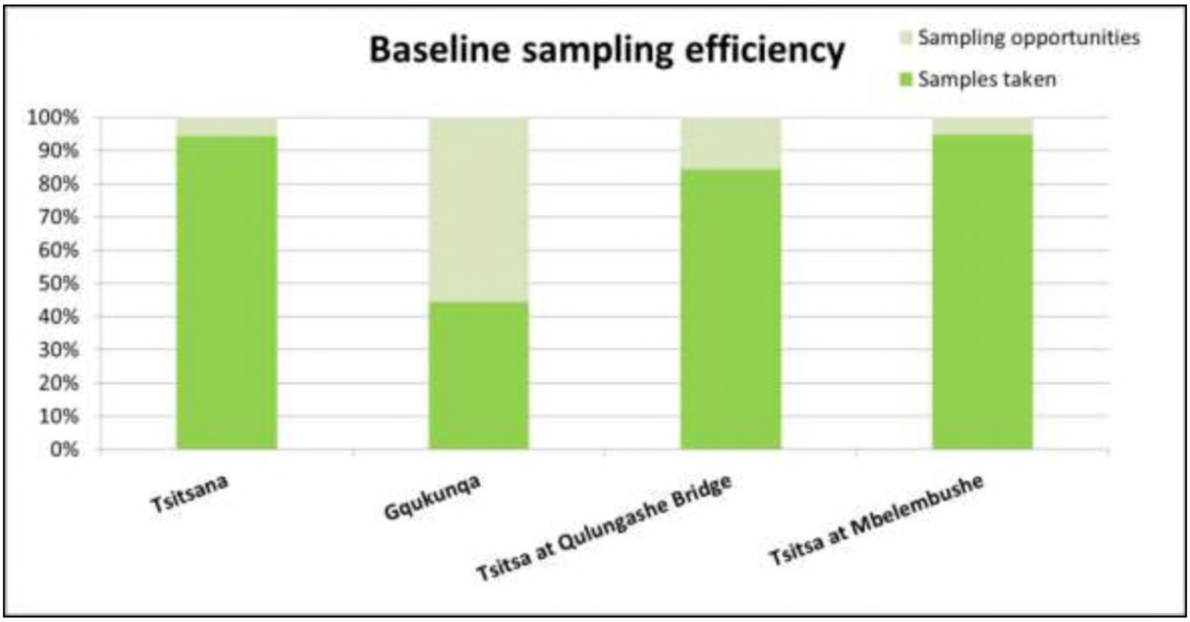


**Figure 27: Graph showing baseline sampling efficiency at each of the four selected sites**

The CTs on the Tsitsana at Lokishini and the Tsitsa at Mbelembushe achieved nearly 95% baseline sampling efficiency, whilst the CT on the Tsitsa at Qulungashe Bridge also performed well, achieving nearly 85% efficiency. Baseline sampling efficiency for the Gqukunqa at Thambekeni was however poor, with the CT taking advantage of fewer than half (~45%) of the baseline sampling opportunities available.

As noted in terms of the temporal consistency of sampling, **Figure 23** and **Figure 26** show that the CTs at the Tsitsana at Lokishini and the Tsitsa at Mbelembushe respectively sampled consistently throughout the recorded period, as their efficiency score suggests. For the Tsitsa at Qulungashe Bridge (**Figure 24**) some gaps in baseline sampling are apparent. Frequent substantial gaps in baseline sampling occurred at the Gqukunqa at Thambekeni (**Figure 25**).

## 6.4 Flood sampling efficiency

Flood sampling was intended to provide a series of SSC data points through the hydrograph at each station that would capture the rapid changes in SSC throughout rising and high water events. Flood sampling efficiency equates to the percentage of daytime flood sampling opportunities captured by the CT at each site throughout the recorded period. For the purposes of this analysis, the presence of any (NB: not *how many*) flood samples close to (within 40 minutes) or during a water rise, and close to (40 minutes either side) of a water peak was used as a measure of flood sampling efficiency.

### *Flood sampling opportunities*

Flood sampling opportunities available to the CTs comprised water rises and peaks that occurred in daylight, in contrast to the continuous opportunities available to installed instrumentation. The flood sampling opportunities that were available to the CTs at each of the four selected sites were analysed using the data represented in **Figure 23, Figure 24, Figure 25** and **Figure** 26. Note that a fault in the DWS level logging equipment was responsible for the “saw-tooth” pattern of water levels recorded for the Tsitsa at Mbelembushe (**Figure 26**) from 05/03/2016, but that water depths can nevertheless be inferred from the trend of the graphed levels.

These data are summarised in **Table 6. Figure 28** illustrates the significant daylight sampling opportunities (as described in **Section 5.4**) as a percentage of the total significant rises and peaks that occurred at the four selected sites.

**Table 6: Total and significant flood sampling opportunities at each of the four selected sites**

| | | RISES | | | PEAKS | | |
|---|---|---|---|---|---|---|---|
| SITE | Events | Total (#) | Daylight (#) | Daylight sampling opportunities (% total events) | Total (#) | Daylight (#) | Daylight sampling opportunities (% total events) |
| Tsitsana at Lokishini | All | 31 | 11 | 35 | 31 | 9 | 29 |
| | **Significant** | **12** | **4** | **33** | **12** | **2** | **17** |
| Tsitsa at Qulungashe Bridge | All | 41 | 31 | 76 | 41 | 12 | 29 |
| | **Significant** | **16** | **14** | **88** | **16** | **4** | **25** |
| Gqukunqa at Thambekeni | All | 24 | 13 | 54 | 24 | 10 | 42 |
| | **Significant** | **13** | **4** | **31** | **13** | **2** | **15** |
| Tsitsa at Mbelembushe | All | 32 | 18 | 56 | 32 | 22 | 69 |
| | **Significant** | **14** | **10** | **71** | **14** | **7** | **50** |

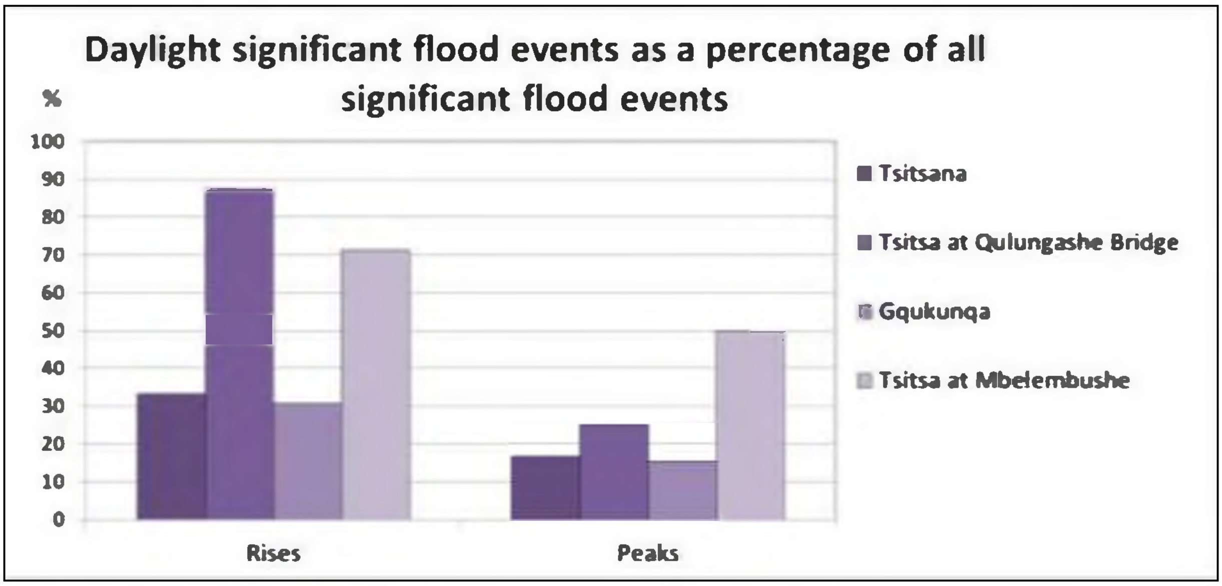


**Figure 28: Graph showing significant daylight flood sampling opportunities as a percentage of all significant flood sampling opportunities at the four selected sites**

In terms of significant flood events, more rises than peaks occurred during daylight at all four monitoring sites. This was probably due to the prevalence of afternoon thunderstorms (Moore 2016) in the study area.

The Tsitsana and Gqukunqa were relatively small catchments (135 km$^2$ and 204 km$^2$). When afternoon storms occurred, the flashiness of these tributary catchments resulted in rapid evening rises and short-duration overnight peaks, as illustrated in **Figure 23** and **Figure 26**.

Few significant daylight rises (four and fourteen rises respectively, or ~34% and ~31% of all significant rises), and even fewer significant daylight peaks (two and four peaks respectively, or ~17% and ~15% of all significant peaks) occurred in the Tsitsana and Gqukunqa. This resulted in relatively few flood sampling opportunities for the CTs at these sites.

The monitoring points on the Tsitsa at Qulungashe Bridge and at Mbelembushe had much larger catchment sizes (1881 $km^2$ and 4285 $km^2$). Flood flows at these main stem sites were more attenuated than at the tributary sites, and often had gentler rises (**Figure 24**, **Figure** 25). These rises were likely to have resulted from the lagged accumulation of flows from the upstream tributaries, rather than as a direct response to a local afternoon storm. This contributed to the higher percentage of daylight opportunities for sampling significant rises at Qulungashe and Mbelembushe (fourteen and ten rises respectively, or ~88% and ~71% of all significant rises). Peaks at these monitoring sites did however still tend to occur overnight, as evidenced by fewer opportunities for flood peak sampling (four and seven peaks respectively, or 25% and 50% of all significant peaks).

### *Floods sampled*

Flood sampling efficiency (the sampling opportunities actually achieved by each CT) at each site was determined by analysing the data presented in **Figure 23, Figure 24, Figure 25** and **Figure 26**. These data are summarised in **Table 7**, and presented in **Figure 29** as the percentage of significant daylight rises and peaks that were flood sampled by the CTs at each of the selected sites throughout the recorded period.

**Table 7: Flood sampling of rises and peaks at each of the four selected sites as a measure of sampling efficiency**

| | | RISES | | | | | PEAKS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **SITE** | **Events** | **Total** | **Daylight** | **Flood sampled** | **Total sampling efficiency (%)** | **Daylight sampling efficiency (%)** | **Total** | **Daylight** | **Flood sampled** | **Total sampling efficiency (%)** | **Daylight sampling efficiency (%)** |
| **Tsitsana at Lokishini** | All | 31 | 11 | 2 | 6.45 | 18.18 | 31 | 9 | 3 | 9.68 | 33.33 |
| | **Significant** | **12** | **4** | **1** | **8.33** | **25.00** | **12** | **2** | **1** | **8.33** | **50.00** |
| **Tsitsa at Qulungashe Bridge** | All | 41 | 31 | 7 | 17.07 | 22.58 | 41 | 12 | 3 | 7.32 | 25.00 |
| | **Significant** | **16** | **14** | **6** | **37.50** | **42.86** | **16** | **4** | **2** | **12.50** | **50.00** |
| **Gqukunqa at Thambekeni** | All | 24 | 13 | 2 | 8.33 | 15.38 | 24 | 10 | 1 | 4.17 | 10.00 |
| | **Significant** | **13** | **4** | **2** | **15.38** | **50.00** | **13** | **2** | **1** | **7.69** | **50.00** |
| **Tsitsa at Mbelembushe** | All | 32 | 18 | 3 | 9.38 | 16.67 | 32 | 22 | 3 | 9.38 | 13.64 |
| | **Significant** | **14** | **10** | **3** | **21.43** | **30.00** | **14** | **7** | **3** | **21.43** | **42.86** |

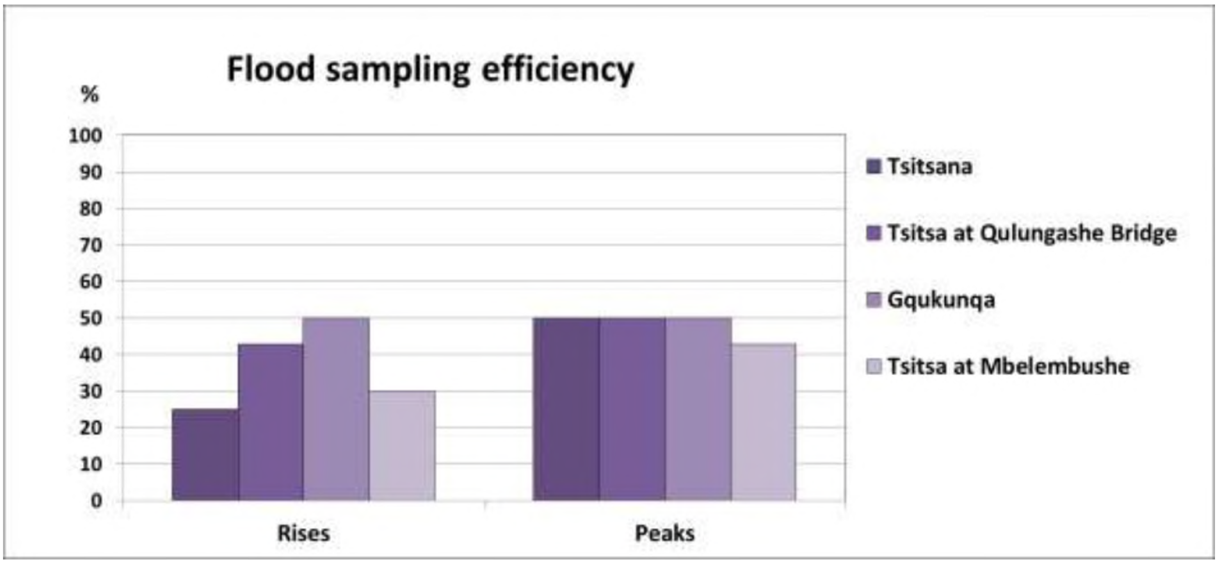


**Figure 29: Graph depicting flood sampling efficiency at each of the selected sites**

Flood sampling efficiency for significant daylight peaks equaled or exceeded that for significant daylight rises at all sites, although flood sampling efficiency of significant daylight flood events lay at or below 50% at all sites. Overall, flood sampling efficiency was poorer than baseline sampling efficiency (**Figure 27**) at all sites except on the Gqukunqa at Thambekeni.

The CT on the Gqukunqa at Thambekeni achieved the best flood sampling efficiency, taking at least one flood sample from half of all the significant daylight rises and peaks that occurred at that site. This contrasted with his achievement of the poorest and temporally most inconsistent baseline sampling (~45% baseline efficiency).

The CT at the Tsitsana at Lokishini achieved the poorest overall flood sampling efficiency, with only a quarter of daylight rises at that site being captured by at least one flood sample, in contrast with her achievement of the most consistent overall baseline sampling rate (95% baseline efficiency), both in terms of the number and consistency of baseline samples taken.

In conclusion, the CT at the Gqukunqa provided the best flood focused data. Despite being apparently less reliable, this CT was responsive to the financial incentive that was intended to ensure that the aims of the flood focused SS sampling programme were achieved. Conversely, the CT at the Tsitsana, despite consistent baseline sampling, was evidently less responsive to this incentive, and collected 25% less flood-focused data.

## 6.5 Flood sampling effectiveness

The analysis of flood sampling effectiveness was undertaken using the data represented in **Figure 23, Figure 24, Figure 25** and **Figure 26.** Firstly, the instances of flood or baseline samples occurring close to (within 40 minutes) or during water level rises or peaks were determined. **Table 8** summarises these data, which are presented in **Figure 30** as the percentage of significant daylight flood events during which CTs took at least one baseline sample or one flood sample.

**Table 8: Flood and baseline sampling effectiveness for total and daylight significant rises and peaks at each of the four selected sites**

| | | RISES | | | | | PEAKS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Sample type** | **Total** | **Daylight** | **Sampled** | **Total sampling effectiveness (%)** | **Daylight sampling effectiveness (%)** | **Total** | **Daylight** | **Sampled** | **Total sampling effectiveness (%)** | **Daylight sampling effectiveness (%)** |
| **Tsitsana at Lokishini** | **Floods** | 12 | 4 | 1 | 8.33 | **25.00** | 12 | 2 | 1 | 8.33 | **50.00** |
| | **Baselines** | 12 | 4 | 1 | 8.33 | 25.00 | 12 | 2 | 0 | 0.00 | 0.00 |
| **Tsitsa at Qulungashe Bridge** | **Floods** | 16 | 14 | 6 | 37.50 | **42.86** | 16 | 4 | 2 | 12.50 | **50.00** |
| | **Baselines** | 16 | 14 | 8 | 50.00 | 57.14 | 16 | 4 | 0 | 0.00 | 0.00 |
| **Gqukunqa at Thambekeni** | **Floods** | 13 | 4 | 2 | 15.38 | **50.00** | 13 | 2 | 1 | 7.69 | **50.00** |
| | **Baselines** | 13 | 4 | 4 | 30.77 | 100.00 | 13 | 2 | 2 | 15.38 | 100.00 |
| **Tsitsa at Mbelembushe** | **Floods** | 14 | 10 | 3 | 21.43 | **30.00** | 14 | 7 | 3 | 21.43 | **42.86** |
| | **Baselines** | 14 | 10 | 8 | 57.14 | 80.00 | 14 | 7 | 1 | 7.14 | 14.29 |

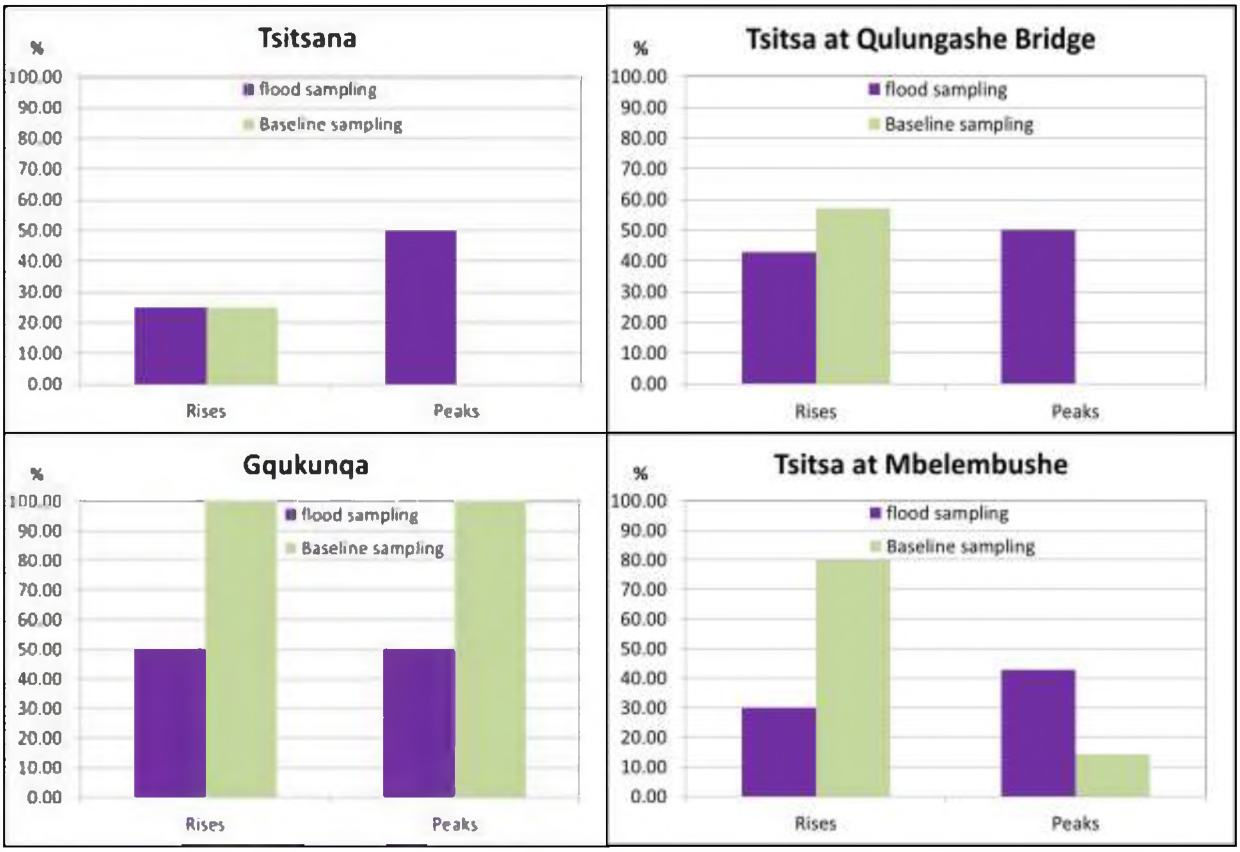


**Figure 30: Graphs comparing the effectiveness of baseline and flood sampling of significant daylight rises and peaks at the four selected sites**

At all sites, bearing in mind that an attenuated water level rise could be sampled by both baseline and flood samples, significant daylight rises were sampled as or more effectively by baseline as by flood sampling. At all sites except the Gqukunqa at Thambekeni, significant daylight peaks were more effectively sampled by flood sampling than by baseline sampling. Whilst baseline sampling captured all the significant daytime rises and peaks for the Gqukunqa at Thambekeni, flood sampling captured only half of them. This was surprising since floods were better captured at that site than at any other. However, a further important criterion of flood sampling effectiveness concerns the *number* of flood samples taken during the rises and peaks summarised in **Table 8**. Flood sample numbers for these events are summarised in **Table 9.**

**Table 9: Flood samples taken during significant daylight rises and peaks**

| **Site** | **RISES** | | **PEAKS** | |
|---|---|---|---|---|
| | **Date** | **Samples (#)** | **Date** | **Samples (#)** |
| **Tsitsana at Lokishini** | 21/01/2016 | 4 | 21/01/2016 | 6 |
| **Tsitsa at Qulungashe Bridge** | 15/01/2016 | 6 | 16/01/2016 | 3 |
| | 05/02/2016 | 3 | | |
| | 17/02/2016 | 3 | | |
| | 18/02/2016 | 4 | | |
| | 08/03/2016 | 8 | | |
| | 09/05/2016 | 7* | 09/05/2016 | 4* |
| **Gqukunqa at Thambekeni** | 18/02/2016 | 21 | | |
| | 08/03/2016 | 16 | 08/03/2016 | 4 |
| **Tsitsa at Mbelembushe** | 16/01/2016 | 10 | 27/01/2016 | 11 |
| | 18/02/2016 | 8 | 19/02/2016 | 3 |
| | 07/04/2016 | 10* | 07/04/2016 | 1* |
| **Total All stations** | **12** | **100** | **7** | **32** |

*rise and peak samples were consecutive readings 45 - 90 minutes apart

Significantly, multiple data points resulted from flood sampling through rises and peaks. This allowed better definition of the SSC levels associated with the water rises and peaks than could be provided by single, widely spaced data points resulting from baseline samples. In only one instance was a sampled water level rise or peak supported by fewer than three flood samples. In that instance (for the peak occurring on 07/04/2016 at the Tsitsa at Mbelembushe) the single flood sample that was taken at the time of the water level peak (18:20:00) was the last in a series of eleven flood samples which had also defined SSC changes throughout the associated water level rise, as illustrated in **Figure 31**.

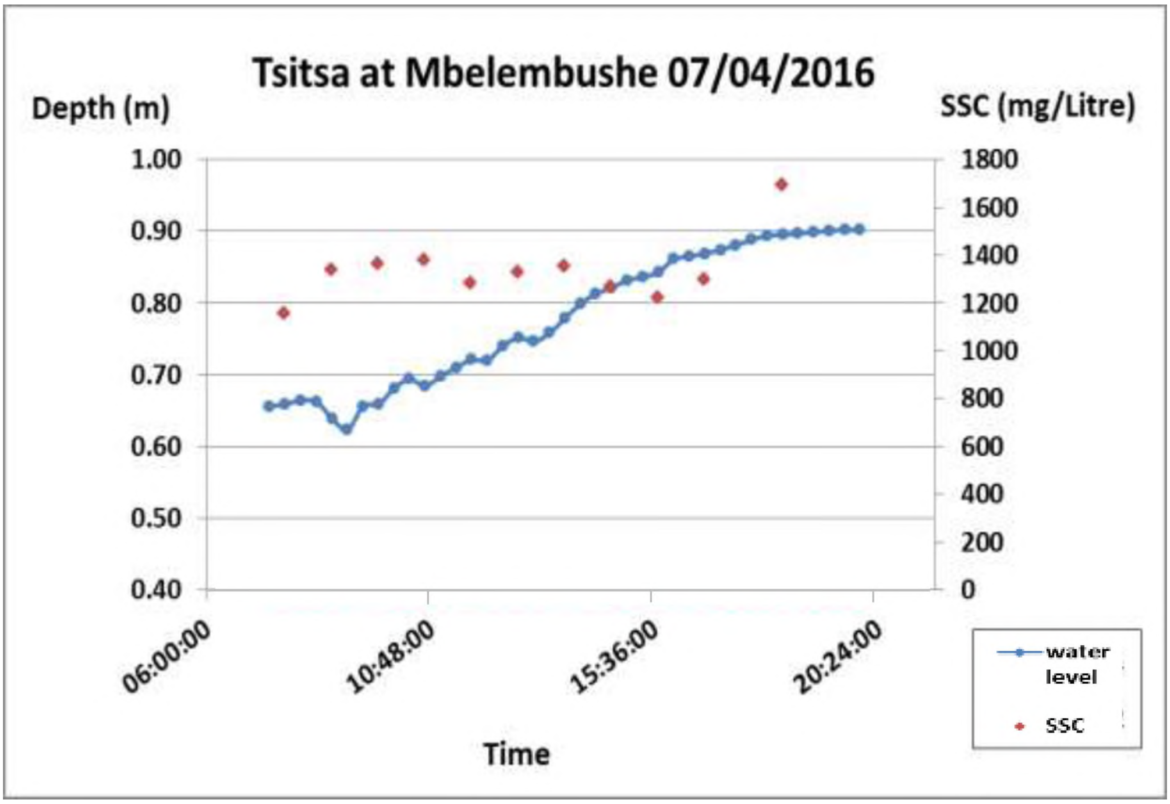


**Figure 31: Flood samples defining SSC changes throughout a water level rise and peak at the Tsitsa at Mbelembushe**

In summary, twice-daily baseline sampling was in most cases an efficient means of direct sampling, whilst rapid flood sampling proved more effective for monitoring "target" flood events. The combination of daylight-only sampling and prevailing weather patterns, rather than individual CT behavior, was therefore revealed as the major constraint on flood sampling effectiveness.

## 6.6 Proficiency of laboratory processes

### *Incomplete SSC records*

The percentage of incomplete SSC records from each site during the project period provided insight into the proficiency of the laboratory process. The data for samples collected and analysed for SSC at each of the selected sites, including incomplete SSC records, are summarised in **Table 10**. 2055 samples were collected at the four sites during the project period. Of these, 1517 were analysed for SSC whilst the remaining 538 were only tested for turbidity due to low visible SS (~<200 ntu).

The results for 45 of the 1517 SSC samples were incomplete, equating to a ~3% loss of data for all the SSC samples analysed, although the percentage of incomplete samples varied from site to site.

**Table 10: Sample data for each of the four selected sites**

| Site | Total records (#) | Analysed for SSC (#) | Incomplete SSC records (#) | Incomplete SSC records (%) |
|---|---|---|---|---|
| **Tsitsana at Lokishini** | 596 | 376 | 19 | 5.05 |
| **Tsitsa at Qulungashe Bridge** | 462 | 316 | 14 | 4.43 |
| **Gqukunqa at Thambekeni** | 538 | 516 | 4 | 0.78 |
| **Tsitsa at Mbelembushe** | 459 | 309 | 8 | 2.59 |
| **TOTAL** | **2055** | **1517** | **45** | **2.97** |

Samples from the Tsitsana at Lokishini were worst affected, with ~5 % of the SSC samples analysed for this site not yielding results. Few incomplete SSC samples originated from the Gqukunqa at Thambekeni, where less than 1% of samples were not analysed to completion. The reasons behind the distribution of incomplete samples throughout the four selected sites are unclear, as samples were not processed in site-specific batches.

The occurrence of many incomplete SSC records would have suggested frequent irregularities including handling accidents, gross errors, and poor process control. Conversely, the absence of incomplete SSC records would have implied that every SSC sample was correctly handled, with all the results for each stage of the laboratory analysis being recorded.

In conclusion, the loss of 3% of samples through handling in the laboratory, whilst better avoided, was nevertheless low. Whilst improvements in sample handling were indicated, this low percentage did not raise grave concerns regarding sample handling in the laboratory.

## 6.7 Precision of laboratory processes

### *Laboratory balance error*

As noted, the mass of a 100 g calibration standard was recorded to four decimal places at intervals (n = 58) to assess the accuracy of the laboratory balance that was used during the SSC analysis.The standard error of the mean associated with the laboratory balance was 0.00034 g with a 95% level of confidence. The balance was used twice during the laboratory process (See **Figure 20**), implying that the resulting SS masses were accurate to ± 0.0007 g. The masses recorded during the SSC laboratory analysis could therefore be affected within this range of error over the project period, contributing to the “noise” level of small but unavoidable errors intrinsic to the process. **Table 11** summarises standard error associated with the minimum, low, medium, and maximum sediment analysed from samples taken at the four selected sites.

**Table 11: Sediment weight and potential percentage error attributable to two laboratory balance weighing operations for samples from the four selected sites**

| *Standard error = ±0.0007 g* | **Tsitsana at Lokishini** | | **Tsitsa at Qulungashe Bridge** | | **Gqukunqa at Thambekeni** | | **Tsitsa at Mbelembushe** | | **ALL** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sediment level** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** |
| **Min** | 0.0021 | ±32.22 | 0.0006 | ±112.76 | 0.0003 | ±225.52 | 0.0091 | ±7.43 | 0.0003 | ±225.52 |
| **Low** | 0.4831 | ±0.142 | 0.9391 | ±0.076 | 1.3007 | ±0.05 | 0.7413 | ±0.09 | 1.3007 | ±0.05 |
| **Medium** | 0.9640 | ±0.072 | 1.8775 | ±0.04 | 2.6012 | ±0.03 | 1.4736 | ±0.05 | 2.6012 | ±0.03 |
| **Max** | 1.445 | ±0.05 | 2.816 | ±0.02 | 3.9016 | ±0.02 | 2.2058 | ±0.03 | 3.9016 | ±0.02 |

This error had a greater impact (225.52% to 7.43%) on samples with minimal to low sediment levels (0.0003 g to 0.0091 g), and very little impact (0.14% to 0.02%) on samples with low, medium and high sediment levels (0.48307 g - 3.94610 g), the upper third of which are the “target” sediment levels of the SS sampling programme. Note that the samples from the Gqukunqa at Thambekeni provided both the highest and lowest sediment values, thus defining the range for the whole sample set.

Whilst the cause of the laboratory balance error is speculative, it could be associated with variations in the laboratory environment, i.e. temperature and humidity, at the time of recording.

### *Negative sediment results*

Instances of negative sediment weights, and therefore SSC values occurred as a result of the laboratory SSC analysis and as noted must be erroneous.

**Table 12** summarises the data for negative sediment instances at each of the four selected sites whilst the instances of negative sediment at each site are illustrated (sorted by magnitude of negative value) in **Figure 32.**

**Table 12: Summary of negative sediment values for the four assessed sites**

| Site | Total SSC samples (#) | Negative sediment values (#) | negative samples (%) | Largest negative weight (g) | Smallest negative weight (g) | Range of negative samples (g) | Mean negative value (g) | Median negative value (g) |
|---|---|---|---|---|---|---|---|---|
| **Tsitsana at Lokishini** | 376 | 77 | 20.48 | -0.5399 | -0.001 | 0.5409 | -0.0438 | -0.0365 |
| **Tsitsa at Qulungashe Bridge** | 316 | 65 | 20.57 | -0.5564 | -0.0011 | -0.5575 | -0.0430 | -0.0208 |
| **Gqukunqa at Thambekeni** | 516 | 7 | 1.36 | -0.3276 | -0.0136 | 0.3412 | -0.0826 | -0.0232 |
| **Tsitsa at Mbelembushe** | 309 | 17 | 5.50 | -0.3768 | -0.0260 | -0.4028 | -0.0853 | -0.0716 |
| **All sites** | **1517** | **166** | **10.94** | **-0.4502*** | **-0.0104*** | **-0.4398*** | **-0.0637*** | **-0.0299**** |

*Average

**Median

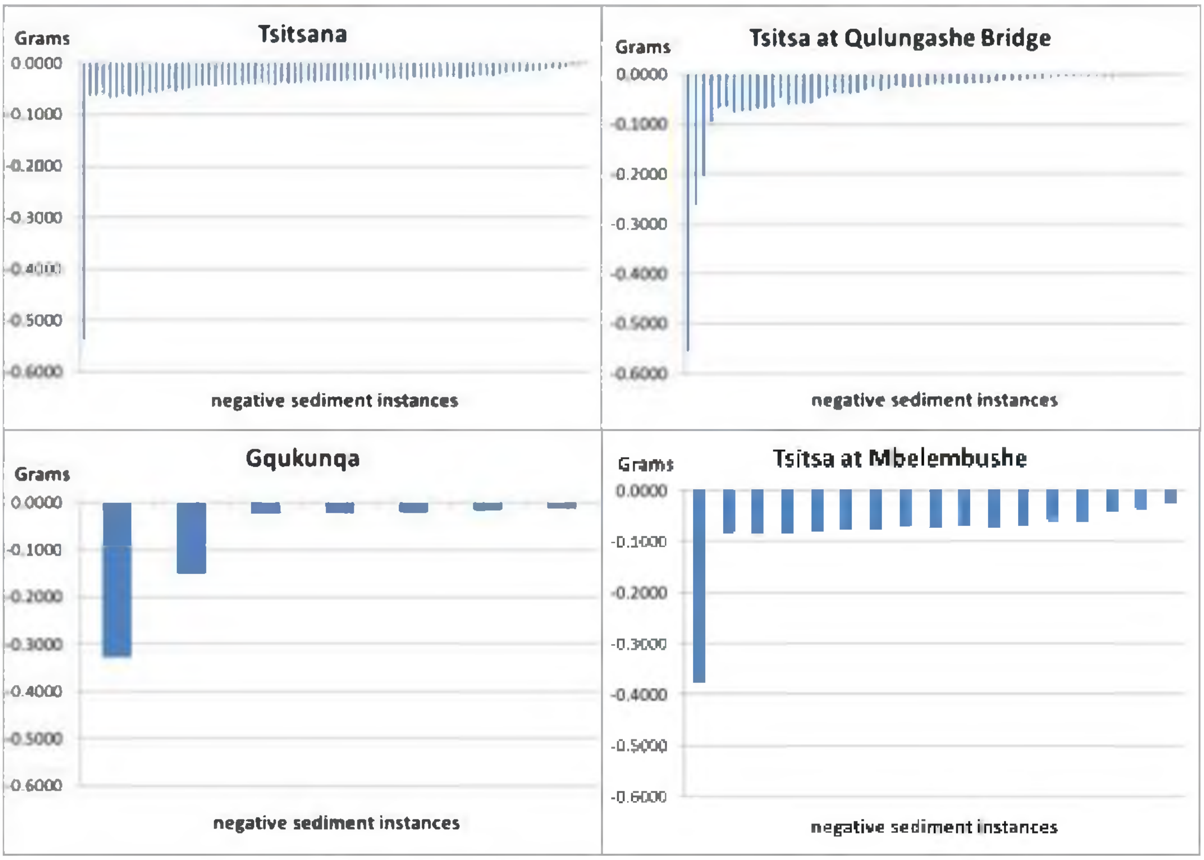


**Figure 32: Graphs showing instances of negative sediment values at each of the four selected sites, sorted by magnitude**

Of the 1517 SSC values derived from the four selected sites, 166 (or ~11%) were negative. Whilst the median negative value was -0.0299 g, the largest negative value was -0.5564 g (for the Tsitsana at Lokishini).

**Figure 32** reveals that two types of negative sediment instances occurred:

- Few (i.e. eight), large (i.e. > -0.1000 g) negative values, perhaps more likely to be due to a process error,
- Many (i.e. 158), smaller (i.e. < -0.0867 g) negative instances, perhaps indicative of the degree of unavoidable inaccuracy (or “noise”) in the laboratory analysis.

This is confirmed by the occurrence at all sites of a smaller median than average negative value. The cause/s, and implications for precision of negative results were investigated. Negative sediment results were suspected to be due to:

- an error or accumulation of errors during the laboratory process (e.g. weighing, washing, and/or drying)
- one or more errors in recording data, and/or
- The inability of the evaporation method of SSC determination to return accurate results, perhaps more evident at lower sediment values.

Analysis of samples from the sites on the Tsitsana and on the Tsitsa at Qulungashe returned many more negative instances (77 and 65 negative samples respectively, equating to ~ 20% of all samples at those sites) than the samples from the sites on the Tsitsa at Mbelembushe and on the Gqukunqa, (Seventeen and seven negative samples respectively, equating to ~ 11% and 5% respectively of all samples).

The accumulation of process errors could not be assessed, since relevant data were only available for the laboratory balance, which as noted contributed an error of =/- 0.0007 g. Errors in recording data were difficult to detect, but were suspected to be responsible for the eight very large negative values, as well as being a likely cause for a batch of 40 records from the Tsitsana, as described in greater detail below.

The following facts emerged when the negative SSC values were examined with reference to the results from measured turbidity and clarity tube readings in order to determine if low sediment values had led to the negative sediment results:

- For the Tsitsana:
    - 32 of the 77 records with negative sediment values had been tested for turbidity, indicating that these were either triple samples or that they had low visible turbidity. Of these 32 samples, 31 had measured turbidity readings of < 200 ntu, i.e. in the low sediment range.
    - 40 of the remaining 47 negative sediment samples for which turbidity was not measured had consecutive sample numbers. This suggests a combination of low sediment levels and a laboratory process error (e.g. entering data in the wrong column) as contributing factors to the high number of records with negative SSC results at the Tsitsana.
    - Clarity tube readings were not analysed for this site since the above factors accounted for the majority of negative values.
- For the Tsitsa at Qulungashe Bridge:
    - 31 of the 65 records with negative sediment values had been tested for turbidity, indicating that these were either triple samples or that they had low visible turbidity.
    - 28 of the 31 had measured turbidity readings of less than 200 ntu, suggesting that low sediment levels contributed to the high number of records with negative sediment results.
    - However, an analysis of the clarity tube readings taken by the CTs revealed conflictingly that all but one (a reading of “35”) were below “25” on a scale of “1” – “90” where a reading of < “30” indicates high sediment and a reading of

    > "50" indicates low sediment. The causes of negative SSC values were therefore not fully resolved at this site.

- For the Gqukunqa:
    - The seven records with negative sediment had not been tested for turbidity, indicating that none were triple samples, and that they had high visible sediment levels.
    - This was confirmed by reviewing the clarity tube readings taken by the CTs, all of which were below "20", on a scale of 1 – 90 where a reading of <30 indicates high sediment and a reading of >70 indicates low sediment. The causes of negative SSC values were therefore not resolved at this site.
- For the Tsitsa at Mbelembushe:
    - All seventeen records with negative SSC values had been tested for turbidity, indicating that these were either triple or "cross-over" samples. All of these had measured turbidity readings of less than 200 ntu, suggesting that low sediment levels were responsible for the negative SSC results.
    - Interestingly, however, all but two of the clarity tube readings fell within the high sediment zone of < "30", with only two readings of "33" and "36" falling in the "medium sediment" zone of "30" to "60", implying that whilst clarity tube readings provide a relatively useful rule of thumb for sediment levels they were empirically unreliable.

In conclusion, negative sediment results were unevenly distributed amongst the sites, and were not confined to low sediment samples. Laboratory error was the probable cause of negative SSC results, since in most cases turbidity measurements and clarity tube readings confirmed the presence of a range of sediment levels in the samples with negative results from the evaporation process. However, both persistent error and episodic or specific errors appeared to occur. Contributing factors may have included:

- Initial air-drying of washed jars for re-weighing. Oven-drying was introduced only after numerous negative sediment values were observed, following which the negative instances sharply decreased;
- Improper cooling of jars taken from the oven and awaiting weighing, thus affecting the balance through warm air up-draught;
- Alternatively, absorption of atmospheric moisture by jars after removal from the drying oven (e.g. overnight or weekends), whilst awaiting weighing, again affecting measurements of mass.
- Damp hands (e.g. from washing jars) whilst weighing which may have affected jar weights, as it was not standard procedure for laboratory assistants to wear gloves.

Given the possibility of multiple causes, the implications of the negative sediment values for the overall precision of the method are difficult to fully ascertain. Certainly, ~11% of samples was an unacceptably high number of negative sediment values and indicated that a review of laboratory procedures was necessary to reduce or eliminate negative values. (E.g. a new, dedicated drying oven was purchased subsequent to the reporting period).

If the eight very high negative values were attributed to gross error, the remaining 158, ranging from -0.0136 g to -0.0867 could be interpreted as the expression of the standard error (or “noise”) intrinsic to the total laboratory process (including the weighing procedures) during this early phase of the project. In the same manner as the derivation of the laboratory balance error, the standard error was derived for the remaining negative values and applied to the sediment values, firstly on a site-by-site basis, and secondly by applying the standard error of all 158 remaining negative values to the sediment results as a single dataset. These data are summarised in **Table 13**.

Table 13: Potential error attributable to negative sediment results on samples from the four selected sites

| | Tsitsana at Lokishini (Standard error = 0.0019 g) | | Tsitsa at Qulungashe Bridge (Standard error = 0.0030 g) | | Gqukunqa at Thambekeni (Standard error = 0.0019 g) | | Tsitsa at Mbelembushe (Standard error = 0.0045 g) | |
|---|---|---|---|---|---|---|---|---|
| | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** | **Sediment (g)** | **Error (%)** |
| Min | 0.0005 | 370.43 | 0.0006 | 501.74 | 0.0003 | 622.82 | 0.0074 | 60.89 |
| Low | 1.3157 | 0.14 | 0.9391 | 0.32 | 1.3007 | 0.14 | 0.7813 | 0.58 |
| Medium | 2.6309 | 0.07 | 1.8775 | 0.16 | 2.6012 | 0.07 | 1.5551 | 0.29 |
| Max | 3.9461 | 0.05 | 2.816 | 0.11 | 3.9016 | 0.05 | 2.329 | 0.19 |

As with the laboratory balance error, this error had a greater impact (622.82% to 49.52%) on samples with minimal to low sediment levels (0.0003 g to 0.0091 g), and very little impact (0.61% to 0.05%) on samples with low, medium and high sediment levels (0.48307 g - 3.94610 g), the upper third of which are the "target" sediment levels of the SS sampling programme. (Note that the samples from the Gqukunqa at Thambekeni provided both the highest and lowest sediment values, thus defining both the sediment and error range for the whole sample set.)

## 6.8 Triplicate sample set analysis

The analysis of the triple samples allowed the evaluation of precision of the CT-based SS sampling method and associated laboratory processes as a whole. It thus provided insight into the degree of confidence with which the data can be used for the estimation and prediction of SS loads and yields in the Tsitsa catchment.

The 28-week reporting period should have resulted in ~28 triple sets at each of the four sites selected for analysis. For various reasons, however, CTs tended not to be diligent regarding the taking of triple samples. The number of triplicate sample sets included in the precision analysis differed at each site depending partly on how many had been collected by the CTs, and partly because triple samples that contained negative or missing SSC values were removed from the precision analysis.

The small percentage (2.64%) of resulting triple sets analysed (a total of 40) compared with the total number of SSC samples (1517) implies that the results of the precision analysis may not be representative, and should be viewed with some caution. **Table 14** summarises the data for the triple samples from each of the four selected sites included in the precision analysis.

**Table 14: Details of triple samples included in analysis of precision**

| Site | Total records (#) | Analysed for SSC (#) | Total triple sets (#) | Triples sets with incomplete or negative SSC records (#) | Triple sets analysed (#) |
|---|---|---|---|---|---|
| **Tsitsana at Lokishini** | 596 | 376 | 17 | 8 | 9 |
| **Tsitsa at Qulungashe Bridge** | 462 | 316 | 15 | 7 | 8 |
| **Gqukunqa at Thambekeni** | 538 | 516 | 11 | 0 | 11 |
| **Tsitsa at Mbelembushe** | 459 | 309 | 24 | 12 | 12 |
| **TOTAL** | **2055** | **1517** | **67** | **27** | **40** |

The coefficient of variation (CV) was determined for the turbidity and SS values of the triple sets. Then, using turbidity as an indicator of sediment level, the relationship between sediment level and the CV of measured turbidity and SSC for the triple sets was determined. **Figure 33** is a scatter graph showing the percentage coefficient of variation (CV) for turbidity and for SS for the triple sample sets from all four sites selected for analysis. The triple samples are indicated in terms of low, medium or high mean turbidity values. Arbitrarily, readings of < 200 ntu were deemed low, readings of 201 ntu – 500 ntu were deemed medium, and readings of > 501 ntu were deemed to indicate high sediment levels. The turbidity meter experienced over-read at sediment levels in excess of 999 ntu.

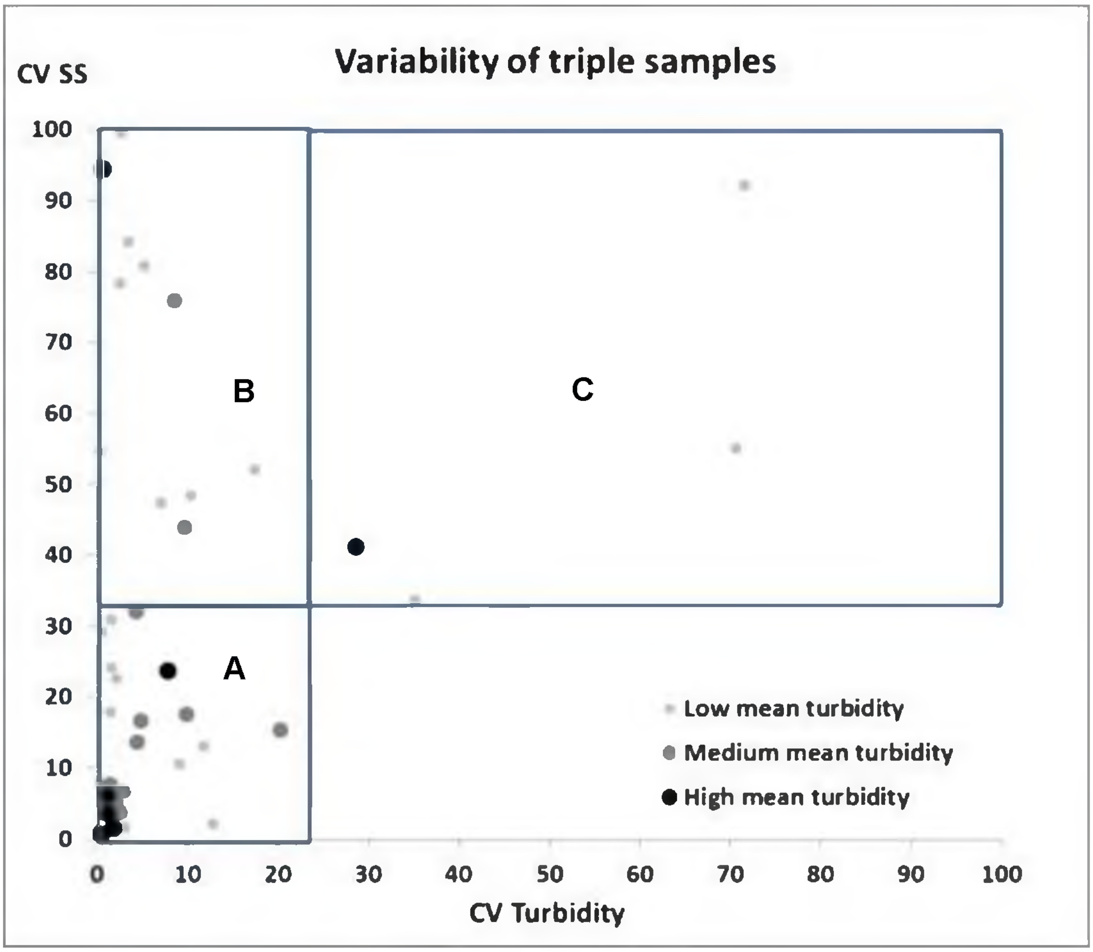


**Figure 33: Graph showing the percentage coefficient of variation (CV) for turbidity and SS from triple samples at each of the four sites selected for analysis**

**Figure 33** reveals three groups of results when comparing the paired turbidity and SS CVs for each set of triples at the four selected sites:

- Group A: Low turbidity CV/low SS CV
- Group B: Low turbidity CV /high SS CV
- Group C: High turbidity CV /high SS CV

Group A (<32% CV turbidity, < 23% CV SS) represents the desired results. CVs falling within this group indicate low natural and low introduced variability, signifying high levels of overall precision throughout the sampling and laboratory process. Group B (<32% CV turbidity, > 23% CV SS) represents less desirable results. CVs falling within this group indicate low natural and sampling variability, but highly variable SS values resulting from inaccuracy in the laboratory. Group C results (>32% CV turbidity, > 23% CV SS) cannot be used as an indication of precision, since the high CVs in this group may indicate either high natural variability, and/or high variability as a result of sampling technique. **Table 15** summarises the relationships between mean turbidity for triple sets and the CV groups described above. These are depicted in **Figure 34**.

**Table 15: The relationship between mean turbidity and CV groups**

| Group | Low mean turbidity | Medium mean turbidity | High mean turbidity | TOTAL | Low mean turbidity (%) | Medium & high mean turbidity (%) |
|---|---|---|---|---|---|---|
| Group A | 10 | 10 | 5 | 25 | 40.0 | 60.0 |
| Group B | 8 | 2 | 1 | 11 | 72.7 | 27.3 |
| Group C | 3 | 0 | 0 | 4 | 75.0 | 25.0 |
| **TOTAL** | **21** | **12** | **7** | 40 | 52.5 | 47.5 |

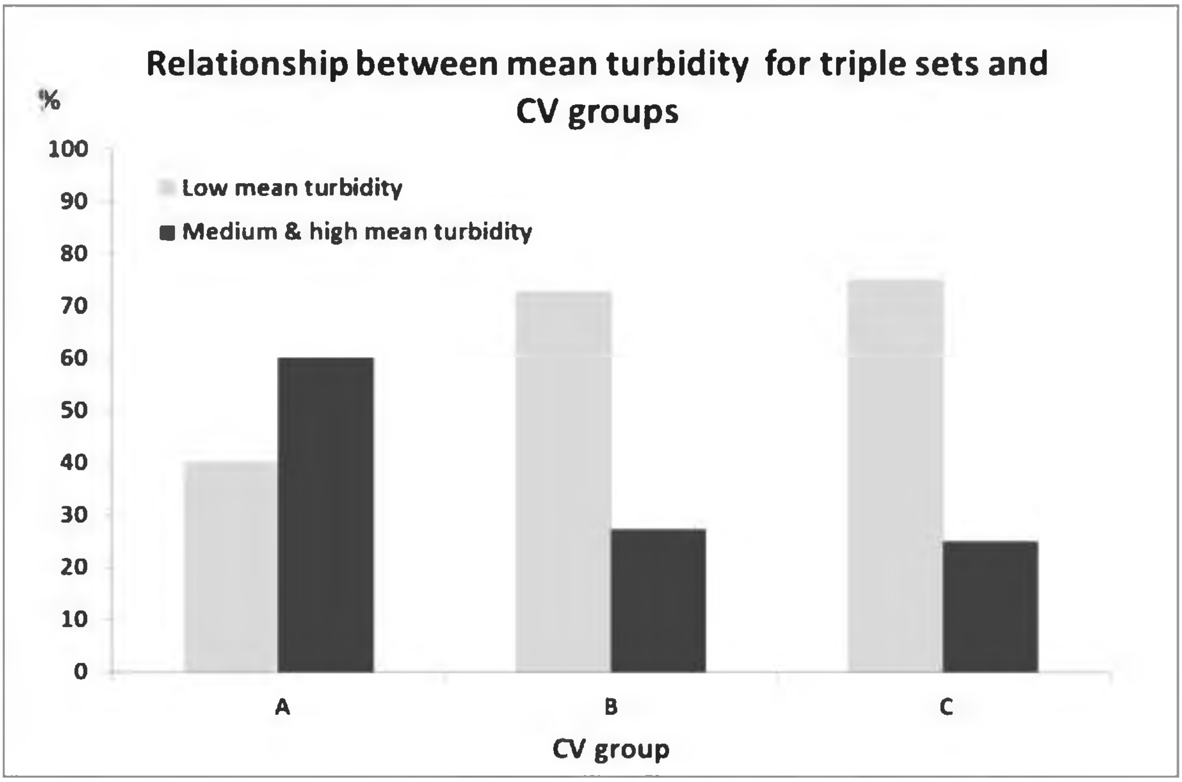


Figure 34: The relationship between average turbidity and CV groups

**Table 15** and **Figure 34** show that most triple sets in Group A had high and medium mean turbidity, whilst Groups B and C were dominated by triple sets with low mean turbidity.

In summary, the analysis of the triple sets shows less than satisfactory levels of laboratory precision, but supports the decision to use measured turbidity as a surrogate for SSC at low sediment levels, and to process only medium and high sediment samples through the laboratory evaporation process.

## 6.9 Water level range

The establishment of an SSC/water level relationship was outside the ambit of this study. However, assessing the potential to establish such a relationship using the data produced by the study provided insight into the scientific validity of the CT-based SS sampling approach. As described in **Chapter 5**, SSC samples should be taken at a range of water levels, with a strong emphasis on flood flows, in order to establish a robust SSC/level or discharge relationship from which to extrapolate SS loads and yields at higher flows.

Water levels at which samples were taken were derived for each of the four selected sites from the data illustrated in **Figure 23**, **Figure 24**, **Figure 25**, and **Figure 26**. These were then analysed to determine the depths of 0 - 25%, 25% - 50%, 50% - 75% and 75% – 100% of the samples during the study period. **Table 16** summarises these data for each of the four study sites, whilst **Figure 35** illustrates the sample depths for each quartile in the form of a stacked bar chart, with the maximum water level recorded at each site indicated in the form of a single point.

**Table 16: Water levels per sample quartile at the four selected sites**

| | Tsitsana at Lokishini | | Tsitsa at Qulungashe Bridge | | Gqukunqa at Thambekeni | | Tsitsa at Mbelembushe | |
|---|---|---|---|---|---|---|---|---|
| **water level** | **Level (m)** | **% of max recorded** | **Level (m)** | **% of max recorded** | **Level (m)** | **% of max recorded** | **Level (m)** | **% of max recorded** |
| **Max recorded level** | 3.72 | 100 | 1.47 | 100 | 1.80 | 100 | 1.27 | 100 |
| **Max sampled level** | 2.44 | 65.59 | 1.07 | 72.79 | 1.18 | 65.56 | 1.22 | 96.06 |
| **75% of samples** | **1.06** | **28.49** | **0.80** | **54.42** | **0.31** | **17.22** | **0.96** | **75.59** |
| **50% of samples** | 0.74 | 19.89 | 0.48 | 32.65 | 0.23 | 12.78 | 0.69 | 54.33 |
| **25% of samples** | 0.52 | 13.98 | 0.25 | 17.01 | 0.08 | 4.44 | 0.33 | 25.98 |
| **Min** | 0.25 | 6.72 | 0.10 | 6.80 | 0.00 | 0.00 | 0.13 | 10.24 |

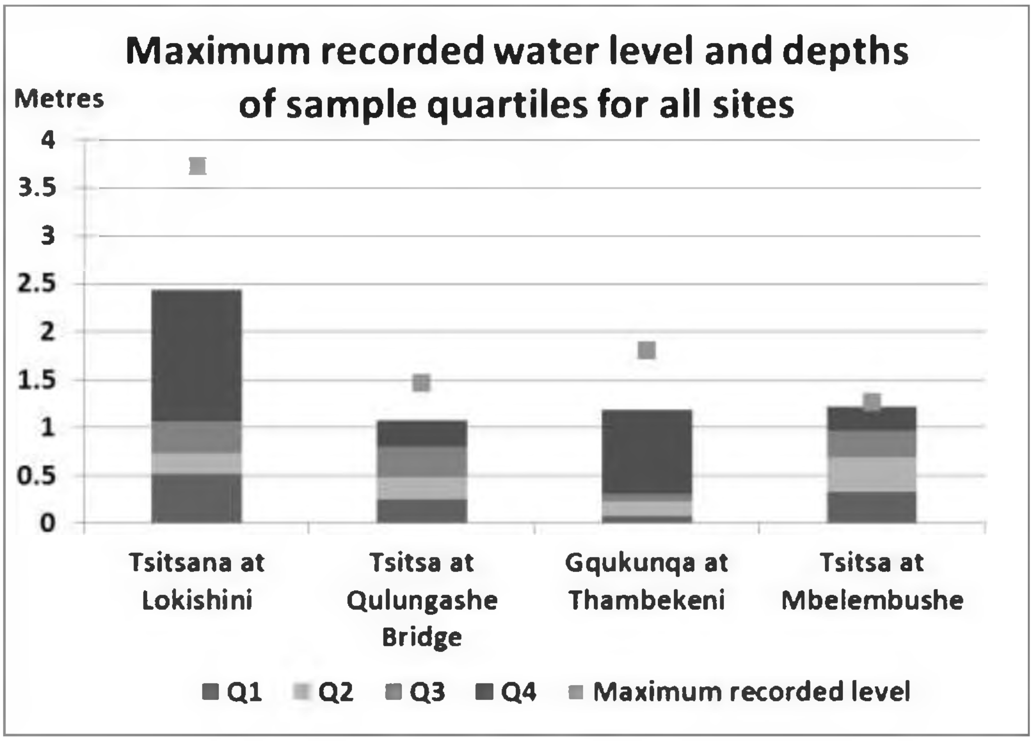


**Figure 35: Stacked bar graph illustrating maximum recorded depth and the depths for sample quartiles at each of the four study sites**

**Table 16** and **Figure 35** reveal that:

- For the Tsitsana at Lokishini, the maximum depth sampled (2.44 m) was only ~66% of the maximum recorded water level (3.72 m), i.e. 34% of the maximum recorded water depth was not sampled at all. Sample depths were poorly distributed, with 75% of samples taken at or below ~28% (1.06 m) of the maximum recorded water level. The high flow samples necessary for extrapolation of sediment concentration and loads were therefore not adequately represented at this site, implying a weak basis for extrapolation of the SS loads and yields associated with higher flows.
- For the Tsitsa at Qulungashe Bridge, the maximum depth sampled (1.07 m) was a relatively robust ~73% of the maximum recorded water level (1.47 m). Sample depths were however skewed towards low water, with 75% of samples taken at or below ~54% (0.80 m) of the maximum recorded water level. The range of sampled water levels was inadequate for high-confidence extrapolation of SS loads and yields associated with higher flows.
- For the Gqukunqa at Thambekeni, the maximum depth sampled was only ~66% (1.18 m) of the maximum recorded water level (1.80 m). Sample depths were very poorly distributed, with 75% of samples taken at or below ~17% of maximum recorded water depth. This provides an extremely poor basis for extrapolation of SS loads and yields associated with higher flows.

- For the Tsitsa at Mbelembushe, the maximum depth sampled (1.22 m) was ~96% of the maximum recorded water depth (1.27 m). Sample depths were evenly distributed, with sample number quartiles closely resembling depth quartiles. This provides a good basis for extrapolation of SS loads and yields associated with higher flows.

These findings are not unexpected given that, as noted, the opportunities for sampling high flows were fewer for the tributary sites than for the main stem sites.

In summary, the Tsitsa at Mbelembushe offered a robust range of SS sample depths from which to extrapolate the sediment loads and yields likely to occur due to higher flows than were sampled during the project period, whilst the Tsitsa at Qulungashe offered an adequate range of sample depths. The range of depths sampled at the two tributary sites, the Tsitsana at Lokishini and the Gqukunqa at Thambekeni offered an inadequate and poor basis respectively for the extrapolation of high-flow SS loads and yields. The relationship between catchment size and sampling opportunities is one that should be borne in mind during sampling programme design.

## 6.10 Conclusion

The evaluation of the CT-based SS sampling programme confirmed that whilst twice-daily baseline sampling was in most cases an efficient means of direct sampling, the series of rapid flood samples were more effective for monitoring “target” flood events, improving the number of data points gathered (and hence confidence in the data) per event.

Afternoon rainfall often led to overnight rises and peaks, particularly in the tributary streams with their smaller “flashier” catchments. Thus, prevailing weather patterns in combination with the restriction to daylight sampling placed the major constraint on flood sampling effectiveness. Despite very short (15 minutes) flood sampling intervals in the tributary catchments, the prevalence of overnight events restricted the number of events sampled. This caused the desired higher flows to be under-sampled, reducing the usefulness of the data as a basis for extrapolation of SSC to higher flows at these sites. At the two sites on the main stem of the Tsitsa River, however, rises and peaks accumulating from upstream rainfall events were of longer duration and could be sampled more effectively both in numbers and through the higher flows, despite the long (1 hour – 90 minute) flood sampling intervals at these sites. The resulting datasets can be used with a higher degree of confidence for the extrapolation of SSC at higher flows, particularly at the most downstream site.

Laboratory activities rather than CT sampling activities were identified as the main negative impact on the proficiency and precision of the method as a whole, although the impact of this was small for the targetted medium and high sediment samples. The evaporation method for SSC analysis was found to be unreliable for low sediment samples, confirming the decision to use measured turbidity as a surrogate for SSC in such samples.

# 7 DISCUSSION

## 7.1 Introduction

This chapter discusses the extent to which the aim and objectives of the study were met, in the context of the existing knowledge reviewed in **Chapter 2**, and through the lens of the findings and conclusions drawn throughout the thesis. Constraints and limitations are discussed, together with recommendations which may assist in overcoming them.

The aim of the project was to design, implement and evaluate a scientifically valid and locally appropriate CT-based approach to SS monitoring for the Tsitsa River catchment, together with a basic laboratory analysis protocol, via the following objectives which were described in **Chapter 1**:

1) Design a flood-focused SS monitoring programme for the Tsitsa River catchment;

2) Develop and implement a CT-based approach to flood-focused SS sampling in accordance with the monitoring programme design;

3) Develop and implement appropriate laboratory processes for the determination of SS concentration;

4) Assess the efficiency of the resulting SS sampling methods.

5) Assess the effectiveness of the resulting SS methods.

6) Assess the proficiency and precision of the resulting SS and analysis methods.

## 7.2 Sampling programme design

Designed in response to the characteristics of the Tsitsa catchment (**Chapter 2.3**), the sampling programme accommodated the SS heterogeneity that, as noted by Schumm (2005) and Horowitz (2013), is to be expected throughout channel width and depth. Spatially, it was designed to provide SS data at sub-catchment scale as demonstrated by Collins and Walling (2004). Temporally, the focus was on flood flows as recommended by Wolman and Millar (1960), Gordon et al (2004), and Horowitz (2013), against a background of sub-daily timestep calendar-based data, over a proposed period of several years.

The design of the Tsitsa River SS sampling programme was chiefly constrained by budget and project timeframes, and heavily influenced by the project scale, purpose, and required data outputs. As remarked by Wren et al. (2000) and Kuhnle (2013), the sampling approach chosen to accommodate such constraints proved a fundamental influence on sampling programme design. These considerations in turn shaped the design of appropriate laboratory protocols to deal with the type and high numbers of samples generated.

Instrumented and researcher-based approaches were rejected for the Tsitsa River catchment due to their high purchase and installation costs, in favour of the CT-based approach to collecting SS data. Qualified technical personnel would have been numerically, temporally and spatially restricted in their sampling opportunities due to the expense of keeping even one such person in the field full-time, and the logistics involved in sampling at sub-catchment scale. An instrumented approach would likely have been limited to one site at the study catchment outlet, which whilst offering continuous data, would severely have curtailed the level of spatial detail that the resulting SS data would have provided.

Temporally, although night-time safety concerns precluded round-the-clock sampling, the sub-daily timestep baseline sampling not only provided far more detailed coverage than Horowitz (2013) noted is commonly achieved, but also greatly improved the potential for CTs to observe and sample flood flows. *Inter alia*, the CT-based approach similarly improved the opportunities for sampling the range of water levels recommended by Horowitz (2013) for robust SSC extrapolations to higher flows.

The study timeframe (December 2015 – ongoing) has exceeded that of any other direct SS sampling programme undertaken in the catchment. In fact there have not, to the author's knowledge, been any other such comprehensive, long term, direct SS sampling programmes in South Africa since DWAF terminated their programme in the 1970s (Rooseboom, Lotriet 1992) Nevertheless, due to the unpredictable and variable rainfall (Moore 2016) and hydrology in the Tsitsa catchment, the total sampling period will likely fall far short of the time required to sample 80 – 85% of the range of flood flows recommended by Horowitz (2013).

In addition to overall project budget and timeframe, other constraints included difficulty in positioning some of the sampling sites indicated by the initial desk study of the catchment drainage system. This was due to physical factors such as the distance of dwellings from potential/desired monitoring points and lack of safe bank and approach areas close to settlements; personal factors such as unwillingness of residents to become involved with the programme due to other commitments or plans to leave the area; and socio-economic factors such as increased criminal activity noted in some areas close to towns and major highways.

There was little or no expertise or first-hand experience on which the researcher could draw in the field of sub-catchment scale direct manual SS sampling in the South African context, beyond the small programme undertaken by van der Waal (2015). This led to a "trial and error" approach to solving the practical challenges presented by programme design and implementation. Techniques and processes for sampling and analysis were often adapted from those developed for use in other countries at a much larger scale and a more institutionalised level, for example those developed by the USGS (Horowitz 2013). Nevertheless, the design of a CT-based direct-sampling SS monitoring programme as envisioned in the first research objective and described in **Chapter 4** was successfully achieved.

## 7.3 The citizen technician-based approach

### *A win-win situation*

The CT-based sampling approach to flood-focused SS sampling that was designed, developed and implemented in terms of the first two objectives was innovative in that it employed local people residing close to sampling sites and opted for manual sampling when global approaches trend towards instrumentation (Ballantine 2015). By including local people in data-gathering activities, project budget could be focussed on improving spatial coverage, allowing significantly more monitoring sites than otherwise would have been feasible for the same cost.

The design of the sampling programme incorporated attributes typical of (though not exclusive to) citizen science projects, such as the inclusion of non-scientists, the use of technology for data gathering and recording, and an emphasis on strict sampling protocols and quality control (Bonney et al. 2009). On the other hand, it did not engage with certain aspects of public involvement which Silvertown (2009) argued provide some of the key benefits to participants in such projects. These aspects include co-construction of problem statements, knowledge-sharing and ownership of the project by the participants for long-term information and problem-solving benefit (Kongo et al. 2010). Nevertheless, the CT-based approach could be described as a win-win situation for both the project team and the CTs.

The "win" for the project team was in the form of achieving the spatial and temporal SS data it required at an acceptable confidence level, as noted in **Chapters 6.8** and **6.9** and discussed in more detail later in this chapter. The "win" for the CTs was in the form of payment and work experience gained close to home.

The option of regularly volunteering substantial periods of time to non-essential activities is not available to the majority of people living in the Tsitsa catchment (**Chapter 3.3**). Citizen science, as widely embraced in the UK, USA, and in Europe, has a long tradition of volunteerism in return for somewhat altruistic and intangible personal rewards (Roy et al 2012). This model is inappropriate for the sustained engagement of rural-dwelling South Africans in data collection activities. Arguably, the opposite is true: a tangible reward is required in return for effort made, and any opportunities to provide employment and contribute to poverty alleviation, particularly in resource-poor and under-developed areas, should be actively grasped by funding agencies. This is not to ignore the benefits provided by citizen involvement in collaborative and co-created projects (e.g. Kongo et al. 2010), but to highlight that this was a *contributory* project, not a collaborative or co-created project as described in **Chapter 2.5**.

The contribution (i.e. monitoring activities) of the CTs constituted *work*, which they were formally contracted and remunerated to undertake. This concept was intrinsic to the design of the monitoring programme. The research team made the assumptions that without the incentive of payment for services the sampling protocols were unlikely to be adhered to, and the programme could not then be expected to provide data of the required confidence level. Quality control and compliance, whilst supported by the ODK platform and smartphone technology (Anokwa et al. 2009), could not have been effectively managed in the absence of a formal agreement which included remuneration for sampling. For example, very few people would willingly *volunteer* to repeatedly spend an entire cold, windy, wet day taking water samples from an exposed riverbank, knowing that their household tasks were neglected, or that they could at least have been warm and dry indoors, in return for nothing other than gratitude and a sense of contributing to the greater good. In contrast to the researchers, (or for example, to the "amateur" or citizen scientist ornithologists/botanists/astronomers described by Silvertown (2009) who extend their hobby interest to a research activity), the CTs had no vested interest in the project beyond the earning opportunity it represented. Tangible benefits received by the CTs included valuable work experience and capacity-building, in an area where such opportunities are scarce. Approximately R 100 000 (~$ 7 300, ~£ 5 400) was paid in total to the eleven CTs over the six-month assessment period. Most of this money was likely to have been spent inside the project area, thus boosting the local economy. Young adults who had initially stated their intention to leave the area remained in their communities to work as CTs, thus maintaining family structures in an area where the outflow of young job-seekers is the norm. Anecdotally, payments were used to educate children, extend houses, purchase household appliances, and start entrepreneurial activities such as catering, and clothing/fabric sales. Awareness of the links between rivers, their catchments, and weather conditions was raised, evidenced by curiosity on the part of the CTs and deductions/observations made conversationally, even though this knowledge was difficult for individuals to relate to the effects of the typically communal land use practices contributing to SS loads and yields.

### *Administration and management*

The training and ongoing input required to manage the administration and logistics associated with the manual sampling programme was significant and was not wholly anticipated, particularly once the identification, recruitment and training phases of the project described in **Chapter 4.4** had been concluded. The field administrator who took over the responsibility of the day-to-day administration and management of the CT "team" from the researcher typically logged 80 – 100 hours per month. This requirement provided an additional employment and capacity-building opportunity for a "non-scientist" which, together with the CTs and laboratory personnel, should be included in the planning and budget of any manual SS sampling programme.

Concurrent ground-truthing of the eleven sites flagged during the desk study, and identifying potential local CTs required a ten day field visit. Initial training and contracting required a further day per CT, and was an intensive and tiring process for all parties given the unfamiliar concepts, equipment and protocols that were introduced and had to be mastered in one session by the CTs. Further, it was not always possible to select a candidate who showed aptitude for the required tasks. Frequently there was little or no choice of candidate CTs, for example if there were few people living in the area or if the person had been selected by the local traditional leadership or by a local landowner. Whilst not occurring within the reporting period, this lack of aptitude or commitment later led to the loss of some CTs with the identification and training of their replacements adding to the administrative load.

Once the CTs were trained and sampling was underway, compliance checking and quality control was continuous via the ODK platform. As the CTs worked through the challenges presented by their tasks, mistakes and misconceptions emerged and were corrected (**Chapter 4.4**), with “top-up” training taking place during subsequent field visits (Bannatyne et al. 2017). Quality control and compliance checking, handling payments, and undertaking field visits required substantial and sustained input throughout the project.

## 7.4 Laboratory protocols

The laboratory process designed and implemented in terms of the third objective and described in **Chapter 4.6** was based on simple equipment and straightforward procedures. It was intended as a “garage” method for bulk SSC analysis that could be relatively cheaply set up in any clean, stable environment and undertaken by non-technical personnel to produce acceptable results. Staffed full time by one laboratory assistant and supplemented occasionally by the researcher and field administrator, the laboratory process coped with the high number of samples received (2 055 in the reporting period and >16 000 to date) and produced acceptable SSC data as noted in **Chapters 6.8** and **6.9** and described in more detail in the following sections of this chapter.

## 7.5 Efficiency and effectiveness

### *Climate and hydrological factors*

The assessment of efficiency and effectiveness was required in terms of the fifth and sixth research outcomes. From observations of CT activities throughout the reporting period, the main constraint on sampling efficiency and effectiveness was expected to have been the performance of the individual CTs, probably as a result of their nature and circumstances. As described in **Chapters 5** and **6,** late afternoon thunderstorms causing overnight water rises and peaks were in fact the primary constraint on CT efficiency and effectiveness, due to the ban on overnight sampling for safety reasons. In another catchment where hydrological responses were more predictable and/or attenuated, this constraint would have had less impact on the CT-based SS sampling method. Instruments such as monitoring probes, or automated pump/rising stage samplers would by contrast have provided 24 hour data coverage with no loss of overnight efficiency or effectiveness (Wren et al. 2000), but as discussed in **Chapter 2.4** would likely have been subject to loss through damage and vandalism, and limited due to expense.

### *Individual performance factors*

Individual CT performance imposed a secondary constraint on sampling efficiency and effectiveness. This included a range of factors that would have been completely avoided if an instrumented or even researcher-based approach had been feasible. The performance of the individual CTs was influenced by their motivation, compliance, and commitment to undertaking the required tasks, as well as their physical ability and intellectual aptitude to do so.

Considerations that may have impacted efficiency and effectiveness include the fitness, age and gender of the potential CT with reference to the distance and steepness of the walk to their sampling site. As already noted in **Chapter 6.2**, community and family obligations and events as well as personality also affected CT performance, and therefore by extension sampling efficiency and effectiveness.

Illustratively, the older housewife living close to the Tsitsana rarely missed a baseline sample, but she either did not observe or could not (due to other commitments) respond to as many rises in water level and flood sampling opportunities as the younger, more independent man living close to the Gqukunqa. Her sampling efficiency was high, but her sampling effectiveness was lower as a result. Conversely, the Gqukunqa CT found the twice-daily routine irksome and frequently left several days of low-flow unsampled, leading to very poor sampling efficiency. He was however highly motivated to earn money and focused his efforts on the sampling of flood flows and achieved more effective data for the Gqukunqa than his apparently more reliable counterpart on the Tsitsana.

### *Appropriate technology*

Appropriate technology was found to be key to the success of the sampling programme. When basic equipment broke, the CTs were able and willing to repair and/or replace these items and thereby avoid loss of efficiency and effectiveness (and loss of earnings).

Ready communication via the smartphones allowed support to be given quickly when challenges arose, and also allowed daily monitoring of activities and river conditions from the research base (as described in **Chapter 4)** in support of sampling protocol and data quality control. Incidents such as leaking clarity tubes and phone malfunctions, or shortages of supplies such as sample jars were quickly reported and the items were replaced during the next monthly field visit. Mobile phone shops are ubiquitous in even the smallest South African towns, allowing charger and battery repair/replacements to be done easily and quickly. Because of the waterproof pouches, no phones were lost due to moisture or submersion, and surprisingly few were otherwise broken, misused, or stolen, although particular individuals seemed more prone to these occurrences than others. The introduction of power-banks solved a general problem of incomplete (<20 samples) flood sample series due to flat phone batteries.

### *Socio-economic and cultural factors*

With experience gained over time, and by including strategies such as the use of interpreters, the training of stand-ins, and the withholding of payment for persistent sampling non-compliance and equipment loss/misuse, many situations that were likely to impact sampling efficiency and effectiveness due to the human factor in the CT-based SS sampling approach were pre-empted or overcome. This was not always the case, however, and although the socio-economic and cultural influences on and benefits arising from the CT-based approach are not the focus of this thesis, they nevertheless had impacts on sampling efficiency and effectiveness (Bannatyne et al. 2017).

An example of cultural impact on sampling efficiency and effectiveness in the South African context was provided by the seasonal occurrence of the traditional initiation period. In June/July and in December it is customary in the Eastern Cape, as in many other areas of South Africa, for young men to be secluded from their communities at initiation schools during their traditional rite of passage into adulthood. Speaking anecdotally of the eleven CTs, it was found that this impacted many of them, even though none was an initiate. Two CTs were absent for several days while they sponsored and mentored family members. A CT who had used her payments to expand her catering business missed a number of sampling opportunities due to her responsibility to provide food to initiates at a school located on her premises. Another CT was temporarily unable to sample at her usual sampling site due to the placing of an initiation hut on the bank opposite. These cultural factors are specific to the area, but it is likely that local traditions and customs (which could be largely ignored in the design of an instrumented programme) may need to be accommodated in the design of a CT-based SS sampling programme in other areas/countries.

What worked well in the Tsitsa River catchment may, due to societal factors, work less well another area. Using the experience gained in the Tsitsa catchment, a more detailed CT-based sampling programme was subsequently established in the nearby Inxu River catchment. Anecdotally, far more disruptions to sampling occurred than had been experienced in the Tsitsa River catchment. These included long absences, non-compliance, and CTs leaving the area altogether at short notice. It emerged in conversation with residents that a number of socio-economic factors particular to the Inxu River catchment may have contributed to the difficulties encountered. These included the proximity to Mthatha, Qumbu and other towns, the local traditional leader's stance on youth development whereby he actively sought training opportunities and jobs for youngsters in the nearby towns, and also a prolonged and at times violent period of recent political and social upheaval in the area which had led to local instabilities and depopulation. These factors all impacted much more on the efficiency and effectiveness of sampling in the Inxu River catchment than in the Tsitsa River catchment.

Community engagement should therefore be undertaken well ahead of establishment of a CT-based network, in order to inform the researcher of the local societal factors which may have a bearing on the sampling programme's long-term success. Again, this requires time and effort to for example meet with members of local traditional authority structures and community-based organisations, as well as with individuals. This engagement could not be completely avoided if implementing an instrumented approach in a communal area, but might nevertheless be much reduced.

## 7.6 Proficiency and precision

The assessment of proficiency was required by the sixth research objective and was reported in **Chapters 4.6** and **6.8.**

Some potential data from the samples collected by the CTs was lost during laboratory processing. This minor loss of proficiency occurred in the laboratory due to poor sample handling, process flow errors leading to incomplete sample analysis, or data recording errors. The laboratory was located at the research base at Rhodes University whilst the study area was 560 km distant. Thus, actions required to improve proficiency were easier to implement in the laboratory than if major sample loss or spoilage had occurred during sampling, e.g. due to mis-labelling or uncontrolled algae growth.

There is a relationship between the cost of sampling and analysis, and the accuracy of the resulting data (Horowitz 2013). There is also a relationship between acceptable error and the purpose for which SSC data are intended (Horowitz 2013). Illustratively, sampling and laboratory costs would be high, and levels of acceptable error would be low where for example SSC analyses were regulatory-driven for the purpose of establishing sediment-related water quality data. Nevertheless, even "world class" SS monitoring programmes conducted by agencies such as the USGS accept error margins in the region of 20% for estimated SS loads and yields (Horowitz 2013).

Whilst total sampling costs (including jar, transport, etc.) in the Tsitsa River catchment were extremely low at < R 200 (or $ 15.00) per sample compared with costs quoted by Horowitz (2013) of R 54 862 (or $ 4 000) per sample, it was nevertheless the intention that errors would remain acceptably low, and data confidence high.

The analysis of the precision of the SS data as required by the sixth research objective was undertaken using triple samples and described in **Chapter 6.8.** It showed that for the medium and high SS samples that were the target of the sampling programme, CVs of turbidity and SS values within the triple sets were generally low. The precision of the CT-based direct SS sampling programme as a whole was therefore good. The main errors occurred in the low SS samples that would be less important in the later determination of SS loads and yields. Furthermore, the absolute errors in low SS samples led to much higher CVs than the same absolute error in a high SS sample.

Where loss of precision occurred, it could be traced to the laboratory process rather than sampling activities (i.e. high CV of SS coupled with low CV of turbidity). Again, the potential for identifying and rectifying problems in e.g. laboratory handling, jar drying, transcription or weighing activities was greater than if inconsistencies in sampling activities had been indicated as the source of imprecision. As noted in **Chapter 5.6**, imprecision that may have resulted from the use of different drying ovens have already been overcome with the purchase of a dedicated oven.

### *Appropriate technology*

The assessment of precision described in **Chapter 6.8** and undertaken in terms of the sixth objective showed that the results from samples taken using the specifically-designed isokinetic pole-and-jar SS sampler were of acceptable precision for the targeted medium and high sediment level samples. Predictably, given the small size of the sample vessel, they were less accurate for low sediment samples.

## 7.7 Implications for the design of citizen technician based suspended sediment sampling programmes

### *Sampling efficiency and effectiveness*

The findings of this study have implications both for the spatial design of CT-based sampling programmes, and for the application of the CT-based approach to other areas in terms of ensuring sampling efficiency and effectiveness. Cost is an important criterion for sampling programme design, in turn largely shaped by data requirements: colloquially, sampling programme managers look for "bang for their buck", i.e. the best quality data for the resources committed to the task.

The findings of the efficiency and effectiveness analysis described in **Chapters 5** and **6** pointed to the fact that in flashy (i.e. small and/or degraded) catchments consistent baseline sampling, whilst commendable, was less effective than responsive and reactive flood sampling in terms of providing representative data. However, successfully monitoring the desired high flow events in such catchments was challenging.

From a design perspective, this could influence not only the positioning of monitoring sites (favouring larger channels), but perhaps also the type of person engaged as a CT vis a vis channel size, as noted earlier in **Section 7.5** of this chapter. The availability of CTs at a particular sampling site was completely limited by their place of residence, but if a choice was possible it could be noted that the nature of the Gqukunqa CT was well suited to sampling the nearby small flashy channel, whilst if the Tsitsana CT had instead lived close to a main channel site rather than a tributary she would likely, given her nature and responsibilities, have sampled both efficiently and more effectively through the longer floods.

The hydrological response of the catchment as a whole, in tandem with the more representative data collected on the main stem of the Tsitsa, points to the fact that depending on the research question, limited resources might be better spent on larger channels. Both the “less consistent” (Qulungashe) and the “more consistent” (Mbelembushe) CTs on the main stem of the Tsitsa River achieved more representative data than either of the tributary CTs. Flood sampling effectively improved data coverage of floods at most sites, but SSC results from smaller, flashier channels, whilst still indicative of SS loads and yields, are very likely to be less representative of overall SS conditions and therefore to have a lower confidence level than those from larger and/or less flashy channels.

Understanding the relationships between SS and discharge in general (Petts, Foster 1985, Knighton 1984), coupled with observations of catchment-specific historical hydrology, catchment characteristics, and likely responses to seasonal and shorter-interval precipitation events (**Chapter 3.5**) thus remains a foundational component of SS sampling design, which can then be adapted to accommodate the CT-based sampling approach based on the findings of this study.

In the scenario of a small, steep, well-connected, degraded, highly flashy catchment, the CT-based approach may fail to provide representative SSC data despite the proximity of sampling sites to dwellings, due to event durations of minutes to hours which are more likely than not to be missed altogether or sampled only on the recession limb of the hydrograph (Gordon et al. 2004). Conversely, in the scenario of a large, healthy catchment, responses to seasonal precipitation are likely to be more gradual, and attenuated by e.g. wetlands, gentle slopes, well-developed soils, and good vegetation cover. Due to far longer event durations, flood sampling on the main stem could even be abandoned in favour of sub-daily timestep routine “baseline” sampling, once the first wet-season rise has occurred, with little or no loss of data confidence. This would allow the study to provide improved spatial data e.g. by including more tributaries, or temporal data e.g. by extending the study period to include more wet seasons and therefore improve data representivity as recommended by Horowitz (2013), or to improve data confidence by locating more sites on the main stem of the river.

Adopting a CT-based approach to SS sampling does not preclude the use of supplementary fixed instrumentation such as probes or rising stage samplers where practical and possible (Kuhnle 2013). A “hybrid” approach in which the drawbacks of one method were compensated by the advantages of another would, where possible, represent an ideal situation. Illustratively, it was the aim of the SS sampling programme in the Tsitsa catchment to compare at catchment scale the data generated by the CT sampling against that generated by a LISST-ABS probe, and it is detrimental to data confidence that this independent benchmarking could not be done due to the loss of the probe.

### *Laboratory proficiency and precision of data*

The laboratory equipment used and the processes developed were basic and intended to be replicable in any clean, dry, spacious environment with reliable electricity and water supply, for example a house or warehouse. Certain aspects would require attention in order to achieve acceptable levels of proficiency and data precision, but all aspects of laboratory set-up and functioning would be relatively easy to achieve regardless of the area to which the SS programme was being adapted.

A stable electricity supply for powering laboratory balances, clean water for washing jars to a high standard, and a dust-free, and possibly moisture-controlled working environment (i.e. air-conditioning in humid climates) would be key requirements for data precision. A stable enclosed housing for the balances would also be essential. Sufficient bench space (e.g. trestle tables) would be required to accommodate the batches of samples moving between the various stages of the SSC analysis, thus preventing process discrepancies that could lead to loss of potential data and therefore laboratory proficiency. In practical terms a storage area for jars and crates arriving from and returning to the field would be needed.

Laboratory equipment costs were relatively low, with laboratory balances and a drying oven representing the major capital items. Non-technical staff with little or no previous laboratory experience were trained to undertake the required processes and record data to an acceptable level of proficiency and precision. A person who had achieved a school leaving certificate and perhaps had had some accounting or administrative experience would likely possess the aptitude and necessary attention to detail required for the task. Taken together, this meant that laboratory set up and running costs would be relatively low. The laboratory could be located where rented premises and staff could easily be found and/or accommodated e.g. in a small town or on a farm near to the research catchment.

Regular oversight and quality control (e.g. by the researcher or a project manager) would be crucial to ensure data precision, particularly since the laboratory processes were highlighted during assessment (**Chapters 5** and **6**) as the main source of such losses. Checking sample process flows, ensuring standards of weighing accuracy (including calibration), double checking data recording and transcription would be amongst the necessary quality control actions.

### *Flexibility*

The CT approach can be contrasted with the example of the LISST-ABS acoustic SSC probe, which as noted was destroyed by lightning three weeks after installation. 18 months passed with no data whatsoever collected from the probe, due to waiting for low water to retrieve the broken item, shipping it to the manufacturer in the USA for diagnostics and repair, bench-testing it on return only to reveal persistent errors, and ultimately returning the probe to the manufacturers for a second time and an unspecified period.

If the probe had been the only means of recording SSC in the Tsitsa catchment, data from two wet seasons would have been completely lost. Conversely, the spatial design of the CT-based programme illustrated in **Figure 12** and based on the approach of Collins and Walling (2004) allowed the relative SS contribution of any temporarily unmonitored site to still be inferred from an analysis of SS results from other up- and/or downstream monitoring sites.

### *Adaptability*

The CT-based approach to direct SS sampling can be adapted to other environmental monitoring applications, particularly in the case of smartphone-based GPS location recording in combination with regular fixed point photography and standardised forms. CTs can use basic equipment such as gauge-plates, sampling vessels and preservatives, and rulers/scale objects in combination with a smartphone to monitor e.g. water levels, insect infestations, vegetation growth, alien invader tree species clearance or infestation, gully development, the impact of soil conservation interventions such as soil sausages and silt fencing, etc., as well as ad hoc events such as fires, flash floods, and extreme weather. If such monitoring activities had been required at or near their SS site, the CTs could have been trained, had the relevant forms uploaded to their smartphone, and thus been given a further opportunity for income and capacity building.

A LISST-ABS probe, on the other hand, can perform only the one function it was manufactured for, with the money typically exiting the country to an overseas manufacturer.

## 7.8 Limitations on the evaluation of the citizen technician-based approach

Some constraints on the CT-based SS sampling approach have been mentioned in the preceding sections of this chapter. There were further limitations on the evaluation of the approach (**Chapters 5** and **6**) which need to be discussed as they may have impacted on the results of the evaluation.

### *Sample size*

Only four of the eleven SS sampling sites and CTs were included in the evaluation of the CT-based approach. This limitation was due to insufficient time being available to process all the data required to include all the sites in the evaluation. The somewhat arbitrary choice of sites, whilst based on knowledge of the sub-catchment and hydrological conditions, and observations of the CTs over the study period, may have led to unrepresentative findings.

### *Time period*

The period of the evaluation was limited to the six-month period including and immediately following monitoring programme inception (**Chapter 4.4** and **4.5**). This has implications for the results of the efficiency, effectiveness, laboratory proficiency and data precision analyses.

During the assessment period, the CTs and laboratory assistant were inexperienced, and the laboratory processes were still being established and piloted. As noted, CT training and correction of procedural errors continued throughout this period, although no changes were made to the sampling protocol.

In the laboratory, although the basic process flow remained largely unchanged, procedural adjustments were made, e.g. sample settling times and handling protocols, the method of removing water from sample jars, ways of packing the drying ovens, changes in sample drying times, changing from air to oven drying of clean jars, and so forth. The laboratory assistant was a graduate student but without extensive laboratory experience. Thus, inconsistencies in laboratory procedures were likely to have led to inconsistencies in the resulting data, but as noted in **Chapter 6,** the effects of the resulting errors were minimal on the target high SSC samples.

The procedure of collecting “triple” samples (**Chapters 4.3** and **6**) contributed to the assessment of precision, but a definitive assessment of accuracy, for example in the form of analysing measured SS samples, was lacking from laboratory quality control protocols.

### *Data*

A wealth of data was collected during the reporting period (and indeed continues to be collected), which was not included in the evaluation of the CT-based approach to SS sampling, either due to time constraints, or due to being beyond the ambit of this study:

- Only water levels, not discharge, were determined.
- SSC was determined (except for “triple” samples) only for visibly high SS samples.
- No SS loads or yields were calculated.

- Clarity tube data were largely ignored in the evaluation of the CT-based approach to SS sampling.
- No particle size analysis was undertaken using the sediment samples retained from the water samples.
- Rainfall data were not used, and the full potential for preliminary flow and sediment routing studies using photographs in combination with rainfall data remains unrealised.
- No remote sensing or GIS work was carried out (in conjunction with rainfall data) to link e.g. catchment characteristics, seasonal vegetation change, or land use change to resulting SS dynamics

## 7.9 Recommendations

### *Data collection*

The CT-based direct SS sampling programme that has been established in the Tsitsa catchment should continue to be funded and to add to the existing SS database. Not only will this enhance data confidence per se, but would also hopefully offer the opportunity to collect data through wet seasons more representative of high rainfall periods.

### *Re-evaluation of the citizen technician-based approach*

The CT-based approach to direct SS sampling should be re-evaluated using the same criteria, possibly including all sampling sites and CTs, and certainly over a different and longer time period more representative of established operating conditions.

### *Quality control*

The ad hoc analysis of samples containing a pre-determined mass of water and sediment should be introduced into the laboratory process flow (in addition to the analysis of “triple” samples) to improve the precision of the laboratory SSC analysis. More frequent balance calibrations and process control checks should be made to improve laboratory proficiency and data precision.

### *Further research*

Further research studies should make use of the available data collected since December 2015 to calibrate existing simulations and estimations of SS loads and yields in the Tsitsa catchment, and to investigate, amongst other things:

- The relative contributions of sub-catchments to SS loads and yields at the proposed Ntabelanga and Lalini Dams;
- The relationships between clarity tube readings, measured turbidity, particle size, and SSC;

- The relationships between ecological infrastructure degradation, catchment characteristics such as vegetation, connectivity, etc., rainfall, and sediment dynamics in the Tsitsa catchment;
- The impact of rehabilitation scenarios on SS dynamics in the Tsitsa catchment;
- The socio-economic and cultural impacts and benefits of the CT-based approach

# 8 CONCLUSION

The dearth of suspended sediment data at catchment (Le Roux 2015), national (Le Roux 2008) and global (Kuhnle 2013) scale is widely acknowledged: There is no argument against the benefit of collecting suspended sediment data. It is, as noted by Wren et al (2000) the manner of collecting such data that presents challenges in terms of cost and data quality.

There is no “one-size-fits-all” approach to collecting SS data to meet these challenges. All sampling and monitoring approaches have their advantages and drawbacks, which should be gauged in terms of not only the purpose and scope of the proposed study, but also with reference to local conditions (Wren et al 2000; Kuhnle 2013).

The citizen technician-based approach to direct suspended sediment sampling that was developed for the Tsitsa River catchment allowed local people living near channels in remote rural areas to be gainfully employed as citizen technicians. Using basic sampling equipment and smartphone-based technology, this approach provided acceptable data on which suspended sediment load and yield estimations can confidently be made. Forthcoming analysis of the SSC data generated by this sampling programme will allow the determination of the relative contributions of the sub-catchments to overall SS load and yield at the sites of the Ntabelanga and Lalini Dam walls as an aid to prioritising catchment rehabilitation interventions intended to sustain rural livelihoods and enhance soil retention. Modelled SS loads and yields for the Tsitsa River catchment can now be verified, and models calibrated, using the SSC data collected using this method.

Further, the citizen technician-based approach can be applied to suspended sediment sampling at a range of scales, and can easily be adapted to other environmental monitoring activities not only in the Tsitsa River catchment but also throughout South and southern Africa and other developing regions.

# REFERENCES

Ambers, R.K. 2001, "Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield", *Journal of Hydrology,* vol. 244, no. 3, pp. 181-200.

Anokwa, Y., Hartung, C., Brunette, W., Borriello, G. & Lerer, A. 2009, "Open source data collection in the developing world", *Computer,* vol. 42, no. 10, pp. 97-99.

Ballantine, D., Hughes, A. & Davies-Colley, R. 2015, "Mutual relationships of suspended sediment, turbidity and visual clarity in New Zealand rivers", *Proceedings of the International Association of Hydrological Sciences,* vol. 367, pp. 265.

Bannatyne, L., Rowntree, K., van der Waal, B. & Nyamela, N. 2017, "Design and implementation of a citizen technician–based suspended sediment monitoring network: Lessons from the Tsitsa River catchment, South Africa", *Water SA,* vol. 43, no. 3, pp. 365-377.

Beven, K.J. & Carling, P. 1989, *Floods: hydrological, sedimentological and geomorphological implications.* John Wiley and Sons Ltd.

BKS (Pty) Ltd 2010, *DWA Water Resource Study in Support of the ASGISA-EC Mzimvubu Development Project Summary Report*, Unpublished.

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K.V. & Shirk, J. 2009, "Citizen science: a developing tool for expanding science knowledge and scientific literacy", *Bioscience,* vol. 59, no. 11, pp. 977-984.

Calmeyer, T. & Muruven, L. 2015, *Environmental Impact Assessment for the Imzimvubu Water Project*, Department of Water and Sanitation, Pretoria.

Citipedia.info 2017, 01 September 2017-last update*, Sunrise, sunset, dusk and dawn for the year - Maclear* [Homepage of Citipedia], [Online]. Available: http://www.citipedia.info/city/sunriseandsunset/South+Africa_Joe+Gqabi+District+Municipality_Maclear_id_980798 [2017, June 03].

Cohen, S., Kettner, A.J. & Syvitski, J.P. 2014, "Global suspended sediment and water discharge dynamics between 1960 and 2010: Continental trends and intra-basin sensitivity", *Global and Planetary Change,* vol. 115, pp. 44-58.

Cohn, J.P. 2008, "Citizen science: Can volunteers do real research?", *Bioscience,* vol. 58, no. 3, pp. 192-197.

Collins, A. & Walling, D. 2004, "Documenting catchment suspended sediment sources: problems, approaches and prospects", *Progress in Physical Geography,* vol. 28, no. 2, pp. 159-196.

Conrad, C.C. & Hilchey, K.G. 2011, "A review of citizen science and community-based environmental monitoring: issues and opportunities", *Environmental monitoring and assessment,* vol. 176, no. 1-4, pp. 273-291.

Crall, A.W., Newman, G.J., Stohlgren, T.J., Holfelder, K.A., Graham, J. & Waller, D.M. 2011, "Assessing citizen science data quality: an invasive species case study", *Conservation Letters,* vol. 4, no. 6, pp. 433-442.

De Vente, J. & Poesen, J. 2005, "Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models", *Earth-Science Reviews,* vol. 71, no. 1, pp. 95-125.

Dickinson, J.L., Shirk, J., Bonter, D., Bonney, R., Crain, R.L., Martin, J., Phillips, T. & Purcell, K. 2012, "The current state of citizen science as a tool for ecological research and public engagement", *Frontiers in Ecology and the Environment,* vol. 10, no. 6, pp. 291-297.

Dillon, J., Stevenson, R.B. & Wals, A.E. 2016, "Special Section: Moving from Citizen to Civic Science to Address Wicked Conservation Problems", *Conservation Biology,* vol. 30, no. 3, pp. -.

Dollar, E.S. 2004, "Fluvial geomorphology", *Progress in Physical Geography,* vol. 28, no. 3, pp. 405-450.

Eutech Instruments 2015, 29 January 2015, 03:56:55-last update*, Eutech Instruments Products By Parameter* [Homepage of Thermo Fischer Scientific Inc], [Online]. Available: https://www.eutechinst.com/pdt-para-turbidity-tn100.html [2017, 11/23].

Fabricius, C., Biggs, H. & Powell, M. 2016, *Ntabelanga and Lalini Ecological Infrastructure Project Research Investment Strategy*, Department of Environmental Affairs, Pretoria South Africa.

Fekete, B.M. & Vörösmarty, C.J. 2002, "The current status of global river discharge monitoring and potential new technologies complementing traditional discharge measurements", *Predictions in Ungauged Basins: PUB kick-off (Proceedings of the PUB kick-off meeting held in Brasilia, 20–22 November 2002). IAHS Publication*.

Ferguson, R. 1981, "Channel form and channel changes", *British rivers,* vol. 90, pp. 125.

Foster, I.D., Dearing, J.A., Grew, R. & Orend, K. 1990, "The sedimentary data base: an appraisal of lake and reservoir sediment based studies of sediment yield.", *The sedimentary data base: an appraisal of lake and reservoir sediment based studies of sediment yield.,* , no. 189, pp. 19-43.

Foster, I.D. & Rowntree, K.M. 2012, "Sediment yield changes in the semi-arid Karoo: a palaeoenvironmental reconstruction of sediments accumulating in Cranemere Reservoir, Eastern Cape, South Africa", *Zeitschrift für Geomorphologie, Supplementary Issues,* vol. 56, no. 3, pp. 131-146.

Fryirs, K. 2013, "(Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem", *Earth Surface Processes and Landforms,* vol. 38, no. 1, pp. 30-46.

Gordon, A.K., Niedballa, J. & Palmer, G.C. 2013, *Sediment as a Physical Water Quality Stressor on Macro-invertebrates: A Contribution to the Development of a Water Quality Guideline for Suspended Solids*, Water Research Commission, Pretoria.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. & Nathan, R.J. 2004, *Stream hydrology: an introduction for ecologists,* John Wiley & Sons.

Gregory, K.J. & Walling, D.E. 1974, *Fluvial processes in instrumented watersheds,* Institute of British Geographers.

Grenfell, S. & Ellery, W. 2009, "Hydrology, sediment transport dynamics and geomorphology of a variable flow river: the Mfolozi River, South Africa", *Water SA,* vol. 35, no. 3, pp. 271-282.

Harvard Humanitarian Initiative 2016, 31/07/2016-last update*, KoBo Toolbox* [Homepage of Harvard Humanitarian Initiative], [Online]. Available: http://www.kobotoolbox.org/ [2016, 08/03].

Harvey, A.M. 2002, "Effective timescales of coupling within fluvial systems", *Geomorphology,* vol. 44, no. 3, pp. 175-201.

Heritage, G. & van Niekerk, A. 1995, "Drought conditions and sediment transport in the Sabie River", *Koedoe,* vol. 38, no. 2, pp. 1-9.

Hicks, D.M. & Gomez, B. 2003, "Sediment transport", *Tools in Fluvial Geomorphology,* , pp. 425-461.

Hicks, D. & Basher, L. 2008, "The signature of an extreme erosion event on suspended sediment loads: Motueka River catchment, South Island, New Zealand", *IAHS-AISH publication,* , pp. 184-191.

Hodgson, D.L. 2017, *Demographic Change in the Upper Tsitsa Catchment: The Integration of Census and Land Cover Data for 2001 and 2011.*, Master of Science edn, Rhodes University, Grahamstown, South Africa.

Horowitz, A.J. 2010, "The use of instrumentally collected-composite samples to estimate the annual fluxes of suspended sediment and sediment-associated chemical constituents", *IAHS-AISH publication,* , pp. 273-281.

Horowitz, A.J. 2010, "A quarter century of declining suspended sediment fluxes in the Mississippi River and the effect of the 1993 flood", *Hydrological Processes,* vol. 24, no. 1, pp. 13-34.

Horowitz, A.J. 2013, "A review of selected inorganic surface water quality-monitoring practices: are we really measuring what we think, and if so, are we doing it right?", *Environmental science & technology,* vol. 47, no. 6, pp. 2471-2486.

Horowitz, A.J., Rinella, F.A., Lamothe, P., Miller, T.L., Edwards, T.K., Roche, R.L. & Rickert, D.A. 1990, "Variations in suspended sediment and associated trace element concentrations in selected riverine cross sections", *Environmental science & technology,* vol. 24, no. 9, pp. 1313-1320.

Horton, R.E. 1945, "Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology", *Geological society of America bulletin,* vol. 56, no. 3, pp. 275-370.

Hyslop, N.P. & White, W.H. 2009, "Estimating precision using duplicate measurements", *Journal of the Air & Waste Management Association,* vol. 59, no. 9, pp. 1032-1039.

Iliso Consulting (Pty) Ltd 2015, *Environmental Impact Assessment for the Mzimvubu Water Project: Environmental Impact Assessment Report*, Department of Water and Sanitation, Pretoria.

Kinnell, P. 2010, "Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review", *Journal of Hydrology,* vol. 385, no. 1, pp. 384-397.

Knighton, D. 1984, "Fluvial forms and processes. Edward Arnold", *Inc., New York,* .

Kongo, V., Kosgei, J., Jewitt, G. & Lorentz, S. 2010, "Establishment of a catchment monitoring network through a participatory approach in a rural community in South Africa", *Hydrology and Earth System Sciences,* vol. 14, no. 12, pp. 2507-2525.

Kuhnle, R. 2013, "9.9 Suspended Load" in *Treatise on Geomorphology*, ed. John F. Schroder, Academic Press, San Diego, pp. 124-136.

Le Roux, J. & Weepener, H. 2015, *Sediment Yield Modelling in the Umzimvubu Catchment*, Water Research Commission, Pretoria.

Le Roux, J.J., Mashimbye, Z.E., Weepener, H.L., Newby, T.S. & Pretorius, D.J. 2008a, *Erosion Status of Priority Tertiary Catchment Areas Identified by the Soil Protection Strategy of the Department of Agriculture*, ISCW Report No. GW/A/2008, Pretoria.

Le Roux, J., Morgenthal, T., Malherbe, J., Pretorius, D. & Sumner, P. 2008b, "Water erosion prediction at a national scale for South Africa", *Water SA,* vol. 34, no. 3, pp. 305-314.

Le Roux, J.J. & Sumner, P. 2012, "Factors controlling gully development: comparing continuous and discontinuous gullies", *Land Degradation & Development,* vol. 23, no. 5, pp. 440-449.

Leopold, L.B. & Maddock, T. 1953, "The hydraulic geometry of stream channels and some physiographic implications", .

Lloyd, C. & Eley, G. 1952, "Graphical solution of probable soil loss formula for Northeastern Region", *J.Soil and Water Conserv,* vol. 7, no. 4, pp. 189-191.

Lubeck, M. 2015, 27 Jan 2015-last update, *Overview of Watershed and Channel Sedimentation* [Homepage of The University Corporation for Atmospheric Research], [Online]. Available: https://www.meted.ucar.edu/training_module.php?id=1123#.Vaoh-vmqsXq [2015, 07/18].

Madikizela, B.R., Dye, A.H. & O'Keeffe, J.H. 2001, *Water quality and faunal studies in the Umzimvubu catchment, Eastern Cape, with particular emphasis on species as indicators of environmental change,* Water Research Commission.

Madikizela, B. & Dye, A. 2003, "Community composition and distribution of macroinvertebrates in the Umzimvubu River, South Africa: a pre-impoundment study", *African journal of aquatic science,* vol. 28, no. 2, pp. 137-149.

McLennan, S.M. 1993, "Weathering and global denudation", *The Journal of geology,* vol. 101, no. 2, pp. 295-303.

Merritt, W.S., Letcher, R.A. & Jakeman, A.J. 2003, "A review of erosion and sediment transport models", *Environmental Modelling & Software,* vol. 18, no. 8, pp. 761-799.

Minkkinen, P. 1986, "Monitoring the precision of routine analyses by using duplicate determinations", *Analytica Chimica Acta,* vol. 191, pp. 369-376.

Moore, N.J. 2016, *Rainfall Erosivity in the Tsitsa Catchment, Eastern Cape, South Africa* , BSc (Hons) edn, Rhodes University, Grahamstown South Africa.

Morgan, R.P.C. 2009, *Soil erosion and conservation,* John Wiley & Sons.

Msadala, v., Gibson, L., Le roux, J., Rooseboom, A. & Basson, G.R. 2010, *Sediment Yield Prediction for South Africa: 2010 edition*, WRC, Pretoria.

Mucina, L. & Rutherford, M.C. 2006, *The vegetation of South Africa, Lesotho and Swaziland.* South African National Biodiversity Institute.

Owens, P. 2005, "Conceptual Models and Budgets for Sediment Management at the River Basin Scale (12 pp)", *Journal of Soils and Sediments,* vol. 5, no. 4, pp. 201-212.

Parsons, A.J., Wainwright, J., Brazier, R.E. & Powell, D.M. 2006, "Is sediment delivery a fallacy?", *Earth Surface Processes and Landforms,* vol. 31, no. 10, pp. 1325-1328.

Partridge, T., Dollar, E., Moolman, J. & Dollar, L. 2010, "The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists", *Transactions of the Royal Society of South Africa,* vol. 65, no. 1, pp. 1-47.

Petts, G. & Foster, I. 1985, *Rivers and landscape,* 1st edn, Univ. of Technology, Loughborough, Loughborough.

Porterfield, G. 1972, *Computation of fluvial-sediment discharge,* US Government Printing Office.

Ringwood, F. 2016, "Encouraging citizen science: laboratories & equipment", *Water&Sanitation Africa,* vol. 11, no. 5, pp. 32.

Robert, A. 2003, *River processes: an introduction to fluvial dynamics,* Arnold.

Rooseboom, A. & Lotriet, H. 1992, "The new sediment yield map for southern Africa", *Erosion and Sediment Transport Monitoring Programmes in River Basins: IAHS Publ,* vol. 210, pp. 527-538.

Rowntree, K.M., Wadeson, R.A. & O'Keeffe, J. 2000, "The development of a geomorphological classification system for the longitudinal zonation of South African rivers", *South African Geographical Journal,* vol. 82, no. 3, pp. 163-172.

Roy, H.E., Pocock, M.J., Preston, C.D., Roy, D.B., Savage, J., Tweddle, J. & Robinson, L. 2012, "Understanding citizen science and environmental monitoring: final report on behalf of UK Environmental Observation Framework", .

Sack, D. & Orme, A. 2013, "1.1 Introduction to the Foundations of Geomorphology", .

Schumm, S.A. 2005, *River variability and complexity,* Cambridge University Press.

Schumm, S.A. & Lichty, R.W. 1965, "Time, space, and causality in geomorphology", *American Journal of Science,* vol. 263, no. 2, pp. 110-119.

Sheppard, S.A. & Terveen, L. 2011, "Quality is a verb: The operationalization of data quality in a citizen science community", *Proceedings of the 7th International Symposium on Wikis and Open Collaboration*ACM, , pp. 29.

Silvertown, J. 2009, "A new dawn for citizen science", *Trends in ecology & evolution,* vol. 24, no. 9, pp. 467-471.

Slaymaker, O. 2003, "The sediment budget as conceptual framework and management tool" in *The Interactions between Sediments and Water* Springer, , pp. 71-82.

Strahler, A.N. 1952, "Dynamic basis of geomorphology", *Geological Society of America Bulletin,* vol. 63, no. 9, pp. 923-938.

Syvitski, J.P. & Milliman, J.D. 2007, "Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean", *The Journal of geology,* vol. 115, no. 1, pp. 1-19.

Thorndycraft, V., Benito, G. & Gregory, K. 2008, "Fluvial geomorphology: A perspective on current status and methods", *Geomorphology,* vol. 98, no. 1, pp. 2-12.

Trumbull, D.J., Bonney, R., Bascom, D. & Cabral, A. 2000, "Thinking scientifically during participation in a citizen-science project", *Science education,* vol. 84, no. 2, pp. 265-275.

Vallabh, P., Lotz-Sisitka, H., O'Donoghue, R. & Schudel, I. 2016, "Mapping epistemic cultures and learning potential of participants in citizen science projects", *Conservation Biology,* vol. 30, no. 3, pp. 540-549.

van der Waal, B.W. 2015, *Sediment Connectivity in the Upper Thina Catchment, Eastern Cape, South Africa*, Rhodes University.

Vercruysse, K., Grabowski, R.C. & Rickson, R. 2017, "Suspended sediment transport dynamics in rivers: multi-scale drivers of temporal variation", *Earth-Science Reviews,* .

Vim, I. 2004, "International vocabulary of basic and general terms in metrology (VIM)", *International Organization,* vol. 2004, pp. 09-14.

Walling, D. 1974, "Suspended sediment and solute yields from a small catchment prior to urbanization", *Fluvial processes in instrumented watersheds,* vol. 6, pp. 169-192.

Walling, D. 1983, "The sediment delivery problem", *Journal of hydrology,* vol. 65, no. 1, pp. 209-237.

Walling, D. 2005, "Tracing suspended sediment sources in catchments and river systems", *Science of the total environment,* vol. 344, no. 1, pp. 159-184.

Walling, D. & Collins, A. 2008, "The catchment sediment budget as a management tool", *Environmental Science & Policy,* vol. 11, no. 2, pp. 136-143.

Walling, D. & Fang, D. 2003, "Recent trends in the suspended sediment loads of the world's rivers", *Global and Planetary Change,* vol. 39, no. 1, pp. 111-126.

Whitelaw, G., Vaughan, H., Craig, B. & Atkinson, D. 2003, "Establishing the Canadian community monitoring network", *Environmental monitoring and assessment,* vol. 88, no. 1-3, pp. 409-418.

Williams, G.P. 1989, "Sediment concentration versus water discharge during single hydrologic events in rivers", *Journal of Hydrology,* vol. 111, no. 1, pp. 89-106.

Wischmeier, W.H. & Smith, D.D. 1978, "Predicting rainfall erosion losses-A guide to conservation planning.", *Predicting rainfall erosion losses-A guide to conservation planning,* U.S. Department of Agriculture, Agriculture. Handbook No. 537.

Wohl, E. 2014, "Time and the rivers flowing: Fluvial geomorphology since 1960", *Geomorphology,* vol. 216, pp. 263-282.

Wolman, M.G. 1977, "Changing needs and opportunities in the sediment field", *Water Resources Research,* vol. 13, no. 1, pp. 50-54.

Wolman, M.G. & Miller, J.P. 1960, "Magnitude and frequency of forces in geomorphic processes", *The Journal of geology,* , pp. 54-74.

Wood, P. 1977, "Controls of variation in suspended sediment concentration in the River Rother, West Sussex, England", *Sedimentology,* vol. 24, no. 3, pp. 437-445.

Wren, D., Barkdoll, B., Kuhnle, R. & Derrow, R. 2000, "Field techniques for suspended-sediment measurement", *Journal of Hydraulic Engineering,* vol. 126, no. 2, pp. 97-104.